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Light sterile neutrinos at $\nu$STORM: decoherence and CP violation
Neutrino properties from cosmology

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The interplay between cosmology and earth based experiments is crucial in order to pin down neutrino physics. Indeed cosmology can provide very tight, yet model dependent, constraints on some neutrino properties. Here we focus on the neutrino mass sum, reviewing the up to date current bounds and showing the results of our forecast of the sensitivity of future experiments. Finally, we discuss the case for sterile neutrinos, explaining how non standard sterile neutrino self-interactions can reconcile the oscillation anomalies with cosmology.

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1 Introduction

One of the cornerstone of particle cosmology is the possibility of constraining neutrino physics using cosmological data. The impact of neutrinos on cosmological observables has been widely studied in the literature [1, 2, 3, 4, 5]. However it is important to stress the complementarity between cosmological constraints and the results of neutrino experiments. Indeed, cosmology is sensitive only to the neutrino mass sum $M_\nu = \Sigma m_\nu$ and to the number of relativistic degrees of freedom $N_{\text{eff}}$. Therefore, the final answer to open questions such as the Dirac vs. Majorana nature, can come only from earth based neutrino experiments.

The remainder of the article is organized as follows: in Section 2 we review the current cosmological upper bounds on the neutrino mass sum and we present a forecast of the sensitivity of future CMB experiments and galaxy surveys. In Section 3 we discuss how the current constraints on the effective number of relativistic degrees of freedom do not leave room for sterile neutrinos in cosmology unless new physics comes into play. Finally, we draw our conclusions in Section 4.

2 Massive neutrinos

Massive neutrinos can be considered as a hot dark matter component because they are relativistic when they decouple from the thermal bath ($T \sim 1$ MeV). Cosmology can measure the hot dark matter density, which is related to the neutrino mass though the following formula:

$$\Omega_\nu h^2 = \frac{M_\nu}{93.14 \, \text{eV}}.$$  \hspace{1cm} (1)

The impact of massive neutrinos on the evolution of the universe is closely related to their mass, i.e. the time of their non relativistic transition: before that neutrinos behave as radiation, while after they represent an additional matter component. This time dependent phenomenology affects the constraints that can be derived from observables located at different redshift.

2.1 Current bounds

If neutrinos have an individual mass smaller than $\sim 0.6$ eV, they are still relativistic at the time of photon decoupling (last scattering surface, $z \sim 1100$). Therefore the Cosmic Microwave Background (CMB) is not the best probe to constrain the neutrino mass. Indeed, the background and perturbation effects of a non zero neutrino mass on the CMB temperature anisotropy power spectrum (TT) can be mimicked

*It has to be stressed that this formula does not account for distortions in the neutrino distribution.
by a variation of other cosmological parameters (see Section 2 for a discussion of the degeneracy problem). Current bounds from Planck (TT only) indicates a neutrino mass smaller than 0.59 eV at 95% c.l. [6].

This bound strongly improves once CMB lensing is taken into account ($M_\nu < 0.14$ eV at 95% c.l.). The reason is that CMB lensing probes the deflection of CMB photons as they travel from the last scattering surface towards us. Thus, CMB lensing is sensitive to the matter distribution at intermediate redshift ($0.1 < z < 5$), when massive neutrinos are already non relativistic.

After the non relativistic transition, neutrinos start free streaming, i.e., because of their high velocity dispersion, they cannot cluster on scales smaller than the so called free streaming scale. The effect on structure formation is twofold: on one hand they do not cluster themselves and on the other hand they slow down the growth of cold dark matter perturbations. The imprint of these effects can be identified in low redshift galaxy surveys, which provide both a geometric information (the Baryonic Acoustic Oscillation (BAO) scale) and a shape information (the overall matter power spectrum $P(k)$). The latter information is more efficient in constraining the neutrino mass sum, because it is sensitive to the characteristic suppression of small scale clustering due to free streaming. However, the shape information is more prone to systematics and, in particular, to the uncertainty on non linear effects. Including both the BAO and $P(k)$ information extracted from the Sloan Digital Sky Survey Data Release 7, the authors of Reference [7] find $M_\nu < 0.13$ eV at 95% c.l. (without CMB lensing). Besides BAO and $P(k)$, a further source of information about the matter distribution is provided by galaxy lensing: the distortion of the images of distant galaxies by intervening matter. Lensing data from the Canada France Hawaii Lensing Survey (CFHTLenS), together with Planck CMB temperature and lensing datasets and BAO, lead to $M_\nu < 0.30$ eV at 95% c.l. [8, 9].

2.2 Future constraints

As we already mentioned, the effect of a larger neutrino mass can be compensated by a variation of other cosmological parameters. Degeneracies among cosmological parameters limit the sensitivity of the data to the parameters. The effect is shown in Figure 1 for the sensitivity of a future CORE-like CMB experiment [11] to the neutrino mass sum. Increasing the neutrino mass sum from 60 meV to 150 meV and keeping all the other parameters constant, apparently induces a detectable effect (green solid line), both in the TT spectrum (left panel) and in the lensing spectrum (right panel). However, if, besides increasing the neutrino mass, we adjust the reduced Hubble constant $H_0 = h \times 100$ km/s/Mpc, so that the sound horizon angular scale at photon decoupling $\theta_s$ remains constant (red dashed line), then the effect is within the observational error (including cosmic variance) in the TT spectrum (left panel). If, at the same time, we also readjust the amplitude of the primordial power spectrum
Figure 1: Relative change in the CMB spectra induced by increasing the summed neutrino mass from $M_\nu = 60$ meV to $M_\nu = 150$ meV. The plots shows the residuals of the lensed $TT$ (left) and lensing potential (right) power spectrum, as a function of multipoles $\ell$. The light/pink and darker/green shaded rectangles refer, respectively, to the binned noise spectrum of a cosmic-variance-limited or CORE-like experiment, with linear bins of width $\Delta \ell = 25$. The physical baryon density $\omega_b$ and the scalar spectral index $n_s$ are kept fixed. In the first case (green solid line) the value of the Hubble constant is fixed at the reference value, while in all the other cases (labeled as fixed $\theta_s$) $h$ decreases in order to keep $\theta_s$ consistent with the reference model. Moreover, in the third case (dotted blue line), we tried to compensate for the changes in the lensing spectrum by increasing $A_s$, and in the fourth case (dotted-dashed black) we aim at the same result by increasing $\omega_{cdm}$.

$A_s$ and the reionization optical depth $\tau_{\text{reio}}$ (blue dotted line), or the cold dark matter density $\omega_{cdm}$ (black dot dashed line), then the effect of the increased neutrino mass is completely swamped in the lensing spectrum as well (right panel).

It should be stressed that the model here is the minimal $\Lambda$CDM plus massive neutrinos, i.e. the parameter space is $\{\omega_b, \omega_{cdm}, h, n_s, A_s, \tau_{\text{reio}}, M_\nu\}$. In the case of an extended cosmological model, e.g. with a varying dark energy equation of state parameter $w$, the degeneracies would be even more severe and the constraints on $M_\nu$ would degrade.

In order to assess the sensitivity of a future CORE-like CMB experiment to the neutrino mass sum, in Reference [10] we perform a Markov Chain Monte Carlo (MCMC) forecast, using the MONTEPYTHON package[12], interfaced with the Boltzmann solver CLASS[13, 14, 15]. For a fiducial neutrino mass sum of 60 meV, close to the minimum allowed value in the normal mass ordering, the sensitivity is $\sigma(M_\nu) = 42$ meV.

---

In order to improve this sensitivity to the neutrino mass sum, it is crucial to disentangle the effect of different parameters by taking into account datasets from different redshift. Therefore, including observables such as galaxy clustering and cosmic shear, extracted from a future Euclid-like galaxy survey, greatly improves the cosmological sensitivity to the neutrino mass sum. The degeneracy breaking mechanism is illustrated in Figure 2. While in the TT spectrum the increase of the neutrino mass could be compensated by fixing $\theta_s$, i.e. decreasing $h$ (red dashed line in Figure 1, left panel), the same adjustment does not work in the matter power spectrum (red dashed line in Figure 2, left panel). In order to compensate for the effect of massive neutrinos in galaxy clustering and shear spectra, other parameters (e.g. $A_s, n_s$) must be varied. Precisely because of this degeneracy breaking mechanism, a joint forecast of a CORE-like CMB experiment and a Euclid-like galaxy survey improves the sensitivity to the neutrino mass sum: $\sigma(M_\nu) = 14$ meV.

Finally, a very promising technique to shed light on the evolution of the Universe at intermediate redshift is the detection of the redshifted 21 cm line with radio telescopes, such as the future Square Kilometer Array (SKA) \cite{16}. References \cite{17,18} have shown...
that the independent measurement of the epoch of reionization by 21cm surveys could improve the determination of the optical depth to reionization$^3$ and thus of the summed neutrino mass. To assess the impact of 21cm surveys on $\sigma(M_\nu)$, we combine the CORE plus Euclid forecast with a gaussian prior on $\tau_{\text{reio}}$ ($\sigma(\tau_{\text{reio}}) = 0.001$ $^{19,18}$). In this case the sensitivity to a fiducial neutrino mass sum of 60 meV becomes $\sigma(M_\nu) = 12$ meV.

### 3 Sterile neutrinos and new physics

The effective number of relativistic degrees of freedom $N_{\text{eff}}$ accounts for any species, besides photons, that are relativistic in the early Universe. In the standard three neutrino flavor scenario $N_{\text{eff}}^{\text{SM}} = 3.046$ $^{20}$. Planck constraints on $N_{\text{eff}}$ ($N_{\text{eff}} = 3.15 \pm 0.23$ $^{21}$) are consistent with the standard value. Light sterile neutrinos, as hinted at by oscillation anomalies, would contribute to $N_{\text{eff}}$ with an additional $\Delta N_{\text{eff}} = 1$ in the 3+1 model ($\Delta N_{\text{eff}} = 2$ in the 3+2 model). Therefore, eV sterile neutrinos are in stark contrast with cosmology, not only because of the constraints on $N_{\text{eff}}$, but also because of the bounds on the hot dark matter density (see Section 2, $M_\nu < 0.13$ eV at 95% c.l.).

In order to accommodate sterile neutrinos in cosmology, we need to introduce some new physics. Non-standard sterile neutrino self-interactions mediated by a new boson can play this role. The interactions delay the sterile neutrino production until after the active neutrino collisional decoupling. Thus, once the sterile states are populated, they are not thermally distributed and their contribution to $N_{\text{eff}}$ is smaller $^{22,23,24,25,26,27}$.

Moreover, if the mediator is a light pseudoscalar with a mass much smaller than the neutrino mass, sterile neutrinos and the mediator recouple at late times, before sterile neutrinos go non relativistic. After the non relativistic transition, slightly before photon decoupling, sterile neutrinos start annihilating into pseudoscalars. As a consequence, the sterile neutrino mass has no visible effect on the cosmological observables. This model makes sterile neutrinos consistent with the cosmological bounds both on $N_{\text{eff}}$ and on $M_\nu$.

### 4 Conclusions

Cosmological constraints on neutrino properties are limited to some specific parameters, namely the hot dark matter density and the effective number of relativistic degrees of freedom, which, under some assumptions about the neutrino phase space

$^3$Notice that the constraints on $\tau_{\text{reio}}$ from 21 cm surveys are strongly affected by astrophysical uncertainties.
distribution, can be interpreted as the neutrino mass sum and the number of neutrino species, respectively.

Concerning the neutrino mass sum, current cosmological upper bounds are by far more stringent than laboratory limits. However, any cosmological result is model dependent. This means that in a (plausible) extended cosmological model the cosmological upper bounds on $M_\nu$ would be relaxed. Our MCMC forecast of the sensitivity of future CMB experiments and galaxy surveys show that a neutrino mass sum close to the minimum allowed value in the normal hierarchy can be detected at more than 4 $\sigma$.

Finally, concerning the effective number of relativistic degrees of freedom, we have mentioned how non-standard self-interactions can reconcile eV sterile neutrinos in cosmology.

References


Supernovae in SuperK-Gd and other experiments

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Core-collapse supernovae are one of the most energetic events in the universe \((10^{46} J)\). When a massive star \((M > 8 M_\odot)\) ignites its last fusion stage where silicon fusion makes iron, its end is then very close. Basically, the core of the star falls inwardly and the gravitational energy is then released in a supernova explosion. The basic picture of this explosion was confirmed by the few neutrinos detected from the SN1987a supernova at Kamiokande, IMB and Baksan detectors. However, there are many details that are still unknown. Since then, a large detector network has grown with better capabilities. Nowadays, in the case of a supernova explosion in our galaxy, the information that we would acquire would allow us to learn much more about these energetic events and constrain our models. Here, I present a brief summary of this network with special emphasis in SuperK-Gd (the upgraded Super-Kamiokande detector with efficient neutron tagging).

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1 Introduction

Core-collapse supernovae (ccSNe) are wonderful laboratories where we can learn a good deal of physics. The crucial importance of neutrinos and the basic mechanism on how massive stars undergo SN explosions was first described by [1, 2]. This mechanism was then confirmed by the two dozen neutrinos detected from the SN1987a SN explosion in the Large Magellanic Cloud on February 23, 1987: the source of their vast energy (from the gravitational collapse of the core of a massive star), the conversion of 99% of this energy into neutrinos and their mean temperature along with the explosion time duration (circa 12 seconds). After travelling 50 kpc, those neutrinos were detected at the Kamiokande II, IMB and Baksan detectors with 11, 8 and 5 neutrino events and fiducial masses of 2140 ton (water Cherenkov), 5000 ton (water Cherenkov) and 200 ton (liquid scintillator), respectively. These neutrinos were mainly detected from inverse beta decay (IBD) reactions: $\nu_e + p \rightarrow n + e^+$. 

Despite the many efforts of several groups working in the theoretical details of ccSN explosions, the details are not fully understood and is still a very active research area. These groups try to simulate SN explosions but until now they have not been completely successful yet. They went from one dimensional computer simulations with perfect spherical symmetry to (still imperfect) three dimensional computer simulations with nonradial motions in the collapsing core of the star. In the early days, it was thought that the infall of the overlaying shells was stopped and then expelled by the bounce of this material on the forming neutron star. However, this bounce-shock mechanism has been replaced by a more successful yet not perfect delayed neutrino-heating mechanism with still many unknowns [3, 4].

2 Current supernova detectors

In parallel to these efforts in the theoretical front, a large network of detectors that would be able to detect SN neutrinos has been growing around the world. In the Kamioka mine (Japan) were Kamiokande was built are now operating two detectors: KamLAND and Super-Kamiokande (SuperK) while the Baksan detector (Northern Caucasus, Russia) is still running.

Other neutrino detectors currently running are the Large Volume Detector (LVD) and Borexino in Gran Sasso (Italy), NOvA at Fermilab (USA), HALO at SNOLAB (Canada) and IceCube at the Amundsen-Scott South Pole station (Antartica). See Table 1. These detectors can be grossly divided by the detector material which in turn determines the main detection channel.
<table>
<thead>
<tr>
<th>Detector</th>
<th>Mass</th>
<th>Detector material</th>
<th>Operation begin</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamLAND</td>
<td>1 kt</td>
<td>liquid scintillator</td>
<td>2002</td>
<td>Japan</td>
</tr>
<tr>
<td>Super-Kamiokande</td>
<td>32 kt</td>
<td>ultra-pure water</td>
<td>1996</td>
<td>Japan</td>
</tr>
<tr>
<td>Baksan</td>
<td>0.3 kt</td>
<td>liquid scintillator</td>
<td>1980</td>
<td>Russia</td>
</tr>
<tr>
<td>LVD</td>
<td>1 kt</td>
<td>liquid scintillator</td>
<td>1992</td>
<td>Italy</td>
</tr>
<tr>
<td>Borexino</td>
<td>0.3 kt</td>
<td>liquid scintillator</td>
<td>2007</td>
<td>Italy</td>
</tr>
<tr>
<td>NOvA</td>
<td>14 kt</td>
<td>liquid scintillator</td>
<td>2014</td>
<td>USA</td>
</tr>
<tr>
<td>HALO</td>
<td>76 t</td>
<td>lead</td>
<td>2010</td>
<td>Canada</td>
</tr>
<tr>
<td>IceCube</td>
<td>1 Gt</td>
<td>antartic ice</td>
<td>2005</td>
<td>(Antartica)</td>
</tr>
</tbody>
</table>

Table 1: List of currently operating SN neutrino detectors.

<table>
<thead>
<tr>
<th>Interaction channel</th>
<th>Events/kton</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_e + p \rightarrow n + e^+ )</td>
<td>300</td>
<td>spectrum distortion from earth matter effect</td>
</tr>
<tr>
<td>( \nu_e + C^{12} \rightarrow e + N^{12}(B^{12}) )</td>
<td>30</td>
<td>tagged by ( N^{12}(B^{12}) ) beta decay</td>
</tr>
<tr>
<td>( \nu + C^{12} \rightarrow \nu + C^{12} + \gamma(15.1,\text{MeV}) )</td>
<td>60</td>
<td>no pointing capability in LSDs</td>
</tr>
<tr>
<td>( \nu + e^- \rightarrow \nu + e^- )</td>
<td>20</td>
<td>all flavours (insensitive to oscillations)</td>
</tr>
<tr>
<td>( \nu + p \rightarrow \nu + p )</td>
<td>300</td>
<td>all flavours (higher energy component)</td>
</tr>
</tbody>
</table>

Table 2: Main interaction channels in liquid scintillator detectors. Events/kton for a SN at the galactic center (10 kpc) are shown.

## 2.1 Liquid scintillator detectors

Liquid scintillator (\( C_nH_{2n} \)) detectors (LSD) have a low energy threshold (below 1 MeV) and have good energy resolution. These detectors can also use the delayed coincidence neutron tagging technique, which is very useful in IBD. An important drawback of LSDs is that they basically offer no SN directionality information since the produced light is almost isotropic. The main interaction channels and the rough number of neutrino events that are expected in these detectors in case of a SN at 10 kpc is shown in Table 2.

Massive stars in their late stages of their evolution are referred as neutrino-cooled stars. During the C, Ne, O and Si fusion phases they emit vast amounts of neutrinos at an increasing rate. In fact, in the last phase of Si fusion, the production of neutrino-antineutrino pairs is such that KamLAND could detect a pre-SN star if this would be close enough [5]. In Figure 1 it is shown the expected spectrum of these neutrinos for a star at 200 pc and compared to geo- and reactor neutrino rates. Given the enormous advantages the detection of a pre-SN represents, KamLAND has prepared a pre-SN alarm system that would be sensitive for stars up to 700 pc.
Figure 1: Expected neutrino spectrum from a pre-SN star at 200 pc and compared to geo- and reactor neutrino rates in KamLAND.

<table>
<thead>
<tr>
<th>Interaction channel</th>
<th>Events</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e + Pb^{208} \rightarrow Bi^{207} + n + e^-$</td>
<td>30</td>
<td>charged current</td>
</tr>
<tr>
<td>$\nu_e + Pb^{208} \rightarrow Bi^{206} + 2n + e^-$</td>
<td>19</td>
<td>charged current</td>
</tr>
<tr>
<td>$\nu_x + Pb^{208} \rightarrow Pb^{207} + n + e^-$</td>
<td>8</td>
<td>neutral current</td>
</tr>
<tr>
<td>$\nu_x + Pb^{208} \rightarrow Pb^{206} + 2n + e^-$</td>
<td>6</td>
<td>neutral current</td>
</tr>
</tbody>
</table>

Table 3: Number of expected neutrinos events for a SN at the centre of the galaxy (10 kpc) for the HALO detector.

2.2 Lead detectors

The HALO detector is a quite unique SN neutrino detector [6]. HALO prioritizes a detector long lifetime and low construction and detector maintenance costs. It consists of about 80 tons of lead as target material. This lead was taken from the decommissioning of the Deep River Cosmic Ray Station and instrumented with He$^3$ neutron counters from the SNO 3rd phase. Neutrons are moderated in polypropylene and the detector runs with SNO electronics. Lead is a neutron rich material and thus, it offers a good sensitivity to $\nu_e$’s through charged current (CC) processes (p $\rightarrow$ n transitions are here suppressed). This is in clear contrast to water Cherenkov and LSDs, which are primarily sensitive to $\nu_e$’s through IBD. HALO is also sensitive to all six $\nu$ and $\nu$ species through neutral current interactions (NC). For a SN at the centre of the galaxy (10 kpc) the expected number of neutrons produced is about 88 neutrons, see Table 3. With an efficiency of about 43%, HALO would detect about 40 neutrons. There is no charged current/neutral current (CC/NC) event distinction but the ratio of 1n/2n events may yield spectral information of the SN neutrino flux. There are plans for HALO-2, a kton-scale lead detector.
2.3 Water Cherenkov detectors

Water Cherenkov detectors have many good features for SN neutrino detection: water is an abundant, convenient and cheap detector material. Thus, despite the light yield is lower than in LSDs, very large instrumented volumes are relatively easy to deploy. IceCube is a Giga-ton detector with kilometre long PMT strings deployed in the ice of the South Pole. Designed for multi-GeV neutrinos, it can detect a low energy $\nu_e$ burst as an increase in the single PMT count rate. In case of a SN neutrino burst the ice would be uniformly illuminated. Therefore, by detecting the correlated increase of single PMT count rates on top of the PMT noise, IceCube can detect subtle temporal features with high statistics [7], see Figure 2. However, IceCube cannot deliver any SN pointing or neutrino energy spectrum information.

SuperK is a 50 kton ultra-pure water detector in Kamioka (Japan). The detector is divided in an outer detector that acts as a veto for cosmic rays and an inner detector of 32 kton viewed by $\sim 11.100$ 20-inch PMTs with a 4.5 MeV kinetic energy threshold. As for LSDs, the most important interaction is IBD, see Table 4. However, electron elastic scattering events carry information about the position of the SN in the sky, which is a unique capability among all SN detectors. Being $\hat{d}_i$ the direction of the $i$-th event and $\hat{d}_{SN}$ the SN direction, then we can define $\cos \theta_{SN} = \hat{d}_i \cdot \hat{d}_{SN}$. In Figure 3 $\cos \theta_{SN}$ is shown for MC events in the following energy ranges: 5-10 MeV, 10-20 MeV, 20-30 MeV and 30-40 MeV. With the elastic scattering events, SuperK can determine the direction of a SN at 10 kpc with an accuracy of 4-5°. From this figure it is clear that if SuperK could remove IBD events the pointing accuracy would be greatly improved.

To achieve this goal, neutron tagging is needed at SuperK. Currently, IBD neu-
<table>
<thead>
<tr>
<th>Interaction channel</th>
<th>Events</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e + p \rightarrow n + e^+$</td>
<td>7300</td>
<td>IBD</td>
</tr>
<tr>
<td>$\nu_x + O^{16} \rightarrow \nu_x + O^{16} + \gamma$</td>
<td>360</td>
<td>$O^{16}$ neutral current $\gamma$</td>
</tr>
<tr>
<td>$\nu_x + e^- \rightarrow \nu_x + e^-$</td>
<td>320</td>
<td>elastic scattering</td>
</tr>
<tr>
<td>$\nu_e + O^{16} \rightarrow e + F^{16}(N^{16})$</td>
<td>100</td>
<td>$O^{16}$ charged current</td>
</tr>
</tbody>
</table>

Table 4: Number of expected neutrino events for a SN at the centre of the galaxy (10 kpc) with a 4.5 MeV kinetic energy threshold (Livermore simulation).

Electrons are captured on protons after $\sim 200$ µs and a 2.2 MeV gamma is then produced. The problem is that this is not efficiently detected. GADZOOKS! was proposed to achieve neutron tagging with high efficiency. The basic idea is to dope with gadolinium (Gd) the otherwise SuperK ultra-pure water. This is done by dissolving Gd sulfate, Gd$_2$(SO$_4$)$_3$. Gd has a thermal neutron capture cross-section of 49000 barn (to be compared to that of the proton of 0.33 barn). With only 0.2% of Gd sulfate (0.1 % of Gd) 90% of the captures will be on Gd. After the neutron capture (capture time of $\sim 30$ µs), a gamma cascade of 8 MeV and shared among 3-4 gammas is produced which can be detected with high efficiency.

The initial motivation for GADZOOKS! was the diffuse SN neutrino background (DSNB), i.e. the neutrinos from all the past ccSN in the history of the visible universe. Although SuperK has the best world limit on DSNB large irreducible backgrounds dominate this search. However, by adding neutron tagging capabilities to SuperK these irreducible backgrounds could be greatly reduced and within 10 years of observation DSNB would be within our reach (with a significance that would depend in the typical SN emission spectrum).

In 2009 the R&D project EGADS (Evaluating Gadolinium’s Action on Detector Systems) was funded in Japan and a new hall in the Kamioka mine near SuperK was excavated. The purpose of the project was to demonstrate the feasibility of GADZOOKS!. EGADS features a 200-ton detector with 240 photo-detectors with its own water purification system (specially designed to remove all impurities in water but to keep Gd). In EGADS, all materials were chosen of the same type as in SuperK in order to mimic the conditions there. On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project. In Figure 4, the Cherenkov light left after 15 m (LL15) is shown for three different sampling positions in the EGADS detector. The blue band indicates typical values for SuperK III and IV. In the same figure, Gd sulfate concentration for the same sampling points is shown. The black dashed line indicates the final Gd sulfate concentration while the vertical bands indicate the Gd sulfate loadings and other experimental events. After the last Gd sulfate loading, the measured LL15 values in EGADS are inside the blue band when running in stable conditions while the Gd sulfate concentration remains stable.
Figure 3: SuperK can determine the SN direction with an accuracy of 4-5° for a SN at 10 kpc.

With efficient neutron tagging, the IBD events could be removed from the \( \cos \theta_{SN} \) distributions, see Figure 4. As a consequence, the direction of a galactic SN would be improved. For a SN at 10 kpc it could be determined with an accuracy of about 3°.

3 Future supernova detectors

A new generation of future detectors is underway. In the next years, we will see new Cherenkov detectors like Hyper-Kamiokande, PINGU and IceCube-Gen2. Hyper-Kamiokande will consist of two tanks of 0.5 Mton total mass and 40% photo-cathode coverage (40000 PMTs). New 50-cm PMTs are being developed with better detection efficiency and timing resolution. Because they will be installed in deeper tanks, these PMTs also designed to have a better pressure tolerance. PINGU and IceCube-Gen2 will represent a low-energy infill extension for IceCube and a substantial expansion to about 10 km\(^3\) of the current IceCube detector, respectively. This will greatly improve IceCube galactic SN sensitivity among other physics goals.

DUNE, a 40 kton liquid Ar detector, is planned to be deployed in the Homestake mine (South Dakota). Designed to be sensitive to neutrinos in the few tens of MeV range and in particular to the \( \nu_e \) component of a SN neutrino burst via CC.

A 20 kton LSD has also been proposed. JUNO, designed for a rich physics program
is designed to achieve an excellent energy resolution and a large fiducial volume. For a SN at 10 kpc, JUNO will see $\sim 5000$ IBD events and $\sim 2000$ all-flavour neutrino-proton elastic scattering events. Because of its neutron tagging capabilities it also aims to study the DSNB.

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References


Figure 5: With an efficient neutron tagging, SuperK SN direction accuracy would be improved from about 4-5° to about 3° for a SN at 10 kpc.


Neutrino Astronomy with IceCube and Beyond

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The IceCube Neutrino Observatory is a cubic kilometer neutrino telescope located at the geographic South Pole. Cherenkov radiation emitted by charged secondary particles from neutrino interactions is observed by IceCube using an array of 5160 photomultiplier tubes embedded between a depth of 1.5 km to 2.5 km in the Antarctic glacial ice. The detection of astrophysical neutrinos is a primary goal of IceCube and has now been realized with the discovery of a diffuse, high-energy flux consisting of neutrino events from tens of TeV up to several PeV. Many analyses have been performed to identify the source of these neutrinos, including correlations with active galactic nuclei, gamma-ray bursts, and the Galactic plane. IceCube also conducts multi-messenger campaigns to alert other observatories of possible neutrino transients in real time. However, the source of these neutrinos remains elusive as no corresponding electromagnetic counterparts have been identified. This proceeding will give an overview of the detection principles of IceCube, the properties of the observed astrophysical neutrinos, the search for corresponding sources (including real-time searches), and plans for a next-generation neutrino detector, IceCube–Gen2.

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1 Neutrino Astronomy

From radio waves to gamma rays, electromagnetic radiation has been the source of a wealth of information about the universe. Unfortunately, photons with energies above 1 TeV are absorbed by extra-galactic background light, making it difficult to detect sources beyond a redshift of 0.1 above this energy [1]. In order to study the universe above this cut-off we need to find an alternative to photons. Cosmic rays tell us that charged particles are accelerated by astrophysical objects up to at least $10^{20}$ eV, but since charged particles are deflected by magnetic fields, the origin of these particles still remains unclear. Since, aside from gravity, neutrinos interact solely via the weak force, they can traverse the universe completely unimpeded and therefore hold the potential to open a new window on astronomy.

2 The IceCube Neutrino Observatory

Neutrinos’ small cross section, the same property that allows them to arrive at Earth unimpeded, also makes them difficult to detect. Observing neutrinos requires a large target mass to make up for the small cross section. In addition, the medium must be transparent in order to observe the light from the secondary particles. The IceCube Neutrino Observatory was built in the Antarctic ice sheet at the South Pole Station.

The fundamental unit of IceCube is the digital optical module (DOM). Each DOM contains a 25 cm photomultiplier tube, high voltage power supply, and digitization and communication electronics. DOMs are aligned on vertical structures called strings, with 60 DOMs per string spaced vertically by 17 m between a depth of 1450 m and 2450 m. There are 86 strings for a total of 5160 DOMs. The strings form a triangular grid with a spacing of 125 m, except for 8 strings arrayed in the center to form a denser formation referred to as DeepCore.

There are three main event selections used for neutrino astronomy: muon tracks, cascades, and high energy starting-events (HESE). Muon tracks have good angular resolution, $\sim 0.7^\circ$ for energies above 10 TeV, but not all of the energy is deposited in the detector and so have comparatively poor energy resolution. With cascades, all of the energy is deposited near the vertex. These events have much better energy resolution than tracks, but at the cost of relatively poor angular resolution. The HESE selection observes events which start in the detector volume, by only selecting events where the initial light occurs on DOMs within the interior of the detector, and vetoing events which start near the edge. Although the events in this selection are either tracks or cascades, from an analysis point of view HESE is a separate event selection.
3 Observation of High-Energy Neutrinos

Using the HESE sample, an analysis performed on 4 years of data found 54 neutrino candidate events with a statistical significance of $6.5\sigma$. In order to describe the data, a maximum likelihood, forward-folding fit of all components (atmospheric muons, atmospheric neutrinos from $\pi/K$ decay, atmospheric neutrinos from charm decay and an astrophysical flux assuming a 1:1:1 flavor ratio) was performed on the energy spectrum. The result of the fit, shown in Figure 1 (left), is $dN/dE = (2.2\pm0.7) \times 10^{-18} \cdot (E/100\text{ TeV})^{-2.58\pm0.25} \cdot \text{GeV}^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$. A maximum likelihood clustering method was used to look for any neutrino point sources in this sample. This test, shown in Figure 1 (right), did not yield significant evidence of clustering, with p-values of 44% and 58% for the shower-only and the all-events tests, respectively. A test for Galactic plane clustering was also performed. Assuming a Galactic width of $2.5^\circ$ around the plane resulted in a p-value of 7% and a variable Galactic width scan resulted in a p-value 2.5% (both p-values are trials corrected.)

A separate diffuse spectral analysis was performed using six years of data with the muon track event sample [3]. At neutrino interaction energies between 191 TeV and 8.3 PeV an astrophysical contribution was observed with a significance of $5.6\sigma$. 
Figure 2: **Left:** Best-fit neutrino spectra for the unbroken power law model using muon neutrino events. The conventional and astrophysical neutrino fluxes are represented by shaded regions indicating one sigma error on the measured spectrum, whereas the solid line represents the upper limit on the prompt neutrino model in [4]. The horizontal width of the astrophysical shaded region denotes the range of neutrino energies which contribute 90% to the total likelihood ratio between the best-fit and the conventional atmospheric-only hypothesis. The crosses show the unfolded spectrum of the high-energy sample discussed above. **Right:** The results of the profile likelihood scan of the flavor composition at Earth. Each point in the triangle corresponds to a ratio $\nu_e : \nu_\mu : \nu_\tau$ as measured on Earth. The individual contributions are read off the three sides of the triangle. The best-fit composition is marked with “x”. 68% and 95% confidence regions are indicated. The ratios corresponding to three flavor composition scenarios at the sources of the neutrinos are marked by the square for pion-decay (0:1:0), circle for muon-damped (1:2:0), and triangle for neutron-beam (1:0:0) sources respectively.

As shown in Figure 2 (left), the data were well described by a power law: $dN/dE = (0.90^{+0.30}_{-0.27}) \times 10^{-18} \cdot (E/100 \text{ TeV})^{-2.13^{+0.13}_{-0.13}} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

The ratio of different neutrino flavors can give important clues to acceleration mechanisms of the source. In [3] we also performed a measurement of the flavor composition of the astrophysical neutrino flux, in which the normalizations of all three flavors were allowed to vary independently. The results, shown in Figure 2 (right), are consistent with pion-decay sources and muon-damped sources but disfavor neutron-beam sources with a significance of 3.6$\sigma$.

In the cascade event sample, in an analysis of the first two years of data a total of 172 events were observed with energies between 10 TeV and 1 PeV [5]. The astrophysical component is also well described by a power law: $dN/dE = (2.3^{+0.7}_{-0.6}) \times$...
Figure 3: Results of different IceCube analyses measuring the astrophysical flux parameters $\Phi_{\text{astro}}$ and $\gamma_{\text{astro}}$. The contour lines are at 90% confidence. The result of the muon track diffuse analysis $[3]$ is shown by the bottom-left solid contour line. The contour obtained by the previous measurement using the same method but using 2 years of data is the dashed line. The results of the HESE analysis $[2]$, cascade sample $[5]$, and the combined analysis $[3]$ are also shown.

The background-only hypothesis is rejected with a significance of 4.7$\sigma$. The results of these analyses along with the results of three other diffuse analyses were combined into a global spectral analysis $[3]$. Assuming the astrophysical neutrino flux to be isotropic and to consist of equal flavors at Earth, the all-flavor spectrum with neutrino energies between 25 TeV and 2.8 PeV is well described by an unbroken power law with a best-fit spectral index $2.50 \pm 0.09$ and a flux at 100 TeV of $6.7^{+1.1}_{-1.2} \cdot 10^{-18}$ GeV$^{-1}$s$^{-1}$sr$^{-1}$ cm$^{-2}$. Note that this flux is the sum of all three neutrino flavors, whereas the numbers quoted earlier in this section were per flavor fluxes. The results of the combined sample spectral fit along with the previously mentioned analyses are shown in Figure 3. Slight tension is seen between the different analyses. Since the analyses which are more sensitive to higher energy neutrinos also have a greater sensitivity in the Northern Hemisphere, this tension may indicate either a spectral hardening at high energies or that the sources in the Northern Hemisphere have a harder spectrum than their southern counterparts.

$10^{-18} \cdot (E/100\text{TeV})^{-2.67^{+0.13}_{-0.13}} \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. The background-only hypothesis is rejected with a significance of 4.7$\sigma$. The results of these analyses along with the results of three other diffuse analyses were combined into a global spectral analysis $[3]$. Assuming the astrophysical neutrino flux to be isotropic and to consist of equal flavors at Earth, the all-flavor spectrum with neutrino energies between 25 TeV and 2.8 PeV is well described by an unbroken power law with a best-fit spectral index $2.50 \pm 0.09$ and a flux at 100 TeV of $6.7^{+1.1}_{-1.2} \cdot 10^{-18}$ GeV$^{-1}$s$^{-1}$sr$^{-1}$ cm$^{-2}$. Note that this flux is the sum of all three neutrino flavors, whereas the numbers quoted earlier in this section were per flavor fluxes. The results of the combined sample spectral fit along with the previously mentioned analyses are shown in Figure 3. Slight tension is seen between the different analyses. Since the analyses which are more sensitive to higher energy neutrinos also have a greater sensitivity in the Northern Hemisphere, this tension may indicate either a spectral hardening at high energies or that the sources in the Northern Hemisphere have a harder spectrum than their southern counterparts.
Figure 4: **Left:** Pre-trial significance map of the all-sky point source scan [6]. The color indicates the negative logarithm of the pre-trial p-value assuming no clustering as the null hypothesis. Shown in Equatorial (J2000) coordinates, a line indicates the Galactic plane. **Right:** Results of the stacked blazar analysis. Neutrino flux upper limits from [8] are shown in colors compared to the diffuse best fit from [3] shown in black. Shown in blue are two separate signal weighting schemes for an $E^{-2.5}$ energy spectrum: equal weighting (dashed line) where blazars are considered to contribute equally to the neutrino flux, and weighting by blazars’ observed gamma-ray luminosity (dotted line). The equal-weighting upper limit for a flux with a harder spectral index of 2.2 is shown in green. Percentages denote the upper limit on the fraction of the integral astrophysical flux.

4 The Search for Astrophysical Sources

To identify the source of the neutrino populations described in the previous section, many analyses have been performed. To date none of them has identified any association with known or unknown astrophysical sources. In seven years of data, from 2008–2015, using an unbinned maximum-likelihood search for local clustering in the muon sample, no significant clustering of neutrinos above background expectation was observed [6]. The map generated by this analysis is shown in Figure 4(left). The negative result of this analysis excludes point sources with a flux above $E^2d\Phi/dE = 10^{-12}$ TeV cm$^{-2}$ s$^{-1}$.

Blazars have been proposed as a possible source of high-energy neutrinos[7]. To investigate this a stacked analysis was performed with blazars from the 2nd Fermi-LAT AGN catalog (2LAC) [8]. No significant excess is observed, constraining the total population of 2LAC blazars to contributing 27% or less of the observed astrophysical neutrino flux, assuming equipartition of neutrino flavors at Earth and the currently favored power law spectral index for the neutrino flux of 2.5. As shown in Figure
Another astrophysical source considered to be a likely source of neutrinos are gamma-ray bursts (GRBs). An analysis incorporating 5 years of muon track events and 1172 observed GRBs found no correlation more significant than expected from background [13]. The limits on the neutrino flux set by this analysis (see Figure 5) disfavor much of the parameter space for the theories on neutrino emission from GRBs. This analysis finds that no more than 1% of the observed astrophysical neutrino flux consists of prompt emission from GRBs that are observable by existing satellites.

Another considered source was the first gravitational wave transient GW150914 observed by the Advanced LIGO detectors on Sept. 14th, 2015. The analysis was performed by looking for neutrino candidates within 500 s of the gravitational wave event.
Figure 6: Conceptual schematic of the proposed high-energy extension to the IceCube detector. The current IceCube is shown in red with DeepCore in green. 120 additional string are added to increase the instrumented volume to $\sim 10 \text{km}^3$. A veto detector, potentially comprised of scintillator detectors, is also envisioned at the surface.

As shown in Figure 5 (right) and consistent with background, three events were observed within this time window, none of them within the region triangulated by LIGO [14].

In order to alert other astronomers about possible neutrino transient events, the IceCube collaboration has developed several real-time alert programs. The neutrino data are processed in real time at the South Pole Station and the most interesting neutrino events are selected to trigger observations with optical and X-ray telescopes aiming for the detection of an electromagnetic counterpart such as a GRB afterglow or a rising supernova light curve. The program is capable of triggering follow-up observations in less than a minute. The optical follow-up program [15] has been sending such alerts to optical telescopes since 2008 and to X-ray telescopes since 2009. The gamma-ray follow-up program has been running since 2012 [16], sending triggers to the MAGIC and VERITAS gamma-ray telescopes. This program focuses on blazar flares by monitoring a predefined list of known blazars and looks for excesses of neutrino events on timescales of up to three weeks.
Figure 7: Example benchmark detector string layouts under study for the high energy extension to IceCube. Each expands about IceCube by adding 120 strings constrained to the South Pole Dark Sector (shaded in light green). Other management areas of the South Pole Station where construction may not be permitted are also shown: the Downwind Sector in yellow, the Clean Air sector in blue, the Quiet Sector in beige, and the Old Station in pink. For the left panel, uniform string spacing of 240 m is shown. The central panel represents a string layout with a denser edge weighting for improved veto efficiency. The right panel shows the so-called banana geometry which seeks to create a very long detector for certain muon tracks.

5 Future Upgrade

Although IceCube has positively identified neutrinos of astrophysical origin, the ability of IceCube to be an efficient tool for neutrino astronomy over the next decade is limited by the modest number of cosmic neutrinos measured, even with a cubic kilometer array. Design studies to increase IceCube’s sensitivity with additional strings outside the current volume are currently underway [17]. This section will describe this effort, referred to as the IceCube–Gen2 High-Energy Array. The design, shown in Figure 6, seeks to increase the instrumented volume to $\sim 10 \text{km}^3$. The high-energy array is proposed to complement the high-density, low-energy sub-array known as PINGU [18]. PINGU targets precision measurements of the atmospheric neutrino oscillation parameters and the determination of the neutrino mass hierarchy.

The optical properties of deep Antarctic ice allow string spacing to be increased to 300 m for energies exceeding 10 TeV. Since angular resolution for muon tracks is proportional to the length of the lever arm, by increasing the size of the detector, the angular resolution will also be improved, further improving point-source sensitivity. Studies to find the optimal geometry and string spacing are currently underway.
Some of the geometries can be seen in Figure 7. All of the designs add 120 strings to the detector within the region of the South Pole station designated as the Dark Sector. Uniform string spacings of 200 m, 240 m, and 300 m, which instrument volumes of $6.0\ \text{km}^3$, $8.0\ \text{km}^3$, and $11.9\ \text{km}^3$ respectively, have been studied. Alternative array designs are also under study. In addition, IceCube–Gen2’s reach may further be enhanced by exploiting the air-shower detection and vetoing capabilities of an extended surface array, and by including an extended 100 km$^2$ radio array to achieve improved sensitivity to neutrinos in the $10^{16}$–$10^{20}$ eV energy range, including cosmogenic neutrinos.

While the design details remain to be finalized, IceCube–Gen2 will reveal an unobstructed view of the universe at PeV energies where most of the universe is opaque to high-energy photons. It will operate simultaneously with the next generation of electromagnetic and gravitational wave detectors, allowing for more multimessenger analyses. With its unprecedented sensitivity and improved angular resolution, this observatory will enable detailed spectral studies as well as potential point source detections and other new discoveries.

References

Status and challenges of neutrino cross sections

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Neutrino oscillations physics entered in the precision era. In this context accelerator-based neutrino experiments need a reduction of systematic errors to the level of a few percent. Today one of the most important sources of systematic errors are the neutrino-nucleus cross sections. The status of our knowledge of these cross sections in the different open channels in the few-GeV region, i.e. the quasielastic, the pion production and the multinucleon emission, is reviewed. Special emphasis is devoted to the multinucleon emission channel, which attracted a lot of attention in the last few years. It is crucial to properly reconstruct the neutrino energy which enters the expression of the oscillation probability. This channel was not included in the generators used for the analyses of the neutrino cross sections and oscillations experiments.

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1 Introduction

Neutrino physics has undergone a spectacular development in the last decades, following the discovery of neutrino oscillations and nowadays is entered in the precision era which needs a reduction of systematic errors to the level of a few percent. The experiments measure the rate of neutrino interactions, which is the convolution of three factors: the neutrino flux, the interaction cross section and the detector efficiency. The detectors of the modern accelerator-based neutrino oscillation experiments are composed of complex nuclei (\(^{12}\text{C}\), \(^{16}\text{O}\), \(^{40}\text{Ar}\), \(^{56}\text{Fe}\)...). In the hundreds-MeV to few-GeV energy region, the neutrino-nucleus cross sections are known with a precision not exceeding 20%, hence represent one of the most important sources of systematic uncertainties. The status of our knowledge in the different open channels in the few-GeV region, i.e. the quasielastic, the pion production and the multinucleon emission, is here briefly reviewed, devoting special emphasis to the multinucleon emission channel. For a more detailed discussion see for example Ref. [1].

2 CCQE, CCQE-like and CC0\(N\pi\)

In the discussion of the charged current quasielastic (CCQE) cross section, the MiniBooNE measurement [2], obtained using a high-statistics sample of \(\nu_\mu\) events on \(^{12}\text{C}\), plays a central role. In this work (as well as in other experiments involving Cherenkov detectors) the quasielastic cross section is defined as the one for processes in which only a muon is detected in the final state, but no pions. However it is possible that in the neutrino interaction, a pion produced via the excitation of the \(\Delta\) resonance escapes detection, for instance because it is reabsorbed in the nucleus. In this case it imitates a quasielastic process. The MiniBooNE analysis corrected for this possibility. After applying this correction, the quasielastic cross section thus defined still displayed an anomaly. The comparison of these results with a prediction based on the relativistic Fermi gas model using in the axial form factor the standard value of the axial cut-off mass \(M_A = 1.03\ \text{GeV}/c^2\), consistent with the one extracted from bubble chamber experiments, reveals a substantial discrepancy. The introduction of more realistic theoretical nuclear models, assuming the validity of the hypothesis that the neutrino interacts with a single nucleon in the nucleus, does not alter this conclusion. A possible solution of this apparent puzzle was suggested in Ref. [3] where the attention was drawn on the existence of additional mechanisms beyond the interaction of the neutrino with a single nucleon in the nucleus, which are susceptible to produce an increase of the quasielastic cross section. The absorption of the \(W\) boson by a single nucleon, which is knocked out (the genuine quasielastic scattering), leading to 1 particle - 1 hole (1p-1h) excitations, is only one possibility. In addition one must consider coupling to nucleons belonging to correlated pairs (NN correla-
tions) and two-nucleon currents arising from meson exchange (MEC). This leads to the excitation of two particle -two hole (2p-2h) states. 3p-3h excitations are also possible. Together they are called np-nh (or multinucleon) excitations. The addition of the np-nh excitations to the genuine quasielastic (1p-1h) contribution leads to an agreement with the MiniBooNE data without any increase of the axial mass.

Processes in which only a final charged lepton is detected, hence including multinucleon excitations, but pion absorption contribution is subtracted, today are usually called quasielastic-like, or CCQE-like. Thus, what MiniBooNE published was not CCQE data, but CCQE-like data. To avoid the confusion of the signal definition, it is increasingly more popular to present the data in terms of the final state particles, such as “1 muon and 0 pion, with any number of protons”. This corresponds to the CCQE-like data without the subtraction of any intrinsic backgrounds (except detector related effects) and it is called CC0π.

After the suggestion [3] of the inclusion of np-nh excitations mechanism as the likely explanation of the MiniBooNE anomaly, the interest of the neutrino scattering and oscillation communities on the multinucleon emission channel rapidly increased. Indeed this channel was not included in the generators used for the analyses of the neutrino cross sections and oscillations experiments.

Concerning the theoretical situation, nowadays several calculations agree on the crucial role of the multinucleon emission in order to explain the MiniBooNE, T2K and MINERvA cross sections. Nevertheless there are some differences on the results obtained for this np-nh channel by the different theoretical approaches. An illustration of the amount of the differences between the results obtained by two theoretical approaches, is given in Fig. 1 taken from Ref. [4], where the $CC0\pi$ flux-integrated double-differential cross section on carbon performed by T2K using the off-axis near detector ND280 is compared with the theoretical calculations of Martini et al. [3] and Nieves et al. [5]. Flux-integrated differential cross sections in terms of the final state topology of the reaction (as in this case $CC0\pi$ instead of CCQE or CCQE-like) are at this moment the golden observables for the theory-experiment comparisons in neutrino scattering. As shown in Ref. [4] the two theoretical approaches give very similar results for the genuine quasielastic calculated in RPA. The major differences are related to the np-nh channel. At the present level of experimental accuracy quantifying the agreement between the T2K data and the two models is not evident; the uncertainties are too large for any conclusive statement. For the moment, from Ref. [4] one can only conclude that both models agree with the data, and the data seems to suggest the presence of np-nh with respect to pure CCQE RPA predictions. This is an important conclusion, since these results represent a successful test of the necessity of the multinucleon emission channel in order to reproduce the data of an experiment with another neutrino flux (but in the same neutrino energy domain) with respect to the one of MiniBooNE. The detailed comparison with the MiniBooNE $\nu_\mu$ [2] and $\bar{\nu}_\mu$ [6] flux integrated CCQE-like double-differential cross sections was published in
Figure 1: Double-differential muon neutrino charged-current cross section on carbon without pions in the final state (CC0π) measured by T2K using the off-axis near detector ND280 compared with the theoretical calculations of Martini et al. [3] and Nieves et al. [5]. The figure is taken from Ref. [4].
Refs. [7, 8, 9, 10]. A comparison with the T2K CC0π and MiniBooNE CCQE-like flux integrated double-differential cross sections has been recently performed also by Megias et al. in Ref. [11]. Also in this case, a better agreement with data is obtained by adding the 2p-2h MEC contributions to the genuine theoretical CCQE results calculated in the SuSAv2 approach.

In the np-nh sector the microscopic calculations of Martini et al., Megias et al. and Nieves et al. are based on the Fermi gas, which is the simplest independent particle model. Even in this simple model an exact relativistic calculation is difficult for several reasons. The first difficulty is that one needs to perform 7-dimensional integrals for a huge number of 2p-2h response Feynman diagrams. Second, divergences in the NN correlations sector and in the angular distribution of the ejected nucleons may appear and need to be regularized. Furthermore the neutrino cross section calculations should be performed for all the kinematics compatible with the experimental neutrino flux. For these reasons an exact relativistic calculation is very demanding with respect to computing, and as a consequence different approximations are employed by the different groups in order to reduce the dimension of the integrals, and to regularize the divergences. The choice of subsets of diagrams and terms to be calculated also presents important differences. For a detailed discussion we refer to Ref. [1]. Here we just mention that one of the major difference between the results of Megias et al. [12] and the results of Martini et al. and Nieves et al. related to the presence or not of 2p-2h contributions in the axial sector and in the vector-axial interference term is now disappeared with the new results of Refs. [13, 11]. The MEC contributions to neutrino-nucleus cross sections in the three different microscopic approaches seem now to be compatible among them. The major differences that still remain in the np-nh sector, are related to the treatment of the NN correlations and NN correlations-MEC interference terms. Beyond all the theoretical models mentioned above, other interesting calculations discussing the 2p-2h excitations in connection with the neutrino scattering recently appeared [14, 15, 16, 17, 18, 19]. For the moment no comparison with neutrino flux-integrated differential cross sections are shown however the results of these approaches, in particular the ab-initio one of Lovato et al. [14, 15, 18] can offer important benchmarks for more phenomenological methods. Some examples are discussed in Ref. [1].

The multinucleon excitations have a strong impact on the reconstruction of the neutrino energy via the quasielastic kinematics-based method, as pointed out and discussed in several papers [20, 21, 22, 23, 24, 25]. This is particularly important for the determination of the neutrino oscillation parameters because data on neutrino oscillation often involve reconstructed neutrino energies while the analyses imply the real neutrino energy. Neutrino oscillation analyses which quantitatively take into account the effect of the np-nh channel started to appear [26, 27]. A possible way to reduce the systematic uncertainties due to the multinucleon emission channel in the neutrino oscillation events by maintaining the QE-based energy reconstruction
method instead of the calorimetric one has been discussed by Mosel et al. in Ref. [28] in connection with DUNE distributions. They suggest to consider “CC0π1p” sample, i.e., final state events with one charged lepton, 0 pions, and 1 proton, instead of traditional “CC0π” sample where the final state particles include one charged lepton and 0 pions, and any number of protons. This more restrictive requirement allows to obtain the true and reconstructed energy results quite close to each other. The price to pay is that one loses a factor 3 in the number of events. Furmanski and Sobczyk proposed to include full energy-momentum conservation on CC0π1p sample to improve the CCQE data sample and energy reconstruction [29]. In order to utilize these ideas in real experiments, we need a careful evaluation of proton measurement systematics.

Precise predictions and measurements of hadronic final states are clearly the next step. The community is moving toward this path. CCQE-like and CC0π cross sections of one-track (muon) and two-track (muon and proton) samples have been published by T2K [30] and MINERvA [31]. Other measurements which clearly go in this direction are the one presented by MINERvA in Ref. [32] where the observed hadronic energy is combined with muon kinematics allowing to give the results in terms of a pair of variables which separate genuine QE and Δ resonance events, like in inclusive electron scattering experiments, and the one of ArgoNeuT on exclusive $\nu_\mu$ CC0π events with 2 protons in the final state, the $(\mu^- + 2p)$ triple coincidence topology [33], like in exclusive electron scattering experiments. From a theoretical point of view only few, and very recent, microscopic calculations have been performed focusing on hadronic information in connection with the neutrino-nucleus scattering. We can essentially mention two studies, one of Ruiz Simo et al. [34] and one of Van Cuyck et al. [19], related to the emission of nucleon pairs induced by MEC and NN short range correlations, respectively. These theoretical calculations refer to $^{12}$C. Since also other nuclear targets, such as $^{16}$O and $^{40}$Ar, are used in present and future neutrino experiments, the mass dependence of multinucleon excitations, strictly related to the range of the pairs interaction, require important investigations.

3 Pion production

The single pion production is the largest misidentified background for both $\nu_\mu$ - disappearance and $\nu_e$ - appearance experiments. However, data-theory agreement remains very unsatisfactory. Nowadays there is no model which can describe MiniBooNE [35, 36], MINERvA [37, 38] and T2K [39] data simultaneously. The complications of pion data analyses lay not only on their primary production models, but also on the fact that all hadronic processes have to be modeled correctly. Combination of data from different channels and different experiments hope to entangle and constrain all processes [1], however, such an approach has been started very recently.
A precise and simultaneous knowledge of $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$ and $\bar{\nu}_e$ cross sections is important in connection to the oscillation experiments aiming at the determination of the neutrino mass ordering and the search for CP violation in the lepton sector, such as T2K, NOvA, Hyper-K and DUNE.

Concerning the neutrino vs antineutrino cross sections, it is well known that they differ by the sign of the vector-axial interference term, the basic asymmetry which follows from the weak interaction theory. This is the reason why the antineutrino cross sections are smaller and they falls more rapidly with the lepton scattering angle and with $Q^2$ than the neutrino ones. The presence of the vector-axial interference term introduces also an additional non-trivial asymmetry. Due to this term the various nuclear responses weigh differently in the neutrino and antineutrino cross sections \cite{40,41}. As a consequence the relative role of multinucleon contribution is different for neutrinos and antineutrinos. Due to the different approximations performed by different groups to study this channel, this relative role presents some differences in the different approaches (for a detailed discussion see Ref. \cite{1}) and represents a potential obstacle in the interpretation of experiments aimed at the measurement of the CP violation.

Turning to the $\nu_e$ cross sections, few published experimental data exist. This is essentially due to the relatively small component of electron-neutrino fluxes with respect to the muon-neutrino ones hence to small statistics. The published flux-integrated differential cross sections are the inclusive ones of T2K \cite{42} and the CCQE-like of MINERvA \cite{43}. The theoretical calculations of Refs. \cite{44,11,45} have been compared with the T2K results \cite{42} and substantially agree with data. Once again this agreement needs the presence of the np-nh excitations. The same conclusion holds also for the $\nu_e$ CCQE-like MINERvA differential cross sections on hydrocarbon \cite{43}, compared with the SuSAv2+MEC approach in Ref. \cite{11}.

$\nu_\mu$ and $\nu_e$ differential cross sections have been compared in Ref. \cite{44}. Due to the different kinematic limits, the $\nu_e$ cross sections are in general expected to be larger than the $\nu_\mu$ ones. However for forward scattering angles this hierarchy is opposite. This appears for the 1p-1h excitations (genuine QE and giant resonances) at low neutrino energies. This behavior is related to a non-trivial dependence of momentum transfer on lepton mass and scattering angle, and to a subtle interplay between lepton kinematic factors and response functions. In the precision era of neutrino oscillation physics the $\nu_e$ cross sections should be known with the same accuracy as the $\nu_\mu$ ones. Trying to deduce the $\nu_e$ cross sections from the experimental $\nu_\mu$ ones can be considered only as a first approximation in the study of the $\nu_e$ interactions.
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References

MicroBooNE and its Cross Section Measurement

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MicroBooNE (the Micro Booster Neutrino Experiment) is a short-baseline neutrino experiment based on the technology of a liquid-argon time-projection chamber (LArTPC), and has recently completed its first year of data-taking in the Fermilab Booster Neutrino Beam. It aims to address the anomalous excess of events with an electromagnetic final state in MiniBooNE, to measure neutrino-argon interaction cross sections, and to provide relevant R&D for the future LArTPC experiments, such as DUNE. In these proceedings, we present the first reconstructed energy spectrum of Michel electrons from cosmic muon decays, the first kinematic distributions of the candidate muon tracks from $\nu_\mu$-argon charged-current interactions, and a demonstration of an electromagnetic shower reconstruction from $\pi^0$s produced by $\nu_\mu$-argon charged-current interactions. The results demonstrate the first fully automated reconstruction and selection algorithms in a large LArTPC and serve as foundations for future measurements.

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NuPhys2016, Prospects in Neutrino Physics
1 The MicroBooNE Experiment

The MicroBooNE experiment is a neutrino experiment aiming to measure oscillation of neutrino flavors and neutrino-nuclear interaction cross sections. Located in the Booster Neutrino Beam (BNB) at Fermilab at a baseline of 470 m, MicroBooNE is the first experiment in the U.S. utilizing a large liquid-argon time-projection chamber (LArTPC) \[1\].

The primary physics goal of MicroBooNE is to address the excess of data events with an electromagnetic object in the regime of neutrino energy of 200 – 500 MeV reported by the MiniBooNE experiment \[2\]. As a Cherenkov detector filled with mineral oil, MiniBooNE was not able to distinguish electrons from photons. If the excess comes from events with an electron, it may imply existence of a sterile neutrino from the interpretation of the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation. On the other hand, if the electromagnetic object in those events is a photon, it may indicate an unknown background component. A LArTPC is able to distinguish electrons and photons by looking for the $\gamma \rightarrow e^+e^-$ topology at the start of an electromagnetic shower, and can thereby be exploited to investigate the MiniBooNE anomaly.

Measuring neutrino-argon interaction cross sections is another goal of the MicroBooNE experiment. Neutrino-nuclear interactions are currently not well understood, and have significant impacts on the precision of neutrino oscillation measurements. In particular, one of the most important neutrino experiments in the next generation, Deep Underground Neutrino Experiment (DUNE) \[3\], aims to address the CP-invariance violation in the lepton sector and the neutrino mass ordering by measuring rates and energy spectra of neutrino oscillation with the LArTPC technology. Therefore, precise measurements of neutrino-argon cross sections at MicroBooNE will be relevant.

In addition, the MicroBooNE detector is utilized to explore astroparticle and exotic physics, such as the detection of neutrinos from core-collapse supernova explosions, and searches for nucleon decays, nucleon oscillation, as well as dark matter candidates. The size of the MicroBooNE detector is not sensitive to most of the searches. However, we can demonstrate the technique, study backgrounds, and probe the thresholds of large LArTPCs. Moreover, LArTPC R&D and detector physics can be performed with MicroBooNE. For example, we demonstrate the purification of liquid argon, the design of the high voltage system, the cold electronics, readout and data acquisition systems. The effects of detector noise, electron recombination and attenuation can also be characterized at MicroBooNE. All the results will provide the DUNE experiment with valuable information.
2 Detector and its Performance

MicroBooNE consists of one time-projection chamber (TPC), with 89 tons of liquid argon in its active volume. As shown in Fig. 1(a), the TPC has dimensions of 10.4 m in the BNB direction, 2.3 m in vertical, and 2.5 m between the cathode and anode, along which a high voltage electric field of 273 V/cm is applied. There are three wire planes at the anode, each oriented by a degree of $\pm 60^\circ$ and $0^\circ$ with respect to the vertical, reading out the deposited charges at 2 MHz. A light collection system consisting of 32 8-inch photomultiplier tubes (PMTs) is mounted behind the anode wire planes. More details about the detector can be found in [4].

Charged particles produced from neutrino-argon interactions ionize argon atoms and create scintillation light. The scintillation light, produced in a time scale of 6 nanoseconds, is collected by the PMTs, determining the event timing, while the ionization electrons slowly drift towards the anode. Those electrons pass through the first two wire planes, leaving induced current, and then are collected in the third wire planes. Assuming a constant drift velocity ($\sim 1.1$ mm/$\mu$s), the electron drift time is proportional to the drift distance, and therefore each wire plane provides a two-dimensional image with the granularity of 3 mm (wire pitch) times 0.6 mm (the sampling rate of digitization under the current high voltage configuration). Fig. 2 illustrates the high spatial resolution of MicroBooNE LArTPC and the capability of characterizing a complicated event topology. A three-dimensional event can be reconstructed from the three two-dimensional images from the three wire planes.

![Figure 1](image1.png)

(a) Schematic drawing of the MicroBooNE cryostat which hosts the TPC. (b) The expected components and energy spectra of the BNB flux at MicroBooNE in the neutrino mode.
MicroBooNE started taking BNB neutrino data on October 15th, 2015. The composition of the BNB flux, dominated by $\nu_\mu$, can be found in Fig. 1(b). The detector and the data acquisition have performed stably [5], and $4 \times 10^{20}$ protons on target (POT) have been recorded as of the date of the conference. Fig. 3 shows the cumulative efficiency of the data acquisition at MicroBooNE.

## 3 Reconstruction of Physics Objects

Fully automated reconstruction algorithms are required to tackle the great amount of charge deposition from particles produced in neutrino-argon interactions, and from particles induced by cosmic rays during the long readout window (4.8 milliseconds) in an event. They are also needed to reduce the bias introduced by a visual scan. To process data collected at the TPC, we start with filtering the noise from the detector electronics [6], and then extract hits from the digital waveforms. Multiple clustering algorithms are applied, associating the hits originating from the same charged parti-
We use a three-dimensional track fitter to reconstruct tracks and remove hits associated to through-going tracks, which likely represent cosmic rays. Fig. 4(a) illustrates reconstructed tracks in an event taken outside the BNB operation window. Subsequently, we reconstruct the remaining hits and obtain tracks, electromagnetic showers, and neutrino-argon interaction vertices. An event containing a neutrino-argon interaction with reconstructed tracks and showers in the final state can be found in Fig. 4(b).

4 First Analyses

Utilizing the reconstructed physics objects, we develop different selection criteria for various analyses. In this section, the first analyses from MicroBooNE will be discussed.

4.1 Michel Electrons

To further understand the detector response in the tens of MeV energy range and the muon identification, we study the energy spectrum of Michel electrons, electrons in the decay products of stopping muons [8].
Figure 4: Three-dimensional reconstructed events from data collected at MicroBooNE: (a) An event containing cosmic rays collected outside the BNB window. The three boxes show the full readout length per event, corresponding to 4.8 milliseconds. The red highlighted box outlines the 1.6 milliseconds after the trigger time. The colored lines represent reconstructed tracks from cosmic rays. (b) An event containing a $\nu_\mu$-argon charged-current interaction with a $\pi^0$ production, selected by a visual scan. The white points are the reconstructed locations of deposited charges in the three-dimensional volume in the TPC. The colored cones represent the geometry of the reconstructed electromagnetic showers, possibly originating from the photons from the decay of the $\pi^0$.

In this analysis, we use muons from cosmic rays. The data sample contains 280,751 events collected outside of the BNB operation windows, corresponding to 1,347 seconds. A set of clustering algorithms are developed, profiling the deposited charges based on the highly resolved topological and calorimetric information provided by the third wire plane, which collects ionization electrons. We identify the tracks as stopping muons by looking for an increase in the charge deposition per unit length towards the end of the track, and the electron candidate is recognized as the track coming after the identified muon stopping point at an angle with respect to the muon track. The reconstruction and selection algorithms are fully automated.

The energy of Michel electrons is calculated from the reconstructed charges at the third (collection) wire plane with appropriate electronic calibration factors and correction factors. The correction factors account for two effects,

- recombination of argon ions and ionization electrons,
• attenuation of the ionization electrons during the drift path owing to the elec-
tronegative contamination in the liquid argon.

In this analysis, constant correction factors are applied; further development and
studies are underway to better model the two effects and the corresponding correc-
tion factors.

Figure 5: The reconstructed energy spectrum of Michel electrons from data and
Monte Carlo simulation. The uncertainty in both data and Monte Carlo simulation
accounts for the statistic uncertainty.

The distribution of the reconstructed energy from Michel electrons is shown in
Fig. 5. The energy distribution of Michel electrons typically has a sharp edge at
52.2 MeV, half the mass of muons. The distortion of the spectrum is owing to the
fact that the radiated photons, which can start the $e^+e^-$ pair production in tens
of centimeters, are poorly included in the energy reconstruction. Nonetheless, the
reasonable agreement between the spectra from the Monte Carlo (MC) simulation
and the data demonstrates our understanding of Michel electrons in LArTPCs. The
remaining difference in the two spectra may come from variation of calibration factors
in different TPC wire channels. Further studies are ongoing to improve the analysis.

4.2 $\nu_\mu$-argon Charged-current Interactions

The measurement of the $\nu_\mu$-argon charged-current interaction cross section provides
us with a foundation for comparisons to theoretical calculations and other experi-
mental results. In addition, it serves as a common starting point for further measurements of exclusive interaction channels, such as the charged-current interaction with the production of a $\pi^0$. Owing to the surface location, the recorded events at MicroBooNE are dominated by cosmic rays, and identifying and removing those background events are challenging. In this analysis, we present multiple kinematic distributions of muons produced from the $\nu_\mu$-argon charged-current interaction. The analysis outlines required tools for data quality and detector stability checks, for physics object reconstructions and event selections. It also guides us towards strategies and required improvements for all MicroBooNE analyses.

A data sample of 546,910 events, corresponding to $4.95 \times 10^{19}$ protons on target, is analyzed. The MC event generator GENIE is used to simulate the neutrino-argon interactions, while the particles induced by cosmic rays in these events are modeled by the CORSIKA simulation program. The passages of particles through the detector are simulated by GEANT4. Further, we exploit data collected outside the BNB operation windows for an estimation of the background events containing no neutrino-argon interaction.

Utilizing the reconstruction algorithms described in Sec. 3, we develop fully automated selection schemes. As a $\nu_\mu$-argon charged-current interaction produces a muon, leaving a long track in the detector, we select such events coincident with the BNB beam timing. One of the schemes and the consequent kinematic distributions are presented in these proceedings. We require

1. a light signal above 50 photoelectrons (P.E.) within the BNB operation window (1.6 $\mu$s, much shorter than the TPC readout window, 4.8 ms), indicating activities coincident with the beam timing,

2. at least a track longer than 70 cm, identifying as the muon candidate,

3. a light signal above 50 P.E. in agreement with the position of the candidate muon track in the beam direction,

4. the reconstructed interaction vertex within the fiducial volume (20 cm from the border in vertical, and 10 cm from the border in the other dimensions), removing events induced by cosmic rays or other background interactions,

5. at least a track starting within 3 cm from the interaction vertex, ensuring the production of charged particles near the vertex,

6. multiple sets of selection criteria on track kinematics for different charged particle multiplicities.
More details can be found in [9].

In the selected sample, we obtain an efficiency convoluted with acceptance of 30%, while obtaining the purity of 65%. The dominant background events originate from cosmic rays. Fig. 6 shows kinematic distributions of the candidate muon tracks, including the length, the angle with respect to the neutrino beam direction ($\theta$), and the azimuthal angle around the beam direction ($\phi$). The pure cosmic ray background events, determined using the data collected outside of the BNB operation window, have been subtracted from those distributions.

The distributions from the MC simulation agree reasonably well with those from the data, indicating our capability of modeling the signal, background events, as well as the detector response. Studies of systematic uncertainties in MicroBooNE are currently underway; nonetheless, we expect the major contributions of the systematic uncertainties would originate from the modeling of the BNB flux, the detector effects (e.g. the detector noise, non-uniformity of the electric field), and the simulation of neutrino-nucleus interactions.

4.3 $\nu_\mu$-argon Charged-current Interactions with $\pi^0$ Production

Reconstruction algorithms for electromagnetic showers are the key step towards the $\nu_\mu \rightarrow \nu_e$ oscillation analysis. The reconstructed invariant $\pi^0$ mass is important to demonstrate the performance of our electromagnetic shower reconstruction algorithms, as it requires both the direction and the energy of the reconstructed electromagnetic showers originating from the photons from the decays of $\pi^0$s. Out of the candidate events of $\nu_\mu$-argon charged-current interactions, we visually select a few events potentially containing a $\pi^0$ production. As illustrated in Fig. 7(a), the $\pi^0$ decays into two photons, each travels a few to a few tens of centimeters and then starts developing an electromagnetic shower. We thereby identify events containing two detached electromagnetic showers pointing back to the interaction vertex, which can be anchored by the beginning of the candidate muon track [10].

Fig. 7(b) shows the reconstructed shower cones and the hits used to form the cones. Developments on calorimetry and studies on systematic uncertainties are currently underway. Further, we have made progress towards fully automated selection exclusively on this interaction channel with a fair efficiency, and plan to obtain results in the near future.
5 Outlook and Summary

MicroBooNE is unique in its physics goals of addressing the anomaly reported by the MiniBooNE experiment, of measuring neutrino-argon cross sections, and of conducting R&D for both astroparticle and exotic physics searches and LArTPC performances. It has been fully operational and stably taking neutrino data for 10 months, recording $4.2 \times 10^{20}$ POT on tape. In these proceedings, we present the first fully automated reconstruction and event selection algorithms for LArTPCs and the first results, the energy spectrum of Michel electrons, the kinematic distributions of $\nu_\mu$-argon charged-current interactions, and the demonstration of the shower reconstruction algorithms with the events containing a $\pi^0$ production. The energy spectrum of Michel electrons is a standard tool used for energy calibrations, while the distributions and the demonstration of the $\nu_\mu$-argon charged-current interactions guide us towards the developments and studies for the final cross section measurements and the neutrino oscillation analyses.

It is important to precisely measure the neutrino-nucleus cross sections as their uncertainties are the major components of the systematic uncertainties of the neutrino oscillation measurements. As of today, only few neutrino-argon cross sections have been reported [11], and therefore the cross sections measured by MicroBooNE would significantly improve our knowledge. In particular, the energy regime of neutrinos produced by BNB, from 200 MeV to 2 GeV, corresponds to the second oscillation maximum of the DUNE experiment. We plan to deliver an inclusive neutrino-argon cross section measurement in 2017, and will obtain several measurements of exclusive and differential cross sections.

In 2018/2019, the Short Baseline Neutrino (SBN) Program will be operational, aiming to answer the question of existence of sterile neutrinos, which could potentially explain the MiniBooNE anomaly in the low energy regime and the earlier anomaly reported by the Liquid Scintillator Neutrino Detector (LSND) [12]. The SBN program will utilize the BNB neutrino beam as the neutrino source, and will contain a near and a far detectors to MicroBooNE. The Short Baseline Near Detector, SBND, will characterize the neutrino beam flux, and have large statistics for neutrino-argon cross section measurements, while the far detector, ICARUS, will be sensitive to the relevant parameter space. MicroBooNE will continue operating as part of the SBN program, and continue to deliver valuable information for the design of future LArTPC experiments, including both the detectors in the SBN program and the detectors in the DUNE experiment.
References


Figure 6: Kinematic distributions of the candidate muon tracks in the selected events: (a) track length, (b) \cos \theta, where \theta denotes the angle of the track with respect to the neutrino beam direction, and (c) \phi, the azimuthal angle around the beam direction. The number of events in the simulation is normalized to that in the data. Events from pure cosmic rays are subtracted. The uncertainty in the Monte Carlo simulation and the data accounts for the statistical uncertainty only. The pions produced from neutral-current interactions misidentified as muon tracks are typically shorter, and contribute to the first two bins in the track length distribution. The efficiency at \phi = \pm \pi/2, corresponding to the vertical direction, is lower because the candidate muon tracks in vertical are more likely to be identified as cosmic rays and are removed.
Figure 7: An event containing a $\nu_\mu$-argon charged-current interaction with a $\pi^0$ production candidate, selected by a visual scan: (a) display with raw digital waveforms collected at the third wire plane, (b) display with reconstructed hits (black points), tracks (red lines), and electromagnetic showers (colored triangles) projected into the third wire plane.
Precise prediction of the neutrino flux is a key ingredient to achieving the physics goals of accelerator-based neutrino experiments. In modern accelerator-based neutrino experiments, neutrino beams are created by colliding protons with a nuclear target. Secondary hadrons are produced in these collisions, and their decays contribute to the neutrino flux. The hadron production is the leading systematic uncertainty source on the neutrino flux prediction; therefore its precise measurement is desirable.

In these proceedings, review of recent hadron production measurements and the latest results from the NA61/SPS Heavy Ion and Neutrino Experiment (NA61/SHINE) are presented. In addition, plans of NA61/SHINE hadron production measurements for the next generation neutrino experiments and NA61/SHINE physics program extension beyond 2020 are discussed.
1 Introduction

In the neutrino oscillation analysis, number of observed neutrino events at the near and far detectors can be written as proportional to the neutrino flux and cross-section:

\[
N_{ND} \propto \int \Phi_{ND} \cdot \sigma \, dE_{\nu} \\
N_{FD} \propto \int \Phi_{FD} \cdot \sigma \cdot P_{osc} \, dE_{\nu} \\
\propto \int R_{FD}^{ND} \cdot \Phi_{ND} \cdot \sigma \cdot P_{osc} \, dE_{\nu}
\]

where \(\Phi_{ND(FD)}\), \(\sigma\), \(P_{osc}\), and \(R_{FD}^{ND}\) denote neutrino flux at the near (far) detector, neutrino cross-section on the target material, the neutrino oscillation probability, and far to near neutrino flux ratio, respectively. As indicated in these equations, well-understood neutrino flux is a key ingredient for the neutrino oscillation analysis.

A typical beamline design in modern accelerator-based neutrino experiments is shown in Figure 1. In modern experiments, neutrino beams are created by colliding protons with a light nuclear target, such as carbon or beryllium targets. Secondary hadrons are produced via primary interactions of beam protons and their decays contribute to the neutrino flux. Some fraction of secondary hadrons re-interacts in target or with other materials out of target. These secondary interactions also produce hadrons which contribute to the neutrino flux. Neutrinos mostly come from decays of charged pions at lower energy region, while kaon contributions to the neutrino flux are getting larger at higher energy region. Therefore, precise hadron production measurements on pions and kaons exiting target are necessary.

![Figure 1: Typical beamline design in modern accelerator-based neutrino experiments.](image)

In general, beam simulation is used to predict the initial neutrino flux at the near and far detectors. Since the hadronic interaction in the target and beamline materials is non-perturbative QCD process, there exists a difficulty of theoretical calculations. Therefore, hadron production simulation relies on models, such as FLUKA [1, 2] or GEANT4 [3]. Individual model shows different predictions, resulting in the large systematic uncertainty on the neutrino flux prediction. Since the hadron production
is known as the leading systematic uncertainty source on the neutrino flux prediction, validations of the hadronic interaction models with precise hadron production measurements are highly desirable.

2 Hadron production measurements

In this section, methodology for hadron production measurements are first discussed. Then, review of recent hadron production experiments and summary of available datasets are presented.

Hadron production experiments perform measurements using two types of target: thin target and replica target. In Figure 2, examples of thin and replica target are shown, which are used in the NA61/SPS Heavy Ion and Neutrino Experiment (NA61/SHINE).

Figure 2: (Left) 2 cm long thin carbon target in the NA61/SHINE experiment. (Right) 90 cm long T2K replica target in the NA61/SHINE experiment.

For the thin target measurement, hadron beams (protons, pions, or kaons) are shot on a few % nuclear interaction length ($\lambda_{int}$) targets. Main goals are to measure: inelastic cross-section, differential cross-section of produced hadrons, and yield of produced hadrons. The thin target measurements are used to constrain systematic uncertainty on the production of secondary hadrons from the primary interactions.

Although various thin target measurements are available to constrain primary interactions, some fraction of the neutrino flux comes from decays of hadrons produced through re-interactions of secondary particles. Only with the thin target measurement, phase space of such production processes are not fully covered, and hence precision of the neutrino flux is limited. One purpose of the replica target measurement is to reduce the systematic uncertainties not covered by the thin target measurements. To reproduce the condition of neutrino oscillation experiments, proton beams with the same momentum are shot on the replica target. For this purpose, main goal is to measure the yields of produced hadrons exiting target.
Thin and replica target measurements are complementary and have been performed by several hadron production experiments. Figure 3 shows an example of existing hadron production cross-section measurements with thin targets [4]. In addition to these available datasets, recent experiments performed further hadron production measurements for both thin and replica targets. The HARP experiment [5] at the CERN PS performed hadron yield measurements using 1.5-15 GeV/c protons on various nuclear target. Datasets taken by HARP are mainly used for the K2K experiment and Fermilab Booster neutrino experiments. In addition, the HARP datasets are also used for the atmospheric neutrino flux prediction. The MIPP experiment [6] at the Fermilab main injector performed hadron production measurements using 120 GeV/c primary protons and 5-90 GeV/c secondary hadrons (\( \pi^\pm, \ K^\pm, \ p, \) or \( \bar{p} \)) on various nuclear target. Datasets taken by the MIPP experiment are mainly used for the Fermilab NuMI beamline neutrino experiments. The NA61/SHINE experiment at the CERN Super Proton Synchrotron (SPS) is the only running hadron production experiment at present and will be reviewed in the next section.

Figure 3: Comparison of hadron production cross-section data with models for protons (left top), charged pions (right top), \( K^+ \) (bottom left), and \( K^- \) (bottom right).
3 NA61/SHINE measurements for T2K

NA61/SHINE is a fixed-target experiment at the CERN SPS, which studies hadron production in hadron-nucleus and nucleus-nucleus collisions for various physics goals. For neutrino physics, hadron beams (protons, pions, and kaons) are collided with a light nuclear target (carbon, aluminum, and beryllium) and spectra of outgoing hadrons are measured to improve precision of the neutrino flux prediction. For the T2K experiment, data taking was completed by 2010 with 31 GeV/c proton beam and the analysis of the ultimate dataset is being finalized.

The NA61/SHINE apparatus is a large acceptance spectrometer on the CERN SPS H2 beamline. Figure 4 shows the NA61/SHINE experimental setup. Main tracking detectors are four large TPCs, where two of them sit inside the super-conducting dipole magnets and other two are located downstream of magnets symmetrically with respect to the beamline. These TPCs provides good momentum reconstruction and particle identification capabilities. Scintillator-based time of flight detectors are located downstream of TPCs, which give complementary particle identification capability especially for the region where the Bethe-Bloch dE/dx curves overlap. Figure 5 shows an example of particle identification based on dE/dx and time of flight information, and its combined performance is shown in Figure 6 [7].

![Figure 4: Top view of the NA61/SHINE facility. In addition to the existing detectors, locations for the new forward TPCs are shown with dotted red line, which starts taking data from summer 2017.](image)

NA61/SHINE published a hadron production measurement with 31 GeV/c proton beam on the thin carbon target ($\sim 0.04 \lambda_{int}$, denote as $p+C$) [8]. Inelastic and production cross-sections were measured with high precision and found good agreement compared to former measurements (Figure 7). In addition, spectra of $\pi^\pm$, $K^\pm$, $p$, $\ldots$
Figure 5: Particle identification performance for 31 GeV/c proton beam on carbon target, as a function of particle momentum. (Left) Bethe-Bloch dE/dx curves for positively charged particles. (Right) The mass squared distribution obtained from the time of flight measurement.

$K^0_S$ and $\Lambda$ were measured and compared with various hadron production models. As an example, Figure 8 shows $\pi^+$ spectra compared with predictions by two hadron production models.

NA61/SHINE published their measurements with the T2K replica target more recently [9]. Yields of $\pi^\pm$ mesons from the surface of the T2K replica target were measured and compared with the FLUKA2011 prediction. Figure 9 shows an example of observed differential yields of $\pi^+$ mesons. In addition, the neutrino flux re-weighted with this T2K replica target measurement was compared with the FLUKA2011 prediction re-weighted with the NA61/SHINE thin target cross-section measurement and found a good agreement between two measurements.

With the NA61/SHINE thin target measurement on p+C interactions, neutrino flux uncertainty at T2K has been successfully reduced about 25% compared to the previous flux uncertainty (Figure 10, left). In addition to the thin target measurement, it was demonstrated that the neutrino flux uncertainty from the pion production contribution can be constrained up to 4% level with the published replica target measurement (Figure 10, right). Improved results will be obtained from four times higher statistics dataset on the T2K replica target taken by NA61/SHINE in 2010 and further flux uncertainty reduction is expected.

4 Future prospects

The next generation neutrino oscillation experiments are being proposed, such as LBNF/DUNE and successor experiments of T2K (T2K Phase 2 and Hyper-Kamiokande experiments). The LBNF beamline will shoot protons with momentum somewhere
Figure 6: Performance of combined dE/dx and time of flight particle identification. Charged particles in the momentum range of 2-3 GeV/c (left) and 4-5 GeV/c (right) are shown.

Figure 7: NA61/SHINE measurement for p+C at 31 GeV/c compared to former measurements. (Left) Inelastic cross-section. (Right) Production cross-section.

between 60 and 120 GeV/c on carbon or beryllium target, similarly as the NuMI beamline with 120 GeV/c protons. Because the primary protons have high momentum, secondary protons tend to be produced beam-forward direction and their re-interactions contribute a lot to the neutrino flux for the LBNF and NuMI beamlines. Therefore, it is very important to measure forward proton productions to further improve the neutrino flux prediction. The T2K beamline will be re-used for its successor experiments with the same beam momentum and upgraded beam intensity, and there exists a possibility to re-design the target for future operations. For all the next generation experiments, hadron production measurements with replica targets are highly desirable once their design is fixed.

NA61/SHINE has started taking data for the LBNF and NuMI beamlines since
Figure 8: Momentum distributions of $\pi^+$ mesons produced in p+C interactions at 31 GeV/$c$ in different polar angle intervals. NA61/SHINE data is compared with predictions of FTF_BIC in Geant4.9.5 and QGSP_BERT in Geant4.10 models.

Figure 9: Spectra of $\pi^+$ (left) and $\pi^-$ (right) mesons at the surface of the T2K replica target produced in p+C interactions at 31 GeV/$c$. NA61/SHINE data (black point) is compared with the FLUKA2011 predictions (blue solid line).

Through 2015 and 2016, various datasets have been taken for the beam simulation tunings: p+C at 31/60/120 GeV/$c$, p+Be at 60/120 GeV/$c$, $\pi^+$/C/Al at 31/60 GeV/$c$, $\pi^+$+Be at 60 GeV/$c$, and $K^+$/C/Al at 60 GeV/$c$. These rich datasets have been collected by NA61/SHINE and being analyzed. In addition, forward TPCs (FTPCs) are being installed to the NA61/SHINE facility to fill the forward direction acceptance gap of the NA61/SHINE facility (as shown in Figure 4). FTPCs will join the data taking since summer 2017 through 2018 and new data will be used to provide the precise neutrino flux prediction for the LBNF and NuMI beamlines.

The NA61/SHINE collaboration is preparing program extension proposal after CERN Long Shutdown 2 (2019-2020). Significant facility modifications are planned
including TPC electronics upgrade which significantly increases readout rate up to 1000 Hz, installation of modern silicon-based tracking detectors surrounding the target which improves vertex reconstruction precision drastically, and new time of flight detectors with high time resolution ($\sigma_{\text{time}} \sim 50\text{ ps}$) which increases particle identification resolution, in addition to the existing large acceptance TPCs. Therefore, it is a great opportunity for the next generation neutrino experiments to perform precise measurements of hadron production based on their demands at the upgraded NA61/SHINE facility.

References

Current Status and Future Plans of T2K

KIRSTY DUFFY
ON BEHALF OF THE T2K COLLABORATION

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T2K is a long-baseline neutrino oscillation experiment, in which a muon neutrino beam is directed over a 295 km baseline from the J-PARC facility to the Super-Kamiokande detector. This allows neutrino oscillation to be studied in two channels: disappearance of muon neutrinos and appearance of electron neutrinos. T2K has collected data using both a neutrino-enhanced and an antineutrino-enhanced beam, and these proceedings present the first T2K results using both neutrino and antineutrino oscillation data. Combining the two data sets gives the first ever sensitivity to neutrino-sector CP violation from T2K data alone, as well as the most precise T2K measurement of the other neutrino oscillation parameters.

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NuPhys2016, Prospects in Neutrino Physics
1 The T2K experiment

The T2K neutrino oscillation experiment [1] uses a 30-GeV proton beam produced at the J-PARC facility in Tokai, on the east coast of Japan, to create a beam of predominantly muon neutrinos or antineutrinos (with around 1% intrinsic contamination from electron neutrinos, and a small “wrong-sign” contamination). The neutrino beam is measured by two detectors located 280 m from the production point, ND280 and INGRID, before being directed over a 295-km baseline to the far detector, Super-Kamiokande (Super-K). T2K uses an off-axis ‘trick’, in which one of the near detectors (ND280) and the far detector are placed 2.5° off axis with respect to the neutrino beam. By the time the beam reaches the far detector, a significant fraction of the neutrinos in the beam have oscillated into electron or tau neutrinos.

The on-axis near detector, INGRID, is composed of a 7+7 cross-shaped array of iron and scintillator detector modules. INGRID data is used indirectly in the T2K oscillation analysis to measure the beam stability and direction, and estimate the uncertainty in the neutrino flux prediction, before the ND280 data are fit.

ND280, the off-axis near detector, is used directly in the oscillation analysis to reduce uncertainties due to the neutrino flux and interaction cross sections. It is a complicated detector, made up of many subdetectors. The oscillation analysis relies in particular on information from the ‘tracker’ region of ND280: two Fine-Grained Detectors (FGDs) interleaved with three Time Projection Chambers (TPCs) in a 0.2 T magnetic field. The FGDs provide scintillator and water targets for neutrino interactions (FGD1 is entirely composed of scintillator, while FGD2 contains both scintillator and water), with excellent vertexing and resolution close to the interaction point. The three TPCs measure interaction products leaving the FGDs with very good momentum resolution and particle identification capability.

The far detector, Super-Kamiokande [2], is a 50-kton (22.5 kton fiducial mass) water Cherenkov detector. It has no magnetic field, so cannot distinguish neutrino from antineutrino interactions. However, the detector is capable of very good lepton flavour identification from the pattern of Cherenkov light produced by a charged particle: it is estimated that the probability for a muon event to be misidentified as an electron is 0.7% [3].

T2K can observe muon neutrino disappearance and electron neutrino appearance. The oscillation probabilities given by the PMNS matrix are [4]:

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \frac{\Delta m^2_{32} L}{4E} + \text{(solar, matter effect terms)}
\]

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \frac{\Delta m^2_{21} L}{4E} \times \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} \sin \delta_{CP} + \text{(CP-even, solar, matter effect terms)}
\]
where the parentheses show the corresponding antineutrino oscillation probabilities. Because of the energy and baseline used for T2K, it is only sensitive to oscillations governed by the mass-squared splitting $\Delta m^2_{32}$, and not to the so-called ‘solar terms’, which are determined by $\Delta m^2_{21}$. The T2K neutrino beam can be run in two configurations: ‘neutrino mode’ (for a neutrino beam composed of mostly $\nu_\mu$), and ‘antineutrino mode’ (for a beam composed of mostly $\bar{\nu}_\mu$). This gives four ‘channels’ that can be used to measure neutrino oscillation: $\nu_\mu$ disappearance, $\nu_e$ appearance, $\bar{\nu}_\mu$ disappearance, and $\bar{\nu}_e$ appearance. These proceedings present the first T2K analysis to fit all four channels simultaneously, using a data set amounting to $7.482 \times 10^{20}$ protons on target (POT) in neutrino mode and $7.471 \times 10^{20}$ POT in antineutrino mode. This gives a precise measurement of the oscillation parameters $\sin^2 \theta_{23}$, $\sin^2 \theta_{13}$, and $\Delta m^2_{32}$, as well as the first sensitivity to $\delta_{CP}$ from T2K alone.

2 Oscillation analysis strategy

The oscillation analysis relies on models for the T2K neutrino flux (informed by external hadron production data [5] and in-situ measurements by INGRID and beam monitors), neutrino interaction cross sections (informed by external neutrino interaction data), and the ND280 and Super-K detector response. Using these models, data samples from ND280 and Super-K are fit simultaneously to produce an estimate of the oscillation parameters. T2K has three separate oscillation analyses, two of which take a slightly different approach to that presented here: the ND280 data are fit first, and the results of that fit propagated to Super-K for a separate oscillation fit. However, all three analyses show very good agreement in the oscillation results.

Only events in which a single Cherenkov ring is detected are included in the Super-K data selection for this analysis, and most events included in the data samples are expected to be quasielastic scattering interactions ($\nu_\alpha + n \rightarrow \alpha^- + p$, where $\alpha$ could be $\mu$ or $e$). The Super-K data are separated into sub-selections by the flavour of lepton presumed to have produced the Cherenkov ring (either electron-like or muon-like). This results in four Super-K data samples in total: neutrino-mode $1R_\mu$ (single-ring muon-like), neutrino-mode $1R_e$ (single-ring electron-like), antineutrino-mode $1R_\mu$, and antineutrino-mode $1R_e$.

The neutrino-mode ND280 data are separated into six selections. Three data samples are defined by the number of pions detected in the final state: $\nu_\mu$ CC 0\pi (which is dominated by quasielastic scattering, the ‘signal’ at Super-K), $\nu_\mu$ CC 1\pi\ (dominated by resonant pion production, an interaction mode which forms significant background at Super-K), and $\nu_\mu$ CC Other (containing all other interactions). These three selections are then applied separately to neutrino interactions in FGD1 and FGD2.

In antineutrino mode, both $\nu_\mu$ and $\bar{\nu}_\mu$ candidate interactions are selected at ND280, since there is a large wrong-sign contamination from $\nu_\mu$ in the antineutrino beam. Because the statistics are lower in these samples, only two categories of sub-sample are defined: $\bar{\nu}_\mu$ (or $\nu_\mu$) CC 1-track (dominated by quasielastic scattering), and $\bar{\nu}_\mu$ (or $\nu_\mu$) CC N-track (where N> 1, containing mostly non-quasielastic interactions). Again,
these selections are applied to interactions in FGD1 and FGD2 separately, resulting in eight antineutrino-mode data samples. The FGD1 $\nu_\mu$ CC 0π, $\nu_\mu$ CC 1-track, and $\bar{\nu}_\mu$ CC 1-track data and pre-fit predictions are shown in Figure 1.

![Figure 1](image_url)

(a) FGD1 $\nu_\mu$ CC 0π selection ($\nu$ mode)

(b) FGD1 $\nu_\mu$ CC 1-track selection ($\bar{\nu}$ mode)

(c) FGD1 $\bar{\nu}_\mu$ CC 1-track selection ($\bar{\nu}$ mode)

Figure 1: A subset of the data selections used at ND280. The pre-fit prediction as a function of reconstructed muon momentum is shown as a stacked histogram, with different colours representing different neutrino interaction modes, and data points are overlaid in black.

Including ND280 data in the fit significantly reduces the systematic uncertainty in the predicted number of events at Super-K. Measuring the ‘unoscillated’ event rate close to the neutrino production point allows the neutrino flux and interaction cross sections to be estimated, as well as determining correlations between flux and cross-section model parameters. Overall this reduces the systematic uncertainty on the number of events in each Super-K data sample from around 12-14% to around 5-6%, as shown in Table 1.

The data are fit using the PMNS framework for neutrino oscillation. Flat priors are used for the oscillation parameters $\sin^2 \theta_{23}$, $\delta_{CP}$, and $\Delta m^2_{32}$ (including a flat prior on the mass hierarchy, determined by the sign of $\Delta m^2_{32}$), and Gaussian priors from external measurements [6] are used for the solar parameters: $\sin^2 2\theta_{12} = 0.846 \pm 0.021$, and $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV$^2$. The data are fit twice: once with a flat prior on $\sin^2 \theta_{13}$,
Table 1: Uncertainty in the total number of events in each Super-K data sample due to different sources of systematic uncertainty.

<table>
<thead>
<tr>
<th>Systematic uncertainty (%)</th>
<th>(\nu 1R_\mu)</th>
<th>(\nu 1R_e)</th>
<th>(\bar{\nu} 1R_\mu)</th>
<th>(\bar{\nu} 1R_e)</th>
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</thead>
<tbody>
<tr>
<td>Flux w/o ND280</td>
<td>7.6</td>
<td>8.9</td>
<td>7.1</td>
<td>8.0</td>
</tr>
<tr>
<td>Cross section w/o ND280</td>
<td>7.7</td>
<td>7.2</td>
<td>9.3</td>
<td>10.1</td>
</tr>
<tr>
<td>Flux and cross section w/ ND280</td>
<td>2.9</td>
<td>4.2</td>
<td>3.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Super-K FSI/SI</td>
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<td>2.5</td>
<td>2.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Super-K detector response</td>
<td>3.9</td>
<td>2.4</td>
<td>3.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Total w/o ND280</td>
<td>12.0</td>
<td>11.9</td>
<td>12.5</td>
<td>13.7</td>
</tr>
<tr>
<td>with ND280</td>
<td>5.0</td>
<td>5.4</td>
<td>5.2</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table 2: Posterior probability (given the T2K data and models used in the analysis) for each combination of the neutrino mass hierarchy and octant of \(\theta_{23}\).
Figure 2: Predicted reconstructed energy spectra for the four data samples in the absence of neutrino oscillations, and after the data fit without reactor constraint on $\sin^2 2\theta_{13}$. The data are overlaid, and the ratio of the data and best-fit prediction to the unoscillated prediction is also shown.

The T2K measurement of $\sin^2 \theta_{13}$ and $\delta_{CP}$ is shown in Figure 4. The 2D credible intervals from data fits with and without the reactor constraint on $\sin^2 2\theta_{13}$ are shown in Figure 4a. Good agreement is seen in both fits, and the T2K measurement of $\sin^2 \theta_{13}$ is consistent with the reactor measurement (shown as a red $\pm 1\sigma$ band). Previous T2K results had no sensitivity to $\delta_{CP}$ when fitting without the reactor constraint, but now that antineutrino-mode data is also being included we see a 90% closed contour.

The one-dimensional posterior probability density as a function of $\delta_{CP}$ from the fit with reactor constraint is shown in Figure 4b. This can be interpreted as the probability – given the T2K data and fitting model – that the true value of $\delta_{CP}$ lies in a given bin on the histogram. The 68% and 90% 1D credible intervals are also shown. The 68% interval contains $\delta_{CP} \in [-2.58, -0.628]$, and the 90% interval covers $\delta_{CP} \in [-3.10, -0.07]$, both excluding the $CP$-conserving values $\delta_{CP} = 0, \pm \pi$.

This is the first time that an experimental 90% exclusion of the $CP$-conserving values of $\delta_{CP}$ has been reported, but it is important to consider the potential effect of statistical fluctuations in this measurement. The sensitivity to $\delta_{CP}$ in T2K is driven by $\nu_e$ and $\bar{\nu}_e$ appearance. Table 3 shows the predicted number of events in the $1R_\mu$ samples.
for a number of different values of $\delta_{CP}$ and the neutrino mass hierarchy, as well as the measured number of events in each data sample. The observed number of events is most consistent with the normal mass hierarchy and $\delta_{CP} = -\pi/2$. In fact, even these parameter values underpredict the neutrino-mode $1R_e$ sample and overpredict the antineutrino-mode $1R_e$ sample. This implies more $CP$ violation than is physically possible in the PMNS framework, and the result is a stronger-than-expected exclusion of $\delta_{CP} = 0$ and $\pm \pi$. However, this could just be due to statistical fluctuations in the two samples, which contain small numbers of events. This is important because statistical fluctuations can go both ways; if we are indeed seeing this stronger-than-expected constraint on $\delta_{CP}$ because of a statistical fluctuation, we may find that the $\delta_{CP}$ constraint gets “worse” as more data are collected if the fluctuation resolves or goes in the other direction.

<table>
<thead>
<tr>
<th>$\delta_{CP}$</th>
<th>$\nu$-mode $1R_e$</th>
<th>$\bar{\nu}$-mode $1R_e$</th>
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<tbody>
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<td>28.7</td>
<td>6.0</td>
</tr>
<tr>
<td>$0$</td>
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</tr>
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<td>$\pi/2$</td>
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</tr>
<tr>
<td>$\pm \pi$</td>
<td>24.1</td>
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</tr>
<tr>
<td>Data</td>
<td>32</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3: Number of events observed in the neutrino-mode and antineutrino-mode $1R_e$ samples and predicted for different oscillation parameters.
(a) Credible intervals in $\sin^2 \theta_{13}$--$\delta_{CP}$ from both fits to T2K data (with and without the reactor constraint on $\sin^2 2\theta_{13}$). The ±1σ band from the reactor constraint is also shown.

(b) 1D posterior probability per bin in $\delta_{CP}$ from the fit to T2K data with the reactor constraint on $\sin^2 2\theta_{13}$. The 68% and 90% 1D credible intervals are also shown.

Figure 4: Results of the fit to T2K data in the parameters $\sin^2 \theta_{13}$ and $\delta_{CP}$.

4 Summary and future prospects

In summary, these proceedings present the first joint analysis of neutrino and antineutrino appearance and disappearance at T2K, using roughly equal amounts of protons on target in neutrino-mode and antineutrino-mode beam. This results in an extremely precise measurement of the oscillation parameters $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$, as well as an independent measurement of $\sin^2 \theta_{13}$, all of which are in agreement with measurements by other experiments. Simultaneously analysing the oscillation of neutrinos and antineutrinos has produced the first ever experimental 90% exclusion of the $CP$-conserving values of $\delta_{CP}$, $\delta_{CP}=0$ and $\pm \pi$, but it is important to remember that the analysis currently has low statistics.

T2K is continuing to collect neutrino data, as well as refine the data selections and neutrino interaction models used in the oscillation analysis, in order to improve on the measurement presented here. Additionally, a number of short- and long-term analysis and detector improvements are under discussion.

One such short-term improvement is the addition of new data samples at Super-K. A new selection has been developed for single-ring electron-like events with one additional delayed Cherenkov ring due to a Michel electron from pion decay. This allows for resonant $\nu_e$ interactions which produce a $\pi^+$. The new sample is expected to add around 10% to the statistics of the neutrino-mode $1R_e$ sample, although the events in this sample may be less sensitive to the neutrino oscillation parameters. Updated results, including this sample, were presented at the Lake Louise Winter Institute 2017[11].

Considering longer-term improvements: T2K has been approved to collect $7.8 \times 10^{21}$
POT, and is expected to do so by around 2021. A proposal is under discussion to begin T2K phase 2 in 2021 and run up until the expected start of the Hyper-Kamiokande experiment in 2026. A main ring power supply upgrade would increase the beam power, allowing T2K phase 2 to collect a predicted total of $20 \times 10^{21}$ POT. An increase in the current of the magnetic horns used to focus the beam, as well as additional Super-K samples and an expanded Super-K fiducial volume is expected to provide around an additional 50% increase in the effective statistics. These statistical improvements would allow T2K phase 2 to reach 3$\sigma$ sensitivity to exclude $\sin(\delta_{CP}) = 0$ if $\delta_{CP}=-\pi/2$ with around $20 \times 10^{21}$ POT, assuming current systematic uncertainties. If the systematic uncertainty on the Super-K prediction can be reduced from $\sim 6\%$ to $\sim 4\%$, then 3$\sigma$ sensitivity is expected with around $15 \times 10^{20}$ POT. As previously demonstrated, the near detector measurement is key to reducing the systematic uncertainty. Therefore, to this end a proposal is being developed to improve the systematic measurement by upgrading ND280 (in particular, by improving the acceptance of the detector).

References

In the next decade several experiments will attempt to determine the neutrino mass hierarchy, i.e. the sign of $Δm^2_{31}$. In the last years it was noticed that the two hierarchies are disjoint hypotheses and, for this reason, Wilks’ theorem cannot be applied: this means that $Δχ^2 = χ^2_H - χ^2_N$ does not follow a one-degree-of-freedom chi-square distribution. It was proven that, under certain assumptions, it follows instead a Gaussian distribution with $σ = 2\sqrt{μ}$. I will present several possible definition of sensitivity and review the approaches proposed in the literature, both within the Bayesian and the frequentist framework, examining advantages and disadvantages and discussing how they should be modified if the conditions for Gaussianity are not fulfilled. I will also discuss the possibility of introducing a new pull parameter in order to avoid the issue related to the non-nested hypotheses and the differences between marginalization and minimization, showing under which conditions the two procedures yield the same $Δχ^2$.
1 The Statistical Problem

In the next decade several experiments will attempt to determine the neutrino mass hierarchy, i.e. the sign of $\Delta m^2_{31}$; if it is positive, the hierarchy is called normal, if negative inverted. To estimate the robustness of the mass hierarchy determination achieved by an experiment we use a test statistic, namely a function of the data whose value is related to the mass hierarchy (for example, it can be larger when the hierarchy is normal). In this work, as test statistic, we will use $\Delta \chi^2$ defined as

$$\Delta \chi^2 = \chi^2_{IH} - \chi^2_{NH} = -2\ln \frac{P(D|IH)}{P(D|NH)}$$

(1)

where $P(D|NH(IH))$ is the likelihood of getting the data $D$ assuming the hierarchy to be normal (inverted). This is not the only possible choice: for example, an alternative test statistic was proposed in [1]. In general, $\chi^2$ can depend on several additional parameters (pull parameters), which are not directly related to the mass hierarchy determination: we will indicate them with $\theta$ (it could represent a a single parameter as well as a vector). There are different ways to treat these parameters, for example in the frequentist approach (which is the approach that will be used in the two examples described below in this section), they should be minimized, namely, using the value of $\theta$ which minimized the $\chi^2$ (best fit value). $\Delta \chi^2$ is now defined as

$$\Delta \chi^2 = \chi^2_{IH}(\hat{\theta}) - \chi^2_{NH}(\hat{\theta})$$

(2)

where $\hat{\theta}$ and $\hat{\hat{\theta}}$ are the best fit values for $\theta$ for each hierarchy, respectively.

Two hypotheses $H_0$ and $H_1$ are called nested if one is a particular case of the other (namely, $H_0 \subset H_1$): for example, $H_0$: “A is equal to zero” versus $H_1$: “A is real”. Under some very general assumptions, Wilks’ theorem states that in the case of nested hypothesis $\Delta \chi^2$ follows a chi-square distribution and the confidence level with which it is possible to reject the hypothesis $H_0$, expressed in the usual form of number of Gaussian standard deviations $n$ (number of $\sigma$’s), is equal to $\sqrt{\Delta \chi^2}$. The relation between $n$ and the probability $p$ for $H_0$ to be true is

$$p = \frac{1}{2} \text{Erfc}(n/\sqrt{2})$$

(3)

A few years ago was noted that the two hierarchies are non-nested (or disjoint) hypotheses and, for this reason, Wilks’ theorem cannot be applied. The main consequence is that the $\Delta \chi^2$ does not follow a one-degree-of freedom chi-square distribution, and the number of $\sigma$’s should not be simply estimated as $\sqrt{\Delta \chi^2}$. Indeed, in the case of the mass hierarchy we are comparing the hypothesis $H_0$: “the sign of $\Delta m^2_{31}$ is +1”

*Here we considered the one-sided Gaussian fluctuation, for the two-sided definition $p \rightarrow 2p$ [2]
with $H_1$: “the sign of $\Delta m^2_{31}$ is -1”; in this case $H_0$ is not a particular case of $H_1$ and Wilks’ theorem cannot be applied: to convince ourselves of this fact, we can notice that $\Delta \chi^2$ defined as Eq. (2) could also be negative, if the hierarchy is inverted, while any quantity that follows a chi-square distribution must always be positive.

Under certain conditions the statistical distribution of $\Delta \chi^2$ can be described to a very good approximation by a Gaussian distribution, with $\mu = \Delta \chi^2$ and $\sigma = 2\sqrt{|\Delta \chi^2|}$, where $\Delta \chi^2$ is the expected value of the test statistic in question: this was first proved by Qian et al. [3], without taking into account the eventual pull parameters (“simple vs. simple” scenario); then this result was extended considering also pull parameters [4, 5, 6], using both the Bayesian and frequentist approaches. This is not the first case in physics of non-nested hypotheses: for example Cousins et al. faced a similar problem discussing the discrimination between spin-1 and spin-2 resonances at LHC [7]. $\Delta \chi^2$ is equal (due to the law of large numbers) to the $\Delta \chi^2$ calculated with the Asimov data set, namely using the theoretical prediction for the expected number of events in every bin; when the $\Delta \chi^2$ follows a Gaussian distribution, the “median experiment” is defined as the experiment where $\Delta \chi^2 = \Delta \chi^2$; while this is always true in the Gaussian case, it is not true in general. If we define as $y_i(\theta_j)$ the expected number of events for every bin $i$, which in general is a function of a certain number of pull parameters $\theta_j$, the conditions that must be fulfilled in order to ensure Gaussianity are

- $y_i$ can be approximated as a linear function of $\theta_j$: this define a P-hyperplane in the N-dimensional space, where N is the number of bins, P is the number of pull parameters
- The hyperplanes for the two hypotheses are parallel around the minima

I will discuss two simplified models, inspired by reactor and accelerator neutrino experiments, to clarify when the conditions for Gaussianity are satisfied.

The possibility to use reactor neutrinos to determine the mass hierarchy was suggested for the first time by Petcov and Piai in 2002 [8]. In this kind of experiment, due to the energy range of neutrinos, the matter effect are completely negligible. Vacuum oscillations depend only on the absolute values of $\Delta m^2$’s, however they obey the relation

$$|\Delta m^2_{31}| = |\Delta m^2_{32}| \pm |\Delta m^2_{21}|$$  \hspace{1cm} (4)

where the sign depends on the mass hierarchy. Studying the interference between 1-2 and 1-3 oscillations it is possible to determine the mass hierarchy, but there is a strong degeneracy between a shift of $\Delta m^2_{31}$ and a change of hierarchy. We considered a model with only one pull parameter, $\Delta m^2_{31}$, ignored the background and assumed an energy resolution of $3%/\sqrt{E}$. The baseline considered was 52 km, and the exposure 120 ktons-years. From Fig. 1 we can see that the Asimov $\chi^2$ is almost exactly parabolic, which is a necessarily condition for the Gaussianity, and the $\Delta \chi^2$ follows a Gaussian distribution.
Figure 1: Left: Asimov $\chi^2$ for normal and inverted hierarchy (black) and parabolic fit (red dashed) in reactor neutrino experiments. Right: statistical distribution of $\Delta \chi^2$

Figure 2: Asimov $\Delta \chi^2$ for different values of $\delta_{CP}$ (accelerator neutrino experiments)

In accelerator neutrino experiments, instead, the mass hierarchy can be obtained by comparing the oscillation probabilities in the neutrino and antineutrino sector. While in reactor neutrino experiments we study the survival probability $P_{e \rightarrow e}$, here we observe the oscillation probability $P_{\mu \rightarrow e}$: one of the consequences is that the strongest degeneracy is now due to $\delta_{CP}$, which is only partially broken by the matter effect: in particular $P_{\mu \rightarrow e}(NH, \delta_{CP} \simeq 90) \approx P_{\mu \rightarrow e}(IH, \delta_{CP} \simeq 270)$. We considered a very simplified model, with one pull parameter, $\delta_{CP}$, and where only the average oscillation probability in the neutrino and antineutrino sector was taken into account (namely, no spectral information); again all the possible sources of background were neglected. The baseline and the expected number of events were the same as a 3+3 years NO$\nu$A run [9]. In Fig. 2 we can see that the Asimov $\chi^2$, in the case of accelerator neutrinos, is not parabolic anymore; this means that the conditions for Gaussianity are no longer fulfilled, as can be seen also from Fig. 3. The asymmetry between the probability density function (pdf) of $\Delta \chi^2$ for certain values of $\delta_{CP}$ is to be expected, and it is due to the partial degeneracy mentioned before.
2 Quantify the Sensitivity to the Mass Hierarchy

2.1 Frequentist Approach

We want to compare a hypothesis $H_0$ (also called “null hypothesis”) with an alternative hypothesis (or set of alternatives) $H_1$. In order to perform a frequentist hypothesis test, we define a test statistic $T$ and a threshold $T_c$ (let us assume that a large value of $T$ means that $H_0$ is unlikely): if, after performing the experiment, we find a value of $T_{\text{obs}} < T_c$, $H_0$ is accepted, otherwise is rejected. In this kind of test, there are two relevant quantities:

- The probability $\alpha$ of rejecting $H_0$ even if it is true; $1 - \alpha$ is called the confidence level (CL)
- The probability $\beta$ of not rejecting $H_0$ even if the alternative hypothesis $H_1$ is true; $1 - \beta$ is called the power of the test

It is important to underline that rejecting $H_0$ does not give, a priori, any information on $H_1$: if a hypothesis test excludes the normal hierarchy with a certain CL, this does not tell us anything about the inverted hierarchy. In [6], the authors suggest to test both hypotheses separately, defining two threshold, $T_{c,NH}$ and $T_{c,IH}$. As test statistic we use $\Delta \chi^2$, defined as (2): if our experiment gives us $\Delta \chi^2 < T_{c,NH}$, the normal hierarchy is rejected, if we find $\Delta \chi^2 > T_{c,IH}$, the inverted hierarchy is rejected. One unappealing consequence of this approach is that, depending on the choices of $T_{c,NH}$ and $T_{c,IH}$, both hierarchies can be accepted or rejected at the same time. The CL that can be achieved depends only on the values of $T_{c,NH}$ and $T_{c,IH}$ (that must be chosen before the experiment), not on the results obtained: for this reason it may be convenient to use the frequentist hypothesis test to estimate the expected sensitivity that can be achieved in a future experiment. In [6], different definitions of sensitivity are proposed:

- The median sensitivity is defined by choosing $T_{c,NH(IH)} = \Delta \chi^2_{IH(NH)}$, namely the expected $\Delta \chi^2$ if the hierarchy is the opposite with respect to what we are testing. In particular, if we assume the symmetric case where $\Delta \chi^2_{NH} = -\Delta \chi^2_{IH} = \Delta \chi^2 > 0$ we have $T_c = ±\Delta \chi^2$. One nice feature of this choice is...
that the CL, expressed as number of $\sigma$’s, takes the well-known form $\sqrt{\Delta \chi^2}$. On the other hand, the power for this kind of test is only 0.5, this means there is only 50% of possibility of getting such a result.

- The crossing sensitivity, instead, is defined, at least in the symmetric case, taking $T_{c,NH} = T_{c,IH} = 0$: the main advantage is that, in this case, the power is equal to the CL (using this criterion, it can be easily defined in a more general scenario); however the number of $\sigma$’s is only $\sqrt{\Delta \chi^2}/2$.

Another common criterion for the discovery is the p-value, which is also defined using the frequentist approach: the difference with the hypothesis test is that while the CL of the latter is defined before the experiment, and the results can only tell if it is achieved or not, the CL of the former depends on the result. The p-value, indeed, is defined as the possibility of finding a “more extreme” value of the test statistic than the observed one; in the case of $\Delta \chi^2$, this means $\Delta \chi^2 > (>)\Delta \chi^2_{\text{obs}}$ if we want to exclude the inverted (normal) hierarchy. Few remarks about this approach:

- It relies on the knowledge of the pdf of $\Delta \chi^2$, however we saw in the previous section that in many cases it can only be determined using Monte Carlo simulations, and it would be difficult to get data reliable at 5 $\sigma$’s or more.

- Moreover, these distributions depend on the value of other parameters: in particular, in the case of accelerator neutrinos the pdf depends strongly on the value of $\delta_{CP}$. How is it possible to define a CL $1 - \alpha$? In [6], for the hypothesis test, the authors suggest to define such a CL when for every value of the pull parameters the CL is at least $1 - \alpha$, however using this approach it is not clear how to take into account eventual pre-existing constraints (for example, if some values of $\delta_{CP}$ are already excluded at 4 $\sigma$’s, should they still be considered?). Another possible solution (at least for the p-value) is to use the best fit values calculated assuming the hierarchy we want to reject: using the first approach the confidence level could be underestimated, while with the second one it could be overestimated.

- The frequentist approach can only estimate the compatibility of each hierarchy with the data, namely the CL with which each hierarchy can be excluded; however even if the normal hierarchy can be excluded with a given CL, this does not necessarily means that the hierarchy is inverted. For example, let us assume that the results of an experiment allow us to exclude the normal hierarchy at 5 $\sigma$’s; it would be incorrect, however, to state that “the hierarchy is determined at 5$\sigma$’s”: indeed, the scenario would be very different if the inverted hierarchy is compatible with the data within 1 $\sigma$ or if it can be excluded at 5 $\sigma$’s, too.

- Finally, it is worth noticing that, while it is true that using the median frequentist sensitivity the CL takes the familiar form of $\sqrt{\Delta \chi^2}$, this is true only for the expected value of $\Delta \chi^2$, not if we use the $\Delta \chi^2$ obtained after we performed the experiment. Indeed, if we assume that analyzing the result of a certain exper-
iment (or global fit) we found $\Delta \chi^2 = 16$, it does not follow that the inverted hierarchy can be excluded at 4 $\sigma$’s: the p-value is equal to the median sensitivity only if $\Delta \chi^2 = \overline{\Delta \chi^2}$, which in general is not true.

### 2.2 Bayesian Approach

While using the frequentist approach it is possible to determine only $P(D|MH)$ (where $MH = NH, IH$), namely the probability of obtain a certain set of data given the mass hierarchy, using Bayes theorem we can calculate directly $P(MH|D)$ (also called posterior probability), which is the probability for the hierarchy to be normal or inverted given the result of an experiment (these two quantities are deeply different and should not be confused). $P(MH|D)$ can be obtained using the formula

$$P(NH|D) = \frac{P(D|NH)\pi(NH)}{P(D|NH)\pi(NH) + P(D|IH)\pi(IH)} = \frac{\pi(NH)}{\pi(NH) + K^{-1}\pi(IH)} \tag{5}$$

where $K = P(D|NH)/P(D|IH) = e^{\Delta \chi^2/2}$ is the Bayes factor (in the last step we used Eq. 2), while $\pi(NH/IH)$ are the priors on the mass hierarchy, namely the degree of belief for some hypothesis (in this case, the mass hierarchies, but priors must be assigned also for all the pul parameters). One of the downside of the Bayesian approach is that the final results depends on the choice of the priors, which are arbitrarily chosen; however in the case of the mass hierarchy there is a very natural solution, namely the symmetric priors, where $\pi(NH) = \pi(IH) = 0.5$.

In [5], the median Bayesian sensitivity is defined as the posterior probability for the mass hierarchy when $\Delta \chi^2 = \overline{\Delta \chi^2}$: this probability can be converted into “number of $\sigma$’s” using Eq. 3. This definition can be used to quantify the sensitivity of a future experiment, however using the Eq. 4 it is possible to calculate this quantity as a function of $\Delta \chi^2$: this means that it can be calculated using only the results of the experiment, while in order to calculate the frequentist CL, one must rely on the knowledge of the pdf of $\Delta \chi^2$. A comparison between the crossing and the median sensitivity (frequentist and bayesian), as a function of $\overline{\Delta \chi^2}$ can be found in Fig. 4 (left panel).

Another advantage of the Bayesian approach is that here all the information can be communicated with a single quantity (the posterior probability) since $P(NH|D) + P(IH|D) = 1$ by construction, while using the frequentist approach there is no trivial relation between $P(D|NH)$ and $P(D|IH)$, however it is important to underline that the two methods provide different (and complementary) information: for example, if one experiment can exclude the normal hierarchy at 5 $\sigma$’s and the inverted at 3 $\sigma$’s, while another one at 4 and 1 $\sigma$’s, respectively, the posterior probability would be roughly the same, even though the two scenarios are very different.

Complications may arise if many pull parameters are present: indeed, while in the frequentist approach usually the eventual pull parameters are minimized, in the
Bayesian approach we must integrate over them (marginalization), with a weight defined by their priors

\[ P(D|MH) = \int d\theta P(D|\theta, MH)\pi(\theta) \]  \hspace{1cm} (6)

However these multi-dimensional integrals are usually difficult to compute. If \( P(D|\theta, MH)\pi(\theta) \) is strongly peaked around its maximum, and if the determinants of the Hessian matrix for the two hierarchies, calculated in the minima, are the same, it is possible to use the Laplace method to prove that marginalization and minimization yield the same \( \Delta\chi^2 \) (which can be obtained from \( P(D|MH) \) using Eq. 2). This method was applied to the two models described in the previous section, the results are shown in Fig. 4 (right panel): we can see that, while in the case of reactor neutrino experiments (at least, in the simplified model considered) this method gives us the correct result to a very good approximation, for accelerator neutrinos this is no longer true: this is to be expected, since we can deduce from Fig. 2 that in case of accelerator neutrinos \( P(D|\theta, MH)\pi(\theta) = e^{-\chi^2/2} \) is not peaked around the maximum.

### 2.3 Additional Parameter

A possible way to avoid the non-nested hypotheses issue for the neutrino mass hierarchy was suggested first in [10] for reactor neutrino experiments, where the authors introduced a new, non-physical pull parameter \( \eta \), rewriting Eq. 2 as \( |\Delta m^2_{31}| = |\Delta m^2_{32}| + (2\eta - 1)|\Delta m^2_{21}| \): when \( \eta = 0 \), the hierarchy is inverted, when \( \eta = 1 \) it is normal: in this way one can reduce our problem of model selection to a simpler problem of parameter fitting; however this approach cannot be used, for example, for accelerator neutrinos, since the matter effect depends on the sign of \( \Delta m^2_{31} \). A similar but more general approach was suggested in [11], where in order to test two hypotheses \( H_0 \) and \( H_1 \), which would generate a spectrum \( g(x) \) and \( f(x) \) respectively,
the authors considered the linear combination \( g(x) + \eta(f(x) - g(x)) \). One advantage of this kind of approach is that the CL for the rejection of both hierarchies can now be expressed in a very compact form, as \( \eta \pm \delta \eta \); on the other hand, however, it requires the introduction of a new pull parameter without physical meaning.

3 Conclusions

We have presented different approaches, within the frequentist and Bayesian frameworks, for the quantification of the sensitivity in the mass hierarchy determination. While there is no “correct” definition and, as long as we are consistent and we specify clearly the convention used, all these approaches can be correct, however it is important to notice that the Bayesian and the frequentist methods give different and complementary information, and it would be preferable to use both, for a more complete analysis.

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References

Summary of the recent PHYSTAT-ν Workshops

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This is a summary of the recent PHYSTAT-ν Workshops in Japan and at Fermilab, on ‘Statistical Issues in Experimental Neutrino Physics’.

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NuPhys2016, Prospects in Neutrino Physics
1 The PHYSTAT Workshop series

The PHYSTAT series of Workshops deals with the statistical issues that arise in analyses in High Energy Physics (and sometimes in Astroparticle Physics). The first two were devoted to the topic of Upper Limits and took place at CERN and at Fermilab in 2000. Since then Workshops have been held at Durham (2002), SLAC (2003), Oxford (2005), and CERN again (2007 and 2011). Information about these can be traced back via ref. [1].

There had not been much participation by neutrino physicists, so it was decided that there should be meetings devoted specifically to the issues that arise in analysing the results of neutrino experiments, one at IPMU in Kashiwa, Japan, and the other at Fermilab; these attracted about 90 and 130 participants respectively. More detailed information is available on their web-sites [2, 3].

2 PHYSTAT-$\nu$ Programmes

The programmes of the two meetings were similar. They consisted of:

- Introductory Statistical Material (see Section 3).
- Summary of Neutrino Physics: What to measure
- Invited and Contributed talks, including talks by Statisticians
- Panel discussion
- Poster session
- Summary talks by a Physicist and by a Statistician (Bob Cousins and David van Dyk at IPMU, Asher Kaboth and Richard Lockhart at Fermilab.)

In addition, at Fermilab there was a talk on the statistical issues involved in the recent discovery of gravitational waves by the LIGO Collaboration.

3 Introductory Topics

This was a brief summary providing information at a simple level on some of the topics that would be discussed more deeply during the rest of the meeting. They included

- Combining results of different analyses: For correlated parameters, this can sensibly produce best values outside the range of the individual values, and greatly reduced uncertainties.
• Coverage: This is a property of statistical procedures for Parameter Determination. For a repeated series of measurements, it is the fraction of parameter ranges that contain the true value.

• Blind Analysis: Various methods are available to prevent the Physics result being known until the analysis is complete. This reduces the possibility of the Physicist subconsciously biasing the result in their preferred prejudice.

• $p$-value: This is the probability of obtaining a measurement at least as discrepant as ours, assuming some hypothesis. They are widely misunderstood as the probability of the hypothesis being true, given the data.

• Significance: $p$-values are commonly converted into significance (i.e number of $\sigma$s), assuming a single-sided Gaussian tail area.

• Combining $p$-values: Their is no unique way of doing this.

• Upper Limits on cross-sections, etc: These can be useful in excluding models.

• LEE = Look Elsewhere Effect: A peak in a spectrum can be due to exciting New Physics or to a boring fluctuation. The probability of this occurring anywhere in an analysis is larger than that for a fluctuation at the position seen in the data.

• Why $5\sigma$ for discovery? See Section 5.6

• Comparing 2 hypotheses: Examples include the Neutrino Mass Hierarchies; whether sterile neutrinos exist; etc.

• Wilks Theorem: See Section 5.8

4 Physics Topics

Within the realm of neutrino physics, subjects for which statistical issues seem particularly relevant and which produced interesting discussions included:

• Fitting parameters for 3 neutrino oscillation situations

• Searching for sterile neutrinos

• Determining the neutrino mass hierarchy

• Determining the CP phase

• Searching for rare processes, e.g. ultra high energy cosmic neutrinos, neutrino-less double beta decay, supernovae neutrinos, etc.

*Although this decay process has no neutrinos, they are involved virtually, and the decay rate could provide information on neutrino properties.
• Neutrino cross-sections
• Reconstruction and classification issues, e.g. for rings in Cerenkov detectors

5 Statistical issues

5.1 Multi-variate techniques
These are widely used in data selection e.g. for preferentially rejecting signal compared with background. Typical techniques are boosted decision trees, neural networks, etc. There is no need to regard neural networks as ‘black boxes’, as it is easy to understand how a network with one hidden layer operates. At the FNAL meeting, there was a talk on Deep Learning, which uses a neural network with many layers of nodes, which are supposed to provide better discrimination.

With any multivariate method, it is important to assess its properties, including sensitivity to systematics; and to ensure that the training events cover the region of phase space that the data occupy.

5.2 Treatment of systematics
In almost all analyses, the expected distribution of data depends not only on the parameter of interest $\phi$ (e.g. the neutrino mass hierarchy), but also on so-called nuisance parameters $n$; they could be other interesting physics parameters (e.g. the CP phase) or various experimental systematics (e.g. the energy scale). To quote a result for $\phi$ requires some procedure for dealing with the nuisance parameter(s).

One possibility is to quote a range for $\phi$ for each value of $n$. This has the advantage that if subsequently the knowledge about $n$ is improved, we can easily incorporate this to obtain an improved range for $\phi$. An alternative is to eliminate $n$ by profiling or marginalisation. The former requires calculating the best value of $n$ ($n_{\text{best}}(\phi)$) for each value of $\phi$. It is sensible to apply this to a likelihood function; then the profile likelihood is given by

$$L_{\text{prof}}(\phi) = L(\phi, n_{\text{best}}(\phi))$$  \hspace{1cm} (1)

On the other hand, marginalisation involves integrating over $n$. It is used to convert the Bayesian posterior probability density $p(\phi, n)$ into one just for $p(\phi)$:

$$p(\phi) = \int p(\phi, n) \, dn$$  \hspace{1cm} (2)

For situations where the likelihood function $L(\phi, n)$ is a two (or more) dimensional Gaussian and the priors are uniform, marginalisation and profiling lead to the same result.
5.3 Non-asymptotic behaviour

With enough data, asymptotic approximations can sometimes be used to simplify an analysis. For example the log-likelihood ratio for two hypotheses $-2 \ln(L_0/L_1)$ involves summations over the observed events, and so by the Central Limit Theorem (CLT) should become Gaussian distributed.

Another example is the expected number of degrees of freedom when fitting the 2-neutrino flavour survival probability $P = 1 - \sin^2 2\theta \sin^2(\Delta m^2 L/E)$ to a lepton energy spectrum; usually there are two free parameters $\sin^2 2\theta$ and $\Delta m^2$, but for small $\Delta m^2 L/E$, the data are sensitive only to the combination $\sin^2 2\theta (\Delta m^2)^2$, unless there is really a lot of data. However, neutrino experiments sometimes have limited statistics, and so the approximation may not be valid. It is then necessary to determine the expected distribution, usually by Monte Carlo simulation.

5.4 Unphysical parameter values

There are often fierce arguments in large collaborations as to whether quoted values for physical parameters with well-defined ranges (e.g. $\sin^2 2\theta$, or the mass of a particle) should be confined to their physical ranges. The answer, of course, depends on how the result is to be used.

5.5 Bayes or Frequentism?

The ‘Bayes versus Frequentism’ choice is often the cause for intense discussion. At the Kashiwa meeting Steve Biller gave a vigorous critique of frequentist approaches.

In other fields, Baysianism tends to be far more used than in Particle Physics. At the LHC, using both Bayesian and Frequentist methods for measuring a given parameter is regarded as desirable. However, Bayesian methods are not recommended for hypothesis testing (i.e. comparing data with different hypotheses) because of the stronger dependence on the choice of the Bayesian prior.

Even for parameter determination, the choice of prior can be non-trivial. For example, should we express our ignorance about the CP phase angle by choosing a prior uniform in angle, or in its sine, or some other functional form?

5.6 Why 5σ for discovery?

For collider experiments, the standard criterion for claiming a discovery involves the $p$-value for the null hypothesis (i.e. no New Physics) $p_0$ being less than $3 \times 10^{-7}$, equivalent to 5σ. Reasons include past experience with incorrect discovery claims at lower levels; the look-elsewhere effect; underestimated systematics; and the fact that ‘extraordinary claims require extraordinary evidence’. Not all analyses are equally affected by the last three points so there is an argument in favour of having a variable discovery criterion, but there clearly are problems in implementing that.
5.7 Why $CL_s$ for exclusion?

Exclusion of $H_1$, an alternative hypothesis involving new physics, usually requires its $p$ value ($p_1$) to be smaller than, say, 0.05. In collider experiments, however, the variable often used is $CL_s = p_1/(1 - p_0)$. This is to provide protection against the 5% chance of excluding $H_1$ even when an analysis has little or no sensitivity to it. Thus $CL_s$ is a conservative modification of a frequentist procedure.

5.8 Wilks Theorem

If we compare our data with two hypotheses $H_0$ and $H_1$, we can use the difference in the two $\chi^2$ (or almost equivalently -2 times the ln-likelihood ratio) to judge which hypothesis better explains the data. This could apply for:

(a) Using a straight line or a quadratic form to fit some data.

(b) A mass spectrum. $H_0$ could be a background only distribution, while $H_1$ could be background plus signal, with the signal parametrised by its mass $M$ and production rate $\mu$.

(c) $H_0$ and $H_1$ could be the normal and inverted neutrino mass hierarchies.

For all these cases, if $\chi^2_1$ for $H_1$ is much smaller than $\chi^2_0$ for $H_0$, we would generally accept $H_1$ in preference to $H_0$. Wilks Theorem gives a way of judging whether or not the difference $\Delta \chi^2 = \chi^2_0 - \chi^2_1$ is small. It applies provided

(i) $H_0$ is true

(ii) The hypotheses are nested i.e. $H_1$ can be reduced to $H_0$ by setting to special values (e.g. zero) any extra parameters in $H_1$ but not in $H_0$

(iii) The extra parameter values to achieve this are all well-defined and not on the boundaries of their allowed ranges.

(iv) There is enough data for asymptotic approximations to be valid.

Thus the theorem applies to situation (a); then $\Delta \chi^2$ should be distributed as $\chi^2$ with the number of degrees of freedom equal to the number of extra parameters in $H_1$. However, it does not apply to (b) (because when $\mu = 0$, $M$ is irrelevant) or to (c) ($H_0$ and $H_1$ are not nested). Even when the theorem does not apply, $\Delta \chi^2$ can still be a useful variable, but its expected distribution must then be determined, usually by simulation.

5.9 Neutrino Mass Hierarchy

For comparing ‘simple’ hypotheses (ones with no free parameters), the Neyman-Pearson lemma\[4\] states that the likelihood ratio is the best data statistic for separating the hypotheses. The situation does not quite apply here, because of experimental nuisance parameters, and also because of uncertainties in the values of other relevant physics parameters (e.g. the CP phase). However $q = -2 \ln(L_{NH}/L_{IH})$ is still likely to be a useful variable, and is used as the data statistic. As already mentioned, by the CLT the distributions of $q$ under the two hypotheses are asymptotically Gaussian,
but the Gaussians are often taken to be approximately symmetrically situated at $\pm T$ and with equal widths $2\sqrt{T}$ (see, for example, references \cite{5, 6}). Whether this is so in particular circumstances needs to be checked by simulation. There are certainly similar Physics examples where it is not so.

5.10 Combining results (e.g. cross-sections) with unknown correlations

When the correlations are unknown, it is impossible to combine different results optimally. Assuming that there are no correlations is not always sensible or conservative.

5.11 Unfolding

In comparing experimental distributions with theoretical predictions, the effects of experimental resolution can be allowed for either by smearing the predictions, or by unfolding the data. The latter is a more difficult procedure. I therefore recommend making available the experimental smearing matrix, rather than unfolding. There are few circumstances in which unfolding is really preferable.

5.12 Statisticians

For all of these discussions, it was extremely valuable having Statisticians at the meetings. At Kashiwa, we had Sara Algeri, Michael Betancourt, David van Dyk, and Shiro Ikeda. Those at Fermilab were David van Dyk, Todd Kufner, Michael Kuusela, Richard Lockhart, Xiao Li Meng, and Aixin Tan. As well as their presentations, it was most valuable having them available for informal discussions during breaks between the sessions.

6 Conclusions

A post-Workshop survey showed that most participants felt that such meetings were worth-while, and would favour having more at a frequency of around 20 nanohertz. Smaller meetings devoted to statistical issues in specific analyses (e.g. the neutrino mass hierarchy) could also be useful.

Another request was for more introductory material than there was time for at these Workshops. LL and Lorenzo Moneta subsequently gave a course of lectures plus computing practicals at CERN\cite{7} and at IPMU\cite{8}.

Some of the large Collaborations at colliders have their own Statistics Committees for dealing with statistical issues arising in their own experiments. Neutrino experiments are in general too small for this, but a possibility would be to have a single forum for discussing statistical problems for all neutrino analyses.
It was gratifying to see that the Neutrino2016 Conference programme contained an invited talk by a Statistician\[9].

References

These proceedings review the two DUNE prototype detectors, namely Single- and Dual-Phase ProtoDUNEs. The detectors, both employing liquid argon Time Projection Chambers (LAr TPCs), are currently being built at CERN as part of the ProtoDUNE experimental programme. Such R&D programme aims at validating the prototypes design and technology, which will eventually be applied to the DUNE Far Detector at the Sanford Underground Research Facility (SURF).

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NuPhys2016, Prospects in Neutrino Physics
1 Introduction

The Deep Underground Neutrino Experiment (DUNE), which mainly aims at studying long-baseline neutrino oscillations, foresees to employ 40,000 tonnes of liquid argon (LAr) split among four detectors to be installed at the Sanford Underground Research Laboratory in Lead, South Dakota. These will be used as far detectors for neutrinos produced 1,300 km away at the Fermi National Accelerator Laboratory in Batavia, Illinois.

As the task is not trivial, to gain experience in building and operating such large scale LAr detectors, an R&D programme is currently underway at CERN. Such programme will operate two prototypes in a dedicated test beam by 2018, with the specific aim of testing the prototypes design, assembly and installation procedures, the detectors operations, as well as data acquisition, storage, processing and analysis under beam conditions.

The two prototypes will both employ Liquid Argon Time Projection Chambers (LAr TPCs) as detection technology, with one prototype only using liquid argon, hereby called ProtoDUNE Single-Phase (SP), and the other using argon in both its gaseous and liquid state, thus the name ProtoDUNE Dual-Phase (DP).

In the past few years, there has been an extensive and increasing effort in terms of R&D, funding, and manpower towards LAr TPCs for studies of neutrinos. These detectors are in fact very close to what a “perfect” neutrino detector is required to do: firstly, providing a large detection mass (at a relatively low cost) to compensate for the small neutrino cross-section; secondly, granting the possibility of distinguishing between $\nu_\mu$ and $\nu_e$ signals.

The first ever built tonne-scale LAr TPC was ICARUS-T600 [1], which was located at Gran Sasso and employed 760 tonnes of liquid argon ($\sim$460 tonnes active mass). The experiment operated between 2010 and 2013, collecting data using the CERN Neutrinos to Gran Sasso (CNGS) beam. It has now been refurbished at CERN and is currently being moved to Fermilab, where it will be used as the far detector in the Short-Baseline Neutrino (SBN) programme. Since then many other SP LAr TPCs have been built, such as ArgoNeuT, LArIAT, MicroBooNE, and the 35 Ton Prototype. As for the dual-phase technology, a 3 litres chamber and a 250 litres one have been constructed and operated at CERN by ETHZ. Currently, the WA105 $3\times1\times1\,\text{m}^3$ prototype, a 5 tonnes active dual-phase LAr TPC, is being commissioned at CERN [2]. The $3\times1\times1\,\text{m}^3$ demonstrator will take data with cosmic muons and, as it features many of the same technical challenges of the ProtoDUNE-DP, it will serve the purpose of test-bench for the detector to come.
2 ProtoDUNE overview

Both protoDUNEs will be located in a dedicated building in the North Area at CERN (EHN1) and placed along two separate beam lines (H2 and H4), provided by the CERN Super Proton Synchrotron (SPS). Both experiments are foreseen to start taking data in autumn 2018 till the planned SPS beam shutdown the same year.

Both detectors will have similar sizes and active mass (450 t for the ProtoDUNE-SP and 300 t for the ProtoDUNE-DP). The cryostats, which contain the LAr target and the TPCs, are identical, with outer dimensions of roughly $11 \times 11 \times 11 \text{ m}^3$ and a total capacity of around $\sim 700 \text{ t of LAr}$. Two independent cryogenic systems fill the tanks and recirculate the liquid argon to guarantee a purity level of around 100 ppt. This is to ensure that the electrons produced by the ionising particles in the medium do not get trapped and reach the charge readout system to later enable track reconstruction.

2.1 Cryostat technology

The cryostats, which are currently being constructed, make use of a “membrane” technology developed by commercial company GTT/France to store and ship liquified natural gas (LNG) at a temperature of $-163 \, ^\circ \text{C}$. The cold vessel is housed in a warm support structure and comprises a primary corrugated stainless steel membrane and a secondary membrane made of Triplex (a composite laminated material composed of a thin sheet of aluminum between two layers of glass cloth and resin [3]). The secondary membrane is inserted between two insulation layers made of polyurethane, with the first layer directly touching and supporting the primary membrane [3]. The same company also built the $3 \times 1 \times 1 \text{ m}^3$ cryostat, albeit using a slightly different design with only one insulated membrane.

A similar membrane cryostat was firstly tested in 2013 with the 35 Ton Prototype. Such membrane cryostat was designed by Fermilab engineers in collaboration with IHI Corporation of Tokyo, Japan. The main goal of the prototype (initially not equipped with a TPC) was to demonstrate that a non-evacuable membrane cryostat of this dimensions (i.e. 35 tonnes of LAr) could reach an oxygen contamination below 200 ppt [4, 5, 6]. The cryostat was successfully operated and after the 11th exchange of volume an electron drift time of 3 mm had been achieved [7]. This corresponds to an oxygen concentration of 100 ppt w/V according to the formula [8, 9, 10, 11]:

$$\tau [\mu \text{s}] = \frac{320 \text{ ppb w/V} \cdot \mu \text{s}}{\rho_{O_2}[\text{parts of O}_2 \text{ w/V}]}$$

(1)

where $\rho_{O_2}$ is the oxygen concentration expressed in units of parts of O$_2$ weight by volume (w/V).
Figure 1: Design of the ProtoDUNE-SP detector. A description of the main parts is given on the picture itself.

3 ProtoDUNE Single-Phase

Before proceeding with the description of the ProtoDUNE-SP, let us see how a single-phase LAr TPC works in general. Ionising particles that traverse the liquid argon will produce electrons and scintillation photons along the track. The charge and light signals arising from the aforementioned processes are together used to make a 3D reconstruction of the particles’ track in the following way. The electrons produced along the track drift under the electric field between cathode and anode, where they induce a transient signal on two wire planes, called induction planes, and are collected on a third one, enabling a 2D image of the track. The scintillation photons are instead collected by photodetectors (usually PMTs) and provide the trigger signal and the reference time for the interaction. By knowing the drift velocity at a given electric field and combining the time zero of the event with the distance travelled by the electrons, the depth of the ionisation track can be reconstructed, hereby achieving a full 3D image of the event.

We now may look at how this is achieved in the the ProtoDUNE-SP. Figure 1 shows a CAD design of the detector inside the cryostat. It is composed of one single cathode plane at the centre and two anode planes on the sides. The high-voltage provided to the cathode is $-180\,\text{kV}$, such that an electric field of $500\,\text{V/cm}$ is present.
between the cathode and each anode. The particles coming from the test beam traverse the detector along the cathode plane. A field cage interconnected by a resistor chain guarantees the uniformity of the field. Ground planes are placed on the top and bottom of the field cage (purple in the figure) to prevent the electric field from entering the ullage region in the top (where the high-voltage feedthrough is inserted) and to shield the cryogenic pipes in the bottom on the membrane. Both anode planes comprise three adjacent Anode Plane Assemblies (APAs). Each APA consists of a grid, two induction planes oriented at ±37.5° with respect to the vertical axis, and a collection plane. Behind the collection plane another layer of wires, a grounded mesh, shields the photon detection system behind (e.g. from “ghost” tracks traversing the collection plane) [12].

As seen previously, a particle entering the LAr will ionise the medium, leaving electrons around the track which will move from the cathode towards one of the two anodes under the influence of the electric field. As just mentioned, the induction and collection planes are screened by a grid. The reason for such grid is the following. Positive ions moving to the cathode induce on the anode plane a signal of the same polarity as that from electrons moving to the anode. It was shown that this induction effect can be eliminated by inserting a grid in front of the induction/collection wire planes and biasing it appropriately [13]. The inductions planes are transparent to the charges and when the drifting electrons pass through them they induce a bipolar signal. In principle, for the event 3D reconstruction only one induction and collection plane are needed, but an extra one allows to reconstruct tracks with ambiguous orientation.

As for the photon detection system, the ProtoDUNE-SP uses Silicon Photomultipliers (SiPMs). Light guides are embedded in the APA structure. These guides are coated in Tetraphenyl-Butadiene (TPB), a wavelength shifter which allows the VUV LAr scintillation light (the spectrum being peaked at ∼128 nm) to be shifted into the visible range. Once wavelength-shifted, photons are collected from the SiPMs mounted at the end of the light guide.

4 ProtoDUNE Dual-Phase

To improve image resolution and increase the signal to noise ratio, dual-phase technology may be used. Let us see how this is achieved by directly describing the ProtoDUNE-DP.

Figure 2 shows the CAD design of the detector housed in the cryogenic vessel. The TPC comprises two independent structures: the drift cage and the charge readout plane (CRP). The first structure is composed of a ground grid with PMTs underneath, a cathode, and the drift cage, whose aluminum shaping field rings allow a uniform electric field. The second structure consists of an extraction grid, Large Electron
Multipliers (LEMs), and the anode readout plane.

Liquid argon fills the cryostat up to 5 mm above the extraction grid, with the rest of the tank being filled with gaseous argon. The scintillation photons produced by particles traversing the LAr (note the beam entrance on the right in Fig. 2) are detected by TPB coated PMTs. As for the ProtoDUNE-SP, the light signal provides the time reference of the event (note that the test beam itself may also give the time reference). The ionisation electrons along the particle’s track are shifted upwards under the 500 V/cm electric field in the drift cage. For 6 m drift distance, 300 kV must be provided to the cathode. As of today, the high-voltage feedthrough used in the $3 \times 1 \times 1 \text{ m}^3$ detector has been successfully tested in liquid argon down to $-300 \text{kV}$ [14]. The same power supply and an analogous design will be used for the high-voltage feedthrough for the ProtoDUNE-DP.

As shown in Fig. 3, the electrons drifting upwards will be eventually extracted into the gaseous phase thanks to a stronger electric field ($\sim 2 \text{kV/cm}$ in the liquid) provided by the extraction grid placed 5 mm below the liquid surface. Once in gas argon, electrons will enter the LEMs, where they undergo charge amplification. LEMs are constructed by drilling submillimeter diameter holes, spaced by a fraction of a mm in a thin printed circuit board, followed by Cu-etching of the hole’s rim [15].

Figure 2: Design of the ProtoDUNE-DP detector with main parts highlighted.
Figure 3: Schematic of the charge readout plane: the electrons are extracted from the liquid into the gas, where they are collimated in the LEMs, undergoing a process called “Townsend avalanche”. The amplified charge is then read by the multilayer PCB anode.

An electrical potential is applied between the conductive plates, creating a strong electric field in the holes (~30 kV/cm, which is below the breakdown voltage of GAr). The drifting electrons are collimated in the holes where they accelerate and create a cascade of secondary electrons, called “Townsend avalanche”. The charge is collected by a multilayer PCB anode [16]. The anode is designed to provide two fully symmetric collection planes, meaning the signal is unipolar only. For each plane a gain of 10 for the charge extracted is foreseen during operations.

Given we have now outlined both single- and dual-phase LAr TPC technology and presented the design of both detectors, we may summarise their differences, identifying advantages and disadvantages.

5 Final remarks

Regarding the ProtoDUNE-SP one clear advantage is that there is no need to adjust the liquid level; instead, for the ProtoDUNE-DP one needs to precisely position the CRP above the liquid surface and keep surface instabilities to a minimum.

Since the SP is segmented into two 3.6 m wide detectors, the high-voltage feedthrough needs to deliver roughly half of the DP voltage for the same electric drift field. On the other end, the longer drift distance is an elegant feature of the ProtoDUNE-DP,
as it allows to construct the TPC with minimum amount of channels and to have one single active volume.

Another advantage of the SP versus the DP is that while in the ProtoDUNE-DP the high-voltage feedthrough needs to go from the top to the cryostat down to the cathode, which adds some mechanical challenges, for the ProtoDUNE-SP the high-voltage feedthrough only needs to penetrate the insulation layer (∼2 m) in order to touch the cathode plane.

On the other end, the DP technology has the huge advantage of relying on two symmetric collection planes, which provide a clearer signal than the induction planes of the SP (smaller, bipolar signals are also harder to simulate and reconstruct than unipolar). Finally, the large signal to noise ratio permits operation at higher granularity (3 mm versus the 5 mm on the SP), besides making the detector less sensitive to the grounding scheme.

References


The Hyper-Kamiokande Experiment

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Hyper-Kamiokande (HK) is a next generation large water Cherenkov detector to be built in Japan, based on the highly successful Super-Kamiokande detector. HK will offer a broad science program such as neutrino oscillation studies, proton decay searches, and neutrino astrophysics with unprecedented sensitivities. This paper describes the overview and physics potential of HK.

PRESENTED AT

NuPhys2016, Prospects in Neutrino Physics
1 The Hyper-Kamiokande project

Hyper-Kamiokande (HK) is a next generation underground water Cherenkov detector. Based on the highly successful Super-Kamiokande (SK), the detector performance will be further enhanced by an order of magnitude larger fiducial mass and higher performance photodetectors. It will have far-reaching sensitivities for a very broad range of science topics, including neutrino oscillation studies, proton decay searches, and neutrino astrophysics.

The current baseline design of HK comprises two cylindrical detectors that are 60 m in height and 74 m in diameter (Fig. 1). The design was revised in the beginning of 2016 as a result of optimization, taking into account the recent technical development [1]. The newly developed 50cm PMT, Hamamatsu R12860, has twice better photon detection efficiency and timing resolution compared to R3600, the PMT used for SK [2]. In addition, it has an improved pressure tolerance so that a deeper tank becomes feasible. Alternative solutions for photosensors are also extensively studied by the international collaboration.

The total (fiducial) mass of water will be 260(190) kton per tank. The inner detector region will be instrumented with 40,000 50 cm high-performance PMTs, corresponding to 40% photo-cathode coverage. The outer detector will be equipped with 6,700 20 cm PMTs. The proposed location for HK is about 8 km south of SK and 1,750 meters water equivalent (or 648 m of rock) deep. A staging between the first and second tank is planned for the construction. In the study described in this paper, the second tank is assumed to become operational at the same site after six years. Recently, a possibility of building the second tank in Korea is explored [3]. It is discussed separately [4].

In this paper, the overview of HK physics program will be described, with an emphasis on the enhancement of capabilities realized with the new design.

Figure 1: Schematic view of one HK detector. From [1].
Figure 2: Expected invariant mass distributions for $p \rightarrow e^+\pi^0$ candidates with ten years of HK. The proton lifetime is assumed to be $1.7 \times 10^{34}$ years. The left (right) plot shows the free (bound) proton enhanced region in the total momentum $p_{\text{tot}}$, $p_{\text{tot}} < 100$ MeV ($100 < p_{\text{tot}} < 250$ MeV). The points (histogram) show the sum of the background and proton decay signal (atmospheric neutrino background).

2 Physics capabilities

2.1 Search for proton decay

2.1.1 $p \rightarrow e^+\pi^0$

Proton decays into a positron and neutral pion, $p \rightarrow e^+\pi^0$, are a dominant decay mode in many GUT models. It also has a very clean experimental signature in a water Cherenkov detector with full reconstruction of the event.

After decades of search, the sensitivity is still improving with advancement of detector technology and analysis technique. One of examples for such a technique is the background suppression with the neutron tagging. In the proton decay events, the probability of neutron emission is rather small, while in the atmospheric neutrino events, which is the dominant background of proton decay searches, often neutrons are produced. Thus, neutron tagging can provide an additional handle to suppress the background for the proton decay search and improve the sensitivity.

The ability to tag the 2.2 MeV photon from neutron capture on hydrogen, $n + p \rightarrow d + \gamma$, in a water Cherenkov detector is demonstrated by the proton decay searches with SK-IV [5]. With 40% photo-coverage and R3600 PMT, the neutron tagging efficiency in SK is about 20%. HK will have a better efficiency for the low energy photons thanks to the higher photon detection efficiency. From the expected number of hits for 2.2 MeV $\gamma$ ray, the neutron tagging efficiency in HK is assumed to be 70%. Gd doping is also investigated as an option to further improve the neutron tagging efficiency, but not considered in this study. Table [1] shows the expected signal efficiency and background rates for HK, compared to those of the SK-IV [5]. Figure [2] shows the reconstructed invariant mass distribution expected with ten years of HK data for the proton lifetime of $1.7 \times 10^{34}$ years.
Table 1: Signal efficiency and background rates for $p \to e^+\pi^0$ at HK and SK-IV \cite{5}.

<table>
<thead>
<tr>
<th></th>
<th>$0 &lt; p_{\text{tot}} &lt; 100 \text{MeV}/c$</th>
<th>$100 &lt; p_{\text{tot}} &lt; 250 \text{MeV}/c$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\epsilon_{\text{sig}}$ [$%$]</td>
<td>$\sigma_e$ [%]</td>
</tr>
<tr>
<td>HK</td>
<td>18.7</td>
<td>6.5</td>
</tr>
<tr>
<td>SK-IV</td>
<td>18.7</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Table 2: Signal efficiency and background rates for $p \to \nu K^+$.

The numbers for SK \cite{6} are also listed.

<table>
<thead>
<tr>
<th>$K^+ \to \mu^+ + \nu$ with prompt $\gamma$</th>
<th>$K^+ \to \pi^+\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{\text{sig}}$ [$%$]</td>
<td>$\sigma_e$ [%]</td>
</tr>
<tr>
<td>HK</td>
<td>12.7</td>
</tr>
<tr>
<td>SK-IV</td>
<td>9.1</td>
</tr>
</tbody>
</table>

2.1.2 $p \to \bar{\nu} K^+$

Proton decays into an antineutrino and a charged kaon, $p \to \bar{\nu} K^+$, are a dominant mode in many of supersymmetric grand unified theories. In a water Cherenkov detector, $K^+$ from proton decay is not directly visible because its momentum is below the Cherenkov threshold, but can be identified from its decay products.

For $K^+ \to \mu^+ + \nu$ (branching fraction 64%), in addition to detecting a monochromatic (236 MeV/c) muon, nuclear de-excitation $\gamma$ ray (6.3 MeV) can be used to tag the signal. Better detection efficiency and timing resolution of the new photosensor will lead to an improved efficiency of low energy $\gamma$ rays.

For $K^+ \to \pi^+\pi^0$ (branching fraction 21%), the $\pi^+$ has a momentum just above the Cherenkov threshold and emits only faint light. With better photon detection efficiency, the detection efficiency of $\pi^+$ will be improved.

Table 2 summarizes the efficiency and background expectation for $p \to \bar{\nu} K^+$ searches. Neutron tagging is also applied for this mode. There is the third method for the $p \to \bar{\nu} K^+$ search, search for an excess in the muon momentum distribution, not shown in the table.

2.1.3 Expected sensitivity for proton decay

Figure 3 shows the estimated $3\sigma$ discovery potential of $p \to e^+\pi^0$ (left) and $p \to \bar{\nu} K^+$ (right) as a function of run time. After 20 years of operation, the expected $3\sigma$ sensitivities for $p \to e^+\pi^0$ and $p \to \bar{\nu} K^+$ are $8.0 \times 10^{34}$ and $2.5 \times 10^{34}$ years, respectively. With HK, there is a large potential to discover the proton decays with lifetime beyond the current lower limit given by SK, $1.6 \times 10^{34}$ years and $5.9 \times 10^{33}$ years.
Figure 3: Estimated $3\sigma$ discovery potential of $p \rightarrow e^+\pi^0$ (left) and $p \rightarrow \nu K^+$ (right) as a function of run time. The red, orange and grey lines correspond to the baseline design of HK, the case for just single tank, and the old design (560 kt fiducial mass with 20% coverage with R3600), respectively. The cyan line shows a 40 kton liquid argon detector, with assumption of a signal efficiency of 45%(97%) and background of 1.0(1.0) events per Megaton·year for $p \rightarrow e^+\pi^0$ ($p \rightarrow \nu K^+$). Systematic errors are included for the HK lines but not for the liquid argon detector.

2.2 Low energy physics

As is demonstrated by SK, a water Cherenkov detector has an excellent potential for broad and rich science with low energy ($\mathcal{O}(1–10)$ MeV) neutrinos. In this energy region, the performance of the detector is mainly limited by number of detected photons. Hence, improved photon detection efficiency of HK will significantly benefit the low energy physics program. In order to fully exploit the improved performance for low energy physics, careful control of background (such as radioactivity and spallation) and water quality, and precise calibration by design and operation of the detector will be necessary. An extensive R&D by international cooperation is under way.

One example of low energy physics that benefits from HK design is the study of solar neutrinos. There is about $2\sigma$ of tension in $\Delta m^2_{21}$ between solar neutrino measurements and KamLAND reactor neutrino measurement [7]. The day-night asymmetry of solar neutrino event rate due to the regeneration of the electron neutrinos through the MSW matter effect in the Earth can provide us a precise determination of $\Delta m^2_{21}$ using $\nu_e$ (in contrast to $\bar{\nu}_e$ from reactors), providing a $5\sigma$ resolution if the difference from KamLAND value persists and 0.3% systematic uncertainty is achieved. The observation of the spectrum upturn in solar neutrino, caused by the transition of the survival probability from the matter dominant to the vacuum dominant energy region, will be possible with the low threshold and high statistics. The precise measurement of the spectrum shape can distinguish the standard neutrino oscillation scenario from
Table 3: The expected number of $\nu_e/\bar{\nu}_e$ candidate events and efficiencies with respect to FCFV events. Normal mass hierarchy with $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed. Background is categorized by the flavor before oscillation.

<table>
<thead>
<tr>
<th>$\nu$ mode</th>
<th>Events</th>
<th>Eff. (%)</th>
<th>$\nu_\mu \rightarrow \nu_e$</th>
<th>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</th>
<th>$\nu_\mu$ CC</th>
<th>$\bar{\nu}_\mu$ CC</th>
<th>$\nu_e$ CC</th>
<th>$\bar{\nu}_e$ CC</th>
<th>NC</th>
<th>BG</th>
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<tr>
<td>2300</td>
<td>63.6</td>
<td>47.3</td>
<td>10</td>
<td>0</td>
<td>347</td>
<td>15</td>
<td>188</td>
<td>560</td>
<td>2880</td>
<td></td>
<td></td>
</tr>
<tr>
<td>289</td>
<td>45.0</td>
<td>70.8</td>
<td>3</td>
<td>3</td>
<td>142</td>
<td>30.8</td>
<td>1.6</td>
<td>1.6</td>
<td>724</td>
<td>2669</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 shows the expected number of events after $\nu_e$ signal selection, for $\sin^2 2\theta_{13} = 5\sigma$ observation of the upturn in the transition region will be possible with HK, if background and calibration level similar to those of SK can be achieved. Also, thanks to the good resolution, measurement of hep neutrino could be possible.

Another important topic is the study of supernova neutrinos, as presented in [2].

2.3 Studies of neutrino oscillation

2.3.1 Long baseline program

Recently, the T2K collaboration reported the first constraint on $\delta_{CP}$ [8, 9, 10], which indicates that the $CP$ violation in the lepton sector may be large, although the statistical significance is still insufficient. The observation and study of the $CP$ asymmetry in the lepton sector, now possible with the comparison of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, is one of the most important topics in particle physics. Precision measurements of oscillation parameters require both large statistics and well controlled systematics. Combining an intense and high quality neutrino beam from J-PARC, the huge mass and high performance of Hyper-K detector, a highly capable near/intermediate detector complex [11], and the full expertise obtained from ongoing T2K/SK experiments, Hyper-K will be the best project to probe the $CP$ violation in the lepton sector and new physics with neutrino oscillation.

The beam power from J-PARC accelerator and its neutrino beamline is expected to be significantly increased in near future. The accelerator upgrade to double the repetition rate is ongoing, to reach the design power of 750 kW and beyond. Based on high intensity studies of the current accelerator performance, it is expected that 1.3 MW beam power can be achieved by the time HK will start operation. The upgrade of the neutrino beamline is also planned to keep up with the upgrade of accelerator power. For the sensitivity estimation of the long baseline experiment using HK, an integrated beam power of 1.3 MW x 10^8 sec, corresponding to ten years, is assumed.

Table 3 shows the expected number of events after $\nu_e$ signal selection, for $\sin^2 2\theta_{13} =$
Figure 4: (Left) Expected significance to exclude $\sin \delta_{CP} = 0$ for normal mass hierarchy. (Right) Expected 68% CL uncertainty of $\delta_{CP}$ as a function of running time.

0.1, $\delta = 0$, and normal mass hierarchy. For each of neutrino and anti-neutrino mode, $\mathcal{O}(1000)$ signal events are expected. The sensitivity is estimated based on a framework developed in T2K experiment [12]. The analysis is the same as one described in [13], except for the update of the systematic uncertainty estimate. A binned likelihood analysis based on the reconstructed neutrino energy distribution is performed using both $\nu_e$ ($\bar{\nu}_e$) appearance and $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance samples simultaneously.

The systematic uncertainty is estimated based on the experience of T2K, with an extrapolation considering improvement expected in HK era. Correlations of systematics between energy bins and flavors are taken into account using an error matrix.

Figure 4(left) shows the expected significance to exclude $\sin \delta_{CP} = 0$ (the $CP$ conserved case). $CP$ violation in the lepton sector can be observed with more than $3(5)\sigma$ significance for 78(62)% of the possible values of $\delta_{CP}$. Figure 4(right) shows the 68% CL uncertainty of $\delta_{CP}$ as a function of the running time. The value of $\delta_{CP}$ can be determined with an uncertainty of 7.2° for $\delta_{CP} = 0^\circ$ or $180^\circ$, and 21° for $\delta_{CP} = \pm 90^\circ$.

Using both $\nu_e$ appearance and $\nu_\mu$ disappearance channels, precise measurements of $\sin^2 \theta_{23}$ and $\Delta m_{32}^2$ will be possible. Expected 1σ uncertainty of $\sin^2 \theta_{23}$ is 0.015(0.006) for $\sin^2 \theta_{23} = 0.5(0.45)$. The uncertainty of $\Delta m_{32}^2$ is expected to reach $< 1\%$.

There will be also a variety of measurements possible with both near and far detectors, such as neutrino-nucleus interaction cross section measurements and search for exotic physics, using the well-understood neutrino beam.

2.3.2 Atmospheric neutrinos

Atmospheric neutrinos provide a wide variety of energy, baseline, and flavor of neutrinos, giving access to complementary information to accelerator neutrinos. In particular, significant modification of neutrino oscillation probabilities in the energy range 2-10 GeV due to matter effects inside the Earth gives a sensitivity to the mass hier-
Figure 5: Mass hierarchy (left) and \( \theta_{23} \) octant (right) sensitivity by a combination of beam and atmospheric neutrinos in HK.

After 10 years, the measurement with atmospheric neutrino alone is expected to resolve the mass hierarchy at \( \sqrt{\Delta \chi^2} > 3 \) for both hierarchy assumptions and when \( \sin^2 \theta_{23} > 0.45 \).

Moreover, the sensitivities are enhanced by a combination of accelerator and atmospheric neutrinos. Figure 5 shows the sensitivities for mass hierarchy (left) and \( \theta_{23} \) octant (right) by a combination of beam and atmospheric neutrinos. The mass hierarchy can be determined with more than 3(5) \( \sigma \) with five (ten) years of data, and the octant of \( \theta_{23} \) can be resolved if \( |\theta_{23} - 45| > 2.5^\circ \) in ten years.

Atmospheric neutrino can study additional topics, such as \( \nu_\tau \) cross section measurement, search for sterile neutrino, and the test of Lorentz invariance. It will also provide information on the chemical composition of Earth’s outer core using matter effect, contributing to the geophysics.

3 Conclusions

Hyper-Kamiokande will have a rich program with world-leading science output. Based on technology well established with past/ongoing experiments, it will realize a fast and robust approach to the \( CP \) violation in the lepton sector and a long term observational program with a wide range of science. An international collaboration of about 300 members from 15 countries is working to promote the project towards realization. Assuming the start of construction in 2018, the data taking is expected to start from 2026.
ACKNOWLEDGEMENTS

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[4] Intae Yu, in these proceedings.


[10] Kirsty Duffy, in these proceedings.


I discuss different theories of leptonic flavor and their capability of describing the features of the lepton sector, namely charged lepton masses, neutrino masses, lepton mixing angles and leptonic (low and high energy) CP phases. In particular, I show examples of theories with an abelian flavor symmetry $G_f$, with a non-abelian $G_f$ as well as theories with non-abelian $G_f$ and CP.
1 Introduction

Charged lepton masses have been determined with high precision

\[ m_e = (0.5109989461 \pm 0.0000000031) \text{ MeV}, \]
\[ m_\mu = (105.6583745 \pm 0.0000024) \text{ MeV}, \]
\[ m_\tau = (1776.86 \pm 0.12) \text{ MeV} \tag{1} \]

and turned out to be strongly hierarchical. In contrast, the neutrino mass spectrum is not yet completely known, but the solar and the atmospheric mass squared differences \( \Delta m^2_{\text{sol}} \) and \( |\Delta m^2_{\text{atm}}| \) have been measured in neutrino oscillation experiments

\[ 7.03 \times 10^{-5} \text{eV}^2 \lesssim \Delta m^2_{\text{sol}} \lesssim 8.09 \times 10^{-5} \text{eV}^2, \quad 2.41 \times 10^{-3} \text{eV}^2 \lesssim |\Delta m^2_{\text{atm}}| \lesssim 2.64 \times 10^{-3} \text{eV}^2 \tag{2} \]

and an upper bound on the sum of the neutrino masses of less than 1 eV is derived from cosmology and beta decay experiments. The 3\( \sigma \) ranges of the three lepton mixing angles, obtained in global fits of the data from neutrino experiments, are

\[ 0.01934 \lesssim \sin^2 \theta_{13} \lesssim 0.02397, \quad 0.271 \lesssim \sin^2 \theta_{12} \lesssim 0.345, \quad 0.385 \lesssim \sin^2 \theta_{23} \lesssim 0.638. \tag{3} \]

The nature of neutrinos, i.e. whether they are Dirac or Majorana particles, is still unknown. The following discussion assumes them to be Majorana particles. However, most of the results also hold for neutrinos being Dirac particles. For now only hints exist for CP violation in the lepton sector.

The strong hierarchy among the charged lepton masses, that is observed among the masses of the up and down type quarks as well, has led to the consideration of abelian flavor symmetries \( G_f \), usually called Froggatt-Nielsen (FN) symmetry \( U(1)_{\text{FN}} \). The different generations of charged leptons carry different charges under \( U(1)_{\text{FN}} \). As \( \sqrt{\Delta m^2_{\text{sol}}/|\Delta m^2_{\text{atm}}|} \sim 1/6 \), neutrino masses exhibit no strong hierarchy and it is thus expected that the neutrino sector is (partly) uncharged under \( U(1)_{\text{FN}} \) (see e.g. below the assignment called leptonic anarchy). A disadvantage is that an FN symmetry is only capable to explain the order of magnitude of observables in terms of the (small) symmetry breaking parameter \( \lambda \).

For a non-abelian \( G_f \) many choices of symmetries are available: if \( G_f \) should be continuous, potentially suitable choices are \( SO(3), SU(2) \) and \( SU(3) \). While for \( G_f \) being discrete indeed an infinite number of potentially suitable choices is known, like the series of dihedral groups \( D_n \) \((n > 2)\), alternating groups \( A_n \) \((n = 4, 5)\), symmetric groups \( S_n \) \((n = 3, 4)\), the series \( \Delta(3n^2) \) and \( \Delta(6n^2) \) for \( n > 1 \). An advantage of such non-abelian \( G_f \) is the possibility to unify the three lepton generations partially, \( L_\alpha \sim 2 + 1 \), or fully, \( L_\alpha \sim 3 \). Furthermore, if broken to non-trivial residual symmetries \( \text{[5]} \), like \( G_f = S_4 \) that is broken to \( Z_3 \) in the charged lepton and to \( Z_2 \times Z_2 \) in the neutrino sector, certain values of the lepton mixing parameters can be predicted, e.g. tri-bi-maximal mixing. Compared to an abelian \( G_f \), model building with a non-abelian \( G_f \) is, however, more challenging, e.g. more fields are needed, the construction of the potential in order to achieve the correct symmetry breaking pattern is non-trivial.

Recently, theories with a discrete non-abelian \( G_f \) have been extended with a CP symmetry \( \text{[6]} \), in particular, in order to also predict the Majorana phases \( \alpha \) and \( \beta \) and in order

\[ \text{[An example of a model with a continuous non-abelian } G_f \text{ is found in [4].} \]
The main problem of the $\mathcal{A}\mu\mathcal{E}$ model is the prediction of a too small $\beta_{12}$ and, in the no SeeSaw case, also a too large value of $\beta_{13}$. Note we have made a reappraisal of Anarchy, given the new experimental results. To make connection with quark masses those based on discrete non-Abelian symmetries (which start at LO with TB or BM mixing).

Over the years there has been a continuous progress in the measurement of neutrino mixing angles. Hence, such a description of the quark sector, quark masses as well as mixing angles. Hence, such a symmetry can be suitable for both leptons and quarks. In addition, it has been shown that to obtain non-trivial values for the Dirac phase $\delta$. If such a theory comprises right-handed (RH) neutrinos, it is possible to generate the baryon asymmetry $Y_B$ of the Universe via (unflavored) leptogenesis. In this case the sign of $Y_B$ can be directly correlated with the results for the low energy CP phases $\alpha, \beta$ and $\delta$.

## 2 Theories with abelian $G_f$

In [8] the following charge assignments of the three generations of the left-handed (LH) lepton doublets $L_\alpha$, RH charged leptons $\alpha_\ell^c$ and RH neutrinos $\nu_\ell^c$ have been analyzed:

- lepton anarchy ($A$): $L_\alpha \sim (0, 0, 0)$, $\alpha_L^c \sim (3, 2, 0)$, $\nu_\ell^c \sim (0, 0, 0)$
- $\mu\tau$-anarchy ($A_{\mu\tau}$): $L_\alpha \sim (1, 0, 0)$, $\alpha_L^c \sim (3, 2, 0)$, $\nu_\ell^c \sim (2, 1, 0)$
- pseudo $\mu\tau$-anarchy ($PA_{\mu\tau}$): $L_\alpha \sim (2, 0, 0)$, $\alpha_L^c \sim (5, 3, 0)$, $\nu_\ell^c \sim (1, -1, 0)$
- hierarchy ($H$): $L_\alpha \sim (2, 1, 0)$, $\alpha_L^c \sim (5, 3, 0)$, $\nu_\ell^c \sim (2, 1, 0)$

The structure of the charged lepton mass matrix $m_l$ and the light neutrino mass matrix $m_\nu$, arising from leptonic anarchy, is

$$m_l \sim \begin{pmatrix} \lambda^3 & \lambda^2 & 1 \\ \lambda^3 & \lambda^2 & 1 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \quad \text{and} \quad m_\nu \sim \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}.$$  \hfill (4)

In figure we display the success of the different charge assignments in describing correctly the lepton masses and mixing angles with respect to $\lambda$ as well as the probability distribution of the values of $\delta$ for a fixed value of $\lambda$, assuming the seesaw mechanism responsible for neutrino masses.

The realization of a model with an FN symmetry is simple. In particular, the breaking of $U(1)_{FN}$ is easily engineered. Furthermore, an FN symmetry is also often used for the description of the quark sector, quark masses as well as mixing angles. Hence, such a symmetry can be suitable for both leptons and quarks.
it can also be compatible with the particle assignment in a grand unified theory. Results, similar to those obtained with an FN symmetry, can also be achieved in extra-dimensional models in which particles are localized differently in the additional dimension(s). For models with an FN symmetry see [9].

3 Theories with non-abelian \( G_f \)

If a discrete non-abelian \( G_f \) is broken to (non-trivial) residual symmetries \( G_e \) in the charged lepton and to \( G_\nu = Z_2 \times Z_2 \) in the neutrino sector, lepton mixing mixing angles and the Dirac phase (up to \( \pi \)) can be fixed [5]. \( G_e \) is chosen in such a way that the three lepton generations can be distinguished, while \( G_\nu \) is always fixed to the maximal residual symmetry for three Majorana neutrinos that does not lead to any constraints on their masses. The requirement that the charged lepton mass matrix \( m_l \) should be invariant under \( G_e \) determines the contribution \( U_e \) of charged leptons to the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix \( U_{PMNS} \), while the request that \( m_\nu \) is invariant under \( G_\nu \) fixes \( U_\nu \). So, also the form of the PMNS mixing matrix \( U_{PMNS} = U_e^\dagger U_\nu \) is given by \( G_e \) and \( G_\nu \), up to possible permutations of rows and columns of \( U_{PMNS} \), since lepton masses are not predicted from \( G_f \), \( G_e \) and \( G_\nu \). Consequently, the lepton mixing angles and the Dirac phase are determined up to these permutations of rows and columns of \( U_{PMNS} \). Furthermore, the columns of \( U_e \) and \( U_\nu \) can be re-phased, so that Majorana phases are in general not fixed.

One of the very first implementations of this approach that leads to non-zero \( \theta_{13} \) and non-maximal \( \theta_{23} \) has been discussed in [10]. The choice of \( G_f \) is \( G_f = \Delta(96) \). The residual symmetries are \( G_e = Z_3 \) and \( G_\nu = Z_2 \times Z_2 \) and lead to a PMNS mixing matrix whose elements have the absolute values

\[
||U_{PMNS}|| = \frac{1}{\sqrt{3}} \left( \begin{array}{ccc} \frac{1}{2} (\sqrt{3} + 1) & 1 & \frac{1}{2} (\sqrt{3} - 1) \\ \frac{1}{2} (\sqrt{3} - 1) & 1 & \frac{1}{2} (\sqrt{3} + 1) \\ \frac{1}{2} (\sqrt{3} + 1) & 1 & \frac{1}{2} (\sqrt{3} - 1) \end{array} \right). \tag{5}
\]

The results for the lepton mixing angles are

\[
\sin^2 \theta_{12} = \sin^2 \theta_{23} = \frac{8 - 2 \sqrt{3}}{13} \approx 0.349 \quad \text{and} \quad \sin^2 \theta_{13} = \frac{2 - \sqrt{3}}{6} \approx 0.045. \tag{6}
\]

The Dirac phase is predicted to be trivial, \( \sin \delta = 0 \). A grand unified theory with \( G_f = \Delta(96) \) has been constructed in [11]. In several studies [12], in particular in [13], series of \( G_f \), possible choices of \( G_e \) and \( G_\nu \) and the resulting mixing patterns have been analyzed. It has been observed that \( \sin \delta = 0 \) follows, if the lepton mixing angles are in accordance with the experimental data.

This approach can be combined with an FN symmetry so that a simultaneous understanding of lepton mixing parameters as well as charged lepton masses becomes possible. For \( G_f \) being discrete, the symmetry breaking scale can be as low as the electroweak scale or even larger than the scale of grand unification which offers great freedom in building models. Explicit model realizations with a non-abelian discrete \( G_f \) are discussed in e.g. [14].
4 Theories with non-abelian $G_f$ and CP

In a scenario with a discrete non-abelian $G_f$ and a CP symmetry, in which both symmetries are broken to (non-trivial) residual groups, it becomes possible to not only determine the lepton mixing angles and $\delta$, but also the Majorana phases $\alpha$ and $\beta$. The CP symmetry that is imposed in the fundamental theory acts in general non-trivially on flavor space [15], i.e. for a set of scalars $\phi_i$ that transform in the same way under the gauge symmetries (and form a multiplet of $G_f$) a CP transformation $X$ acts as

$$
\phi_i \to X_{ij} \phi_j^* \quad \text{with} \quad XX^\dagger = XX^* = 1.
$$

(7)

In order to consistently combine $G_f$ and CP certain conditions have to be fulfilled [6, 16]. In the following examples all such conditions are fulfilled. The approach for fixing lepton mixing angles and predicting leptonic CP phases, presented in [6], assumes $G_f$ and CP and as residual symmetries $G_e$ and $G_{\nu}$. While $G_e$ has to fulfill the same constraints as in the approach without CP, $G_{\nu}$ is chosen as the direct product of a $Z_2$ symmetry, contained in $G_f$, and the CP symmetry. Thanks to the latter choice it becomes possible to also predict the Majorana phases. Furthermore, one real free parameter, which affects in general all lepton mixing parameters, is introduced in the PMNS mixing matrix, since $G_{\nu}$ is no longer the maximal residual symmetry $Z_2 \times Z_2$. A consequence of this free real parameter is the possibility to obtain results for lepton mixing angles in agreement with experimental data and, at the same time, to achieve non-trivial values of the Dirac phase $\delta$. The actual form of the PMNS mixing matrix in this approach is obtained from the contribution $U_e$ to lepton mixing from charged leptons, determined by $G_e$, and the contribution $U_\nu$ from neutrinos, which is subject to $G_{\nu} = Z_2 \times CP$. It can be shown that $U_\nu$ can be written as $U_\nu = \Omega_\nu R(\theta) K_\nu$ and thus $U_{PMNS}$ reads

$$
U_{PMNS} = U_e^\dagger \Omega_\nu R(\theta) K_\nu
$$

(8)

with $\Omega_\nu$ being determined by the CP transformation $X$ and the residual $Z_2$ flavor symmetry, $R(\theta)$ being a rotation in one plane through the free parameter $\theta$, $0 \leq \theta < \pi$, and $K_\nu$ a diagonal matrix with entries $\pm 1$ and $\pm i$. The latter is related to the request to achieve positive neutrino masses. Like the approach given in the preceding section, also here lepton masses are unconstrained. Hence, all statements made hold up to possible permutations of rows and columns of the PMNS mixing matrix.

One example that shows the predictive power of this approach has been discussed in [6]. For $G_f = S_4$, $G_e = Z_3$ and $G_{\nu} = Z_2 \times CP$ the PMNS mixing matrix is of the form

$$
U_{PMNS} = \frac{1}{\sqrt{6}} \begin{pmatrix}
2 \cos \theta & \sqrt{2} & 2 \sin \theta \\
- \cos \theta + i \sqrt{3} \sin \theta & \sqrt{2} & - \sin \theta - i \sqrt{3} \cos \theta \\
- \cos \theta - i \sqrt{3} \sin \theta & \sqrt{2} & - \sin \theta + i \sqrt{3} \cos \theta
\end{pmatrix} K_\nu
$$

(9)

which leads to lepton mixing angles

$$
\sin^2 \theta_{13} = \frac{2}{3} \sin^2 \theta, \quad \sin^2 \theta_{12} = \frac{1}{2 + \cos 2\theta}, \quad \sin^2 \theta_{23} = \frac{1}{2}
$$

(10)

and CP phases

$$
|\sin \delta| = 1, \quad \sin \alpha = 0 \quad \text{and} \quad \sin \beta = 0.
$$

(11)
\[ s \begin{array}{cccc|cc} & \sin^2 \theta_{13} & \sin^2 \theta_{12} & \sin^2 \theta_{23} & \sin \delta & \sin \alpha = \sin \beta \\ \hline s = 1 & 0.0220 & 0.318 & 0.579 & 0.936 & -1/\sqrt{2} \\ & 0.0220 & 0.318 & 0.421 & -0.936 & -1/\sqrt{2} \\ s = 2 & 0.0216 & 0.319 & 0.645 & -0.739 & 1 \\ s = 4 & 0.0220 & 0.318 & 0.5 & \mp 1 & 0 \end{array} \]

Table 1: Results for lepton mixing parameters from \( G_f = \Delta(6n^2) \) with \( n = 8 \), \( m = 4 \) and different CP transformations \( X(s) \). The matrix \( K_\nu \) is chosen as trivial. The absolute value of \( \sin \delta \) is large and the two Majorana phases \( \alpha \) and \( \beta \) take different values for different \( s \).

The Dirac phase is thus maximal, whereas both Majorana phases are trivial. Furthermore, the atmospheric mixing angle is fixed to be maximal. The reactor and the solar mixing angle depend on the free parameter \( \theta \) and for \( \theta \approx 0.18 \) or \( \theta \approx 2.96 \) both, \( \theta_{13} \) and \( \theta_{12} \), are in agreement with experimental data. In [17] a supersymmetric model for the lepton sector with the gauge group of the Standard Model has been constructed. In this model LH leptons are unified in a(n irreducible, faithful) triplet, whereas RH charged leptons are singlets of \( S_4 \). Both symmetries, \( S_4 \) and CP, are broken spontaneously at a high energy scale. The above-estimated size of \( \theta \), needed for achieving values of \( \theta_{13} \) and \( \theta_{12} \) consistent with experimental data, can be naturally explained in this model. Furthermore, neutrinos are predicted to follow normal mass ordering (NO) and the values of the neutrino masses \( m_i \) are

\[ m_1 \approx 0.016 \text{eV}, \quad m_2 \approx 0.018 \text{eV}, \quad m_3 \approx 0.052 \text{eV}. \] (12)

In addition, the Majorana phases are fixed to the values \( \alpha = \pi \) and \( \beta = \pi \) so that \( m_{ee} \), the quantity measurable in neutrinoless double beta decay, is \( m_{ee} \approx 0.003 \text{eV} \). The charged lepton mass hierarchy is also naturally described, since charged lepton masses arise from operators of different dimension.

In [18] (see also [19]) the series \( \Delta(3n^2) \) and \( \Delta(6n^2) \) combined with CP have been analyzed in detail. The residual symmetries \( G_e \) and \( G_\nu \) are fixed to \( G_e = \mathbb{Z}_3 \) and \( G_\nu = \mathbb{Z}_2 \times \text{CP} \). It has been shown that for these types of residual symmetries only four cases of mixing patterns can arise that lead to lepton mixing angles potentially compatible with experimental data. One particularly interesting case, called Case 3 b.1) in [18], has the following features: the first column of the PMNS mixing matrix is fixed via the choice of the residual flavor symmetry \( \mathbb{Z}_2(m) \) (\( m \) integer); the solar mixing angle constrains \( m \) to fulfill \( m \approx n/2 \); the free parameter \( \theta \) is fixed by the reactor mixing angle and for \( m = n/2 \) a lower limit on the CP violation via the Dirac phase is found

\[ |\sin \delta| \gtrsim 0.71 \] (13)

and both Majorana phases \( \alpha \) and \( \beta \) depend on the CP transformation \( X(s) \) only

\[ |\sin \alpha| = |\sin \beta| = |\sin 6 \phi_s| \quad \text{with} \quad \phi_s = \frac{\pi s}{n} \quad \text{and} \quad s = 0, \ldots, n - 1. \] (14)

In table [1] results for the lepton mixing parameters are shown for \( \Delta(6n^2) \) with \( n = 8 \) and \( m = 4 \) and different values \( s \).

The fact that both, lepton mixing angles and Majorana phases, are strongly constrained leads also to strong restrictions on \( m_{ee} \), even if the neutrino mass spectrum is not constrained.
parameters appearing in the correction to $Y_m$ the sign of $\epsilon_Y$ in this approach. In figure 3 the results for Dirac Yukawa coupling $Y$ in the same triplet as LH leptons $L_I$ seesaw mechanism. For $10^{12}$ the residual symmetry in the charged lepton sector. Taking these corrections into account, $Y$ are included. A particularly interesting case is that corrections to from neutrinos to the PMNS mixing matrix is $m$ masses to be invariant under the breaking scheme of $G$ asymmetries $10^\alpha$ the Universe can be generated via unflavored leptogenesis $[20]$. Given the predictive power of the approach with $G_f$ and CP regarding leptonic CP phases it has been applied in $[21]$ to a scenario with three RH neutrinos $N_i$. $N_i$ transform in the same triplet as LH leptons $L_\alpha$. They give masses to light neutrinos via the type-I seesaw mechanism. For $10^{12}$ GeV $\lesssim M_i \lesssim 10^{14}$ GeV the baryon asymmetry $Y_B$ of the CP, $G_e$ and $G_\nu$ used in table 1. Blue areas indicate $m_{ee}$ for NO, while orange areas refer to $m_{ee}$ for inverted mass ordering. In dark colors the impact of the restrictions on the lepton mixing parameters on $m_{ee}$ is displayed, assuming for neutrino masses only the experimental constraints. For comparison in light colors the ranges of $m_{ee}$ are shown, as obtained from the experimentally preferred $3\sigma$ intervals of the lepton mixing parameters and neutrino masses. The darkest color highlights $K_\nu$ trivial.

Figure 2: Results for $m_{ee}$ with respect to the lightest neutrino mass $m_0$ for the choices of $G_f$, CP, $G_e$ and $G_\nu$ used in table 1. Blue areas indicate $m_{ee}$ for NO, while orange areas refer to $m_{ee}$ for inverted mass ordering. In dark colors the impact of the restrictions on the lepton mixing parameters on $m_{ee}$ is displayed, assuming for neutrino masses only the experimental constraints. For comparison in light colors the ranges of $m_{ee}$ are shown, as obtained from the experimentally preferred $3\sigma$ intervals of the lepton mixing parameters and neutrino masses. The darkest color highlights $K_\nu$ trivial.

Beyond the request to reproduce experimental bounds on the sum of the neutrino masses and to match the measured mass squared differences $\Delta m^2_{sol}$ and $\Delta m^2_{atm}$. This is exemplified in figure 2 for the choices of $G_f$, CP, $G_e$ and $G_\nu$ used in table 1.

Given the predictive power of the approach with $G_f$ and CP regarding leptonic CP phases it has been applied in $[21]$ to a scenario with three RH neutrinos $N_i$. $N_i$ transform in the same triplet as LH leptons $L_\alpha$. They give masses to light neutrinos via the type-I seesaw mechanism. For $10^{12}$ GeV $\lesssim M_i \lesssim 10^{14}$ GeV the baryon asymmetry $Y_B$ of the CP, $G_e$ and $G_\nu$ used in table 1. Blue areas indicate $m_{ee}$ for NO, while orange areas refer to $m_{ee}$ for inverted mass ordering. In dark colors the impact of the restrictions on the lepton mixing parameters on $m_{ee}$ is displayed, assuming for neutrino masses only the experimental constraints. For comparison in light colors the ranges of $m_{ee}$ are shown, as obtained from the experimentally preferred $3\sigma$ intervals of the lepton mixing parameters and neutrino masses. The darkest color highlights $K_\nu$ trivial.

For $10^{12}$ GeV $\lesssim M_i \lesssim 10^{14}$ GeV the baryon asymmetry $Y_B$ of the Universe can be generated via unflavored leptogenesis $[20]$. $Y_B \sim 10^{-3} \epsilon \eta$. A value of $Y_B$ in accordance with experimental data $[21]$, $Y_B = (8.65 \pm 0.09) \times 10^{-11}$, can be achieved for CP asymmetries $10^{-4} \lesssim \epsilon \lesssim 10^{-7}$ for efficiency factors $10^{-3} \lesssim \eta \lesssim 1$. In order to implement the breaking scheme of $G_f$ and CP, as described before, the charged lepton sector is taken to be invariant under $G_e$, while the mass matrix $M_R$ of RH neutrinos preserves $G_\nu$ and the Dirac Yukawa coupling $Y_D$ is invariant under $G_f$ and CP. As a consequence, light neutrino masses $m_i$ are inversely proportional to RH neutrino masses $M_i$ and the contribution $U_\nu$ from neutrinos to the PMNS mixing matrix is $U_\nu = U_R = \Omega_\nu R(\theta) K_\nu$. Since charged leptons do not contribute to lepton mixing in the chosen basis, $U_{PMNS} = U_\nu$. Computing the CP asymmetries $\epsilon_i$, arising from the decay of $N_i$, they are found to vanish. This has already been observed in scenarios with $G_f$ only $[22]$. Thus, non-zero $\epsilon_i$ can be achieved, if corrections are included. A particularly interesting case is that corrections to $Y_D$ are considered that are proportional to a (small) symmetry breaking parameter $\kappa$ and are invariant under $G_e$, the residual symmetry in the charged lepton sector. Taking these corrections into account,

$$\epsilon_i \propto \kappa^2.$$  

(15)

Hence $\kappa \sim 10^{-2+3}$ explains correctly the size of the CP asymmetries. Most importantly, the sign of $\epsilon_i$ (and consequently also $Y_B$) can be fixed, because all CP phases are determined in this approach. In figure 3 the results for $Y_B$ as function of the lightest neutrino mass $m_0$ are shown. The light-blue, red and green areas arise from the variation of order one parameters appearing in the correction to $Y_D$. The choice of $G_f$, CP, $G_e$ and $G_\nu$ is the
Figure 3: Results for the baryon asymmetry $Y_B$ of the Universe with respect to the lightest neutrino mass $m_0$ for the choice of $G_f$, CP, $G_e$ and $G_\nu$ as in table 1 and figure 2. Light neutrino masses have NO. Light-blue, red and green areas refer to different choices of the parameters in the correction to $Y_B$. The dark-blue area indicates the experimentally measured value of $Y_B$. For the choices $s = 1$ and $s = 2$ (predominantly) positive or negative $Y_B$ is achieved for certain ranges of $m_0$. The same as in table 1 and figure 2. As can be clearly seen, for certain choices of CP, $s = 1$ and $s = 2$, and certain ranges of $m_0$, $Y_B$ is (predominantly) positive or negative, whereas for the choice $s = 4$ no such preference is visible. The explanation for this observation is that for $s = 1$ the Majorana phase $\alpha$ fulfills $\sin \alpha < 0$, whereas for $s = 2$ we find $\sin \alpha > 0$. For $s = 4$ the CP phases $\alpha$ and $\beta$ are trivial and only $\sin \delta$ is non-vanishing. Studies of flavored leptogenesis in scenarios with $G_f$ and CP can be found in [23].

5 Conclusions

I have discussed for different flavor symmetries $G_f$ (abelian and non-abelian, continuous and discrete, combined with CP or not) their predictive power regarding lepton masses and lepton mixing parameters, in particular leptonic CP phases. While an FN symmetry is suitable for (charged lepton) mass hierarchies and for explaining the gross structure of the mixing pattern, non-abelian $G_f$, especially if chosen to be discrete and broken non-trivially, can explain all three lepton mixing angles and the Dirac phase $\delta$. However, their predictive power regarding CP phases is limited, since only one CP phase can be determined. A combination of non-abelian discrete $G_f$ and CP is most powerful in constraining all lepton mixing parameters and can also restrict high energy CP phases that are relevant for the baryon asymmetry $Y_B$ of the Universe in leptogenesis scenarios. I have also briefly shown that in concrete models the predictive power can be further increased, e.g. the neutrino mass ordering is predicted and the Majorana phases are entirely fixed.

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References


Non-Unitarity vs sterile neutrinos at DUNE

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Neutrino masses are one of the most promising open windows to physics beyond the Standard Model (SM). Several extensions of the SM which accommodate neutrino masses require the addition of right-handed neutrinos to its particle content. These extra fermions will either be kinematically accessible (sterile neutrinos) or not (deviations from Unitarity of the PMNS matrix) but at some point they will impact neutrino oscillation searches. We explore the differences and similitudes between the two cases and compare their present bounds with the expected sensitivities of DUNE. We conclude that Non-Unitarity (NU) effects are too constrained to impact present or near future neutrino oscillation facilities but that sterile neutrinos can play an important role at long baseline experiments.

PRESENTED AT

NuPhys2016, Prospects in Neutrino Physics
1 Introduction

The simplest extension of the Standard Model (SM) of particle physics able to account for the evidence for neutrino masses and mixings consists in the addition of right-handed neutrinos to its particle content. The new physics scale is the Majorana mass of the new states and, since it is not related to the electroweak symmetry breaking mechanism, there is no theoretical guidance for its value. A large Majorana scale leads to the celebrated seesaw mechanism [1–4], providing a very natural explanation of the lightness of neutrino masses. Conversely, a light neutrino mass could also naturally stem from a symmetry argument [5–11]. This proceeding is based on [12] where we analyze the phenomenological impact of these new physics in neutrino oscillation facilities. If the new mass scale is kinematically accessible in meson decays, the sterile states will be produced in the neutrino beam. On the other hand, if the extra neutrinos are too heavy to be produced, the effective $3 \times 3$ PMNS matrix will show unitarity deviations. We will refer to these situations as sterile and Non-Unitary (NU) neutrino oscillations, respectively. The aim of our work is to discuss the similitudes and differences among these two regimes clarifying in which limit they lead to the same neutrino oscillation phenomenology.

2 Non-unitarity and sterile $\nu$ phenomenology

If $n$ extra right-handed neutrinos are added to the SM Lagrangian, the full mixing matrix (including both light and heavy states) can be written as

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix},$$

where $N$ represents the $3 \times 3$ active-light sub-block (i.e., the PMNS matrix), which will no longer be unitary. Here, $\Theta$ is the $3 \times n$ sub-block that includes the mixing between active and heavy states, while the $R$ and $S$ sub-blocks define the mixing of the sterile states with the light and heavy states, respectively. Note that both $R$ and $S$ are not involved when considering oscillations among active flavours.

2.1 Non-unitarity case

In the case of NU, only the light states are kinematically accessible and the amplitude for producing one of these states and a charged lepton of flavour $\alpha$ in a particular decay is proportional to the mixing matrix element $N_{\alpha i}^*$. In the mass eigenstate basis, the evolution of the produced neutrino state is given by the Hamiltonian [13]

$$H = \frac{1}{2E} \begin{pmatrix} 0 & 0 & \Delta m_{21}^2 \\ 0 & 0 & 0 \\ \Delta m_{31}^2 & 0 & 0 \end{pmatrix} + N^\dagger \begin{pmatrix} V_{CC} + V_{NC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix} N,$$

where

$$V_{CC} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{and} \quad V_{NC} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}.$$
where \( V_{CC} = \sqrt{2} G_F n_e \) and \( V_{NC} = -G_F n_n/\sqrt{2} \) are the charged-current (CC) and neutral-current (NC) matter potentials, respectively. The amplitude for a neutrino in the mass eigenstate \( j \) to interact as a neutrino of flavour \( \beta \) is given by the mixing matrix element \( N_{\beta j} \), which means that the oscillation probability will be given by

\[
P_{\alpha\beta} = |(N S^0 N^\dagger)_{\beta\alpha}|^2,
\]

where \( S^0 = \exp(-i H L) \) for a constant matter potential. Here \( P_{\alpha\beta} \) denotes the “theoretical” oscillation probabilities, defined as the ratio between the observed number of events divided by the product of the SM-predicted flux times cross section. However, in practice neutrino oscillation experiments do not measure \( P_{\alpha\beta} \). Most present and future experiments rather determine the flux and cross sections via near detector data and extrapolate to the far detector by correcting for the different geometries, angular apertures, and detection cross sections. For the near detector, we assume that the phases corresponding to the propagation of the light neutrinos have not yet developed significantly and therefore \( S^0 = I \), resulting in the experimentally inferred probability

\[
\mathcal{P}_{\alpha\beta} = \frac{|(N S^0 N^\dagger)_{\beta\alpha}|^2}{((N N^\dagger)_{\alpha\alpha})^2}.
\]

In the SM limit the matrix \( N \) becomes unitary and \( \mathcal{P}_{\alpha\beta} = P_{\alpha\beta} \) as expected.

### 2.2 Sterile neutrino case

In the sterile neutrino scenario, all of the states are kinematically accessible and the oscillation evolution matrix \( S \), involving both light and heavy states, takes the form

\[
S = US^0 U^\dagger,
\]

where \( S^0 \) is the full \((3+n) \times (3+n)\) evolution matrix expressed in the mass eigenbasis. For vacuum oscillations, we find that \( S^0 = \text{diag} (\exp(-i \Delta m^2_{ij} L/2E)) \). Therefore, the active neutrino \( 3 \times 3 \) sub-block \( S \) can be simplified to

\[
S_{\alpha\beta} = \sum_{i \in \text{light}} N_{\alpha i} S^0_{ij} N_{\beta j}^* + \sum_{J \in \text{heavy}} \Theta_{\alpha J} \Theta_{\beta J}^* \Phi_J,
\]

where \( \alpha, \beta \) stand for active neutrino flavors, \( \Phi_J \) is the phase factor acquired by the heavy state \( J \) as it propagates, and \( S^0 \) is defined in the same way as in the NU case. In the limit \( \Delta m^2_{ij} L/E \gg 1 \), the oscillations are too fast to be resolved at the detector and only an averaged-out effect is observable. In this averaged-out limit, the cross terms between the first and second term average to zero and we find

\[
P_{\alpha\beta} = |S_{\alpha\beta}|^2 = \sum_i N_{\alpha i} S^0_{ij} N_{\beta j}^*|^2 + \mathcal{O}(\Theta^4),
\]

(7)
which recovers the same expression as in the NU case given in Eq. (3). For oscillations in the presence of matter, the sterile neutrino oscillations will be subjected to a matter potential

$$H_{\text{mat}}^f = \begin{pmatrix} V_{3\times3} & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}$$

with

$$V_{3\times3} = \begin{pmatrix} V_{CC} + V_{NC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix}.$$  

(8)

If the matter potential is small in comparison to the light-heavy energy splitting $\Delta m_{ij}^2/2E$, the light-heavy mixing in matter will be given by

$$\tilde{\Theta}_{aJ} = \Theta_{aJ} + \frac{2E}{\Delta m_{ij}^2}(\delta_{ae}V_{CC}\Theta_{eJ} + \Theta_{aJ}V_{NC})$$

(9)

to first order in perturbation theory. In the limit $\Delta m_{ij}^2/2E \gg V_{CC}, V_{NC}$, we cannot therefore neglect the difference between the heavy mass eigenstates in vacuum and in matter, and apply Eq. (7). Thus, the matter Hamiltonian in the light sector can be computed in exactly the same way as for the NU scenario and we find again the same expressions for the theoretical probability in Eq. (3) as for the NU case, at leading order in $\Theta$.

Also in the sterile neutrino case the impact of the near detector measurements on the extraction of the experimentally measurable probability should be taken into account. In this work we will always assume that the oscillations due to the additional heavy states are averaged out at the far detector. However, this might not be the case at the near detector. We will focus on the following two scenarios:

1. The light-heavy oscillations are averaged out already at the near detector. For practical purposes, the oscillation phenomenology in this case is identical to the NU case and Eq. (4) also applies. For the experimental setup of DUNE, with a peak neutrino energy of $\sim 2.5$ GeV and a near detector distance of $\sim 0.5$ km, this is the case when $\Delta m^2 \gtrsim 100 \text{ eV}^2$.

2. The light-heavy oscillations have not yet develop at the near detector, but are averaged out at the far detector. In this case, the near detector would measure the SM fluxes and cross sections, and therefore the denominator in Eq. (4) would be equal to one. In this case, the experimental probability would coincide with the “theoretical” probability in Eq. (3). This scenario is the one implicitly assumed in many phenomenological studies. For DUNE, since the far detector baseline is 1300 km, this would be the case only in the region $0.1 \text{ eV}^2 \lesssim \Delta m^2 < 1 \text{ eV}^2$. 

3
3 Parametrizations

The non-unitarity effects stemming from the heavy-active neutrino mixing can be parameterized as

$$N = TU = (I - \alpha)U \quad \text{where} \quad \alpha = (1 - T) = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}, \quad (10)$$

where $T$ is a lower triangular matrix \cite{14,16} and $\alpha_{\alpha\beta} \ll 1$. In Eq. (10) $U$ is a unitary matrix that is equivalent to the standard PMNS matrix up to small corrections proportional to the deviations encoded in $\alpha$. When the normalization at the near detector is considered, it effectively cancels any leading order dependence on $\alpha_{\beta\beta}$ in disappearance channels in vacuum. Expanding in $\alpha_{\delta\gamma}$ we obtain

$$P_{\alpha\beta} \simeq \left| (1 + \alpha_{\alpha\alpha} - \alpha_{\beta\beta}) (US^0U^\dagger)_{\alpha\beta} - \sum_{\delta \neq \alpha} \alpha_{\alpha\delta} (US^0U^\dagger)_{\delta\beta} - \sum_{\delta \neq \beta} \alpha_{\beta\delta}^* (US^0U^\dagger)_{\alpha\delta} \right|^2 \quad (11)$$

When $\alpha = \beta$ the dependence on $\alpha_{\beta\beta}$ cancels out. This shows how relevant the role of the near detectors is regarding the sensitivity to the new physics parameters.

An alternative and widely used parameterization is $N = (1 - \eta)U'$ where $\eta = \eta^\dagger$ and $U'$ is a unitary matrix \cite{17,18}. The mapping between this hermitian parameterization and the triangular parametrization given in Eq. (10) is provided in \cite{12}.

4 Present constraints on deviations from unitarity

PMNS NU from very heavy extra neutrinos modifies precision electroweak and flavour observables (see for instance \cite{13,19,21}). These modification translate into very strong upper limits on the $\alpha$ parameters taken from Ref. \cite{21} and listed in the left column in Table \ref{tab:constraints}. However, for sterile neutrinos with masses below the electroweak scale these stringent constraints are lost, since all mass eigenstates are kinematically available in the observables used to derive the constraints and unitarity is therefore restored. The sensitivity of oscillation experiments to sterile neutrino mixing will depend on the actual value of the sterile neutrino mass, which determines if the corresponding $\Delta m^2$ leads to oscillations for the energy and baseline that characterize the experimental setup. Once oscillations are averaged-out, the constraints derived will become independent of $\Delta m^2$. The bounds in the middle column apply for $\Delta m^2 \gtrsim 100 \text{ eV}^2$ and will thus be relevant when the sterile neutrino oscillations are in the averaged-out regimes for both the near and far detectors of most long-baseline experiments. The bounds in the right column apply for $\Delta m^2 \sim 0.1 - 1 \text{ eV}^2$ and will thus be relevant when the sterile neutrino oscillations are in the averaged-out
regime for the far detector, but not for the near detector. For a more comprehensive breakdown of the available constraints and their ranges of applicability, we refer the interested reader to Appendix A of [12].

### Table 1: Current upper bounds on the $\alpha$ parameters. The limits are shown at $2\sigma$ for the NU case and 95% CL (1 d.o.f.) for the light sterile neutrino limit.

<table>
<thead>
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<th>“Non-Unitarity”</th>
<th>“Light steriles”</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$(m &gt; EW)$</td>
<td>$\Delta m^2 \gtrsim 100$ eV$^2$</td>
</tr>
<tr>
<td>$\alpha_{ee}$</td>
<td>$1.3 \cdot 10^{-3}$ [21]</td>
<td>$2.4 \cdot 10^{-2}$ [22]</td>
</tr>
<tr>
<td>$\alpha_{\mu\mu}$</td>
<td>$2.2 \cdot 10^{-4}$ [21]</td>
<td>$2.2 \cdot 10^{-2}$ [23]</td>
</tr>
<tr>
<td>$\alpha_{\tau\tau}$</td>
<td>$2.8 \cdot 10^{-3}$ [21]</td>
<td>$1.0 \cdot 10^{-1}$ [23]</td>
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<td>$</td>
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5 DUNE sensitivities

The choice of the facility under study is motivated by the strong matter effects that characterize the DUNE setup and that allow to probe not only the source and detector effects induced by the new physics in a given channel $P_{\alpha\beta}$, but also the matter effects which now provide sensitivity to other $\alpha_{\gamma\rho}$ parameters not necessarily satisfying $\gamma, \rho \leq \alpha$ or $\gamma, \rho \leq \beta$. In the fit, the assumed true values for the standard oscillation parameters are set according to their current best-fits from Ref. [27]. The mixing angles and squared-mass splittings are allowed to vary in the simulations, using a Gaussian prior corresponding to their current experimental uncertainties from Ref. [27] centered around their true values. The CP-violating phase is left completely free during the simulations, and its true value is set to $\delta_{CP} = -\pi/2$. We have performed simulations for two distinct new physics scenarios. In the first case (ND averaged) we normalize the oscillation probabilities according to Eq. (4). For the DUNE setup, the requirement for having averaged-out oscillations at the near detector translates to the condition $\Delta m^2 \gtrsim 100$ eV$^2$. The second scenario (ND undeveloped) would correspond to the case where sterile neutrino oscillations are averaged out at the far detector but have not yet developed at the near detector (this is $0.1 \text{ eV}^2 \lesssim \Delta m^2 < 1 \text{ eV}^2$ for the
Figure 1: Expected frequentist allowed regions at 1σ, 90% and 2σ for DUNE. The sensitivity to the $\alpha_{\beta\delta}$ parameters not shown here can be found in [12].

DUNE setup). In this case, no extra normalization is needed and the oscillation probability is directly given by Eq. (3). Figure 1 shows the expected sensitivities to the new physics parameters. These have been obtained by assuming that the true values of all $\alpha$ entries are zero to obtain the corresponding expected number of events, and fitting for the corresponding parameters while marginalizing over all other standard and new physics parameters. The resulting frequentist allowed regions are shown at at 1σ, 90%, and 2σ C.L. The case in which DUNE data is complemented by our present prior constraints on the sterile neutrino mixing (middle and right columns of Tab. 1 for the ND averaged and undeveloped scenarios respectively) is depicted with dashed lines while the for the solid lines no prior constraints were included. Notice that the sensitivities obtained for all parameters fall at least one order of magnitude short of the current bounds on the NU from heavy neutrino scenario presented in Tab. 1 (left column). It is remarkable that the sensitivity to the real part of $\alpha_{\tau\mu}$ improves for the ND undeveloped scenario through the combination of DUNE data and the present priors with respect to both datasets independently, showing an interesting synergy between data sets. Another conclusion that can be drawn from Fig. 1 is that
the sensitivities to the diagonal parameters $\alpha_{ee}$ and $\alpha_{\mu\mu}$ are significantly stronger for the ND undeveloped (right panels) as compared to the ND averaged scenario (left panels). This was to be expected since the source and detection effects that provide a leading order sensitivity to the diagonal parameters are totally or partially cancelled once the normalization of Eq. (4) is included (see Eq. (11)). In the disappearance channel both effects cancel in the ratio, while for the appearance channel there is a partial cancellation that only allows the experiment to be sensitive to the combination $\alpha_{ee} - \alpha_{\mu\mu}$. This leads to a pronounced correlation among $\alpha_{ee}$ and $\alpha_{\mu\mu}$, seen in the upper left panel of Fig. 1. In summary, if both near and far detectors are affected by the new physics in the same way (as it is the case when the sterile neutrino oscillations are averaged out at both detectors, or in the NU scenario) their effects are more difficult to observe since they cannot be disentangled from the flux and cross section determination at the near detector.

6 Conclusions

We have shown that, when the sterile neutrino oscillations are averaged out (and at leading order in the small heavy-active mixing angles) both kinematically accessible sterile neutrinos and PMNS NU stemming from heavy new physics lead to the same modifications in the neutrino oscillation probabilities. However, the present constraints which apply to these two scenarios are very different. Indeed, PMNS NU is bounded at the per mille level, or even better for some elements, through precision electroweak and flavour observables, while sterile neutrino mixing in the averaged-out regime is allowed at the percent level since it can only be probed via oscillation experiments themselves. Thus, no impact in present or near-future oscillation facilities from PMNS NU is expected while sterile neutrino mixing could potentially be discovered by them if the sterile neutrinos are light enough to be produced at the source. Indeed, our simulations confirm that PMNS NU is beyond the reach of high precision experiments such as DUNE, but that sterile neutrino oscillations could manifest in several possible interesting ways. Through these simulations the importance of correctly accounting for the impact of the near detector was made evident. For instance, a very significant increase in the sensitivity to the new physics parameters $\alpha_{ee}$, $\alpha_{\mu\mu}$ was found for the case in which the near detector is not affected in the same way as the far detector.

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References


Atmospheric neutrinos and new physics

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We discuss recent searches for new physics using high-energy atmospheric neutrino data from IceCube, namely sterile neutrinos with masses in the range $\Delta m^2 = 0.01 \text{ eV}^2 - 10 \text{ eV}^2$, and non-standard interactions (NSI) in the $\nu_\mu - \nu_\tau$ sector. We also present a brief review of the current status of NSI theory and phenomenology.

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1 Introduction

Neutrino oscillation experiments have established that neutrinos are massive, which in turn requires physics beyond the Standard Model (SM). The new physics scale is unknown, but if sufficiently low, the particles involved in neutrino mass generation could have an impact in neutrino oscillations. Atmospheric neutrinos provide an ideal tool to test new physics, as their spectrum covers a huge energy range ($\sim 1 - 10^5$ GeV) and they may travel distances across the Earth from tens to several thousands kilometers, for different zenith angles. While most previous analyses have focused on relatively low-energy, $\mathcal{O}(10$ GeV), atmospheric neutrino data, in the following we discuss the potential of the high energy ($> 100$ GeV) atmospheric neutrinos at IceCube to set constraints on light sterile neutrinos and non-standard interactions (NSI) in the $\nu_\mu - \nu_\tau$ sector.

2 Sterile neutrino searches

Sterile neutrinos with mass in the eV range can account for the anomalies found in short-baseline accelerator (LSND, MiniBooNE), reactor and gallium (with high intensity radioactive sources ) oscillation experiments.

Atmospheric neutrino data would be affected by additional (beyond 3 flavour) oscillations into sterile neutrinos in this mass range. At high energies, $E_\nu > 100$ GeV, oscillations due to the known atmospheric and solar mass splittings have wavelengths larger than the Earth diameter and can be neglected, while matter effects can enhance the transition between active and sterile neutrinos with $\Delta m^2 = 0.01$ eV$^2 - 10$ eV$^2$, leading to detectable energy and zenith angle distortions of the neutrino flux.

The IceCube collaboration has performed a search for $(\nu_\mu + \bar{\nu}_\mu)$ disappearance through oscillation into a sterile neutrino using the publicly available IceCube one-year upgoing muon sample IC86 (IceCube 86-string configuration), which contains 20145 muons corresponding to atmospheric neutrinos in the approximate energy range 320 GeV to 20 TeV. The full active and sterile neutrino evolution has been performed by employing the $\nu$-SQuIDS package. The resulting 90% CL exclusion limits are shown in Fig. 1, together with limits from previous experiments and global fits for reference.

3 Neutrino non-standard interactions

For recent reviews about NSI, and a complete list of references, see, e.g., Refs. [2, 3].

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*See talks by A. Palazzo and C. Buck in this conference for details about such anomalies.*
3.1 Theory

Neutral current (NC) neutrino NSI, also called matter NSI, can be parametrized via model-independent, effective four-fermion operators as follows:

\[ \mathcal{L}_{\text{NC NSI}}^{\alpha \beta} = -2 \sqrt{2} G_F \varepsilon_{i,P}^{\alpha \beta} (\bar{\nu}_\alpha \gamma_\mu L \nu_\beta)(\bar{f} \gamma^\mu P f), \]

where \( \varepsilon_{\alpha,\beta}^{i,P} \) are the NC NSI parameters (by hermiticity \( \varepsilon_{\alpha,\beta}^{i,P} = (\varepsilon_{\beta,\alpha}^{i,P})^* \)), \( P = \{ L, R \} \) (with \( L \) and \( R \) the left and right quirality projectors) and \( f \) is any SM fermion; charged-current (CC) NSI can be described analogously. Model-independent bounds on CC NSI, which affect neutrino’s production and detection, are generally one order of magnitude stronger than NC ones [9], that mainly modify neutrino propagation; thus we neglect CC NSI in the following.

It is desirable that the four-fermion vertices in eq. (1) arise in an \( SU(2) \times U(1)_Y \) gauge invariant theory, where they can be generated by operators of dimension six, eight and larger. In general, new physics which induces the dimension 6 operator also induces an operator involving charged leptons, with a coefficient of the same order by \( SU(2) \) invariance. Charged lepton physics imposes tight constraints on these coefficients of dimension 6 operators, rendering neutrino NSI unobservable. There are only two UV completions (at tree level) in which neutrino NC NSI can be induced by dimension six operators without the charged-lepton counterpart, and...
without fine-tuned ad-hoc cancellations: one $SU(2)$ singlet scalar with $Y = 1$ and non-canonical neutrino kinetic terms due to mixing with heavy SM singlet fermions which are integrated out. In this last case, after diagonalising and normalising the neutrino kinetic terms, a non-unitary lepton mixing matrix is generated that leads to NC NSI just for neutrinos. However, a detailed study of this class of scenarios shows that the constraints on the NC NSI turn out to be even stronger than the ones for operators which also produce interactions of four charged fermions at the same level: typically $\varepsilon^{fR}_{\alpha\beta} < \mathcal{O}(10^{-3})$, too small to be observable in current neutrino oscillation experiments. The only exception is the case of non-unitarity effects produced by mixing with sterile neutrinos in the keV range, which allows for NC NSI parameters of $\mathcal{O}(10^{-2})$ (see also talk by J. Lopez-Pavon in this conference).

At dimension 8 or larger, in principle an operator as in equation (1) can appear at tree level without any charged lepton counterpart and generate sizeable NC NSI; in practice, constructing ($SU(2)_L \times U(1)_Y$ gauge-invariant) UV completions with large neutrino NSI and consistent with all current experimental constraints, requires a certain amount of fine-tuning, although they cannot be completely excluded.

Recently, it has been considered the possibility of generating the NC NSI in models based on a new $U(1)'$ gauge interaction with a light gauge boson mass $\sim 10$ MeV. Since for neutrino propagation only forward scattering is relevant, the effective coupling in eq. (1) can be used even for neutrino energies much higher than the mediator mass, while in scattering experiments such as NuTeV the effects are strongly suppressed, allowing to satisfy current bounds while having potentially sizeable NC NSI.

### 3.2 Phenomenology

In the presence of NC NSI, the effective Hamiltonian that controls neutrino propagation in matter can be written as

$$H(E_\nu, x) = \frac{1}{2E_\nu} U M^2 U^\dagger + \text{diag}(V_e, 0, 0) + \sum_f V_f \varepsilon^{fV},$$

where $U$ is the PMNS mixing matrix, $M^2 = \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})$, with $\Delta m^2_{ij} \equiv m^2_i - m^2_j$ the neutrino mass square differences and $V_f(x) = \sqrt{2} G_F n_f(x)$, with $n_f(x)$ the number density of fermion $f$. The effect of NSI is encoded in the last term of Eq. (2), where $\varepsilon^{fV}$ is the matrix in lepton flavor space that contains the vector combination of the NSI chiral parameters, $\varepsilon^{fV}_{\alpha\beta} \equiv \varepsilon^{fR}_{\alpha\beta} + \varepsilon^{fL}_{\alpha\beta}$. For antineutrinos, the matter potentials change sign, $V_f \rightarrow -V_f$, and $U \rightarrow U^\ast$. It is convenient to define effective NSI parameters for a given medium by normalizing the fermion number density, $n_f$, to the density of $d$-quarks, $n_d$,

$$\varepsilon_{\alpha\beta} \equiv \sum_f \frac{n_f}{n_d} \varepsilon^{fV}_{\alpha\beta},$$

3
so that \( \sum f V f \varepsilon \equiv V_e r \varepsilon = V_d \varepsilon \), and \( r = n_d / n_e \). For the Earth, \( n_n \approx n_p \) and therefore, \( r \approx 3 \). Notice that oscillation experiments are only sensitive to the differences between the diagonal terms in the matter potential, e.g., \( \varepsilon'_{aa} \equiv \varepsilon_{aa} - \varepsilon_{\mu\mu} \).

The upper bounds on \( \varepsilon_{\alpha\beta}^{NP} \) from neutrino oscillation and scattering data are rather weak. Even more, in addition to the standard LMA solution to solar neutrino data, there is another solution called LMA-Dark which requires NSI with effective couplings \( \varepsilon_{ee}^{qV} - \varepsilon_{\mu\mu}^{qV} \) as large as the SM ones, as well as a solar mixing angle in the second octant, and implies an ambiguity in the neutrino mass ordering \([10, 11]\). The degeneracy between the two solutions can be lifted by a combined analysis of data from oscillation experiments with the neutrino scattering experiments CHARM and NuTeV, provided the neutrino NSI take place with down quarks, and the mediators are not much lighter than the electroweak scale \([12]\). For light mediators, the LMA-Dark solution can be ruled out at DUNE \([13]\) or in future coherent neutrino-nucleus scattering experiments \([12]\).

Off-diagonal NSI \( \varepsilon_{\tau\ell}^{qV} \sim \mathcal{O}(0.1) \) is also slightly favoured, due to the suppression of the upturn on low energy spectrum of solar neutrinos, which is in a mild tension with the standard neutrino oscillation scenario \([11]\); such NSI can be tested by atmospheric neutrinos at Hyper-Kamiokande \([14]\).

Many atmospheric neutrino’s NSI analysis restrict to the \( \nu_{\mu} - \nu_{\tau} \) sector, however allowing for all non-vanishing \( \varepsilon_{\alpha\beta} \) in the \( \nu_e - \nu_{\tau} \) sector leads to a matter potential that mimics vacuum oscillations \( \nu_{\mu} \rightarrow \nu_{\tau} \) with the same \( E_\nu \) dependence, but modified mixing and mass differences, along the parabola \( \varepsilon_{\tau\tau} = |\varepsilon_{\tau\tau}|^2/(1 + \varepsilon_{ee}) \). As a consequence, \( \mathcal{O}(1) \) values of \( \varepsilon_{\tau\tau}, \varepsilon_{e\tau} \) are possible in this region. We disregard this somehow fine-tuned possibility and consider the effect of \( \nu_{\mu} - \nu_{\tau} \) NSI in the high energy atmospheric neutrino sample at IceCube.

### 3.3 NSI with atmospheric neutrinos at IceCube

This section is based on \([15]\), where details of the analysis can be found. The relative size of NSI with respect to standard neutrino oscillations depends on the neutrino energy, therefore atmospheric neutrino data provides the possibility of exploiting the NSI energy dependence over a large range of energies and baselines in order set stronger constraints.

The standard evolution Hamiltonian for neutrinos in a medium includes the coherent forward scattering on fermions of the type \( f, \nu_\alpha + f \rightarrow \nu_\beta + f \), given by the matter interaction potential in Eq. \((2)\), which affects neutrino oscillations. As the neutrino-nucleon cross section increases with energy, for energies above \( \sim \mathrm{TeV} \), the neutrino flux gets attenuated: neutrinos are absorbed via CC interactions and redistributed (degraded in energy) via NC ones. On the other hand, the \( \nu_{\tau} \) flux regeneration effect is negligible for the high-energy IceCube sample of atmospheric neutrinos analysed.

We have used the density matrix formalism to describe the neutrino propaga-
Figure 2: Left panel: Comparison of the ratios of propagated to unpropagated atmospheric $\nu_\mu$ (solid lines) and $\bar{\nu}_\mu$ (dashed lines) fluxes for $\varepsilon_{\mu\tau} = 0.006$ (thick red lines) and $\varepsilon_{\mu\tau} = 0$ (thin green lines). Right panel: Comparison of the ratios of atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ fluxes at the detector (after propagation) with NSI to those without NSI, for two values of $\varepsilon_{\mu\tau}$. In both panels, $\cos \theta_z = -1$ and $\varepsilon' = 0$. The gray area corresponds to the energy interval that produced 90% of the events in the entire sample considered here in the absence of NSI effects.

In order to understand this behaviour, it is illustrative to study analytically the oscillation probabilities for two neutrinos in the approximation of constant matter density and neglecting inelastic scattering. When vacuum and matter NSI terms are of the same order of magnitude ($\Delta m_{31}^2/2E_\nu \sim V_{NSI}$, with $V_{NSI} = V_d \sqrt{4 \varepsilon^2_{\mu\tau} + \varepsilon'^2}$), the transition probability after propagating a distance $L$ reads

$$P(\nu_\mu \to \nu_\tau) \simeq (\sin 2\theta_{23} \frac{\Delta m_{31}^2}{2E_\nu} + 2 V_d \varepsilon_{\mu\tau})^2 \left(\frac{L}{2}\right)^2,$$

while the NSI matter term has opposite sign for antineutrinos. However in the high-energy limit the matter NSI term dominates over vacuum oscillations, and for $V_{NSI}/L \ll 1$ the two-neutrino transition probability is approximately given by

$$P(\nu_\mu \to \nu_\tau) \simeq (\sin^2 2\xi) \varepsilon^2_{\mu\tau} = (\varepsilon_{\mu\tau} V_d L)^2,$$

which is proportional to $\varepsilon^2_{\mu\tau}$ and becomes independent of $\varepsilon'$. As a consequence, the high-energy IceCube atmospheric neutrino data cannot significantly constrain the
diagonal NSI parameter $\epsilon'$, so in our analysis we use a prior on $\epsilon'$ based on SK limits \cite{16}, which were obtained from data at lower energies: $|\epsilon'| = |\epsilon_{\tau\tau} - \epsilon_{\mu\mu}| < 0.049$ at 90\% confidence level (C.L.). From these results, we set the 1\% C.L. prior on $\epsilon'$ to $\sigma_{\epsilon'} = 0.040$.

In our analysis we use the same IceCube data sample as in the search for light sterile neutrino signatures described in sec. 2 \cite{1}. In order to perform the analysis, we used the public IceCube Monte Carlo that models the detector realistically and allows us to relate physical quantities, as the neutrino energy and direction, to observables, as the reconstructed muon energy and zenith angle.

To evaluate the impact of possible systematic uncertainties, we have included the following nuisance parameters: normalization of the atmospheric neutrino flux, $N$, pion-to-kaon ratio in the atmospheric neutrino flux, $\pi/K$, spectral index of the atmospheric neutrino spectrum, $\Delta\gamma$, uncertainties in the efficiency of the digital optical modules of the detector, DOM$_{\text{eff}}$, and current uncertainties in $\Delta m^2_{31}$ and $\theta_{23}$. In addition, we have considered several combinations of primary cosmic-ray flux and hadronic interaction models, being our default choice the Honda-Gaisser model and Gaisser-Hillas H3a correction (HG-GH-H3a) for the primary cosmic-ray flux and the QGSJET-II-4 hadronic model. We show in the right panel of Fig. 3 the effect of this source of uncertainty in the posterior probabilities of $\epsilon_{\mu\tau}$.

In this way we have obtained the most up-to-date limits on the off-diagonal NSI parameter $\epsilon_{\mu\tau}$ and showed they currently depend very little on the systematic uncertainties. For our default combination of models, we find

$$-6.0 \times 10^{-3} < \epsilon_{\mu\tau} < 5.4 \times 10^{-3}, \quad 90\% \text{ credible interval (C.I.)},$$

and similar results from all the other possible combinations. Our bound is comparable to the one obtained in \cite{17}, using 79-string IceCube configuration and DeepCore data, although they do not include nuisance parameters in their analysis.

4 Summary

We have described two recent examples of the potential of high-energy atmospheric neutrino data from IceCube to constrain new physics, namely the search for sterile neutrinos by the IceCube collaboration (Fig. 1) and the limits on off-diagonal $\nu_{\mu} - \nu_{\tau}$ NSI, both using the one-year upgoing muon sample, IceCube 86-string configuration. We have obtained the limit $-6.0 \times 10^{-3} < \epsilon_{\mu\tau} < 5.4 \times 10^{-3}$ (90\% credible interval), and showed that systematics currently affect very little this bound. We also provide a forecast of the future sensitivity to NSI by simulating 10 years of high-energy neutrino data in IceCube. Fig. 3 summarizes our findings.

\footnote{https://icecube.wisc.edu/science/data/IC86-sterile-neutrino}
Figure 3: **Left panel:** Comparison of the 68% and 95% credible contours in the $\varepsilon_{\mu\tau} - \varepsilon'$ plane for our default analysis (filled blue regions) with those obtained when all nuisance parameters are fixed at their default values (red closed curves). We also show the result expected in the case of no NSI after 10 years of data taking (black closed curves). **Right panel:** Posterior probabilities of $\varepsilon_{\mu\tau}$, after marginalizing with respect to the rest of parameters, for the four combinations of primary cosmic-ray spectrum and hadronic models.

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References


Several anomalies observed in short-baseline neutrino experiments indicate that the standard 3-flavor framework may be incomplete and point towards the existence of light sterile neutrinos. Here, we present a concise review of the status of the neutrino oscillations within the 3+1 scheme, which is a minimal extension of the standard 3-flavor framework with one sterile neutrino species. We emphasize the potential role of LBL experiments in the searches of CP violation connected to sterile neutrinos and their complementarity with the SBL experiments.

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1 Introduction

A long series of experiments performed in the last twenty years has established that neutrinos are massive and mix. Although the 3-flavor framework has been nailed out as the only one able to describe simultaneously all data collected in solar, atmospheric, reactor and accelerator neutrino experiments, some “anomalous” results have been reported in short-baseline (SBL) neutrino oscillation measurements, which cannot be explained in such a scheme (see [1] for a recent review). The most popular interpretation of these anomalies involves new light sterile neutrinos (with mass in the eV range) which mix with the three ordinary “active” species.

In the simplest scenario, dubbed as 3+1 scheme, only one sterile neutrino species is introduced. The fourth mass eigenstate $\nu_4$ is separated from the standard “triplet” $(\nu_1, \nu_2, \nu_3)$ by a large ($\sim 1 \text{eV}^2$) squared-mass, giving rise to the hierarchical spectrum $|\Delta m^2_{12}| \ll |\Delta m^2_{13}| \ll |\Delta m^2_{14}|$. The $4 \times 4$ mixing matrix can be parametrized as 

$$U = \tilde{R}_{34} R_{24} \tilde{R}_{14} R_{23} \tilde{R}_{13} R_{12},$$

where $R_{ij}$ ($\tilde{R}_{ij}$) is a real (complex) $4 \times 4$ rotation in the $(i,j)$ plane. The complex rotations depend on the CP-phases $\delta_{ij}$.

By construction, the 3 + 1 scheme predicts sizable oscillation effects at the short baselines where the new frequency $\Delta_{14} = \Delta m^2_{14} L / 4E$ ($L$ being the baseline and $E$ the neutrino energy) is of order one. However, sterile neutrinos may leave their signs also in non-short-baseline experiments. In these setups the new oscillations get averaged because they are very fast ($\Delta_{14} \gg 1$) and the manifestation of active-sterile oscillations is more subtle.

In the solar sector, for example, the admixture of the electron neutrino with the $\nu_4$ mass eigenstate (parametrized by the matrix element $U_{e4}$) leads to small deviations from the unitarity of the $(\nu_1, \nu_2, \nu_3)$ sub-system (see [3, 4, 5]). In the atmospheric neutrinos, as first evidenced in [6], at very high [$O(\text{TeV})$] energies, a striking MSW resonant behavior is expected, which leads to a distortion of the zenith angle distributions. Finally, as first evidenced in [2], sterile neutrino oscillations can be probed also in the long-baseline (LBL) accelerator experiments, where they give rise to new interference phenomena. This circumstance is of particular interest in view of the world-wide program of new LBL facilities.

In what follows we concisely describe the anomalous SBL results and describe the potential role of LBL experiments in the searches of CP violation (CPV) related to sterile neutrinos.

2 The LSND and MiniBoone anomalies

Accelerator experiments with baselines of a few tens of meters and neutrino energies of a few tens of MeV can effectively probe neutrino oscillations occurring at
$\Delta m^2 \sim 1\, \text{eV}^2$. Their results are usually interpreted introducing a new mixing angle $\theta$ and a new mass-squared difference $\Delta m^2$. In the 3+1 framework the following identifications are valid: $\Delta m^2 \equiv \Delta m^2_{14}$ and $\sin^2 2\theta \equiv 4|U_{e4}|^2|U_{\mu 4}|^2$. The anomalous result recorded at the LSND experiment [7] was the first piece of data pointing towards light sterile neutrinos. Such an experiment, designed to study $\nu_\mu \to \nu_e$ transitions, detected an excess of electron antineutrino events at the $\sim 3.8\sigma$ level. The experiment KARMEN [8], having a design very similar to LSND, observed no such a signal, but could not rule out entirely the mass-mixing parameter region allowed by LSND. The experiment MiniBooNE [9], sensitive both to $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions, seems to lend support to the LSND finding.

An independent test of the LSND and MiniBooNE anomalies has been recently carried out at the long-baseline experiments ICARUS [10] and OPERA [11]. In these experiments, due to the high energy of the beam ($<E> \sim 17\, \text{GeV}$), the 3-flavor effects induced by non-zero $\theta_{13}$ are negligible. As a result, the experiments are sensitive to sterile neutrino oscillations, although these are completely averaged out due to the high value $L/E \sim 36.5\, \text{m/MeV}$, and appear as an enhancement of the expected rate of events. Both collaborations have performed the analysis in an effective 2-flavor description. However, in [12] it has been pointed out that in the 3+1 scheme important corrections arise due to the presence of a new genuinely 4-flavor interference term in the transition probability. In addition, in the 4-flavor framework the $\nu_e$ beam contamination is not a fixed quantity like in the 2-flavor scheme. A consistent 4-flavor analysis [12] of ICARUS and OPERA leads to a substantial weakening (by a factor of $\sim 3$) of the upper bounds on the sterile neutrino mixing. ICARUS and OPERA are not sensitive enough to rule out the mass-mixing region preferred by LSND and MiniBooNE, and can only restrict the allowed region to values of $\sin^2 2\theta < \text{few} \times 10^{-2}$.

3 The reactor and gallium anomalies

The re-calculations of the reactor antineutrino spectra performed in [13, 14] have given new momentum to the study of light sterile neutrinos. These calculations indicate fluxes which are $\sim 3.5\%$ higher than previous estimates and have raised the so-called reactor antineutrino anomaly [15]. In fact, adopting these fluxes, the SBL reactor measurements show a deficit with respect to the theoretical expectations.

The recent high statistics measurements of the antineutrino spectra performed by Daya Bay [16], Double Chooz [17] and RENO [18] (and more recently also by NEOS [19]) have evidenced an unexpected bump around 5 MeV in the prompt energy spectrum, deviating from the predictions at the $\sim 4\sigma$ level. The bump structure appears to be similar at the near and far detectors and is positively correlated with the reactor power. This strongly disfavors a possible explanation in terms of new-physics (for example super-light sterile neutrinos [20]). This unexpected feature of
the spectrum evidences that our understanding of the reactor spectra is incomplete and reinforces the case for a revision of the current reactor flux predictions. To this regard, it has been recently pointed out [21] (see also [22]), that if one hypothesizes that the reactor anomaly is not due to active-sterile neutrino oscillations, it can be explained entirely by a miscalculation of the $^{235}\text{U}$ reactor antineutrino flux.

An apparently unrelated deficit has been found in the solar neutrino experiments GALLEX and SAGE [23] using high intensity radioactive sources. The statistical significance of the deficit fluctuates around the $3\sigma$ level slightly depending on the assumptions made on the theoretical estimate of the cross section $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$. While the anomaly may represent a signal of new physics, both a systematic error in the Ge extraction efficiency or in the theoretical estimate of the cross-section remain possible alternative explanations.

Both the reactor and gallium anomalies can be interpreted in terms of a phenomenon of electron neutrino disappearance driven by sterile neutrino oscillations. In an effective 2-flavor scheme the results can be described by a new mass-squared difference $\Delta m^2$ and an effective mixing angle $\theta$. In a 3+1 framework the following identifications hold: $\Delta m^2 \equiv \Delta m^2_{14}$ and $\sin^2 2\theta \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$. The simultaneous explanation of both anomalies requires values of $\Delta m^2 \sim 1.7 \text{eV}^2$ and $\sin^2 2\theta \sim 0.1$ (see [24]). The inclusion of the recent results from the reactor experiment NEOS [19] tends to shift downward the best fit value of the mixing angle to $\sin^2 2\theta \sim 0.08$ (see [24]). It should be noted that, if the best fit point lies in the region indicated by NEOS, the detection of a signal at the future SBL experiments will be more challenging than originally envisaged.

The results of NEOS deserve some further comment. A raster scan analysis made by the collaboration excludes the hypothesis of oscillations at the 90% C.L. On the other hand, the expansion of the $\Delta \chi^2$ evidences a preference for sterile neutrino oscillations at roughly $2\sigma$ in 2 d.o.f. (standard 3-flavor case disfavored at $\Delta \chi^2 = 6.5$). In addition, the region of parameters identified by NEOS lies inside the region allowed by all the current SBL data (see [24]). We think that these two findings are intriguing and deserve more attention.

4 Sterile neutrinos at long-baseline experiments

The short-baseline experiments are without doubt the best place where to look for sterile neutrinos and certainly, if a breakthrough will come, it will take place at a SBL experiment. However, the SBL experiments have an intrinsic limitation which would impede to further study the properties of the 3+1 scheme. In particular, they are insensitive to the three CP-violation phases involved in such a scheme. In fact, CP-violation is a genuine 3-flavor phenomenon, whose observation requires the sensitivity to the interference between at least two independent oscillation frequencies.
In a SBL experiment only the new largest oscillation frequency ($\Delta_{14} \sim 1$) is visible, while both the atmospheric and the solar splittings are substantially unobservable ($\Delta_{13} \simeq \Delta_{12} \simeq 0$). Therefore, this class of experiments is blind to CP-violation effects. Other kinds of experiments are necessary to access the CP violation induced by sterile neutrinos. We are lucky because these experiments already exist. We are talking of the LBL experiments, both those already operational and the planned ones. As a matter of fact, although such experiments were originally designed to seek the standard CP-phase $\delta$, they are also capable to provide information about other sources of CP violation. This is not obvious a priori and it is true only because, as we will see below, a new interference term arises in the presence of sterile neutrinos, which has exactly the same order of magnitude of the standard 3-flavor interference term.

We recall that the LBL experiments, when working in the $\nu_\mu \to \nu_e$ (and $\bar{\nu}_\mu \to \bar{\nu}_e$) appearance channel are sensitive to the 3-flavor CPV because, at long baselines, the $\nu_\mu \to \nu_e$ transition amplitude develops an interference term between the atmospheric ($\Delta m^2_{13}$-driven) and the solar ($\Delta m^2_{12}$-driven) oscillations, which depends on the CP-phase $\delta$. As first evidenced in [2], in the presence of sterile neutrinos a new interference term arises, which depends not only from $\delta \equiv \delta_{13}$ but also from one new CP-phase ($\delta_{14}$). From the discussion made in [2] (see also [25]), it emerges that the transition probability can be approximated as the sum of three terms

\[ P^4_{\mu e} \simeq P^\text{ATM} + P^\text{INT}_I + P^\text{INT}_{II} \tag{2} \]

The first term represents the positive-definite atmospheric transition probability, while the other two terms (which can assume both positive and negative values) are due to interference. The first of them is related to the well-known standard atmospheric-solar interference, while the second is driven by the atmospheric-sterile interference. We now observe that the transition probability depends on the three small mixing angles $\theta_{13}, \theta_{14}, \theta_{24},$ and that it occurs that these mixing angles have the same order of magnitude $\epsilon \sim 0.15$. In addition, we note that the ratio of the solar and atmospheric squared-mass splittings $\alpha \equiv \Delta m^2_{12}/\Delta m^2_{13} \simeq \pm 0.03$, which is of order $\epsilon^2$. Keeping terms up to the third order, in vacuum, one finds [2]

\[ P^\text{ATM} \simeq 4s^2_{23}s^2_{13}\sin^2\Delta, \tag{3} \]
\[ P^\text{INT}_I \simeq 8s_{13}s_{12}c_{12}s_{23}c_{23}(\alpha \Delta) \sin \Delta \cos(\Delta + \delta_{13}), \tag{4} \]
\[ P^\text{INT}_{II} \simeq 4s_{14}s_{24}s_{13}s_{23} \sin \Delta \sin(\Delta + \delta_{13} - \delta_{14}), \tag{5} \]

where $s_{ij} \equiv \sin \theta_{ij}$, $c_{ij} \equiv \cos \theta_{ij}$ and $\Delta \equiv \Delta m^2_{13} L/4E$ is the atmospheric oscillating

\*In the $3+N_s$ schemes with $N_s > 1$, CPV could be observed at SBL experiments. However, these setups can probe only a limited number of all the CP phases involved in the model. In contrast, LBL experiments have access to all such phases. For example, in the $3+2$ scheme, the SBL experiments are sensitive only to one CP-phase over a total of five observable CP-phases.
Figure 1: Regions allowed by the combination of the SBL and LBL data (NOνA and T2K) together with the $\theta_{13}$-sensitive reactor results. Figure taken from [28].

frequency. The matter effects slightly modify the transition probability leaving the picture described above almost unaltered (see [2, 25] for details).

Remarkably, for typical values of the mixing angles preferred by the current global 3+1 fits [24], the amplitude of the new interference term is almost identical to that of the standard one. As a consequence, one expects some sensitivity of the LBL experiments NOνA [26] and T2K [27] to the non-standard CP-phase $\delta_{14}$. Therefore, these two experiments and their constraints on the CP-phase $\delta_{14}$, should be included in any accurate analysis of the 3+1 scheme. This has been done in the work [28], where a joint analysis of SBL and LBL data has been presented for the first time.

Figure 1, taken from such a work, displays the projections of the $\Delta \chi^2$ for inverted hierarchy (IH). The left-bottom panel reports the projection on the plane of the two mixing angles ($\theta_{14}, \theta_{24}$). The other two panels display the constraints in the plane formed by each one of the two mixing angles and the new CP-phase $\delta_{14}$. Similar results (not shown) are obtained for normal hierarchy (NH). The three contours are drawn for $\Delta \chi^2 = 2.3, 4.6, 6.0$, corresponding to 68%, 90% and 95% C.L. for 2 d.o.f. The overall goodness of fit is acceptable (GoF = 24%), while the parameter goodness of fit, which measures the statistical compatibility between the appearance and disappearance data sets, is lower (GoF = 7%). This implies that even if the closed contours presented for the two new mixing angles $\theta_{14}$ and $\theta_{24}$ exclude the 3-
Figure 2: DUNE discovery potential of the CPV induced by the three CP phases involved in the 3+1 scheme. See the text for details. Figure taken from [30].

Given that NOνA and T2K possess already a weak sensitivity to the new CP-phase δ_{14}, it is very interesting to ask how things will improve at the planned LBL experiments. This issue has been investigated in detail in the works [29, 30, 31] (see also [32, 33]). In Fig. 2, taken from [30], we provide an illustrative example concerning the DUNE experiment. The bands displayed in the left, middle and right panels represent the discovery potential of the CPV induced, respectively, by δ_{13}, δ_{14} and δ_{34}. The thinner (magenta) bands correspond to the case in which all the three new mixing angles have the same value θ_{14} = θ_{24} = θ_{34} = 90°. The thicker (green) bands correspond to the situation in which θ_{14} = θ_{24} = 90° and θ_{34} = 30°. In each panel, the bands were obtained by varying the true values of the two undisplayed CP-phases in the range [−π, π]. In all cases, marginalization over the hierarchy was performed with NH as true choice. From Fig. 2 we learn that the sensitivity to δ_{14} will substantially increase at DUNE at the price of losing some information on the standard CP phase δ_{13}.

5 Conclusions

We have presented a concise discussion of the current phenomenology of light sterile neutrinos. In the case of a discovery at a new short-baseline experiment we will face
the challenge of determining all the parameters that govern the extended framework and in particular the new CP-violating phases. In this context LBL experiments can give an important contribution being sensitive to new CP-violation phenomena. Therefore, the two classes of experiments (SBL and LBL) will be synergic in the searches of sterile neutrinos.

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References

Sterile Neutrinos: Reactor Experiments

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Nuclear reactors are strong, pure and well localized sources of electron antineutrinos with energies in the few MeV range. Therefore they provide a suitable environment to study neutrino properties, in particular neutrino oscillation parameters. Recent predictions of the expected antineutrino flux at nuclear reactors are about 6% higher than the average rate measured in different experiments. This discrepancy, known as the reactor antineutrino anomaly, is significant at the 2.5\(\sigma\) level.

Several new experiments are searching for the origin of this observed neutrino deficit. One hypothesis to be tested is an oscillation to another neutrino state. In a three flavor model reactor neutrinos do not oscillate at baselines below 100 m. Hence, if such an oscillation is observed, it would imply the existence of at least one light sterile neutrino state not participating in weak interactions. Such a discovery would open the gate for new physics beyond the Standard Model.

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NuPhys2016, Prospects in Neutrino Physics
1 Introduction

Many neutrino experiments in the last two decades have shown that neutrinos oscillate. This quantum mechanical effect is driven by the existence of different neutrino mass eigenstates which are not identical to the three known flavor eigenstates. Reactor neutrino experiments played a crucial role in measuring the oscillation parameters. The KamLAND experiment in Japan improved our knowledge on the “solar” mixing parameters [1]. The smallest of the three neutrino mixing angles, $\theta_{13}$, was recently determined by the $\sim1$ km baseline experiments Double Chooz [2], Daya Bay [3] and RENO [4].

Nuclear reactors produce electron antineutrinos in the $\beta$-decay of the neutron rich fission fragments in the reactor core. On average, there are six antineutrinos emitted per fission, resulting in an isotropic flux of more than $10^{20}$ neutrinos per GW of thermal power in every second. Besides a precise knowledge of the thermal power of the reactor and the distance to the detector, the time dependent fractional fission rates of the four main isotopes $^{235}$U, $^{238}$U, $^{239}$Pu and $^{241}$Pu need to be modelled. However, the main uncertainty in the flux predictions is coming from the neutrino energy spectrum of each fission isotope.

The standard reaction used to detect the electron antineutrinos is the inverse beta decay (IBD) on protons, typically in organic liquid scintillator (LS) detectors. In this reaction a coincidence signal of a prompt positron and a delayed neutron event is produced. The energy threshold for the IBD is at 1.8 MeV. The prompt positron deposits its kinetic energy in the neutrino detector and finally annihilates with an electron which produces two 511 keV gammas. The “visible energy” in the detector is about 0.8 MeV less than the energy of the incoming neutrino. The neutron produced in the IBD reaction is mainly captured on hydrogen for the case of an unloaded LS. In this delayed event a 2.2 MeV gamma is emitted. For better background discrimination the LS is often doped with gadolinium (Gd) increasing the gamma energy upon neutron capture to about 8 MeV and reducing the coincidence time significantly. For improved event localization the Gd can be replaced by $^6$Li, which decays into a triton and an alpha particle after neutron capture.

2 The reactor antineutrino anomaly

In the context of the $\theta_{13}$ experiments, the neutrino flux predictions at nuclear reactors were re-evaluated [5] [6]. These new calculations revealed an increase of the flux prediction of few percent as compared to the Schreckenbach et al. predictions [7] [8], which provided the reference spectra before. All different conversion methods for the $^{235}$U, $^{239}$Pu and $^{241}$Pu neutrino spectra rely on the measured beta spectra at the Institut Laue-Langevin (ILL) in the early 1980ies [9]. The normalization shift
of the recent flux predictions is the main contribution to the observed discrepancy to the reactor neutrino data. However, there are other effects which enhanced the significance of the data to prediction difference. Among those are the addition of non-equilibrium effects in the calculations and a shift of the measured neutron lifetime within the last 30 years. The neutron lifetime has a direct impact on the calculations of the IBD cross-section.

This reactor antineutrino anomaly \cite{10} of an electron antineutrino deficit observed few meters from the reactor core, could be interpreted as an oscillation into another neutrino state. However, this would require a splitting between the squared neutrino mass eigenstates involved in this oscillation which is at the order of 1 eV$^2$. This is significantly higher than the known mass splittings in the three flavor paradigm and therefore requires at least a fourth neutrino state. Since there can only be three active light neutrinos participating in weak interactions, a fourth generation would have to be sterile. The allowed oscillation parameter region that could explain the reactor anomaly is similar to the one of the longstanding LSND anomaly \cite{11}. Moreover, such an oscillation could also explain the slightly lower than expected values found in the neutrino source calibration runs of the solar neutrino experiments GALLEX \cite{12} and SAGE \cite{13}. There are many reactor neutrino experiments, which just started or are currently under construction, addressing the question of the light sterile neutrinos. Some of them will be discussed in more detail in the next section.

The recent $\theta_{13}$ experiments also observed spectral distortions in the neutrino spectrum known as reactor “shape anomaly” \cite{14,15,16}. The main feature of this distortions is an excess in the measured reactor neutrino spectrum as compared to the predicted shape around 5 MeV. Sterile neutrinos would not explain this shape anomaly, which is more likely attributed to nuclear and reactor physics. The new generation of experiments might be able to identify if this shape distortion is common to all fission isotopes or caused by only part of them. Some experiments are operated at highly enriched reactors (HEU) in which mainly $^{235}$U fissions contribute. Other experiments use commercial reactors in which several U and Pu isotopes contribute (LEU reactors). If the neutrino spectra of HEU and LEU reactors are compared it might show if the 5 MeV excess is solely due to the $^{235}$U contributions or similar for all isotopes.

3 Very short baseline experiments

Experiments search for sterile neutrinos at nuclear reactors by checking for oscillation effects in the energy spectrum, in the neutrino rate at different baselines or both. The detector requirements are low background environment, high energy resolution, precise energy scale knowledge and a baseline in the 10 m range or even below. Segmentation and modularity also help to improve the sensitivity. On the reactor side a strong, but compact core is desirable.
3.1 Nucifer

The Nucifer experiment \cite{17} was running at a baseline of about 7 m from the 70 MW OSIRIS HEU reactor at CEA Saclay in France. Nucifer was designed and motivated in the context of reactor monitoring and safeguard applications. There is interest from the International Atomic Energy Agency (IAEA) in a continuous monitoring of the fissile content in a nuclear reactor through non-intrusive techniques to reduce the risk of proliferation of nuclear weapons. With Nucifer it was demonstrated that the presence of 1.5 kg of Pu could be detected inside a Osiris-like core with a $\sim$1 ton detector opening the possibility of a first societal application of neutrino physics.

In principle, Nucifer can also be used to probe the reactor antineutrino anomaly. However the lack of precision in the neutrino flux prediction and the high rate of accidental background do not allow for strong statements regarding the sterile neutrino search. Nevertheless, a new data point provided by Nucifer is now included in global analyses giving further constraints on the allowed parameter space.

3.2 NEOS

As the Nucifer detector also the NEOS detector \cite{18} has an unsegmented target volume consisting of about 1 m$^3$ of Gd-loading organic liquid scintillator (Gd-LS). The main differences between Nucifer and NEOS are the reactor and the signal to background ratio. NEOS is operated at a commercial LEU reactor with a thermal power of 2.8 GW providing a strong neutrino flux. The signal to background ratio at the site of the detector at a baseline of 25 m is above 20. NEOS reported an impressive precision on their energy scale with a systematic uncertainty of only 0.5%.

Due to the high statistics of about 2000 detected antineutrinos per day it was possible with NEOS to confirm the spectral distortion around 5 MeV with high significance. The collaboration reported that their data could exclude the parameter space of $\sin^2(2\theta_{14})$ below 0.1 for $\Delta m^2_{41}$ ranging from 0.2 eV$^2$ to 2.3 eV$^2$ at a confidence level of 90% \cite{18}. This exclusion area already disfavours some of the best fit points in global analyses. The minimum $\chi^2$ value in a 3+1 hypothesis was found for the pair $(\sin^2(2\theta_{14}), \Delta m^2_{41}) = (0.05, 1.73 \text{ eV}^2)$, but overall no strong evidence for 3+1 neutrino oscillations were observed in this experiment.

3.3 DANSS

In the DANSS experiment \cite{19} a highly segmented detector with 1 m$^3$ of plastic scintillator is operated at the 3 GW reactor of the Kalinin nuclear power plant in Russia. The high power of this commercial reactor in combination with the rather short baseline of 10 – 12 m provides a high statistics neutrino signal of about 5000 IBD events per day. The detector setup can be moved up and down to test different
neutrino oscillation lengths at 3 different positions. The site has a 50 m.w.e. shielding which limits the cosmic background to 5% of the neutrino signal. The basic element of the DANSS detector are plastic scintillator strips (1x4x100 cm$^3$) co-extruded with a white layer for light containment. This polystyrene based coating contains 6% of Gd oxide corresponding to 0.35 wt.% of pure Gd with respect to the target material.

The concept was tested with DANSSino, a prototype detector with 2 modules. The elements are designed identically as the 50 modules used in the full scale detector. Each module consists of 50 scintillator strips. With DANSSino it was possible to study the background level and even reactor antineutrinos could be measured at a rate of 70 IBDs per day with a signal to noise ratio around unity. The full scale experiment started data taking in 2016.

3.4 Neutrino-4

Another experiment in Russia is the Neutrino-4 project [20] at the 100 MW SM-3 reactor. As in Nucifer or NEOS the IBD reactions are detected in a Gd-LS target with a total volume of 3 m$^3$. The detector is moveable with the closest position to the reactor at about 7 m and the longest baseline at 11 m. The expected neutrino rate is 1000 events per day. The main challenge in Neutrino-4 is the control of the background level. In a 350 liters prototype the rate due to cosmic background was about 4 times higher than the neutrino signal. Now the project is running with the full scale detector as well. The detector is surrounded by layers of active (12 cm scintillator plates) and passive (60 tons of steel, lead and borated polyethylene) shielding.

3.5 Stereo

The Stereo experiment at the Institut Laue-Langevin (ILL) in Grenoble, France, is measuring neutrinos 10 m away from a compact 58 MW research reactor highly enriched in $^{235}$U. The 2.2 m long detector has a neutrino target segmented in six identical cells, all of them filled with a Gd-LS. Stereo aims to measure the relative distortions of the neutrino energy spectrum in these cells caused by neutrino oscillation at different distances from the reactor core. The more than 1800 liters of neutrino target are surrounded by another 2100 liters of Gd-free LS to detect escaping gammas. The produced scintillation light is collected by a set of 48 photomultiplier tubes (PMTs) of 8 inch diameter which are separated from the LS by an acrylic buffer and n-dodecane.

As a consequence of the reactor vicinity and the surrounding neutron beam lines, the STEREO environment has a rather high background level of neutrons and gammas. For that reason a heavy shielding made of $\text{B}_4\text{C}$, lead and borated polyethylene surrounds the detector. In addition, a water-Cherenkov veto on top of the detector tags cosmic muons at the shallow depth of the site. The STEREO experiment started data taking in November 2016 and detects 400 neutrinos per day in reactor-on phases.
After a period of 2 years Stereo should be able to probe the main part of the allowed parameter region of the reactor antineutrino anomaly.

3.6 SoLid

The sterile neutrino search in SoLid \cite{21} will be performed between 5.5 and 10 m from the highly enriched uranium core of the BR2 reactor in Belgium. The experimental concept is based on precise localisation of the IBD events combined with a high neutron-gamma discrimination capability. To achieve this goal, a composite scintillator design is applied. The neutrino target is made out of 5 cm cubes of polyvinyl toluene scintillator (PVT). The energy depositions of annihilation gammas in neighbouring cubes can be used to tag the prompt positron of the IBD interaction. On one face of each PVT cube there is a neutron sensitive layer of $^{6}$LiF:ZnS(Ag). The cubes are optically separated by reflective Tyvek for optimized light collection. After thermalization in the PVT cube the IBD neutron has 50% probability to be captured on a $^{6}$Li nucleus. Such an interaction results in the production of an alpha and a triton particle. Most of the 4.78 MeV energy of those two particles is deposited inside the ZnS(Ag) inorganic scintillator. The time profile of the photon production in the ZnS is much slower ($\mu$s scale) than the one of PVT signals (ns scale). These characteristic time signatures can be used for further background discrimination. The technology was successfully tested in a 288 kg prototype module. The PVT cubes were arranged in 9 frames each with 16x16 cubes.

3.7 Prospect

In the phase I of the PROSPECT experiment \cite{22} short baseline oscillations are studied in a movable detector at baselines from 7 – 12 m. The 85 MW High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory in the US provides a pure $^{235}$U neutrino spectrum. This spectrum could be measured with a precision in a segmented LS detector loaded with $^{6}$Li. In the detector design the target volume is 3000 l with 120 optically separated moduls (each 15x15x120 cm$^3$) including double ended PMT readout. As in the other similar experiments the key challenge of Prospect is background reduction. Efficient background suppression should be achieved using vertex information and pulse shape discrimination separating electron/gamma like events from heavy recoils. In this way, a signal to background ratio of better than 1:1 is predicted.

Prospect was undergoing a staged approach in prototype and shielding developments. Tests on the Li-loaded LS were started on the 100 ml scale to characterize the liquid properties. First background studies were then performed in a 1.7 l cell which was upscaled to 23 l for further LS and background studies. In Spring 2016 a prototype with 2 moduls with the dimensions of the full scale detector was developed. The
measurements with the 3 ton detector is expected to commence in 2017 and should run for 3 years. Afterwards in a phase II of the experiment PROSPECT could be upgraded with a second detector at 15 − 19 m baseline for further improvement of the sensitivity.

4 Summary

The tension between the observed rate of reactor antineutrinos at short baselines with most recent flux predictions triggered the development of several new experiments searching for oscillations into sterile neutrinos. To obtain a convincing sterile neutrino signature the main features of such experiments should include short baselines (∼10 m), segmentation and/or movability as well as effective background suppression techniques.

In Table 1 several experiments are listed which either published results recently, started data taking or are currently under construction. With those strong efforts in the field the next years should allow to prove the existence of light sterile neutrinos or exclude the currently allowed region for ∼eV mass splittings. Since several of these reactor experiments are operated at compact cores highly enriched in $^{235}\text{U}$, high precision measurements of the associated neutrino spectrum will be obtained. This should give new insights into the observed distortions in the neutrino spectra of the km baseline $\theta_{13}$ experiments as compared to the predictions.

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Right-handed neutrinos: the hunt is on!

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The possibility of the existence of right-handed neutrinos remains one of the most important open questions in particle physics, as they can help elucidate the problems of neutrino masses, matter-antimatter asymmetry, and dark matter. Interest in this topic has been increasing in recent years with the proposal of new experimental avenues by which right-handed neutrinos with masses below the electroweak scale could be detected directly using displaced-vertex signatures. At the forefront of such endeavours, the proposed SHiP proton beam-dump experiment is designed for a large acceptance to new weakly-coupled particles and low backgrounds. It is capable of probing right-handed neutrinos with masses below 5 GeV and mixings several orders of magnitude smaller than current constraints, in regions favoured by cosmology. To probe higher masses (up to 30 GeV), a promising novel approach is to identify displaced vertices from right-handed neutrinos produced in $W$ decays at LHC experiments.

PRESENTED AT

1 Introduction

The phenomenon of neutrino oscillations, showing that neutrinos have masses, provides the first unambiguous microscopic evidence of physics beyond the Standard Model. The electroweak theory was confirmed with the discovery of the Higgs boson in 2012 at the Large Hadron Collider (LHC) and by further measurements of its properties. No signs of new physics have been found so far at the LHC even at its highest collision energies, indicating that, barring neutrino masses, the Standard Model provides a valid description of nature at least up to the TeV scale. It can thus be argued that the greatest challenge faced by experimental particle physics today is to answer the fundamental questions posed by neutrinos: the nature, hierarchy, and absolute scale of neutrino masses; the possibility of CP violation in the neutrino sector; and the possible existence of right-handed neutrinos.

Figure 1: Left: summary of the particle states in the Standard Model, indicating left-handed and right-handed fermions separately. All particles in this table have been experimentally observed. Right: three right-handed neutrinos $N_{1,2,3}$ are added and given Majorana masses below the electroweak scale to solve the problems of neutrino masses, dark matter, and matter-antimatter asymmetry in the Universe [1].

Remarkably, the hypothesis of three right-handed neutrinos with Majorana masses below the electroweak scale (hereafter termed Heavy Neutral Leptons, or HNLs) in combination with CP violation in the neutrino sector can address at once the three fundamental questions of the origins of neutrino masses, dark matter, and the excess of matter over antimatter in the Universe [1, 2] (see Fig. 1). Being neutral with respect to the electromagnetic, weak, and strong interactions, HNLs are extremely elusive particles which could manifest themselves only through gravitational interactions and by mixing with neutrinos. This mixing is required to obtain small neutrino masses through the seesaw mechanism but needs to be tiny to generate matter-antimatter asymmetry and to evade existing experimental constraints. This means that HNL
production in a laboratory would only be possible at the highest beam intensities $^{[3]}$, in addition to the high beam energies required to access high HNL masses. The small mixing also leads to a long lifetime and a typical signature of a displaced decay.

2 The SHiP experiment

A promising strategy to search for HNLs with masses of the order of the GeV is production through hadron decays at high-intensity proton beam-dump facilities. Searches for displaced decays of HNLs with masses up to 0.4 GeV were made using neutrino production through pion and kaon decays, the most sensitive to date with the PS191 experiment at CERN $^{[4]}$. Searches were also made using charmed meson decays to access masses up to 2 GeV, the most sensitive to date with the CHARM experiment at CERN $^{[4]}$ and the NuTeV experiment at Fermilab $^{[6]}$. For higher HNL masses, up to 75 GeV, the best constraints come from an analysis of LEP1 data with the DELPHI experiment, where an HNL would be produced in a $Z$ decay and detected as either a prompt or a displaced vertex $^{[7]}$.

SHiP is a general-purpose fixed-target facility proposed at the CERN SPS to search for particles with very low couplings to the Standard Model $^{[8, 9, 10]}$. The 400 GeV proton beam extracted from the SPS will be dumped on a high density target with the aim of accumulating $2 \times 10^{20}$ protons on target during 5 years of operation. It will produce a large number of neutrinos through hadron decays, following the same principle as that of the CHARM and NuTeV experiments. In particular, neutrinos from decays of hadrons containing $c$ or $b$ quarks can potentially mix with HNLs with masses up to 5 GeV. The charm production at SHiP, with an expected total of $\sim 5 \times 10^{16}$ neutrinos produced in charm decays, largely surpasses that of any other existing or planned facility, allowing to probe very small coupling strengths and resulting in the HNLs, if produced, to travel very large distances until they decay.

In its current design, the SHiP experiment comprises a target followed by a hadron absorber, a muon shield, a 50 m long, 5–10 m wide decay volume and a spectrometer similar to the LHCb detector, as shown in Fig. 2. The active muon shield is a set of magnets designed to minimise the flux of muons entering the vessel while allowing to have the vessel as close as possible to the target $^{[11]}$. The experiment as a whole is optimised to reconstruct and identify decays from new long-lived neutral particles and reject backgrounds which could mimic such decays $^{[10, 12]}$.

An HNL signal in SHiP is characterised by opposite-sign tracks which cross inside the decay volume, containing at least one particle identified as an electron or a muon, and whose reconstructed parent particle trajectory has its origin at the production target. Backgrounds can possibly arise from neutrino interactions in the vessel, decays of long-lived neutral hadrons, and random crossings of charged particles entering the vessel. Neutrino production in the forward direction is reduced by stopping hadrons
in a dense absorber before they decay, and neutrino interactions are minimised by evacuating the air in the vessel. The other types of backgrounds can be vetoed by surrounding the decay volume with tagging detectors. One additional handle to reject random crossings is to measure and match the arrival times of the particles forming the vertex with a high precision (100 ps resolution or better) using a dedicated timing detector. Simulations show that the combined use of the active muon shield, veto taggers surrounding the vessel, the timing detector, track momentum and pointing measurements, and muon-pion separation, can reduce the backgrounds to 0.1 events in a sample of $2 \times 10^{20}$ protons on target \[10\].

The experimental facility is also ideally suited for studying interactions of tau neutrinos. For this purpose, it will host an emulsion cloud chamber followed by a muon spectrometer upstream of the hidden-particle decay volume.

### 3 Heavy neutrino searches at the LHC

It is generally assumed that new particles accessible at the LHC with masses below 100 GeV would already have been discovered at the LEP, HERA and Tevatron colliders \[13\]. The HNL is an interesting exception. Neutrinos from $W$ and $Z$ decays provide the most efficient way to probe HNLs in the mass range $5 - 80$ GeV. At previous colliders, they amounted only to a few millions and it was not possible to probe
Figure 3: Typical process by which a $W$ boson would decay into a long-lived HNL by mixing with a neutrino. The prompt charged lepton is essential for triggering and the displaced vertex allows an efficient background rejection. The leptons from the $W$ decay and the HNL decay can have either opposite or same charge due to the Majorana nature of the HNL, and they can be all three flavours depending on the HNL mixing matrix. The hadronic HNL decay mode (into a charged lepton and two quarks) and the leptonic mode (into two charged leptons and a neutrino) have their respective advantages and should both be considered in the search.

coupling strengths below $10^{-5}$, corresponding to prompt decays for HNL masses above 2.5 GeV. Thus, in previous searches, the vertex displacement could generally not be used as a discriminant against backgrounds, which are important at hadron colliders due to large QCD cross sections. As a consequence, the best current constraints in the HNL mass range $2 - 75$ GeV come from an analysis with the Delphi experiment at LEP1 using $\sim 10^6$ neutrinos from $Z$ decays [7].

By contrast, a total of $\sim 10^9$ neutrinos from $W$ boson decays were produced at the LHC (ATLAS and CMS) in run-1, and an additional $\sim 10^9$ for every 15 fb$^{-1}$ is being produced in run-2 in 13 TeV collisions since 2016. The process of HNL production through on-shell $W$s and its subsequent decay is illustrated in Fig. 3. It offers two important advantages: the possibility to trigger on the prompt charged lepton from the $W$ decay, and the possibility to efficiently reduce backgrounds by requiring a displaced (>few mm) vertex. Searches using displaced-vertex signatures performed so far at ATLAS [14, 15, 16, 17, 18] and CMS [19, 20, 21, 22, 23] considered the new neutral particles to be decay products of other particles more massive than a $W$, leading to high transverse momentum ($p_T$) displaced decay products. None of these provided any relevant sensitivity to HNLs due to the high-$p_T$ requirements on the particles from the displaced vertex or to the requirement that two displaced vertices should be reconstructed in the same event. However, these searches demonstrate that displaced vertices can be reconstructed with a reasonable efficiency in ATLAS.
and CMS, and that backgrounds that give rise to such displaced vertices can be kept under control. A well-designed analysis at ATLAS or CMS would be able to probe for the existence of HNLs with masses in the range $3 - 30$ GeV with a sensitivity which largely surpasses existing LEP constraints and is relevant for BAU generation \cite{24, 25}.

For masses higher than 30 GeV, HNLs produced through on-shell or off-shell $W$ decays would decay promptly. For background reduction one has then to rely on their Majorana nature and require a signature of no opposite-sign same-flavour prompt lepton pairs \cite{25}. Searches of this type were made in 8 TeV collisions at ATLAS \cite{26} and CMS \cite{27}, setting limits on the HNL mixing to muon neutrinos in the mass range $50 - 500$ GeV. It should be noted though that the regions of masses and mixings probed using this strategy are not favoured by models of leptogenesis \cite{28}.

4 Expected sensitivities

Assuming the layout of the SHiP experiment which is described in the technical proposal \cite{10}, with $2 \times 10^{20}$ protons on target and acceptance and backgrounds with a basic event selection estimated from simulations, one obtains the sensitivity curve shown in blue in Fig. 4. This is only a preliminary estimate as the experiment is still being optimised for a trade-off between cost and performance, but it indicates clearly that SHiP will be able to dig deeply into the most favoured regions of the parameter space.

The curves shown in red and purple in Fig. 4 show rough expected sensitivities of dedicated ATLAS and CMS analyses using the full LHC run-3 dataset with a signature of a displaced vertex or prompt no opposite-charge same-sign leptons, respectively. For the displaced-vertex signature, both leptonic and hadronic HNL decays are considered, with a reconstructed vertex mass cut set to $> 4.5$ GeV for the hadronic channel to reduce hadronic backgrounds. Other assumptions made are: zero background, 60% trigger efficiency, 20% vertex selection efficiency, and 50% efficiency for the final selection cuts. For the prompt analysis, the same assumptions as in Ref. \cite{25} are made. While the efficiency and background assumptions still need to be confirmed with detailed studies, it is clear that dedicated HNL searches at the LHC will largely surpass the existing LEP constraints in the mass range $3 - 50$ GeV.

5 Summary

The proposed SHiP experiment plans to use the CERN SPS high-intensity proton beam to probe the smallest possible HNL mixings to neutrinos – several orders of magnitude smaller than current limits in the $0.4 - 3$ GeV HNL mass range. SHiP is widely recognised as an important complement to existing CERN programmes after LHC run-2. In a complementary manner, displaced-vertex signatures at ATLAS and
Figure 4: Rough expectations for 95% c.l. exclusion in the HNL coupling strength ($U^2$ with dominant mixing to $\nu_\mu$) vs. mass plane in SHiP and ATLAS/CMS. The specifications of the SHiP technical proposal [10] are assumed. For ATLAS and CMS at run-3 and high-luminosity LHC, 300 fb$^{-1}$ and 3000 fb$^{-1}$ of 14 TeV proton-proton collisions are assumed, respectively. $U^2$ is constrained from below by the observed neutrino masses and by primordial nucleosynthesis (BBN) [29]. Upper constraints on $U^2$ are shown for two different models accounting for baryon asymmetry in the Universe (BAU): model 1 uses one HNL for dark matter [29] while model 2 requires all three HNLs to contribute to BAU [30]. Direct [4, 5, 6, 7, 27] and indirect [31, 32] experimental limits are indicated as dashed green and brown lines, respectively.

CMS allow to access higher HNL masses thanks to a high rate of $W$ boson production. These two approaches offer unique opportunities to probe the existence of right-handed neutrinos below the electroweak scale by direct production and detection at the CERN laboratory within a 10-year time scale. The reward is potentially very high, as such particles can shed light on the mechanisms behind the observed neutrino masses and the generation of baryon asymmetry in the Universe.
References


Several new generation experiments searching for neutrinoless double beta decay ($0\nu\beta\beta$) have become operational over the last five years. This report summarizes the present status of the experimental search and discusses peculiarities, challenges and reached half-life limits/sensitivities in these experiments. So far, no evidence for $0\nu\beta\beta$ has been found. Starting from the current situation, the paper addresses the question whether an experiment alone will be able to proof unambiguously $0\nu\beta\beta$ decay and which would be the key-requirements to succeed in this.

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NuPhys2016, Prospects in Neutrino Physics
1 Introduction

Many extensions of the Standard Model of Particle Physics predict that neutrinos are their own anti-particles (Majorana particles) [1]. One consequence thereof might be lepton number violation (LNV). This again would allow for a rare process called neutrinoless double beta decay ($0\nu\beta\beta$), in which an atom with mass and charge number ($A, Z$) decays via ($A, Z+2)+2e^-$. The observation of $0\nu\beta\beta$ decay would have far-reaching implications. On one side, the observable half-life, i.e. $T^{0\nu}_{1/2}$, is inversely proportional to the effective neutrino mass $\langle m_{\beta\beta} \rangle$ and thus allows to establish the mass hierarchy of neutrinos. It allows to test predictions not only of left-right symmetric models, but also those including right handed currents and heavy neutral leptons [2]. Further, by linking lepton number violation with CP violation (leptogenesis) [3], neutrinos could be responsible for the unsolved problem in cosmology that barionic matter prevails over antimatter.

Over the last decade, $0\nu\beta\beta$ search has seen a boost with new experiments becoming operational and several more in preparation. Some of them use the $\beta\beta$ isotopes $^{136}\text{Xe}$, $^{76}\text{Ge}$, $^{130}\text{Te}$ or $^{82}\text{Se}$, other ones plan to deploy also $^{48}\text{Ca}$, $^{100}\text{Mo}$, $^{116}\text{Cd}$ or $^{150}\text{Nd}$. Even though different detection techniques are considered, they all measure the sum of the energies of the outgoing electrons released in the $\beta\beta$ decays. So, the non-LNV and already observed $2\nu\beta\beta$ decay channel leads to a beta-like spectrum, while $0\nu\beta\beta$ decays would lead to a Gaussian peak at the $Q_{\beta\beta}$ value. The latter corresponds to the mass difference of the parent and daughter nuclide. By looking at the leading experiments in the field, the $T^{0\nu}_{1/2}$ half-life has to be beyond $5\times10^{25}$ yr, i.e. 15 orders of magnitude longer than the age of the universe. This explains the stringent requirements to the experimental programs in terms of energy resolution, detector efficiencies and background suppression capabilities.

This paper reviews the present status of $0\nu\beta\beta$ decay searches by presenting the new generation experiments, that are already operational or will start presumably data collection in the next year. Detector performance, background conditions, hardware upgrades and $T^{0\nu}_{1/2} / \langle m_{\beta\beta} \rangle$ sensitivities, that have been achieved or are designed, are outlined. Based on this information, the draft concludes with the scenario that $0\nu\beta\beta$ decay does exist and highlights the pre-requirements needed for a single experiment to proof unambiguously the existence of $0\nu\beta\beta$ decay.

2 Experimental search for $0\nu\beta\beta$ decay in 2016

CUORE The Cryogenic Underground Observatory for Rare Events (CUORE) makes use of a bolometric technique to search for $0\nu\beta\beta$ decays. $\text{TeO}_2$ crystals are cooled down to (10-15) mK using helium inside a multi-layer copper cryostat surrounded by ancient Roman lead. Energy depositions are absorbed by the crystals and registered
by thermistors as a temperature increase. Similar to Ge semiconductors, TeO$_2$ crystals have excellent energy resolutions of 0.2% at the $Q_{\beta\beta}$ value and large total detector efficiencies of 78-87%.

As a first step towards CUORE, one tower ('CUORE-0') containing 52 TeO$_2$ crystals with a total mass of 39 kg was assembled. Correspondingly, the fiducial $\beta\beta$ mass of $^{130}$Te was 11 kg. The observed background at $Q_{\beta\beta}$ is 0.058 cts/(keV·kg·yr) and consists mainly of surface $\alpha$-events. The achieved sensitivity in 2015 after 2 yr of data collection is $T^{0\nu}_{1/2} > 2.7 \times 10^{24}$ yr (90% C.L.). Together with the data set of the prototype Cuoricino it amounts to $T^{0\nu}_{1/2} > 4 \times 10^{24}$ yr (90% C.L.) [4].

In the meantime, the CUORE detector array consisting of 19 CUORE-0 like towers with a total mass of 988 kg and a $\beta\beta$ mass of 206 kg has been completed. After cooling down and commissioning, data acquisition is scheduled to start in the first quarter of 2017 [5]. The designed sensitivity after a 5 yr run will be $T^{0\nu}_{1/2} > 9.5 \times 10^{25}$ yr (90% C.L.), which translates into $\langle m_{\beta\beta} \rangle < (0.05-0.13)$ eV [6].

GERDA  The GERmanium Detector Array (GERDA) consists of high purity germanium detectors enriched in $^{76}$Ge at (86-88)%). Similar to bolometers, Ge diodes have excellent energy resolutions of 0.2% and the obtained detector efficiencies are again high, namely 62-66%. The diodes are mounted on low mass copper holders and submersed into liquid argon (LAr) inside a 64 m$^3$ cryostat. The LAr serves as coolant and passive shield against external radiation.

In Phase I of the experiment (2011-2013) mainly detectors from former $0\nu\beta\beta$ decay experiments were deployed, which amounted to 17.7 kg. Even though an unexpectedly strong concentration of the contaminant $^{42}$Ar was encountered, it was possible to achieve a background of 0.01 cts/(keV·kg·yr). By performing a blind analysis on the 21.6 kg·yr dataset, GERDA achieved a half-life limit of $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yr (90% C.L.) [7] and thus $\langle m_{\beta\beta} \rangle < (0.2-0.4)$ eV [7].

A two-years lasting upgrade phase followed, in which 30 new detectors of 20 kg were produced, characterized and deployed in addition to the old ones. The design of the new detectors was optimized allowing for an improved energy resolution and enhanced pulse shape performance. Two LAr scintillation light read-outs were also developed and installed for further background reduction.

Phase II started in December 2015. First data were released in mid 2016 and comprised 10 kg·yr. A background of 0.001 cts/(keV·kg·yr) was achieved for the new detectors. A half-life limit of $T^{0\nu}_{1/2}$ of $> 5.4 \times 10^{25}$ yr (90% C.L.) was deduced [8]. A second data release is planned for 2017.

GERDA plans to gain an exposure of 100 kg·yr under quasi background-free conditions allowing for a half-life sensitivity of $T^{0\nu}_{1/2} > 2 \times 10^{26}$ yr after $\sim 4$ yr of operation.
KamLAND-Zen The KAmioka Liquid Scintillator Anti-Neutrino Detector (KamLAND) is a multi-purpose detector originally designed for solar, geo- and reactor-neutrino measurements. In recent years the physics program was extended to $0\nu\beta\beta$ decay search leading to the KamLAND-Zen experiment. Herein, a smaller inner balloon containing xenon-loaded scintillator was installed in the center of the larger spherical vessel filled with 1000 tons of ultra-radiopure organic liquid scintillator (LS). The latter one acts in this case as a superb active background veto. In Phase I (2011-2012) of the experiment, a mini-balloon with $R<1.54$ m and xenon enriched in $^{136}$Xe at 91% was used. The $\beta\beta$ mass was 320 kg, but the total detection efficiency after all cuts only 25% and the energy resolution at $Q_{\beta\beta}$ is 10%. An unknown strong background peak appeared close to $Q_{\beta\beta}$, which was identified as $^{110m}$Ag, a fall-out product of the Fukushima reactor accident. Based on an exposure of 89.5 kg·yr, a half-life limit of $T_{1/2}^{0\nu}>1.9\times10^{25}$ yr (90% C.L.) was obtained [9]. After Xe extraction, several scintillator purification campaigns followed reducing successfully the $^{110m}$Ag content. In the following Phase II (2013-2016) 504 kg·yr of data were collected. This led to a half-life limit of $>9.2\times10^{25}$ yr (90% C.L.). By combining both results, the $T_{1/2}^{0\nu}$ limit becomes $>1.1\times10^{26}$ yr (90% C.L.) and $\langle m_{\beta\beta}\rangle<(0.06-0.16)$ eV [10]. These are the best limits achieved in the field so far.

In 2016, the KamLAND-Zen collaboration prepared the upgrade for Phase 3, in which a sensitivity of $\langle m_{\beta\beta}\rangle<0.04$ eV should be reached. So, 750 kg of enriched Xe were dissolved in LS and the nylon mini-balloon was replaced with a two-fold larger and cleaner one. Recently, a leak was discovered, such that the latter one has to be replaced as well. Delayed by this, data collection will start in mid 2017 [11].

EXO The Enriched Xenon Observatory (EXO) experiment uses a pressurized time projection chamber (TPC) filled with liquid xenon (LXe) as source and detection medium. The xenon is enriched in $^{136}$Xe at 81% and is cooled down with a high-purity heat transfer fluid inside a radiopure copper cryostat. The cylindrical TPC has two wire grids at both ends with different applied voltages that lead to a drift field. Behind the grids large area avalanche photodiodes are mounted. Both detection methods combined allow to read out simultaneously charge and scintillation light produced by ionisation, as well as to reconstruct the 3D-position of events and to suppress background via pulse shape analysis.

In Phase I (2011-2014) of EXO-200, 150 kg of enriched LXe were deployed. Data were collected for a total of 100 kg·yr and with a high detector efficiency of 85%. A background of 0.0017 cts/(keV·kg·yr) was achieved, however at a modest energy resolution of 3.7%. (31±4) events within 2σ around $Q_{\beta\beta}$ were observed, still compatible with the background model [12]. A half-life limit of $T_{1/2}^{0\nu}>1.1\times10^{25}$ yr (90% C.L.) was established, which converts into $\langle m_{\beta\beta}\rangle<(0.19-0.45)$ eV.

In Phase II (started in the first quarter of 2016), the collaboration succeeded to
improve the energy resolution to 3% and to obtain lower background levels via an improved pulse shape technique and reduced Rn levels. The goal sensitivity after a 3 yr run will be $T^{0\nu}_{1/2} > 5.7 \times 10^{26}$ yr (90% C.L.), correspondingly $\langle m_{\beta\beta} \rangle < 0.09$ eV [13].

**Other Demonstrators** The *Majorana Demonstrator* operates 30 kg of $^{76}$Ge enriched detectors in two large vacuum cryostats embedded within a passive shield of ultrapure copper, lead and neutron moderators. A first module became operational at the beginning of 2016, the second module has been commissioned and data collection started in the second half of 2016. The background is at the designed level of 0.01 cts/(keV·kg·yr). Start of data blinding is planned for the near future [14]. The entire setup will reach a half-life limit of $T^{0\nu}_{1/2} > 4 \times 10^{25}$ yr after 1 yr of running [15].

The *SuperNEMO Demonstrator* is based on the design principles of the NEMO-3 tracking calorimeter. It will consist of $\beta\beta$ emitting foils sandwiched between multi-wire chambers for track reconstruction, and calorimeter walls for energy determination. This will allow for the unique opportunity to reconstruct the full kinematics of background and $0\nu\beta\beta$-like events. In 2016, two calorimeter walls were installed, commissioning of the trackers is planned in the first quarter of 2017 [16]. 7 kg of $^{82}$Se are planned to be used, but also other isotopes will be considered. If successful, 20 Demonstrator modules might be installed afterwards in the framework of SuperNEMO. The goal sensitivity after a 5 yr operation would be $T^{0\nu}_{1/2} > 1 \times 10^{26}$ yr (90% C.L.), which corresponds to $\langle m_{\beta\beta} \rangle < (0.04-0.10)$ eV.

Other experiments and R&D projects are in the pipeline and some of them will become operational within the next years. A discussion about them is omitted here, since it is covered in another NuPhys2016 talk by S. Di Domizio.

### 3 Roadmap for an unambiguous $0\nu\beta\beta$ discovery

In the past it was repeatedly stated, that there is no $\beta\beta$ isotope and technique that ideally fulfill all the following advantages: a high $Q_{\beta\beta}$ value, a convenient $G^{0\nu}$ factor, a high natural isotopic fraction, enrichment possibilities, low isotope costs, low efforts in detector production, background suppression capabilities, high energy resolutions, easy and fast handling/operation of detectors. Further it was argued, that at least two independent experiments using different isotopes and thus different $Q_{\beta\beta}$ values would be needed to proof unambiguously the $0\nu\beta\beta$ discovery achieved by a certain experiment. So, waiting for a second experiment would be mandatory.

The first argument is certainly true. Regarding the second one, however, the question is, whether a single experiment will be able to provide a stringent proof, when discovering a $\gamma$-line at $Q_{\beta\beta}$ of a given isotope. The present situation of $0\nu\beta\beta$ decay experiments helps in figuring out the requirements for an experiment to check with high confidence a potentially observed $0\nu\beta\beta$-decay. The following four-steps roadmap

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4
can be defined:

1. **Increase experimental sensitivity** The experimental $T_{1/2}^{0\nu}$ sensitivity has to be in reach of the $0\nu\beta\beta$ decay half-life. Former and present experiments mostly excluded the degenerate neutrino mass scenario. In the case of the inverted mass hierarchy, the $\langle m_{\beta\beta} \rangle$ is in the range of (0.01-0.04) eV. $T_{1/2}^{0\nu}$ sensitivities of $\left(10^{26}-10^{28}\right)$ yr will be needed for a full coverage of this parameter space. Based on presently used technologies, several feasibility studies for experiments aiming at this goal are ongoing (KamLAND2-Zen, LEGeND, nEXO).

2. **$\gamma$-peak detection at $Q_{\beta\beta}$ value** By establishing the proper experimental sensitivity, data should show a $\gamma$-line at the expected $Q_{\beta\beta}$-value. Other radioactive nuclear transitions or processes induced e.g. by neutrons should be excluded via nuclear data bases and background simulations.

3. **Excluding unknown $\gamma$-lines that are not from $0\nu\beta\beta$ decays** Unknown nuclear processes such as forbidden transitions of higher order might appear in the spectrum and mimic a $0\nu\beta\beta$-decay $\gamma$-line. Two options can be pursued to overcome this difficulty:

   - Measure the topology of energy depositions: $\beta\beta$ decays are single-site (SS) energy depositions, since the outgoing electrons are stopped within tiny detector volumes of few mm$^3$. On the contrary, $\gamma$-rays of similar energy often undergo Compton scattering and deposit the energy in multiple sites (MS) of a detector, with distances up to tens of cm from each other. Detectors operated in dense arrays such in GERDA might be used to reject MS events by detecting coincident signals. Single detectors that can measure the time-resolved pulse structure of signals might be able to distinguish directly between SS and MS events. Indeed, this so-called pulse shape analysis is a well established technique already in use by the Majorana and GERDA collaborations, as well as the EXO collaboration.

   - Extract the daughter nuclide: A simultaneous detection of a $0\nu\beta\beta$-like signal and a shortly after extraction of a stable $0\nu\beta\beta$-decay daughter nuclide, e.g. $^{136}$Ba from $^{136}$Xe or $^{76}$Se from $^{76}$Ge, would proof the $\beta\beta$ nature of the parent nuclide. In solid state detectors, an extraction is not possible, but in a fluid. Indeed, the EXO collaboration is testing different techniques to isolate $^{136}$Ba atoms from the $\beta\beta$ detector mass. Most of these attempts still face different challenges: reduction of extraction times, increase of extraction efficiencies and adaption laboratory to the large-scale experiment conditions.

4. **Separation of $2\nu\beta\beta$ from $0\nu\beta\beta$ events:** Even though an experiment might succeed to discriminate SS from MS events with a very high efficiency, one type
the tail of the $2\nu\beta\beta$ spectrum increasingly overlap with the $0\nu\beta\beta$ peak, the worse the energy resolution and the smaller the $2\nu\beta\beta$ half-life $T_{1/2}^{2\nu}$ is. For the isotopes used in the current experiments, $T_{1/2}^{2\nu}$ varies between $10^{18}$ and $10^{21}$ yr. The most convenient isotopes are $^{136}$Xe and $^{76}$Ge with $T_{1/2}^{2\nu}$ half-lives of $2.17 \times 10^{21}$ and $1.9 \times 10^{21}$ yr correspondingly. For both leading experiments, KamLAND-Zen and GERDA, the corresponding $2\nu\beta\beta$ spectra and $0\nu\beta\beta$-peaks using the currently achieved sensitivities are shown in Figures 1 and 2. The blue/green line corresponds to the spectrum excluding/including the energy resolution of the detectors. In the case of KamLAND-Zen, the energy resolution is only 10% and $2\nu\beta\beta$ events swap largely into the $0\nu\beta\beta$-peak region. Contrarily for GERDA the energy resolution is 0.2% and the $2\nu\beta\beta$ tail is still far away from the $0\nu\beta\beta$-peak.

In order to assess the situation in the near future, it is opportune to have a look at the performance and projected sensitivity of current $\beta\beta$ experiments and define the following signal-to-background parametrisation:

$$R = 1 + \frac{B(2\nu\beta\beta)}{S(0\nu\beta\beta)}$$

(1)

$B(2\nu\beta\beta)$ and $S(0\nu\beta\beta)$ stand for the $2\nu\beta\beta$ background and the $0\nu\beta\beta$ signal in the same energy window, respectively. Ideally, $R$ is equal 1. By applying a cut on $0\nu\beta\beta$ peak events one will loose $0\nu\beta\beta$ events, but also keep $R$ close to unity. An example is given in Figure 3 and 4: the cut is set here to 88% $0\nu\beta\beta$ survival fraction. For KamLAND-Zen and EXO, the $R$ parameter goes beyond 2 already for $T_{1/2}^{0\nu}$ half-lives of $\sim 1 \times 10^{26}$ and $\sim 3 \times 10^{26}$ yr. For EXO it will be problematic after reaching $10^{28}$ yr. For GERDA, Majorana and CUORE it is not critical at
Figure 3: Sketch of a 88% cut applied on $0\nu\beta\beta$ peak signals.

Figure 4: Parameter $R$ for projected sensitivities of current $\beta\beta$ experiments.

4 Conclusions

Several new generation $\beta\beta$ experiments have become operational in the last 5 years. Few of them have already concluded a first phase and - after substantial hardware upgrades - started/are preparing for next phases.

New generation experiments have reached half-life sensitivities of $T_{1/2}^{0\nu} \sim 10^{25}-10^{26}$ yr. The best sensitivities have been obtained by the KamLAND-Zen and GERDA experiment: 5.6*10^{25} yr and 4.0*10^{25} yr at 90% C.L., correspondingly. KamLAND-Zen will probably be the first experiment being able to go beyond $10^{26}$ yr and to enter the inverted mass hierarchy regime.

Most experiments were affected by unexpected non negligible background components: KamLAND-Zen faced an $^{119m}$Ag pollution, GERDA experienced a high $^{42}$Ar concentration in the liquid argon, CUORE had to cope with surface $\alpha$ contamination and EXO with air-borne Rn. Nonetheless, in most cases it was possible to adopt counter actions and reach finally the designed background levels. Moreover, GERDA will be the first quasi background-free experiment for the goal sensitivity of $T_{1/2}^{0\nu} > 2 \times 10^{26}$ yr.

Beyond that, the experience from present $\beta\beta$ experiments teach us, that some experiments (i.e. large scale scintillator detectors) are more suitable for pushing the $T_{1/2}^{0\nu}$ sensitivity, while other approaches (i.e. solid state detectors) are more appropriate...
for a $0\nu\beta\beta$-peak discovery, under the assumption that excellent energy resolutions and quasi background-free conditions can be met.

References


Future prospects for neutrinoless double-beta decay

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The study of neutrinoless double-beta decay plays a fundamental role in the understanding of neutrino physics. Its observation would prove that neutrinos are Majorana particles and that lepton number is not conserved. Experimental searches demand detectors with a very large source mass and extremely low background. We report on planned future experimental searches and discuss their expected sensitivities.

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NuPhys2016, Prospects in Neutrino Physics
1 Introduction

Double-beta decay [1] is a rare spontaneous process in which the atomic number of a nucleus changes by two units. It can only occur in some even-even nuclei where single-beta decay is energetically forbidden. Two-neutrino double-beta decay mode (2νDBD) conserves the lepton number and is allowed by the Standard Model of particle physics. It is the rarest decay ever observed, with half-lives in the range (10^{19} – 10^{24}) y [2]. Neutrinoless double-beta decay (0νDBD) has never been observed and the half-life lower limits are in the range (10^{21} – 10^{26}) y. Its observation would prove that the total lepton number is not conserved, and that neutrinos are Majorana particles [3]. Under the assumption that 0νDBD takes place by the exchange of a light Majorana neutrino, the inverse of the decay half-life can be written as

\[
\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}^2 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}, \tag{1}
\]

where \(G_{0\nu} \) represents the decay phase-space, \( M_{0\nu} \) is a matrix element that accounts for the nuclear part of the decay, \( m_e \) is the electron mass, and \( \langle m_{\beta\beta} \rangle = |\sum_i U_{ei}^2 m_i| \) is a function of the neutrino masses and the neutrino mixing matrix elements. Formula (1) links the experimentally measurable decay half-life to \( \langle m_{\beta\beta} \rangle \), which encloses information about neutrino properties. \( \langle m_{\beta\beta} \rangle \) can be expressed as a function of four unknown parameters: the sign of \( \Delta m^2_{23} \), the mass of the lightest neutrino, and two Majorana phases. This is represented in fig. 1 reprinted from [4].

![Figure 1: Allowed value for \( \langle m_{\beta\beta} \rangle \) as a function of the mass of the lightest neutrino for normal (NH, red band) and inverted (IH, green band) neutrino mass hierarchy. Reprinted from [4].](image)

Figure 1: Allowed value for \( \langle m_{\beta\beta} \rangle \) as a function of the mass of the lightest neutrino for normal (NH, red band) and inverted (IH, green band) neutrino mass hierarchy. Reprinted from [4].
If the assumption of the exchange of a light Majorana neutrino is valid, then 0νDBD could also give information on the neutrino mass hierarchy and the absolute scale. Moreover this assumption allows to compare the sensitivity of 0νDBD searches based on different isotopes. This comes at the cost of introducing uncertainties from the theoretical calculation of $M^{0\nu}$, which cannot be performed exactly. Several models exist that make different approximations, leading to results whose reliability is difficult to assess. A big effort has been put in these calculations in recent years, resulting into a better agreement between different models. See e.g. [9] for a recent review.

In principle 0νDBD has a clear experimental signature. The sum-energy of the two emitted electrons is fixed and equal to $Q_{\beta\beta}$, the Q-value of the decay. This signal is qualitatively different from that of 2νDBD, in which part of the energy is carried away undetected by the two anti-neutrinos, resulting in a continuous energy spectrum extending up to $Q_{\beta\beta}$. The value of $Q_{\beta\beta}$ and other relevant quantities are reported in table 1 for a selection of experimentally interesting isotopes. $Q_{\beta\beta}$ lies in the energy range of natural radioactivity, which represents the dominant source of background for experiments. Since the signal must be maximized and the background minimized, all experiments searching for 0νDBD share the need for a large number of source isotopes, a low background and a good energy resolution.

After a brief review of the current status of the experimental searches, we consider as a target sensitivity for future experiments the full exploration of the values of $\langle m_{\beta\beta} \rangle$ corresponding to the inverted-hierarchy region of the neutrino mass. We then conclude discussing the experimental techniques that will be used and some of the proposed future experiments.

### 2 Present status of experimental searches

The best 0νDBD half-life limits available at present come from experiments studying $^{130}$Te, $^{76}$Ge and $^{136}$Xe (see table 1). These translate into $\langle m_{\beta\beta} \rangle$ upper limits of (270–760) meV, (150–330) meV and (61–165) meV for $^{130}$Te, $^{76}$Ge and $^{136}$Xe respectively.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$Q_{\beta\beta}$ [keV]</th>
<th>i.a. [%]</th>
<th>$T_{1/2}(0\nu$DBD) [$10^{25}$ y]</th>
<th>$T_{1/2}(2\nu$DBD) [$10^{21}$ y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge</td>
<td>2039</td>
<td>7.61</td>
<td>&gt;5.3 [5]</td>
<td>1.65±0.14</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2995</td>
<td>8.73</td>
<td>&gt;0.036 [6]</td>
<td>0.092±0.007</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3034</td>
<td>9.63</td>
<td>&gt;0.11 [6]</td>
<td>0.0071±0.0004</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>2528</td>
<td>34.17</td>
<td>&gt;0.40 [7]</td>
<td>0.69±0.13</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>2479</td>
<td>8.87</td>
<td>&gt;11 [8]</td>
<td>2.19±0.06</td>
</tr>
</tbody>
</table>

Table 1: Q-value, isotopic abundance, 0νDBD half-life limits and 2νDBD half-life measurements (from [2]) for a selection of double-beta decay candidate isotopes.
The $^{130}$Te result was obtained by CUORE-0 [7] with an array of 52 TeO$_2$ crystals operated as cryogenic calorimeters. The detector had a total $^{130}$Te mass of 11 kg, an energy resolution of 5 keV FWHM and a background at $Q_{\beta\beta}$ of 0.058 counts/(keV·kg·y). CUORE [10] is a larger and more sensitive version of CUORE-0 that will start data taking in 2017. The mass of $^{130}$Te is 206 kg and the expected background at $Q_{\beta\beta}$ is 0.01 counts/(keV·kg·y). If these performance parameters will be met, CUORE will have a $\langle m_{\beta\beta} \rangle$ sensitivity in the range (50 – 130) meV.

The $^{76}$Ge result was obtained by GERDA [5] using bare germanium detectors enriched in $^{76}$Ge. The total detector mass is 35.2 kg, with enrichment in $^{76}$Ge going from 7.8% to 87%. The energy resolution is 3 keV in the best detectors, and the background at $Q_{\beta\beta}$ is as low as 0.001 counts/(keV·kg·y). The GERDA collaboration plans to continue taking data in the current configuration until an exposure of 100 kg·y will be obtained. The expected half-life sensitivity will be about 2·10$^{26}$ y.

The $^{136}$Xe result was obtained by the KamLAND-Zen [8] collaboration by dissolving xenon in the ultra-pure liquid scintillator of the KamLAND detector. The total amount of $^{136}$Xe was of 340 kg but the amount of useful isotope mass was sensibly reduced by the fiducial volume cut imposed during data analysis. The poor energy resolution, 270 keV FWHM, was compensated by the large mass and by the extremely low background of $\sim$160 counts/(ton·y) in the region of interest (ROI). In 2017 the KamLAND-Zen collaboration plans to reach a sensitivity of about 40 meV on $\langle m_{\beta\beta} \rangle$ by performing minor upgrades to the current detector configuration.

3 Sensitivity of future searches

Present and near-future experimental searches have sensitivities on $\langle m_{\beta\beta} \rangle$ not better than (40–50) meV. In this section we discuss the general features of future experiments taking as a target a sensitivity on $\langle m_{\beta\beta} \rangle$ of about 15 meV, which corresponds to the full exploration of the inverted region of the neutrino mass-hierarchy. Using nuclear matrix elements from [9], this translates into half-life sensitivities roughly in the range (10$^{27}$ – 10$^{28}$) y. We begin discussing the formula that give a rough estimate of the sensitivity $S_{0\nu}$ of a given experiment. It has different expressions, depending on whether or not the background can be considered negligible. If the background is not negligible, then we have

$$S_{0\nu} \propto \eta \varepsilon \sqrt{\frac{M t}{b \Delta E}},$$

where $\eta$ is the isotopic abundance of the DBD isotope, $\varepsilon$ is the detection efficiency, $M$ is the total detector mass, $t$ is the measurement time, $b$ is the background index expressed in counts/(keV·kg·y) and $\Delta E$ is the FWHM energy resolution. If instead the background is negligible, we have

$$S_{0\nu} \propto \eta \varepsilon M t.$$
This condition is verified when the total number of expected background counts over the whole duration of the experiment is negligible, i.e. when \( M \Delta t \Delta E < 1 \), and is obviously preferable because the sensitivity scales linearly with the detector mass. We note that presently GERDA is the only experiment that was able to obtain this condition of zero-background.

For a given \( 0\nu DBD \) half-life, the number of expected signal counts \( N_s \) can be expressed as \( N_s = \ln 2 \varepsilon N_{\beta\beta} t / T_{1/2}^{0\nu} \), where \( \varepsilon \) is the detection efficiency and \( N_{\beta\beta} \) is the number of isotopes under observation. Even when the zero-background condition is met, observing a number of signal counts of the order of 1 over a data taking period of the order of one year would demand for a number of source isotopes \( N_{\beta\beta} \sim T_{1/2}^{0\nu} / (1 \text{y}) \). Therefore about \( \left( 10^{27} - 10^{28} \right) \) source isotopes are needed for a sensitivity of \( \sim 15 \text{ meV} \) on \( \langle m_{\beta\beta} \rangle \). This roughly corresponds to one ton of active source mass.

Background from radioactivity represents the major concern for most present experiments, and will be probably the most challenging scientific problem to address in the future. However, even assuming that this background contribution could be made negligible, there is still a background coming from the high-energy tail of the \( 2\nu DBD \) spectrum that cannot be eliminated. The number of background counts from \( 2\nu DBD \) in an energy window of width \( \Delta E \) around \( Q_{\beta\beta} \) can be expressed as [1]

\[
N_{2\nu} \sim \frac{1}{T_{1/2}^{2\nu} Q_{\beta\beta}^5} \frac{\Delta E^6}{Q_{\beta\beta}^5}.
\]

It is therefore preferable to have small \( \Delta E \) and large \( Q_{\beta\beta} \) and \( T_{1/2}^{2\nu} \). Moreover, even when other background sources are made negligible, energy resolution still remains an important parameter for \( 0\nu DBD \) searches.

Other considerations are related to the choice of the source isotope to be investigated and of the experimental technique to be used. The two choices are often not disjoint, because certain experimental techniques can only be exploited for some isotopes. This is true for example for Ge-diodes or Xe-TPCs, which will be discussed in the next section. Concerning the isotope choice, essentially two factors come into play. The first is related to \( Q_{\beta\beta} \). Isotopes with large \( Q_{\beta\beta} \) are preferable because they allow to obtain lower background levels. This is not only due to the fact that the background for \( 2\nu DBD \) is smaller for larger \( Q_{\beta\beta} \), but also because the radioactive background is lower at higher energy. In this regard a clear distinction can be made between isotopes with \( Q_{\beta\beta} \) smaller or larger than 2615 keV, which is the energy of the most intense \( \gamma \)-line from natural radioactivity. Other important aspects are the isotopic abundance of the isotope under investigation and the cost for its enrichment [I]. Finally, one could wonder if there are isotopes with a larger expected signal rate for a given amount of source mass. As pointed out in [12], this does not turn out to be the case, as all interesting isotopes are almost equivalent in this regard.
4 Future searches

We now discuss the experimental techniques that will be used in future $0\nu$DBD searches and present some of the most promising experiments that implement them.

4.1 Germanium detectors

Germanium detectors feature superior energy resolution and allow to discriminate very effectively between single-site (electron-like) and multi-site ($\gamma$-like) energy releases. This experimental technique can only be applied to $^{76}$Ge, that has a not so high $Q_{\beta\beta}$ of 2039 keV. Nevertheless, thanks to particle discrimination germanium experiments already demonstrated background rates as low as 0.001 counts/(keV·kg·y). The mass scalability of this technique can be extended to the ton scale, but probably not much more than that. Enrichment in $^{76}$Ge is feasible and already used in experiments, however it is somehow expensive if compared to other isotopes.

The GERDA [5] and Majorana [13] experiments aim at building a ton-scale germanium experiment, joining their scientific and financial efforts. GERDA was already discussed in section 2, it demonstrated the possibility to obtain an energy resolution of 3 keV FWHM and background as low as 2 counts/(ton·y) in the ROI. The experiment is currently running with a total detector mass of 36 kg. Majorana is currently more focused on the radioassay of the materials to be used in the construction of a ton-scale detector [14]. A background of less than 3.5 counts/(ton·y) in the ROI is expected, however the current prototype detectors measured a slightly higher background corresponding to about 23 counts/(ton·y).

4.2 Bolometric detectors

Bolometers feature an energy resolution ($\sim$5 keV) comparable to that of germanium detectors and can be exploited to investigate several isotopes. It has been already demonstrated by CUORE that the detector mass can be extended up to the ton scale, but it probably cannot be increased much more than that. Radioactive background is the main concern for current bolometric experiments, but the situation can be improved by the introduction of active background rejection techniques. This is what is planned for CUPID [15] [16], an upgrade of CUORE with particle-identification capabilities aiming at a background of 0.1 counts/(ton·y) in the ROI and a $\langle m_{\beta\beta} \rangle$ sensitivity in the 15 meV range. Two possible strategies are being considered. The first is to use enriched $^{130}$TeO$_2$ crystals and to perform particle discrimination based on the Cerenkov radiation emitted by $0\nu$DBD electrons and not by background $\alpha$ particles. The second is to move to an isotope with $Q_{\beta\beta}$ above 2615 keV and use enriched scintillating crystals such as Zn$^{82}$Se or Li$^{100}$MoO$_4$. In this case the particle discrimination would be based on the different light yield of electrons and $\alpha$ particles.
Another promising bolometric experiment is AMoRE [17]. It is still at a preliminary stage, but the plan is to build an array of $^{48}$Ca$^{100}$MoO$_4$ scintillating bolometers with a mass of 200 kg and a background of about 1 counts/(ton·y) in the ROI. The expected sensitivity on $\langle m_{\beta\beta}\rangle$ is of about 15 meV.

### 4.3 Xenon time-projection chambers

Noble gas or liquid time-projection chambers (TPC) are widely employed in rare event searches. TPCs for $0\nu$DBD are filled with xenon enriched in $^{136}$Xe. The radioactive contaminations can be made very low, and there are R&D activities aiming at tagging the Ba$^{++}$ daughter nucleus emitted in double-beta decay. If these R&D succeed, only the background from 2$\nu$DBD would remain. Gaseous TPC are filled with $^{enr}$Xe at pressure as high as 10 bar. In this environment electrons tracks are a few cm long, and background suppression based on event-topology reconstruction can be performed. In high-pressure gaseous TPCs the mass scalability is possible, but obviously harder than in liquid TPCs. The energy resolution can be smaller than 1% FWHM at $Q_{\beta\beta}$, fairly adequate to make 2$\nu$DBD background negligible. In liquid xenon TPCs it is easier to increase the source mass, but the energy resolution is not optimal.

EXO is a liquid xenon TPC containing 150 kg of $^{enr}$Xe. The energy resolution at $Q_{\beta\beta}$ is 3.5% FWHM and the background is of about $10^{-3}$ counts/(keV·kg·y). A planned extension of EXO, called nEXO [18], will contain 5 ton of enriched xenon. Thanks to the better self-shielding of the larger detector volume, and if the energy resolution will be improved to 2.5% FWHM, nEXO could be able to obtain a background of about 2 counts/(ton·y) in the ROI, or even lower if Ba$^{++}$ tagging will be implemented. The expected sensitivity on $\langle m_{\beta\beta}\rangle$ will be (15 – 25) meV. The NEXT collaboration will start operating a 100 kg high pressure xenon TPC in 2018 [19]. The expected energy resolution and background at $Q_{\beta\beta}$ are 0.7% FWHM and less than $10^{-3}$ counts/(keV·kg·y) respectively. A ton scale experiment would have background of about 10 counts/(ton·y) in the ROI, but this can be reduced by improving the energy resolution and the design of the detector. The PandaX-III project [20] plans to build a 1-ton xenon experiment made of five identical high-pressure xenon TPC of 200 kg each. The expected energy resolution and background at $Q_{\beta\beta}$ are 1% FWHM and about 1.5 counts/(ton·y), resulting in a $\langle m_{\beta\beta}\rangle$ sensitivity of (20 – 50) meV.

### 4.4 Tracking detectors

Tracking detectors are different from other $0\nu$DBD techniques because here the source isotope is not embedded in the detector. It is deposited on foils, and the track and energy of the emitted electrons are measured by conventional gas detectors and calorimeters. This approach allows to investigate any isotope that can undergo double-beta decay. Energy resolution is quite poor, because part of the electrons energy is released.
in the source foils themselves and is not measured. This problem is mitigated by making the source foils very thin, but this imposes severe limits in the mass scalability of this technique. Nevertheless the reconstruction of the electron tracks provides excellent background suppression and allows to study the angular distribution of the decay [21]. This feature would be very important to study decay mechanism alternative to the exchange of a light Majorana neutrino.

The SuperNEMO collaboration plans to build a tracking experiment with a source mass of about 100 kg of $^{82}$Se. This isotope has a $Q_{\beta\beta}$ above 2615 keV and the 2$\nu$DBD half-life is long enough to make its contribution to the background negligible. The projected sensitivity on $\langle m_{\beta\beta} \rangle$ is in the (50 – 100) meV range. The detector will be composed by 20 identical modules. The commissioning of the first prototype module was completed recently, it contains a source mass of 7 kg in $^{82}$Se, and the measured energy resolution is 8% FWHM at 1 MeV.

### 4.5 Loaded liquid scintillators

Large volume liquid scintillator detectors can be loaded with double-beta decay isotopes, and can obtain source masses that are hardly achievable with other techniques. Future experiments are considering $^{130}$Te and $^{136}$Xe as isotopes, which are relatively cheap to enrich. Energy resolution is far from being optimal, but is compensated by the very low background and the large mass. As already discussed in section 2, a very effective demonstration of this technique is KamLAND-Zen. A planned upgrade of this experiment will see the deployment of one ton of enriched xenon, resulting in an expected sensitivity of about 20 meV on $\langle m_{\beta\beta} \rangle$. This will be possible only after a major detector upgrade that will reduce the energy resolution at $Q_{\beta\beta}$ to 5% FWHM and therefore mitigate the background from 0$\nu$DBD decay. A similar approach is being pursued by the SNO+ experiment [22]. In this case the plan is to load 780 ton of liquid scintillator with 0.5% in mass of natural tellurium. This will correspond to about 1.3 ton of $^{130}$Te, or about 0.25 ton after fiducial volume cuts. The data taking is expected to start in about two years, and after five years of data taking, the expected sensitivity on $\langle m_{\beta\beta} \rangle$ is of (40 – 90) meV. Using $^{130}$Te instead of natural tellurium, or increasing its concentration, could increase the sensitivity in the future.

### 5 Conclusion

We discussed the target sensitivity of future neutrinoless double-beta decay experiments aiming at the full exploration of the inverted region of the neutrino mass-hierarchy, and the scientific challenges they will have to face. The targets to be achieved are a source mass of the order of one ton and a background of about one count/(ton·y) in the region of interest. No experiment at present can fulfill these
requirements, but promising proposals could meet them in the next decade.

References

Charged lepton flavour violation: precise background calculation and effective field theoretical interpretation

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This note reviews recent theoretical developments in the study of charged lepton flavour violation. The first part illustrates the status of precise next-to-leading order quantum electrodynamics calculations for the background of charged lepton flavour-violating processes, with a focus on the muonic “rare” and “radiative” decays. Phenomenological implications of these computations and their impact on present and future experiments will be discussed. The second part describes the recent progress in the effective field theory interpretation of charged lepton-flavour violating observables in connection with different energy scales. A systematic approach is briefly presented and applications on muonic and tauonic observables are reported. This note is submitted as part of the conference proceedings for ”NuPhys2016: Prospects in Neutrino Physics”.

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1 Introduction

Lepton flavour-violating transitions in the charged lepton sector are accidentally forbidden in the Standard Model (SM). Even with the inclusion of neutrino masses, such processes are extremely suppressed and, consequently, any potential signal of charged lepton flavour violation (cLFV) should be interpreted as an indication of new physics (NP). Therefore, an extended experimental programme has been ongoing for decades in the search for fundamental cLFV interactions [1–12].

Recently, systematic efforts have been devoted to understanding the theoretical aspects related to the interpretation of the absence of cLFV signals in terms of limits on beyond the SM (BSM) physics. On the one hand, these studies progressed onto the determination of the next-to-leading order (NLO) quantum electrodynamics (QED) background of cLFV decays, on the other hand they brought a better understanding of the effective field theoretical interpretation of the absence of signals in terms of limits on Wilson coefficients of the SM extended with dimension-six operators (SMEFT).

Concerning the first research line, a precise background calculation was carried out for the so-called “radiative” [13–15] and “rare” [16, 17] decays, i.e. for the processes \( l \to l' \gamma + 2\nu \) and \( l \to 3l' + 2\nu \) (or \( l \to l'' + 2l'' + 2\nu \)), respectively. Both these channels are important\(^*\) for the determination of the limits on the branching ratios (BRs) of the two cLFV processes \( l \to l' \gamma \) and \( l \to 3l' \) (or \( l \to l' + 2l'' \)) because they provide an identical signal in the circumstance where invisible energy tends to zero, especially in view of the new experimental plans to improve the exploring power on these channels by MEG II [18] and Mu3e [19] for the muonic case, and Belle II [20] for the tauonic case.

For the phenomenological interpretation of the absence of a signal in terms of limits on the parameter space of potential BSM scenarios, a systematic effective field theory (EFT) treatment was proposed [21, 22] and further developed with a particular focus on the muonic coherent LFV transitions [23, 24]. This approach consists of expanding the SM (either in its unbroken or broken phase) through a set of higher-dimensional operators with respect to a mass scale parameter, where the latter represents the energy scale at which NP interactions are generated by an ultra-violet (UV) complete theory, hence allowing one to interpret NP effects in terms of deviations from the SM interactions. Moreover, this is the most powerful method to interpret the impact of correlation effects among operators at different energy scales on cLFV observables.

In the next sections, the main recent literature on these research lines will be reviewed and potential future theoretical prospects will be presented. Wherever possible, the broader picture that connects cLFV with neutrino Physics and UV completions of the SM will be discussed. Finally, literature on other relevant cLFV processes, such as the incoherent \( \mu \to e \) conversion in nuclei and the neutrinoless double beta decay will also be mentioned.

\(^*\)However, they only represent the fundamental background. The leading source of background consists of accidental fake signals.
2 Precise calculations for experimental backgrounds of cLFV transitions

The fundamental backgrounds for low-energy cLFV transitions are the radiative and rare leptonic decays, i.e. the processes \( l \to l' \gamma + 2\nu \) and \( l \to 3l' + 2\nu \), respectively. Indeed, when the energy of the neutrino pair in the final state becomes very small, the two processes are irreducible backgrounds of the forbidden \( l \to l' \gamma \) and \( l \to 3l' \) decay modes. Hence, the determination of these decay rates is important for the precise determination of the limits on the cLFV BRs.

In the last six decades, the radiative decay of the muon has been widely investigated [25–29]; however, the current experimental knowledge is rather unsatisfactory: the Particle Data Group (PDG) value \( \text{BR}(\mu \to e2\nu\gamma) = (1.4 \pm 0.4) \times 10^{-2} \) is affected by an uncertainty of about 30% [30]. The tau lepton and its radiative decays \( \tau \to \mu 2\nu\gamma \) and \( \tau \to e 2\nu\gamma \) has also been studied by CLEO [31], BaBar [32] and Belle [33], and the current PDG values are \( \text{BR}(\tau \to \mu 2\nu\gamma) = (3.68 \pm 0.10) \times 10^{-3} \) and \( \text{BR}(\tau \to e 2\nu\gamma) = (1.84 \pm 0.05) \times 10^{-2} \). From the theoretical point of view, calculations for the radiative lepton decay are performed in the Fermi theory because full SM corrections are smaller than the NLO QED corrections, hence having no impact on the phenomenological interpretation of current experimental data [34, 35]. While tree-level calculations have been available since the 50s of the last century [36–38], it is only recently that full NLO QED computations have been performed, first in [13, 14] and then in [15].

In particular, in [15] a fully differential Monte Carlo study was presented for the radiative decay of an arbitrarily polarised lepton and maintaining a non-vanishing mass for the lepton of the final state, thus enabling the implementation of arbitrary cuts to mimic closely the experimental framework. The NLO QED matrix elements were computed both in conventional dimensional regularisation \(^\dagger\) and the four-dimensional helicity scheme \(^\S\) (FDH) [52], and full agreement was found for the final physical result \(^\P\). On top of this, the on-shell scheme was adopted to renormalise masses and couplings, and soft infra-red (IR) singularities were treated by means of the Frixione–Kunszt–Signer (FKS) subtraction method [55, 56].

Apart from the precise calculation of background for tailored studies at specific experiments, other phenomenological issues are clarified by this computation: in [13], a discrepancy of \( \sim 3.5\sigma \) was found between the theoretical prediction and the BaBar result for the tau radiative decay in association with an electron. The crucial point is that this measurement was done using rather stringent cuts on the final state and then converted to the standard cut. However, the sizeable terms proportional to \( \log(m_e/m_\tau) \) of the QED NLO correction play a fundamental role in such conversion, and [15] shows that their systematic inclusion may reduce the tension to \( \sim 1\sigma \).

\(^\dagger\)Hereafter, to make the quantity well defined, a standard experimental cut on the photon energy \( \omega_0 = 10 \) MeV is understood.

\(^\S\)Exploiting the tools FeynRules [39], FeynArts [40], FormCalc [41, 42], Form [43] and LoopTools [41].

\(^\P\)Exploiting a modified version of the program GoSam [44], plus the tools Ninja [45–47], golem95 [48, 49] and OneLOop [50, 51].

\(^\dagger\)The equivalence between the two schemes is described in [53]. See also [54] and references therein for a recent review on regularisation schemes.
The only experimental information available for the rare leptonic decay regards the muonic $\mu \to 3e + 2\nu$ transition measured long ago by the SINDRUM collaboration [57] and the $\tau \to 3e + 2\nu$ measured by CLEO [58], and their corresponding values according to the PDG [30] are $\text{BR}(\mu \to 3e + 2\nu) = (3.4\pm0.4)\times10^{-5}$ and $\text{BR}(\tau \to 3e + \nu) = (2.8\pm1.5)\times10^{-5}$.

As regards the theoretical approach to the estimation of the BRs, in complete analogy with the radiative decay, the calculation is performed in the framework of the Fermi theory. On top of tree-level studies [59–62], recently the QED NLO corrections also became available [16, 17].

Specifically, in [17] the rare decay was computed for a polarised muon in the initial state and maintaining a non-vanishing mass for the lepton of the final state by means of a fully differential Monte Carlo program. The NLO QED matrix elements were computed in the FDH scheme and soft IR singularities were treated by means of the FKS subtraction method, as described in the previous subsection.

The most important outcome of such computation concerns the differential distribution of the BR with respect to the invisible energy $E_{\text{inv}}$ carried by the neutrino pair. This distribution displays an interesting behaviour in the limit $E_{\text{inv}} \to 0$, which is the region where the background mimics the cLFV signals; here, the NLO QED corrections are negative and approaching $\sim -10\%$. Hence, there are substantially fewer background events than expected from the simplistic tree-level computation, and this has a favourable impact on the efficiency of the searches for cLFV signals.

### 3 EFTs for cLFV observables

In the absence of any evidence for NP at high-energy colliders, the EFT approach to BSM physics is becoming more and more popular in the particle physics community. The SMEFT or analogous setups with the inclusion of higher-dimensional operators [63–68] has become a standard mainstream approach adopted for phenomenological studies of the Higgs boson [69–71], neutrino sector [72], $B$-physics [73–75], et cetera.

In the past few years, a lot of effort has also been devoted to including the study of cLFV observables in a consistent EFT approach with higher-dimensional operators. In this connection, the one-loop matching of a subset of dimension-six operators with the $l \to l'\gamma$ dipole interaction was performed in [76], then the complete set was considered in [21] where also renormalisation-group evolution (RGE) effects of the operators were taken into account in a systematic way\footnote{An independent calculation of the complete set of SMEFT operators anomalous dimensions was presented in [77–79].}. Consequently, it was possible to interpret the MEG limits on $\text{BR}(\mu \to e\gamma)$ [80] and the BaBar/Belle limit on $\text{BR}(\tau \to e(\mu)\gamma)$ [5, 6] in terms of new constraints on the parameter space of some SMEFT Wilson coefficients defined at the high-energy scale that were previously unbounded by low-energy experiments.

Thereafter, the impact of specific low- and high-energy searches was compared in [22]. In this connection, it was found that LFV decays of the $Z$-boson (i.e. $Z \to l_1l_2$) are much more constrained from low-energy experiments than from the limits of current (and possibly future, as discussed also in [81]) direct searches at high energy.
Then, the study of cLFV within the framework of a QED EFT** was performed systematically in a one-loop†† RGE-improved scenario [23, 24, 91]. Focusing on the muonic sector, the three processes $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$ and coherent nuclear $\mu \rightarrow e$ conversion were studied considering the RGE of the Wilson coefficients between the electroweak and the experimental scale ($\Lambda = m_\mu$ for the muonic decays and $\Lambda \simeq 1$ GeV for the conversion in nuclei). As a result, muonic decay and conversion rates were interpreted as functions of the Wilson coefficients at any scale up to $m_W$. Taking the experimental limits on these processes as input, it was found that a considerable set of Wilson coefficients unbounded in the tree-level approach were instead severely constrained. In addition, correlations among operators were studied both in the light of current data and future experimental prospects, illustrating the complementarity of searches planned for the MEG II [18], Mu3e [19] and COMET/Mu2e [92, 93] experiments.

Keeping in mind the ultimate goal of the EFT approach, it is worth mentioning that a plethora of UV-complete models designed for the most different reasons can be matched effectively to cLFV operators and become part of the discussed analysis‡‡.

Finally, one should also bear in mind that the dimension-up-to-six operatorial setup is not sufficient to include lepton-number violation in the systematic approach described above, and more should be done to effectively describe UV-complete scenarios that provide incoherent $\mu \rightarrow e$ conversion in nuclei [97–99] and the neutrinoless double beta decay [100–102].

4 Conclusion

This document reviewed recent developments and literature concerning cLFV in the context of precise calculations for irreducible backgrounds and EFT interpretation of the current and future outcomes of cLFV experiments.

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**Exploiting the same operatorial basis introduced by [82, 83].
††In addition, specific leading order two-loop terms of the RGE were included to provide important qualitative new effects. Previous constraints on Wilson coefficients have been extracted at the scale of the experiments for cLFV lepton–quark [84, 85], lepton–tau [86, 87], four-lepton [88] and lepton–gluon [89] operators. Furthermore, in [90], the impact of LFV tensor and axial-vector four-fermion operators that couple to the spin of nucleons was studied.
‡‡See [94–96] for model setups that are favourable to the interpretation of neutrino observables.
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Flavour symmetric connections with CLFV

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Flavons are crucial for understanding lepton mixing in models with non-Abelian discrete symmetries. They also result in charged lepton flavour violation (CLFV) via the couplings with leptons. I emphasise that the flavon-triggered CLFV succeeds strong connections with lepton flavour mixing. Relations between branching ratios of CLFV decays and mixing angles are discussed, and CLFV sum rules are obtained. Flavons with masses around hundreds of GeV are consistent by current CLFV measurements.

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1 Introduction

Non-Abelian discrete flavour symmetries are directly motivated by large mixing angles measured by neutrino oscillation experiments \cite{1}. Leptonic flavour mixing is explained as the result of the group structure and irreducible representations of the symmetry. One milestone is the realisation of tri-bimaximal (TBM) mixing \cite{2} in $A_4$ \cite{3, 4}. The TBM mixing predicts $\theta_{12} = 35.3^\circ$ and $\theta_{23} = 45^\circ$, still consistent with current oscillation data in $3\sigma$ ranges. However, after observations of a relatively sizable $\theta_{13}$ \cite{5}, specific modifications to TBM should be considered.

Flavons play a key role in flavour model constructions \cite{6}. They gain vacuum expectation values (VEVs) with special directions and lead to the break of the flavour symmetry. Different residual symmetries may be roughly preserved in different flavon VEVs, and flavour mixing is achieved from their misalignment. The small breaking of the residual symmetries result in deviations of the mixing \cite{7}.

Couplings between flavons and leptons not only explain flavour mixing, but also contribute to charged lepton flavour violation (CLFV) \cite{8, 9, 10, 11, 12, 13, 14, 15, 16}. Strongly constrained by flavour symmetries and experimental data, flavon-triggered CLFV shows special properties identified with other new physics contributions \cite{17}. In what follows, I will discuss this phenomenology and its essential connection with flavour symmetries. For definiteness, the flavour symmetry is chosen to be $A_4$.

2 Basic structures of $A_4$ flavour models

Without lose of generality, I show how TBM is realized in most $A_4$ flavour models. Assuming $A_4$ is a flavour symmetry conserved at some high scale, it is broken when the energy scale decreases, but some residual symmetries are preserved, $Z_3 \subset A_4$ in the charged lepton sector, and $Z_2 \subset A_4$ in the neutrino sector\footnote{Another $Z'_2$ symmetry, which is not a subset of $A_4$, is usually preserved accidentally after $A_4$ breaking.}. The lepton mass matrices are constrained by the residual symmetries. The tri-bimaximal mixing is a result of the mismatch between the two residual symmetries. These residual symmetries are not precisely preserved. The small breaking of the residual symmetries leads to corrections to the flavour mixing, and gives rise to the non-zero $\theta_{13}$ and the Dirac CP-violating phase $\delta$.

New scalars called flavons are necessary to be introduced in flavour models. They gain VEVs with special directions, driving non-trivial lepton mass structures and further realizing flavour mixing. In the simplest case, we need at least two $A_4$-pseudo-triplet flavons, $\varphi$ and $\chi$, one for charged leptons and the other for neutrinos. Combining flavons with leptons and the Higgs, we arrive at effective $A_4$-invariant
operators as follows,
\[-\mathcal{L}_l = \frac{y_e}{\Lambda} (\overline{t}_L \varphi)_1 e_R H + \frac{y_\mu}{\Lambda} (\overline{t}_L \varphi)_1 \nu_R H + \frac{y_\tau}{\Lambda} (\overline{t}_L \varphi)_1 \tau_R H + \text{h.c.} + \cdots,\]
\[-\mathcal{L}_\nu = \frac{y_1}{2\Lambda} ((\overline{t}_L \ell_L^c)_3 s_3 \chi)_1 \tilde{H} \tilde{H} + \frac{y_2}{2\Lambda^2} (\overline{t}_L \ell_L^c)_1 \eta \tilde{H} \tilde{H} + \text{h.c.} + \cdots,\] (1)

where \(\eta\) is an \(A_4\)-invariant scalar and the dots stand for subleading higher dimensional operators. Once the flavons take VEVs with the following directions
\[\langle \varphi \rangle \propto (1, 0, 0)^T, \quad \langle \chi \rangle \propto (1, 1, 1)^T,\] (2)
in the Altarelli-Feruglio basis \[\dagger\] the charged leptons and neutrinos gain special Yukawa structures, or equivalently, mass structures as
\[Y_l \propto M_l \propto \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix}, \quad Y_\nu \propto M_\nu \propto \begin{pmatrix} a + 2b & -b & -b \\ -b & 2b & a - b \\ -b & a - b & 2b \end{pmatrix}.\] (3)

And eventually, from them, the TBM mixing is obtained.

To be consistent with data, the residual symmetries should be broken, and corrections to the mixing must be included. Sources for the breaking include

- higher dimensional operators involving different flavons in the Yukawa couplings. For example, VEVs of the 3-dimensional products of \(\chi\) and \(\varphi\) take this direction \((2, -1, -1)^T\) or \((0, 1, -1)^T\). They break \(Z_3\) or \(Z_2\), depending on whether they contribute to charged lepton Yukawa coupling or neutrino Yukawa coupling, respectively.

- shifts of the flavon VEVs. They may be resulted from the coupling between different flavons in the potential or interference by other field. The shift of the flavon VEV will not only contribute to lepton Yukawa couplings, but also modify the flavon masses and mixing directly.

These sources may not be independent of each other, and contribute to flavour mixing at the same time.

A very economical approach based on the second source is proposed in Ref. \[\dagger\]. In this approach, flavon cross couplings between \(\varphi\) and \(\chi\) break the residual symmetries, shift the VEVs from Eq. (2) to
\[\langle \varphi \rangle \propto (1, \epsilon_\varphi, \epsilon_\varphi^*)^T, \quad \langle \chi \rangle \propto (1 - 2\epsilon_\chi, 1 + \epsilon_\chi, 1 + \epsilon_\chi)^T,\] (4)

\[\dagger\] The directions of flavon VEVs are not unique, but basis-dependent. A basis transformation \(\rho(g) \rightarrow U \rho(g) U^{-1}\) for the triplet representation \(\rho(g)\) for \(g \in A_4\) will change the VEVs \(\langle \varphi \rangle\) and \(\langle \chi \rangle\) to \(U \langle \varphi \rangle\) and \(U \langle \chi \rangle\), respectively. Flavour mixing, which are identified as the misalignment between different VEVs, will not be changed under this basis transformation. The follow-up discussion will be fixed in the Altarelli-Feruglio basis. In this basis, the simplest triplet is a pseudo-real one, with \(\varphi_1^* = \varphi_1, \varphi_2^* = \varphi_3,\) and \(\chi_1^* = \chi_1, \chi_2^* = \chi_3\) being required.
Here, $\epsilon_\varphi$ and $\epsilon_\chi$ are small parameters with $\epsilon_\varphi$ being complex and $\epsilon_\chi$ real. The PMNS matrix is approximately given by $U_{\text{PMNS}} = U_l^\dagger(\epsilon_\varphi)U_{\text{TBM}}U_\nu(\epsilon_\chi)$ with $U_l(\epsilon_\varphi)$ and $U_\nu(\epsilon_\chi)$ representing $Z_3$- and $Z_2$-breaking effects, characterised by $\epsilon_\varphi$ and $\epsilon_\chi$, respectively. Deviations of mixing parameters from those in TBM are expressed as

$$\sin \theta_{13} \approx \sqrt{2}|\text{Im}(\epsilon_\varphi)|, \quad \sin \theta_{12} \approx \frac{1 - 2\text{Re}(\epsilon_\varphi) + 2\epsilon_\chi}{\sqrt{3}}, \quad \sin \theta_{23} \approx \frac{1 + \text{Re}(\epsilon_\varphi)}{\sqrt{2}},$$  \hspace{1cm} (5)

Furthermore, a sum rule between the mixing angle $\theta_{13}$ and CP-violating phase,

$$\delta \approx \mp(90^\circ + \sqrt{2}\theta_{13})$$  \hspace{1cm} (6)

for $\text{Im}(\epsilon_\varphi) >, < 0$, respectively, is obtained. I show the numerical results for the correlation between $\theta_{12}$ and $\theta_{23}$ and the allowed parameter space of $|\epsilon_\varphi|$ vs $\epsilon_\chi$ in Fig. 1, where $3\sigma$ range data of mixing angles in [18] have been used.

Figure 1: Theoretical prediction of mixing angles (left panel) and the allowed parameter space of $|\epsilon_\varphi|$ vs $\epsilon_\chi$ (right panel). The straight line corresponds to $\epsilon_\chi = 0$.

3 CLFV induced by flavons

The fact that neutrinos have masses and leptons mix is a convincing evidence of new physics. If there is a mechanism which can explain leptonic flavour mixing, it may also contribute to CLFV since neutrinos and left-handed charged leptons are unified in the electroweak symmetry.

There are already some papers in the literature discussing the connections between CLFV and flavour symmetries. These papers have analysed the following contributions within flavour models. Higher dimensional operators which are not forbidden by $A_4$ [8]. Contributions of superpartners of leptons or flavons, since most of the flavour models are built in the framework of supersymmetry [8, 11, 15]. Flavons as
SU(2)\textsubscript{L}-doublet Higgs \cite{10, 13, 14, 16} and KK modes from warped flavour models \cite{12} have also been discussed in some sense.

I will pay more attention to the essential contribution of the flavour symmetry to CLFV. Here are my guiding principles:

- **Simplicity.** Only SM fields and gauge-invariant flavons will be included. Extra degrees of freedom not essential for explaining flavour mixing will be avoided.

- **Rigour.** Non-trivial properties of the 3-dimensional Altarelli-Feruglio representation of \( A_4 \) will be taken care.

- **Consistency with data.** To be consistent with oscillation data, NLO corrections to the mixing will be specified. How these corrections contribute to and connect with CLFV will be analysed carefully.

- **Testability.** Unique features that can distinguish CLFV induced by non-Abelian discrete symmetry from other new physics will be emphasised.

These considerations lead us to the contribution only from the minimal extension of the SM that can explain oscillation data, namely, those flavons and necessary couplings with leptons. As \( Z_3 \) is a roughly preserved symmetry in the charged lepton sector, I will classify them into two parts: those consistent with the \( Z_3 \) residual symmetry and those contradicting it.

### 3.1 \( Z_3 \)-perserving channels

From the Lagrangian terms in Eq. (1), we can write out the couplings between flavons and charged leptons explicitly as

\[
\mathcal{L}_I^{\text{eff}} = \frac{m_e}{v_\phi} (\bar{e}_L e_R \varphi_1 + \bar{\mu}_L \mu_R \varphi_2 + \bar{\tau}_L \tau_R \varphi_2^*) \\
+ \frac{m_\mu}{v_\phi} (\bar{\mu}_L \mu_R \varphi_1 + \bar{\tau}_L \tau_R \varphi_2 + \bar{e}_L e_R \varphi_2^*) \\
+ \frac{m_\tau}{v_\phi} (\tau_L \tau_R \varphi_1 + \bar{\tau}_L \tau_R \varphi_2 + \bar{e}_L e_R \varphi_2^*) + \text{h.c.}
\] (7)

The \( Z_3 \) symmetry corresponds to the invariance under the transformation

\[
(e_{L,R}, \varphi_1) \rightarrow (e_{L,R}, \varphi_1), \\
(\mu_{L,R}, \varphi_2) \rightarrow \omega^2 (\mu_{L,R}, \varphi_2), \\
(\tau_{L,R}, \varphi_2^*) \rightarrow \omega (\tau_{L,R}, \varphi_2^*)
\] (8)

where \( \omega = e^{2\pi i/3} \). Namely, \( e_{L,R}, \varphi_1 \) are invariant under the transformation of \( Z_3 \), \( \mu_{L,R}, \varphi_2 \) are covariant with a \( Z_3 \) charge 2, and \( \tau_{L,R} \) are covariant with a \( Z_3 \) charge.
1. While the $Z_3$-invariant flavon $\varphi_1$ induces flavour-conserving processes, the $Z_3$-covariant flavon $\varphi_2$ is the main source of CLFV. As $e$, $\mu$ and $\tau$ take different $Z_3$ charges, it is easy to prove that the only allowed processes are $\tau^- \rightarrow \mu^+e^-e^-$ and $\tau^- \rightarrow e^+\mu^-\mu^-$. The other 3-body decay and all radiative decay modes are forbidden by the $Z_3$ symmetry [9].

In the case of transfer momentum much lower than the scale of flavour symmetry and flavon masses, one can integrate out $\varphi_1$ and $\varphi_2$, and derive the effective 4-fermion interactions. Those for $\tau^- \rightarrow \mu^+e^-e^-$ and $\tau^- \rightarrow e^+\mu^-\mu^-$ can be expressed as

\[
\frac{m_{\mu}m_{\tau}}{v^2} \frac{1}{m^2_{\varphi_1}} (\bar{e}_L\mu_R)(\bar{e}_L\tau_R), \quad \frac{m_{\mu}m_{\tau}}{v^2} \frac{1}{m^2_{\varphi_2}} (\bar{\mu}_R e_L)(\bar{\mu}_L\tau_R),
\]

respectively. The coefficients are the same, from which we get approximatively equal branching ratios of these two processes

\[
\text{Br}(\tau^- \rightarrow \mu^+e^-e^-) \approx \text{Br}(\tau^- \rightarrow e^+\mu^-\mu^-),
\]

both suppressed by $(\frac{m_{\mu}m_{\tau}v^2}{m^2_{\varphi_1}m^2_{\varphi_2}})^2$. Assuming flavon VEV and flavon mass around the electroweak scale, the branching ratios are still two orders of magnitude below current experimental upper limit [17].

3.2 $Z_3$-breaking channels

Then we consider $Z_3$-breaking CLFV channels. Since the $Z_3$-breaking effect can give rise to non-zero $\theta_{13}$ and possible deviations of the other mixing parameters from their leading results, this effect should also be included in the discussion of CLFV. As there may be different $Z_3$-breaking origins, it is hard to do a generic analysis for the $Z_3$-breaking CLFV processes. To simplify the discussion, I will consider, as in [17], the $Z_3$-breaking from only flavon cross couplings.

The breaking of $Z_3$ contributing to CLFV can be distinguished into three parts:

- the mixing of left-handed charged leptons $e_L$, $\mu_L$ and $\tau_L$, i.e., $U_l(e_\varphi^1)$;
- the mixing between $Z_3$-invariant flavon $\varphi_1$ and $Z_3$-covariant one $\varphi_2$;
- the mass splitting between the two real degrees of freedom of $\varphi_2$.

We put these contributions into CLFV 3-body and radiative decay processes, and find all these decay modes are allowed. Compared with the $Z_3$-preserving processes, they are further suppressed by the additional parameter $\epsilon_\varphi$.

\footnote{There is also a small mixing of right-handed charged leptons $e_R$, $\mu_R$ and $\tau_R$, it is suppressed by both $\epsilon_\varphi$ and the hierarchy of charged lepton masses due to arrangements of these particles as singlets in $A_4$, i.e., $e_R, \mu_R, \tau_R \sim 1, 1', 1''$.}
For the 3-body decay processes, branching ratio sum rules of $\tau$ decays are observed:

$$2(B_{\mu^+\mu^-e^-} - 2B_{\mu^+\mu^-\mu^-})^2 + (5B_{e^+e^-\mu^-} + 10B_{\mu^+\mu^-\mu^-} - 6B_{\mu^+\mu^-e^-})B_{e^+e^-\mu^-} = 0,$$

$$B_{e^+e^-\mu^-} \approx 8|\epsilon|\phi^2 Br(\tau^- \to \mu^+e^-e^-).$$ \hspace{1cm} (11)

Here, $B_{\mu^+\mu^-e^-}$, $B_{\mu^+\mu^-\mu^-}$, $B_{e^+e^-\mu^-}$ are branching ratios of $\tau^- \to \mu^+\mu^-e^-$, $\tau^- \to \mu^+\mu^-\mu^-$, and $\tau^- \to e^+e^-\mu^-$, respectively. In the limit $m_{\phi_1} \ll m_{\phi_2}$, we get $B_{\mu^+\mu^-e^-} \approx 2B_{\mu^+\mu^-\mu^-} \gg B_{e^+e^-\mu^-}$, and on the contrary, we obtain $B_{\mu^+\mu^-e^-} \approx 4B_{\mu^+\mu^-\mu^-} \approx 2B_{e^+e^-\mu^-}$. These processes are weaker than the $Z_3$-preserving processes because of the $\epsilon_\phi$ suppression. For $\tau^- \to e^+e^-e^-$ and $\mu^- \to e^+e^-e^-$, their branching ratios are suppressed by electron mass, thus, far away from experimental limit.

Radiative decays are also allowed by cross couplings. $\tau^- \to \mu^-\gamma$ and $\tau^- \to e^-\gamma$ are induced by the mixing between charged lepton flavour eigenstates and by the mixing between $\varphi_1$ and $\varphi_2$. The approximately equal branching ratios are predicted,

$$Br(\tau^- \to e^-\gamma) \approx Br(\tau^- \to \mu^-\gamma).$$ \hspace{1cm} (12)

Assuming the flavon VEV and masses above the electroweak scale, these branching ratios $\lesssim 10^{-11}$, 3 orders of magnitude below the current best experimental limits.

![Figure 2: Flavon VEV and $\varphi_2$ mass constrained by $\mu^- \to e^-\gamma$ experiments. $|\epsilon|_\varphi$ is fixed at 0.1 for generating $\theta_{13}$. The current (MEG) and future (MEG II) constraints are set to be $Br(\mu^- \to e^-\gamma) < 4.2 \times 10^{-13}$ and $4 \times 10^{-14}$, respectively.](image)
complex flavon $\varphi_2$. This process is suppressed by $\epsilon_\varphi$ and $m_\mu$, but it has been measured more precisely than the $\tau$ decay. Regions of $v_\varphi$ and $m_{\varphi_2}$ allowed by current experiments and testable at the near future experiments are shown in Fig. [2]. The current upper limit is given by the MEG experiment, around $4.2 \times 10^{-13}$ (90% CL) [19]. By fixing the flavon VEV at the electroweak scale, we obtain the lower limit of the $\varphi_2$ mass is around 500 GeV. In the future, MEG II will push the upper limit of the branching ratio to $4 \times 10^{-14}$ [20]. This experiment will have the potential to exclude a large parameter space.

4 Conclusion

Flavour symmetries are usually treated as the origin of leptonic flavour mixing. The newly introduced interactions in flavour models will not only generate flavour structure in lepton mass matrices, but also contribute to CLFV processes. The flavon-triggered CLFV has strong connections with the symmetries. In $A_4$ models, all CLFV processes can be classified by the residual symmetry $Z_3$. The only allowed $Z_3$-preserving processes are $\tau^- \to \mu^+ e^- e^-$, $\tau^- \to e^+ \mu^- \mu^-$ and their conjugate processes. All the other 3-body and radiative decays are $Z_3$-breaking. Several CLFV sum rules are obtained. This is a highlighted feature to connect non-Abelian discrete flavour symmetries with CLFV. While the $Z_3$-preserving processes are suppressed by charged lepton masses, the $Z_3$-breaking processes are further suppressed due to the consistency with oscillation data. The current experimental constraints are loose. Hundreds of GeV scale flavon VEV and mass are still allowed.

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References


The ERC ENUBET Project: high precision neutrino flux measurements in conventional neutrino beams

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The challenges of precision neutrino physics require measurements of absolute neutrino cross sections at the GeV scale with exquisite (1%) precision. This precision is presently limited by the uncertainties on neutrino flux at the source; their reduction by one order of magnitude can be achieved monitoring the positron production in the decay tunnel originating from the $K_{e3}$ decays of charged kaons in a sign and momentum selected narrow band beam. This novel technique enables the measurement of the most relevant cross sections for CP violation ($\nu_e$ and $\bar{\nu}_e$) with a precision of 1% and requires a special instrumented beam-line. Such non-conventional beam-line will be developed in the framework of the ENUBET Horizon-2020 Consolidator Grant, recently approved by the European Research Council. The project, the first experimental results on ultra-compact calorimeters that can be embedded in the instrumented decay tunnel and the advances on the simulation of the beamline are presented. We also discuss the detector and accelerator activities that are planned in 2016-2021.

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1 Conventional and monitored neutrino beams

In conventional beamlines the decay tunnel is a passive region and the knowledge of the neutrino flux relies on ab-initio simulations that take into account the proton-target interactions, the reinteraction of secondaries, their tracking and decay. Despite the use of hadro-production data from dedicated experiments and of ancillary measurements (proton intensity, horn currents, beam-target misalignment etc.), the precision on the flux prediction is usually limited to 7-10%.

A very precise measurement of the $\nu_e (\overline{\nu}_e)$ flux can be achieved by directly monitoring in an instrumented decay tunnel the production of large angle positrons (electrons) from $K_{e3}$ decays ($K^{+(-)} \rightarrow \pi^0 e^{+(-)} \nu_e (\overline{\nu}_e)$) in a sign and momentum-selected narrow band beam [1]. The $e^+$ rate gives a direct estimate of the $\nu_e$ flux that is not affected by beam related systematics arising from the number of PoT, the hadro-production cross sections and the secondary meson focusing efficiency of the beamline, and this method could reduce the uncertainty on the $\nu$ flux normalization down to 1%.

2 The ENUBET project

The ENUBET (Enhanced NeUtrino BEams from kaon Tagging) project is intended to demonstrate the feasibility of the monitored beam approach, by designing and constructing a detector able to identify positrons from $K_{e3}$ decays in the harsh environment of a neutrino beam decay tunnel [2]. It will also study the accelerator issues and the the precise layout of the kaon/pion focusing and transport system. The project has been approved by the ERC (CoG, P.I. A. Longhin, Host Institution INFN) for a five year duration (since 1 June 2016) and a 2.0 MEUR budget. A controlled neutrino source, like the one proposed by ENUBET, could be exploited by future experiments aiming at $O(1\%)$ precision in the electron neutrino cross section measurement. It could be also exploited in a phase-II sterile neutrino search, especially in case of a positive signal from the upcoming short baseline experiments. Finally, ENUBET intends to set the first milestone towards a “time-tagged neutrino beam”, where the $\nu$ at the detector is time-correlated with the produced $e^+$ in the decay tunnel.

The ENUBET reference design (Figure 1) foresees a secondary beam with an average momentum of 8.5 GeV and a $\pm 20\%$ momentum bite. The tagging detector is a hollow cylinder surrounding a fraction of the decay tunnel and it is instrumented with a calorimeter for $e/\pi$ separation and a photon veto to separate electromagnetic showers from $\pi^0$ decays or prompt $e^+$ from $K_{e3}$.

The choice of a high secondary energy and of a short tunnel (50 m) reduces the $\nu_e$ content of the beam coming from muon decays in flight with respect to the ones from $K_{e3}$ and enhances the $\nu_e/\nu_\mu$ ratio. Furthermore the resulting positron energy is large
Figure 1: The ENUBET beamline. On the right a section of the decay tunnel instrumented with arrays of calorimeter modules (UCM, in orange) and with the photon veto (in yellow) is also shown.

enough for an efficient identification through calorimetric techniques and the produced neutrino spectrum matches the one of interest for future long baseline experiments. The emittance of the secondary beam (few mrad over $10 \times 10 \text{ cm}^2$) and the radius of the tunnel are optimized in order to prevent undecayed secondaries and muons from pion decay from hitting the calorimeter.

Studies in the preparatory phase of ENUBET have shown that, employing a 500 t neutrino detector (e.g. ICARUS at Fermilab or ProtoDune-SP/DP at CERN) located 100 m from the entrance of the decay tunnel and a 30 GeV (450 GeV) proton driver, $5 \times 10^{20}$ ($5 \times 10^{19}$) PoT would be required to provide a sample of $10^4$ tagged $\nu_e^{CC}$ interactions. The tagging detector can be safely operated in terms of pile-up, dose, etc. if local particle rates are below $\sim 1 \text{ MHz/cm}^2$; this implies that the proton extraction length cannot be shorter than 1 ms. On the other side, longer extractions significantly exceeding 10 ms are disfavoured if secondary focusing is achieved by magnetic horns. The use of a very efficient focusing system based on DC operated magnets can overcome this limitation and can offer the possibility of reducing particle rates to the level needed to match current detector time resolutions for the operation of the facility also in “time-tagged” mode. Within ENUBET, proton extraction schemes compatible with accelerators at CERN, J-PARC and Fermilab will be investigated.

3 Detector prototyping and simulation

In order to cope with the needs of a high $e/\pi$ separation capability and of a radiation hard, fast-responsive and cost-effective setup, the choice of the tunnel instrumentation has fallen on a shashlik calorimeter with longitudinal segmentation. The basic unit of the calorimeter, the Ultra-Compact Module (UCM), is made of five, 15 mm thick,
iron layers interleaved by 5 mm thick plastic scintillator tiles. The total length of the module (10 cm) corresponds to 4.3 $X_0$ and its transverse size is of $3 \times 3$ cm$^2$. Nine wavelength shifting fibers crossing the UCM are connected directly to 1 mm$^2$ SiPMs through a plastic holder (Figure 2, left). SiPMs are hosted on a PCB and the output signals are summed and routed toward the front-end electronics by copper-kapton lines. Unlike conventional shashlik calorimeters, this scheme avoids the occurrence of large passive regions usually needed to bundle the fibers and route them to a common photo-sensor, thus greatly improving the homogeneity in the longitudinal sampling.

Figure 2: (Left) A single UCM. (Right) Electron energy resolution versus beam energy for data obtained in the CERN-PS T9 exposure (red dots), compared to MC simulation (blue stars) [4].

UCM prototypes were developed by the INFN SCENTT collaboration; they were tested with cosmic rays and characterized with charged particles in the 1-5 GeV range at the CERN-PS East Area facility [3, 4]. The results have proven the linearity of the calorimeter response in the considered energy range without saturation up to 4 GeV and an energy resolution of 18% at 1 GeV (Figure 2, right), well within the requirements of $25\%/\sqrt{E}$ for an efficient $e/\pi$ separation.

The performances of the full instrumented tunnel were simulated with GEANT4 [5]. The particle identification algorithms employed rely on the pattern of energy deposit along the UCMs through a multivariate approach based on a neural network (Figure 3); the information from hits in the photon veto is used for the $\pi^0$ rejection [6]. For a positron tagging efficiency of 49%, the $\pi^\pm$ and $\pi^0$ mis-identification probabilities are 2.9% and 1.2% respectively, confirming that the UCM technique is appropriate for the ENUBET needs.

In November 2016 a module composed of 56 UCMs in 7 longitudinal layers ($\sim30$ $X_0$), complemented by an outer module acting as energy catcher, have been exposed to electron and pions with various incidence angles at the CERN-PS; the analysis of these data, currently on going, will allow to test the $e/\pi$ performance under realistic conditions. Further prototype exposures to charged particles (CERN) and neutrons...
The photon veto will be γ-irradiated at the INFN-LNF BTF. Finally, a full demonstrator (3 m in length, 180° coverage) will be assembled and tested at CERN.

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References

Machine Learning-based Energy Reconstruction for Water-Cherenkov detectors

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Hyper-Kamiokande (Hyper-K) is a proposed next generation underground water Cherenkov (WCh) experiment. The far detector will measure the oscillated neutrino flux from the long-baseline neutrino experiment using 0.6 GeV neutrinos produced by a 1.3 MW proton beam at J-PARC. It has a broad program of physics and astrophysics mainly focusing on the precise measurement of the lepton neutrino mixing matrix and the CP asymmetry. The unoscillated neutrino flux will be measured by an intermediate WCh detector. One of the proposed designs is the Tokai Intermediate Tank for the Unoscillated Spectrum (TITUS). WCh detectors are instrumented with photomultipliers to detect the Cherenkov light emitted from charged particles which are produced by neutrino interactions. The detection of light is used to measure the energy, position and direction of the charged particles. We propose machine learning-based methods to reconstruct the energy of charged particles in WCh detectors and present our results for the TITUS configuration.

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NuPhys2016, Prospects in Neutrino Physics
1 Introduction

The Hyper-K experiment is a proposed 0.5 Mton water Cherenkov detector which will act as the far detector for the future long-baseline neutrino program in Japan [1]. It will measure the oscillated spectrum of the neutrino beam produced by the proton synchrotron in J-PARC. The detector will be placed at 2.5° off the beam axis, resulting in a narrow neutrino beam profile peaked at the $P(\nu_\mu \rightarrow \nu_e)$ oscillation maximum of 0.6 GeV at 295 km. The main focus of the experiment is the precise measurement of the leptonic CP asymmetry. To minimise uncertainties due to the modelling of neutrino interactions and hence the neutrino flux, an intermediate detector, TITUS [2], using the same target material as the far detector has been proposed. This is a 2 kton water Cherenkov detector aiming to measure the neutrino spectrum before oscillation. Water Cherenkov detectors detect neutrino interactions using the photons emitted when the charged particles traverse the water volume. The Cherenkov photons are collected by photomultipliers (PMTs) and are used to reconstruct the energy, position and direction of the charged particles. Previously, the energy reconstruction of the charged particles for the TITUS detector was performing using look up tables [2]. We propose a new approach using machine learning-based methods for the energy reconstruction.

2 Machine Learning Energy Reconstruction

Machine learning methods are gaining popularity as quick and efficient tools in multidisciplinary problems. A wide variety of algorithms ranging from neural networks to boosted decision trees are implemented in several software packages. For this study, we compared neural networks with boosted decision trees using an appropriate selection of input variables for the energy reconstruction of charged particles in water Cherenkov detectors. Here, we present the two best options of machine learning algorithms for our problem. These are boosted decision trees with Gradient Boost (BDTG) implemented in the ROOT-TMVA [3] and the Scikit [4] package. This method was applied to both muons and electrons produced by $\nu_\mu$ and $\nu_e$ events respectively with comparable performance.

2.1 Input Variables

The boosted decision trees are trained using appropriate input variables and the Monte Carlo (MC) muon energy. The weights produced for each variable during the training phase are used for the estimation of the muon energy. The input variables which are selected for the energy reconstruction are:

i) The number of hits in PMTs: The number of photoelectrons (pes) in PMTs are clustered according to time coincidences under the Cherenkov hypothesis and the
total number of selected hits in clusters is measured.
i) The number of photoelectrons in rings: To take into account the possibility that in high energies more than one particles produce Cherenkov rings, the observed photoelectrons are grouped in rings. Then, the total number of photoelectrons for the observed rings is measured.

iii) The vertical distances from the reconstructed track direction to the detector walls

iv) The track length calculated as the distance between the first and last PMT hit under the hypothesis of Cherenkov emission angle.

Variables (i) and (ii) have a strong dependence on the MC muon energy as it is shown in Figure 1. The last pair of variables is used to take into account the event topology, thus compensating for events that escape the instrumented volume.

![Figure 1: The number of hits in PMTs (left plot) and the number of photoelectrons in rings (right plot) as a function of the MC muon energy.](image)

### 2.2 Results on the Energy Reconstruction

The BDTG algorithms from the TMVA and the Scikit package were trained and tested for muon events using the input variables described in Section 2.1. The results of the energy resolution as a function of the MC muon energy are shown in Figure 2. The energy resolution is defined as:

\[
\Delta E \over E = \frac{\text{MC muon energy} - \text{Reconstructed muon energy}}{\text{MC muon energy}} \times 100
\]

Both methods have comparable performance resulting in a very good energy reconstruction for muon energies from 200 MeV to 600 MeV which is the area of interest. This is shown in Figure 3. Both methods lead to a better energy resolution compared to the TITUS method using look up tables with analogous input variables. The use of the BDTG from the Scikit package leads to a lower standard deviation and therefore better energy reconstruction for high energy muons (with energies above 2 MeV).
Figure 2: The mean and standard deviation of the resolution distribution in bins of energy for the BDTG from the TMVA (left plot) and the Scikit (right plot) package. GeV). Both methods will be further optimised and tested with other approaches in the future.

Figure 3: The distribution of the energy resolution for muon energies from 200 MeV to 600 MeV for the TMVA and the Scikit package and for the TITUS look up tables. In Figure 4 (left) the muon energy resolution using the TITUS look up tables with analogous input variables is shown. This approach leads to larger deviations in the energy resolution across the whole muon energy range.

To understand why the results on the energy reconstruction with TITUS look up tables are worse than the machine learning approach we created new look up tables using only the number of photoelectrons in rings. As it is shown in Figure 4 (right), these look up tables have better performance for muon energies below 1 GeV. This is due to the fact that the TITUS look up tables assume a spherical event topology instead of a cylindrical one. When this bias is eliminated and only the number of photoelectrons is used their performance is improved. However, both look up tables result in worse energy resolution compared to the BDTGs.
For the results mentioned above, all simulated events have been used. However, for detailed analysis studies, only events in a fiducial volume are taken into account. These are events that are well-contained in the detector and deposit most of their energy in the instrumented volume. The energy resolution for events in a cylindrical fiducial volume 1 m away from each detector wall is shown in Figure 5 for the TMVA (left) and the Scikit (right) BDTG. Both methods lead to a very good energy resolution for this subsample of events across the whole muon energy range.

Figure 5: The mean and standard deviation of the resolution distribution in bins of energy for the BDTG from the TMVA (left plot) and the Scikit (right plot) package for events in a fiducial volume.
3 Conclusion

A new method for the energy reconstruction using BDTGs with appropriate input variables from ROOT-TMVA and Scikit packages was presented. The results for both BDTGs are comparable and better than the standard TITUS approach using look up tables, thus improving the standard deviation of the energy resolution. This method can be used to reconstruct both the muon and electron energy, thus constituting a new technique for the energy reconstruction in water Cherenkov detectors.

References

Results from the OPERA Experiment

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The OPERA experiment reached its main goal by proving the appearance of $\nu_\tau$ in the CNGS $\nu_\mu$ beam. A sample of five $\nu_\tau$ candidates was collected allowing to reject the null hypothesis at 5.1$\sigma$. The estimation of $\Delta m_{23}^2$ in “appearance mode” has been obtained. Updates on the search for $\nu_\mu \rightarrow \nu_e$ oscillations and on the search for sterile neutrino mixing in the $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ channels are also reported.

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1 Introduction

The OPERA experiment at the Gran Sasso Lab was exposed to the CNGS $\nu_\mu$ beam, 730 km away from the beam source.

The CNGS was a conventional neutrino beam optimised for $\nu_\tau$ appearance search. Unlike other neutrino beams designed to measure $\nu_\mu$ disappearance at the atmospheric squared-mass splitting scale, the mean energy (17 GeV) of the CNGS was not tuned at the oscillation maximum which for $L = 730$ km is at $E_\nu \sim 1.5$ GeV, i.e. below the $\tau$ production threshold. The prompt $\nu_\tau$ contamination was negligible, $\mathcal{O}(10^{-6})$; the $\nu_e$ component was relatively small: in terms of CC interactions, the $\nu_e$ and $\bar{\nu}_e$ contaminations were together $< 1\%$.

The total exposure to the CNGS beam ($17.97 \times 10^{19}$ protons on target, PoT) resulted in 19505 neutrino interactions in the OPERA target fiducial volume.

The OPERA detector was made of two identical super modules (SMs) each consisting of a target section made of lead/emulsion-film modules, of a scintillator tracker detector, needed to pre-localize neutrino interactions within the target, and of a muon spectrometer. The topology of neutrino interactions were recorded in emulsion cloud chamber detectors (ECC bricks) with submicrometric spatial resolution. Each brick was a stack of 56 $1 \text{ mm}$ thick lead plates, and 57 nuclear emulsion films with a $12.7 \times 10.2 \text{ cm}^2$ cross section, a thickness of $\sim 10 X_0$ and a mass of 8.3 kg. In the bricks, the momenta of charged particles were measured by their multiple Coulomb scattering in the lead plates. A changeable sheet (CS) doublet consisting of a pair of emulsion films was attached to the downstream face of each brick. The full OPERA target was segmented in about 150000 bricks, arranged in each SM in 31 walls. Downstream of each target wall two orthogonal planes of electronic target trackers (TTs), made of 2.6 cm wide scintillator strips, recorded the position and deposited energy of charged particles. A spectrometer, consisting of iron core magnets instrumented with resistive plate chambers and drift tubes was mounted downstream of each target module. The spectrometers are used to identify muons, determine their charge, and measure their momentum with an accuracy of about 20\%. A detailed description of the OPERA detector can be found in Ref. [1].

2 Data processing

Neutrino events were classified either as $1\mu$, i.e. events with at least one track tagged as a muon, or as $0\mu$ [2]. A dedicated program reconstructs tracks in the electronic detectors and builds a 3D probability map for bricks to contain the neutrino vertex. The CS films of the brick with the highest probability are developed and analysed with high-speed automatic optical microscopes [2], searching for tracks compatible with the TT prediction. The tracks found in the CS doublet are extrapolated to
the most downstream film of the brick and then followed upstream in the brick until the stopping point (primary vertex). A procedure is then applied to detect charged and neutral decay topologies, secondary interactions or photon conversions in the neighborhood of the primary vertex. If a secondary vertex is found a full kinematical analysis is performed extending the scanned volume and following the tracks also in the downstream bricks. This analysis integrates the complementary information provided by emulsions and electronic detectors, making use of the angles measured in the emulsion films, the momenta determined by multiple Coulomb scattering measured in the brick, the momenta measured by the magnetic spectrometers, and the total energy deposited in the instrumented target acting as a calorimeter [2]. The energy of photons and electrons is also estimated using calorimetric techniques [3]. The details of the event analysis procedure are described in Ref. [4].

3 Results on neutrino oscillations

3.1 $\nu_\mu \rightarrow \nu_\tau$

Five events out of all 0$\mu$ events and 1$\mu$ events with $p_\mu < 15$ GeV/c fulfill the topological and kinematical cuts required for $\nu_\tau$ candidates [5]. In one of them the $\tau$ lepton undergoes a muonic decay [6], one event is a $\tau \rightarrow 3h$ decay [7], and three events are $\tau \rightarrow 1h$ decays [8, 9].

The numbers of expected signal and background events are estimated from the simulated CNGS flux [10]. The expected detectable signal events in the 0$\mu$ events and 1$\mu$ samples are obtained using the reconstruction efficiencies and the $\nu_\tau$ event rate in the flux normalised to the detected $\nu_\mu$ interactions. A similar normalisation procedure is also used in the background expectation. The details of the signal and background estimation are described in Ref. [7]. The expected numbers of $\nu_\tau$ events for each decay channel are computed assuming $\Delta m^2_{23} = 2.44 \times 10^{-3}$ eV$^2$ [11] and maximal mixing (see Table 1). The total expected signal amounts to 2.64 ± 0.53 events. The total systematic uncertainty on the expected signal is then set to 20% [5].

The main sources of background in the search for $\nu_\tau$ appearance are charmed particle decays, hadronic interactions and large-angle muon scattering (LAS). The uncertainties on the charm and hadronic backgrounds are 20% [11] and 30% [5], respectively. A recent re-evaluation of the LAS background led to a significant reduction of its contribution [12]. From this study it follows that the number of LAS background events that satisfy the selection criteria amounts to [$1.2 \pm 0.1$(stat.)$\pm 0.6$(sys.)]$\times 10^{-7}/\nu_\mu^{CC}$ interactions. The estimated background events for the analysed data set with the corresponding uncertainties are listed in Table 1. The total expected background amounts to 0.25 ± 0.05 events.

The significance of the observed $\nu_\tau$ candidates is evaluated as the probability that the background can produce a fluctuation greater than or equal to the observed
number of events. Two test statistics are used, one based on the Fisher’s method, the other one based on the profile likelihood ratio. Both methods exclude the background-only hypothesis with a significance of 5.1 σ [5]. The observed number of ντ candidates is also compatible with the expectations in the three neutrino oscillation framework. Based on the number of observed signal candidates ∆m^2_{23} has been evaluated in “appearance mode” for the first time. Assuming full mixing the 90% C.L. interval for ∆m^2_{23} is [2 \times 10^{-3}, 5 \times 10^{-3}] eV^2 [5].

### 3.2 νμ → νe

The possibility to efficiently disentangle electrons from photon conversion in the ECC bricks bases the search for oscillations in the νμ → νe channel. A dedicated procedure is applied to 0µ events aiming at identifying “shower hints” from track multiplicity in the changeable sheet doublets. An additional scanning of volume extending from the most downstream film up to the interaction vertex is performed in order to reconstruct electromagnetic showers. Events with a shower initiated by a single track emerging from the primary vertex are classified as νe candidates. A first result corresponding to $5.3 \times 10^{19}$ pot was published in Ref. [3]. The search has been extended to the whole data set yielding 34 νe candidates. The expected number of νe CC interactions due to the intrinsic beam contamination is 37 ± 5. Background events amount to 1.2 ± 0.1. They arise from misidentified π0 in νμ interactions without a reconstructed muon and ντ CC interactions with τ decaying into an electron. In the whole energy range 2.9±0.4 oscillated νe CC events are expected assuming $\sin^2 2\theta_{13} = 0.098$, $\sin^2 2\theta_{23} = 1$, $\Delta m^2_{23} = 2.44 \times 10^{-3}$ eV^2, $\delta_{CP} = 0$, and neglecting matter effects. In conclusion, the number of observed events is compatible with the 3-flavour oscillation model.

### 3.3 Search for sterile neutrino mixing

The results on ντ appearance have been interpreted in the context of the 3+1 neutrino model deriving limits on oscillations induced by a massive sterile neutrino. Exclusion regions are obtained in the ($\Delta m^2_{41}, \sin^2 2\theta_{\mu\tau}$) parameter space. The limits on $\Delta m^2_{41}$ are extended up to $10^{-2}$ eV^2 for relatively large mixing, $\sin^2 2\theta_{\mu\tau} > 0.5$. At large values of $\Delta m^2_{41}$ ($> 1$ eV^2), marginalising over the CP-violating phase, values of the
effective mixing parameter $\sin^2 2\theta_{\mu\tau} > 0.119$ are excluded at 90% C.L. [13].

In Ref. [3] the number of $\nu_e$ candidates was compared to the expectation from an approximated two-state model parametrised in terms of two effective parameters, $\Delta m^2_{\text{new}}$ and $\theta_{\text{new}}$. The approximation is valid assuming $CP$ conservation, neglecting standard oscillations, treated as a background, and for large values of $\Delta m^2_{\text{new}} (> 0.1\ eV^2)$. To optimise the sensitivity only events below 30 GeV were considered. Six events were observed to be compared to an expectation of $9.4 \pm 1.3\ (\text{syst.})$. For large $\Delta m^2_{\text{new}}$ values the 90% C.L. upper limit on $\sin^2 2\theta_{\text{new}}$ is at $7.2 \times 10^{-3}$. This analysis is being updated in the 3+1 neutrino model using the whole $\nu_e$ data sample.

4 Conclusions

The OPERA experiment has discovered $\nu_\tau$ appearance with a significance of 5.1 $\sigma$ observing 5 $\nu_\tau$ candidates with a background of 0.25 events.

The results on $\nu_\mu \to \nu_\tau$ search, compatible with the standard 3$\nu$ model, have been used to constrain the parameter space of oscillations induced by a massive sterile neutrino. Limits on the sterile neutrino mixing have also been derived in the $\nu_\mu \to \nu_e$ appearance channel.

In order to estimate oscillation parameters with reduced statistical uncertainty an analysis using a selection with released cuts and multivariate techniques is being performed. The unique feature of the OPERA experiment to identify all neutrino flavours will allow a joint fit of all oscillation data.

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Phenomenology of a Neutrino-DM Coupling: The Scalar Case

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Dark matter (DM) and neutrinos are the two most compelling pieces of evidence of new physics beyond the Standard Model of Particle Physics but these are often treated as belonging to two different sectors. Yet DM-neutrino interactions are known to have cosmological consequences. Here, we study the scenario of a scalar DM candidate coupled to left-handed neutrinos via a Dirac mediator. We determine the mass of a DM candidate that yields the right DM relic abundance in a thermal scenario and it is consistent with large-scale structure formation. In order to satisfy both constraints, a complex DM candidate should have a mass larger than 8.14 keV while the mass of a real DM candidate should be above 18.1 eV, independently of the value of the DM-neutrino coupling.

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1 Introduction

The discovery of neutrino masses together with the presence of dark matter (DM) strongly suggest the existence of new physics beyond the Standard Model of Particle Physics. Consequently, models were proposed to explain both phenomena (and in particular the relic density and neutrino masses) in a minimalistic way [1]. Such attempts generally consider a DM-neutrino interaction term which can lead to a rich phenomenology in the Early Universe. Furthermore, such interactions introduce the possibility of detecting neutrinos that are produced from DM self-annihilation at neutrino detectors on Earth [2]. So far only a limited number of models have been considered in the literature for dark matter-neutrino interactions [3]. However, given that DM particles have not been found yet and that the mechanism by which neutrinos acquire a mass remains unsettled, it is worth investigating a larger number of scenarios and examine whether they are compatible with known constraints.

In this paper, we will consider the scenario of a scalar DM candidate coupled to left-handed neutrinos via a Dirac fermion* so that:

\[ \mathcal{L}_{\text{int}} \supset -g \chi N R \nu L + \text{h.c.} , \]  

where \( N \) is the Dirac mediator and \( \chi \) the DM candidate. Such coupling can arise by introducing a Dirac \( SU(2) \) doublet like in supersymmetric models [3]. If on the other hand, \( N \) is a singlet, the coupling can be generated in Inert Doublet models where the scalar \( \chi \) belongs to an \( SU(2) \) doublet. Since the aim of this paper is to study the cosmological implications of the coupling \( g \), we take the DM and mediator masses as free parameters and we don’t discuss any model specific bounds.

The paper is structured as follows: In the next section we will briefly review the different experimental signatures considered to test our scenario and we will discuss the results in Section 3. Finally, we will conclude in Section 4.

2 Cosmological signatures

A DM-neutrino interaction induces processes such as the annihilation of DM to neutrinos and the elastic scattering between neutrinos and DM particles. If this is the dominant annihilation channel for thermal freeze-out, the thermally averaged annihilation cross section of DM to neutrinos will set the amount of DM that we observe today (i.e. the relic density), for which \( \langle \sigma v \rangle_{\text{Th}} \simeq 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \) is required. As we impose the DM candidate’s relic density to be smaller or equal to the observed

* This is done as a proof of concept and we leave the full discussion of all possible scenarios consistent with Lorentz invariance where a DM candidate can interact with neutrinos to a future paper that will be released shortly.
abundance, $\Omega_{DM} h^2 = 0.1188$ [4], we obtain a lower bound on the strength of the DM-neutrino interaction.

It has also been shown that the elastic scattering between neutrinos and DM can lead to a suppression of small-scale structures in the Universe (known as collisional damping) [5], since it allows for DM to be in equilibrium with neutrinos even after chemical decoupling. Therefore, the DM takes longer to free-stream and could lead to a further suppression of such structures. By confronting the large-scale structure predictions to observations, the relevant constraint for the scenario considered is [5]

$$\sigma_{el} < 10^{-48} \left( \frac{m_{DM}}{\text{MeV}} \right) \left( \frac{T_0}{2.35 \times 10^{-4} \text{eV}} \right)^2 \text{cm}^2,$$

for an energy dependent cross section, with $T_0$ the neutrino temperature today.

Finally, in the presence of DM-neutrino interactions, one can search for a flux of neutrinos and anti-neutrinos produced from DM annihilation at rest in regions with a high DM density like the Milky Way. Such a flux would be monochromatic since each neutrino will carry an energy equal to the DM mass and could be detected at neutrino detectors on Earth. For this scenario, the relevant constraints in the total annihilation cross section of DM to neutrinos can be set using the Super-Kamiokande (SK) Phase I data from the supernova relic neutrino search following the analysis done in [2]. Nevertheless, the results including SK Phases I-III are expected to be similar [6].

### 3 Results

We compute the thermal annihilation cross section to left-handed neutrinos and the elastic scattering cross section between DM and left-handed neutrinos in the limit $m_\nu \to 0$, which is summarized in Table 1. Fig. 1 shows the allowed parameter space considering the relevant constraints. The colored contours correspond to different values for the elastic scattering cross section. It is worth noting that, for the scalar to be a viable DM candidate, $m_N > m_{DM}$ so that the DM remains stable. Consequently, the parameter space below the diagonal in Fig. 1 is excluded.

<table>
<thead>
<tr>
<th></th>
<th>Complex DM</th>
<th>Real DM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle \sigma v \rangle \propto$</td>
<td>$g^4 v^2_{\text{CM}} \frac{m_{DM}^2}{(m_{DM}^2 + m_N^2)^2}$</td>
<td>$g^4 v^4_{\text{CM}} \frac{m_{DM}^6}{(m_{DM}^2 + m_N^2)^4}$</td>
</tr>
<tr>
<td>$\sigma_{el} \propto$</td>
<td>$g^4 E^2_{\nu} \frac{1}{(m_{DM}^2 - m_N^2)^2}$</td>
<td>$g^4 E^4_{\nu} \frac{m_{DM}^4}{(m_{DM}^2 - m_N^2)^4}$</td>
</tr>
</tbody>
</table>

Table 1: Relevant terms of the expressions for the annihilation and the elastic scattering cross sections for a complex and a real DM candidate when $m_{DM} \neq m_N$. 

2
Figure 1: Relevant parameter space in the $m_N - m_{DM}$ plane with $g = 1$ for complex DM (left) and real DM (right). The light red and orange regions correspond to DM overproduction and the 90% C.L. bound from the SK search using $v_{CM} = \frac{1}{3}$ c and $v_{CM} = 10^{-3}$ c respectively. The dashed area represents the excluded region from collisional damping while the brown vertical line refers to the lower bound from Planck effective number of neutrino species measurement. The red star is the point from which both the relic density and the collisional damping constraints are satisfied.

The cross sections for real DM are more suppressed due to the $v_{CM}^4$ and $E_\nu^4$ dependence, which in turn translates into weaker bounds as can be seen in Fig. 1. However, in the degenerate regime (i.e. $m_{DM} \sim m_N$) $\sigma_{el} \propto g^4/m_{DM}^2$ which shows as an enhancement of the elastic cross section along the diagonal in Fig. 1. Moreover, the p and d-wave dependence of the annihilation cross section implies that $\langle \sigma v_r \rangle$ today is very small since $v_{CM} \sim 10^{-3}$ c today. Consequently, neutrino detectors do not provide any bounds for large DM masses and the constraints from the SK analysis only apply to the complex DM scenario as it is less suppressed.

As can be seen from Table 1, the coupling $g$ enters with the same power in the annihilation and elastic scattering cross sections. Hence, we can impose $\langle \sigma v_r \rangle \sim 3 \times 10^{-26}$ cm$^3$ s$^{-1}$ to get a coupling independent expression for the elastic scattering, which can be compared to the collisional damping constraint in Eq. 2:

$$\sigma_{el} \simeq 5.41 \times 10^{-55} \left( \frac{T_0}{2.35 \times 10^{-4} \text{ eV}} \right)^2 \left( \frac{m_{DM}}{\text{MeV}} \right)^{-2} \left( \frac{\langle \sigma v_r \rangle}{3 \times 10^{-26} \text{ cm}^3/\text{s}} \right) \text{ cm}^2,$$

(3)

for complex DM when $m_N > m_{DM}$ and

$$\sigma_{el} \simeq 1.96 \times 10^{-72} \left( \frac{T_0}{2.35 \times 10^{-4} \text{ eV}} \right)^4 \left( \frac{m_{DM}}{\text{MeV}} \right)^{-4} \left( \frac{\langle \sigma v_r \rangle}{3 \times 10^{-26} \text{ cm}^3/\text{s}} \right) \text{ cm}^2,$$

(4)

for real DM when $m_N > m_{DM}$, where we have assumed $E_\nu \sim T_0$ today. Therefore, if we want to satisfy the collisional damping and relic density constraints in the limit
$m_N > m_{DM}$, we require DM masses larger than 8.14 keV (18.1 eV) and mediator masses larger than 87.7 MeV (6.97 keV) for complex (real) DM for any coupling $g$ (red star in Fig. 1). Nevertheless, it has been shown that the effective number of neutrino species when DM is in thermal equilibrium with neutrinos is only consistent with Planck measurements for $m_{DM} \gtrsim 10$ MeV for both scenarios [7]. This corresponds to $m_N \gtrsim 3.55$ GeV for complex DM and $m_N \gtrsim 0.14$ GeV for real DM and imposes stronger bounds than the collisional damping constraint.

This analysis shows that there are subtleties when analyzing the different scenarios that can lead to a very distinct phenomenology. This is also the case when, for example, one considers a Majorana mediator instead of a Dirac mediator since this could produce Lepton Number Violating processes such as $\chi\chi \rightarrow \nu_L\nu_L$.

4 Conclusion

The study of neutrino-DM interactions is a powerful tool to constraint the masses of the DM and its mediator since it provides a variety of cosmological observables to contrast with the theoretical predictions. Furthermore, the complementarity of such observables with model-specific predictions allows us to understand better what the nature of the DM particle could be. Here we have only discussed the scenario of scalar DM coupled to neutrinos via a Dirac mediator, but a full study of all the possible scenarios will help us to determine the allowed values of the parameter space for DM candidates and mediators of different spins.

References

Muon antineutrino charged-current cross sections without pions in the final state at T2K

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T2K (Tokai to Kamioka) is a long-baseline neutrino oscillation experiment located in Japan and designed to measure neutrino flavor oscillation using an off-axis neutrino beam. Data collected recently with an antineutrino beam allows T2K to measure cross sections for antineutrinos at an energy around 600 MeV using the off-axis near detector. These measurements, along with the analogous for neutrinos, are vital inputs to neutrino oscillation analyses and their interpretation. In this work preliminary results on the simultaneous extraction of the muon neutrino and antineutrino charged-current cross sections without pions in the final state is presented. The two cross sections will be measured as a function of muon kinematic allowing to evaluate the sum, difference and asymmetry between the two cross sections. These results are useful for comparison and tuning of theoretical models of nuclear effects such as multinucleon interactions (also know as 2 particle-2 hole processes).

PRESENTED AT


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1 Introduction

Modern neutrino oscillation experiments use neutrino beams with energies around 1 GeV, where the main interaction channel is the charged current quasi-elastic scattering (CCQE). This brings to the necessity of a correct modelling of this process. The K2K experiment [1], MiniBoone experiment [2] together with other experiments, using carbon as target, measured a kinematic distributions of the outgoing muons in CCQE interactions not consistent with the prediction of the Relativistic Fermi Gas (RFG) nuclear model [3, 4]. Many theoretical models have been proposed to describe the nuclear effects in (anti-)neutrino scattering [5, 6, 7]. They predict the existence of multinucleon emission (np-nh) that produces an increase in the CCQE-like cross section, since the additional outgoing nucleons in the final state could remain undetected, mimicking a QE interaction. In reference [8] it has been pointed out that the multinucleon emission can contribute in a different way in \( \nu_\mu \) and \( \bar{\nu}_\mu \) interactions. This gives the possibility to isolate the np-nh contribution looking at different linear combinations of the neutrino and antineutrino cross-sections. During the last two years T2K collected data in antineutrino mode opening the possibility to study the antineutrino cross section.

2 The near detector of the T2K experiment

The T2K off-axis near detector (ND280) is a fully magnetized particle tracking detector located 280 m downstream of the beam target and 2.5 degrees off the neutrino beam center. Placed inside the refurbished UA1/NOMAD magnet which provide a magnetic field of 0.2 T, it consists of a \( \pi^0 \) detector (P\O D), two Fine Grained Detectors (FGDs) and three gas Time Projection Chambers (TPCs), surrounded by an electromagnetic calorimeter (Ecal) as shown in Fig. 1. The FGDs, composed of finely segmented scintillator bars, serve as targets for neutrino interactions and provide tracking capabilities which allow measurements of short tracks. Upstream FGD (FGD1) contains only scintillator bars arranged in x and y directions with respect to the beam direction, while in downstream FGD (FGD2) there are additional water layers placed in between scintillator layers. The two FGDs are installed amongst the TPCs designed for 3D track reconstruction, particle identification and determination of momentum and charge. The ECals are sampling calorimeters consisting of layers of plastic scintillator and layers of lead. They allow reconstruction of tracks and showers in order to further distinguish between muons, electrons and pions.

![Figure 1: View of ND280](9)
3 Analysis strategy and preliminary results

The cross sections are simultaneously extracted using a binned likelihood fit in muon kinematic variables (similar to the method used in Ref. 10). In this work only preliminary results using only the Monte Carlo (MC) prediction are shown. The MC generator used is NEUT 5.3.2 which uses the Llewellyn-Smith formalism 11 to model CCQE interactions, the Spectral Function (SF) model by Behnar et al. 12 as nuclear model and a nominal axial mass $M^A_{QE}$ set to 1.21 GeV. Multinucleon interactions are modeled with an implementation of the model by Nieves et al. 7.

Figure 2: Muon momentum distribution for signal (top left) and control regions in the $\nu_\mu$ selection: CC-1$\pi^+$ (top right) and CC-Other (bottom center). MC is normalized to the number of proton on target (POT) in real data ($\sim$5.73$\times$10$^{20}$).

Figure 3: Muon momentum distribution for CC-1Track (left) and CC-NTracks (right) sample in the $\bar{\nu}_\mu$ selection. MC is normalized to the number of POT in real data ($\sim$3.67$\times$10$^{20}$).

The FGD1 is used as the target and tracks are reconstructed in TPC1, if they are backward-going or in TPC2 if they are forward-going or in the Ecal around the FGD if they have an high angle respect to the beam direction. The timing information between each subdetector is used as well to reconstruct the sense of the track. The backward-going and high angle tracks are selected only in the $\nu_\mu$ selection; a similar selection for the $\bar{\nu}_\mu$ events is foreseen as future improvement. The muon candidate is identified as the highest-momentum negatively (positively) charged track which passes the TPC particle identification cut for the $\nu_\mu$ ($\bar{\nu}_\mu$) selection. The selected
charged-current (CC) sample for the $\nu_\mu$ selection is split into three subsamples: CC-0$\pi$ characterized by one $\mu^-$ and any number of protons in the final state, CC-1$\pi^+$ by one $\mu^-$ and one $\pi^+$ and CC-Other by all the other events. In the $\bar{\nu}_\mu$ the CC sample is split in two subsample: CC-1Track characterized by only one $\mu^+$ and CC-NTracks with more than one track. The CC-1$\pi^+$, CC-Other and CC-NTracks subsamples act as control regions in order to extract from data the normalization and the shape of the background. The results of the selection are shown in Fig. 2 and 3 for the $\nu_\mu$ and $\bar{\nu}_\mu$ respectively. Another future improvement to the $\bar{\nu}_\mu$ selection will be to split the CC sample in the same three subsamples selected in the $\nu_\mu$ selection in order to have the same signal and control regions definition in both the selections.

A preliminary result obtained fitting the NEUT MC prediction with itself (Asimov data set) is shown in Fig. 4. The comparison between the nominal distribution and the result of the fit procedure show perfect agreement, as expected with a well designed analysis.

![Figure 4](image1.png)

**Figure 4:** Fit of the NEUT MC prediction with itself for one bin in cosine of the scattering angle of the outgoing muon for $\nu_\mu$ (left) and $\bar{\nu}_\mu$ (right) as a function of muon momentum with statistical error bar only.

![Figure 5](image2.png)

**Figure 5:** Preliminary evaluation of the systematic errors affecting the $\nu_\mu$ (left) and $\bar{\nu}_\mu$ (right) cross section for one bin in cosine of the scattering angle of the outgoing muon and as a function of muon momentum.

The flux, model and detector uncertainties are treated as nuisance parameters adding a penalty term to the likelihood and are evaluated with ‘toy’ Monte Carlo experiments.
The background model parameters are constrained by fitting the signal regions simultaneously with the control regions. A first evaluation of the systematics are shown in Fig. 5, where the different colors indicates the different type of systematic. To evaluate the statistical uncertainty the number of reconstructed events in each bin is fluctuated according to the Poisson distribution.

4 Conclusion

The study of muon neutrino and antineutrino cross sections will lead to a deeper understanding of the cross section model for the CCQE scattering, vital for any oscillation analysis in long baseline experiments in the near and far future. In this work the selection of the signal regions and the control regions has been shown with a first estimation of the systematic uncertainties. The improved selection for the $\bar{\nu}_\mu$ sample is foreseen. After this improvements the systematics related with the detector will be evaluated. Along with the neutrino and antineutrino cross sections also different linear combination of the two will be evaluated.

References

CUORE is the first ton-scale experiment based on the bolometric technique to search for neutrinoless double-beta decay. Its core is made of 988 TeO$_2$ crystals cooled down to 10 mK. The temperature must be as stable as possible during detector operations, for an integrated live-time of about 5 years. To reach these goals, a dedicated cryogenic system has been developed. Temperature stabilization of the crystals response will be performed to compensate for residual instabilities. External vibrations that can deteriorate the crystals energy resolution, are dumped thanks to a suspension system. Moreover, a thorough selection and cleaning process performed on the construction material will allow the abatement of the radioactive backgrounds. Here the key aspects of the systems are presented.
1 Introduction

If the neutrino is a Majorana particle, some atomic nuclei can undergo neutrinoless double beta decay ($0\nu\beta\beta$) \cite{1}, with a straightforward signature: a mono-energetic peak, given by the sum of the energies of the two electrons in the final state, around the Q-value of the atomic transition. Nevertheless, the predicted half life $T_{1/2}^{0\nu}$ of the process, greater than $10^{25} - 10^{26}$ yr, makes the experimental search extremely challenging. Such a challenge is worth the effort, since a measure of $0\nu\beta\beta$ would give information on the neutrino mass hierarchy, but would also represent a discovery of physics beyond the Standard Model. In fact, the Majorana nature of the neutrino and the lepton number violation would be proven; the latter representing a possible source of the matter-antimatter asymmetry in the early universe.

In this proceeding, the key aspects of the CUORE experiment, that will search for $0\nu\beta\beta$ decay of the $^{130}$Te isotope, are discussed.

2 CUORE

The CUORE experiment \cite{2} (scheme shown in fig. 1a) is located at the LNGS underground facility, at an average depth of ~3600 m water equivalent, to suppress the natural environmental radioactivity background (at LNGS the muon, gamma and neutron fluxes are $\Phi_\mu = 3 \cdot 10^{-8} \mu/(cm^2 \cdot s)$, $\Phi_\gamma = 0.73 \gamma/(cm^2 \cdot s)$, $\Phi_n < 4 \cdot 10^{-6} n/(cm^2 \cdot s)$ below 10 MeV, respectively). It exploits TeO$_2$ crystals both as source for the $0\nu\beta\beta$ decay and as particle detectors for the pair of electrons in the final state. The energy $E$ deposited by the electrons is measured through the temperature rise $\Delta T$ of the crystals. At low temperatures $\Delta T \propto (E/T^3)e^{-t/\tau}$, with a decay time $\tau \propto T^3$. The experiment is a ton-scale detector, with a core of 988 TeO$_2$ crystals with a total mass of 742 kg arranged in 19 towers. A massive detector is mandatory for a good sensitivity to the $0\nu\beta\beta$ process, which is $[T_{1/2}^{0\nu}]_{sens.} \propto \sqrt{M \cdot t / \Delta E \cdot B}$, where $M$ is the mass of the $^{130}$Te isotope, $t$ is the exposure time, $\Delta E$ the energy resolution and $B$ the number of background events.

Taking into account the considerations above, the following main challenging experimental goals can be identified: to achieve measurable, constant and fast signals at a given energy, the ~1 ton-scale detector has to be cooled down to cryogenic and stable temperatures; a good sensitivity can be obtained only if the detector is run in a low background environment, allowing high energy resolution and low number of background events.

An important test-bench for the development of the CUORE experiment has been the CUORE-0 prototype \cite{3}. CUORE-0 detector was a CUORE-style tower of TeO$_2$ crystals, built following all the protocols developed to produce, clean and assemble the CUORE detector components, thus representing an important opportunity to

1
test the CUORE assembly line and the material cleaning techniques. Moreover, the prototype allowed to validate both the background model and energy resolution, and to obtain physics results [4]: the upper limit on the effective Majorana mass is shown in fig. 1b (result combined with that from the previous prototype Cuoricino). CUORE-0 obtained a total background at the region of interest (ROI) of $0.058 \pm 0.004$ counts/(keV · kg · yr) and an energy resolution of 5 keV FWHM at 2615 keV.

3 Key factors to reach the CUORE goals

The main key factors to reach the goals of the CUORE experiment are: the cryogenic system, the suspension system and the material cleaning and assembling.

3.1 Cryogenic system

The CUORE cryostat consists of 6 nested vessels corresponding to different temperature stages (see fig. 1a). The outermost shield, Outer Vacuum Chamber (OVC), at room temperature, and the Inner Vacuum Chamber (IVC), at 4 K, are vacuum-tight, and are separated by an intermediate radiation shield maintained at a temperature of $\sim 40$ K. A system of 5 Pulse Tubes (PTs), mounted on the OVC top plate, allow the cooling of the 40 K shield and of the IVC. Since PTs are cryocoolers, the cryostat is cryogen-free and a high duty cycle is achievable, minimising data-taking dead times. Nevertheless, the use of only PTs would require months to bring the detector from room temperature to the operations temperature, given the detector mass. Thus a Fast Cooling System (FCS) has been developed. Helium gas is circulated through a separate cryocooler, where a system of heat exchangers cools the gas down to less than 40 K. The He gas is then injected into the IVC. This system allows to reduce the cool down period of the whole detector to few weeks. Inside the IVC there are three radiation shields at 600 mK, 50 mK and the coldest one at 10 mK. The coldest temperature is achieved through a $^3$He/$^4$He dilution refrigerator (DU), specifically designed for CUORE by Leiden Cryogenics. A system of temperature stabilisation has been developed to correct possible drifts of the operation temperature of 10 mK. To attenuate neutron and $\gamma$-ray backgrounds, the cryostat is surrounded by layers of borated polyethylene, boric-acid powder, and lead bricks. A further suppression of $\gamma$-rays from the cryostat materials is obtained with additional lead layers inside the cryostat, including ancient Roman lead [5].

3.2 Suspension system

Mechanical noise is a source of background that generates energy dissipation into the crystals, worsening their energy resolution. A suspension system provides a mechanical decoupling of the detector from the outside environment. The system minimizes
the transmission of mechanical vibrations due to seismic noise and operations of the cryocoolers and pumps. The detector is hung by the Y-Beam through cables made out of stainless steal tie bars, Kevlar ropes and copper bars; damping the horizontal oscillations. This part of the system has three important characteristics: is able to sustain the detector weight of $\sim 1.2$ ton; has a low thermal conductivity, being in contact with the 10 mK shield; has a low radioactive contamination, being close to the crystals. Three minus-K springs connect the Y-beam to the Main Support Plate (MSP), attenuating the noise of $\sim 35$ dB. Minus-K springs provide vertical-motion isolation by a stiff spring that supports the weight load, the Y-beam and the detector, combined with a negative-stiffness mechanism. The net vertical stiffness is made very low without affecting the static load-supporting capability of the spring. Beam-columns connected in series with the vertical-motion isolator provide horizontal-motion isolation. The result is a compact passive isolator capable of very low vertical and horizontal natural frequencies and very high internal structural frequencies. Elastometers are mounted at the structure basis, acting as seismic isolators.

### 3.3 Material cleaning and assembling

An important hazard for the CUORE sensitivity to the $0\nu\beta\beta$ process, is the background coming from the radioactive contaminations in the cryostat radiation shields, from the mechanical structure of the towers and from the crystals themselves. This background contribution has to be reduced as much as possible. A strict protocol has been adopted for the crystals production, together with a thorough campaign for the selection of the material used to prepare the crystals [6]. This allowed to reduce the presence of environmental radioactivity in the crystals. New cleaning techniques have been developed at the Laboratori Nazionali di Legnaro dell’INFN (LNL) and employed for the copper surfaces, among which: tumbling, electropolishing, chemical etching, magnetron plasma. These have been applied to clean the 10 mK cryostat shield, made out of ferrules and internal tiles, and the parts of the towers. The cleaning techniques are aimed to remove a thin layer of the components’ surface, so that dirt and impurities due to handling and manufacturing are removed. Moreover, a strict protocol has been adopted for each step of the CUORE towers construction: temperature sensors gluing, tower assembly, wire bonding, tower storage. All in nitrogen atmosphere and within glove boxes to avoid radioactive recontamination.

### 4 Summary

A great effort was made to design and develop CUORE in order to achieve, in the ROI, a background of 0.01 counts/(keV · kg · yr) and an energy resolution of 5 keV FWHM. These values will allow to set an upper limit on the $0\nu\beta\beta$ process half life of

3
$T_{1/2}^{0\nu} > 9.5 \times 10^{25}$ yr at 90% C.L. in 5 years, interpreted as upper limit on the effective Majorana mass (see fig. 1b), and to probe the DAMA/LIBRA Dark Matter positive signal region, exploiting the matched filter technique to extract low energy signals.

The cryostat has been commissioned with full load, but no detector installed, during spring 2016, reaching a stable base temperature of $\sim 6.3$ mK over more than 70 days. The full detector has been installed on the Tower Support Plate (TSP) during August 2016, and the cryostat closed by the end of November 2016. The detector has been cooled down and commissioning operations have been performed, allowing to debug the full system: check of DAQ and electronic chain, optimization of the noise and mechanical vibrations, optimization of trigger thresholds. The CUORE experiment is now starting to take the first data for physics analyses.

![Diagram of CUORE cryostat](a) Scheme of CUORE cryostat

![Diagram of effective Majorana mass sensitivity](b) Effective Majorana mass sensitivity

Figure 1

References

Creating the Baryon Asymmetry from Lepto-Bubbles

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We propose a new mechanism of baryogenesis which proceeds via a CP-violating phase transition. During this phase transition, the coupling of the Weinberg operator is dynamically realised and subsequently a lepton asymmetry is generated via the non-zero interference of this operator at different times. This new scenario of leptogenesis provides a direct connection between the baryon asymmetry, low energy neutrino parameters and leptonic flavour models.

**PRESENTED AT**

NuPhys2016, Prospects in Neutrino Physics
1 Introduction

In spite of the abundance of baryogenesis models, the matter anti-matter asymmetry remains an unresolved issue. Common to all dynamical mechanisms of baryogenesis is the necessity to satisfy Sakharov’s conditions \cite{1}: processes must violate baryon number, C and CP-symmetry and finally provide a departure from thermal equilibrium. Popular scenarios of high-scale thermal leptogenesis use the out-of-equilibrium decays of heavy particles, such as sterile neutrinos, to produce a lepton asymmetry which is subsequently converted to a baryon asymmetry via electroweak sphaleron processes \cite{2}. In addition to providing a possible solution to the baryon asymmetry, thermal leptogenesis also explains small neutrino masses. There are also low-scale leptogenesis mechanisms in which the mass of the sterile neutrinos is below the electroweak scale. The lepton asymmetry is generated via the oscillations of these sterile states \cite{3}. In both high and low-scale leptogenesis, the details of the neutrino mass model must be specified.

In this paper we propose a completely new scenario of leptogenesis which proceeds via a CP-violating phase transition and henceforth will be referred to as the CPPT mechanism. This phase transition produces bubbles which are leptonically CP-violating, namely lepto-bubbles. The generation of the lepton asymmetry occurs below the neutrino mass generation scale and therefore the particular neutrino mass model need not be specified. In addition to providing a novel solution to the matter anti-matter asymmetry, our mechanism establishes a connection between this asymmetry and the flavour structure of the lepton sector \cite{4, 5}.

This short paper is structured as follows: in Section 2 and Section 3 we discuss our basic assumptions, outline the CPPT mechanism and the computational method namely the Closed-Time Path Formalism. In Section 4 we give details of the lepton asymmetry calculation and estimate the temperature at which the phase transition occurs and finally we discuss and summarise in Section 5 and Section 6 respectively.

2 The CPPT Mechanism

We assume neutrinos are Majorana in nature and therefore, to leading order, their mass model reduces to the lepton number violating Weinberg operator

\[ \mathcal{L}_W = \frac{\lambda_{\alpha\beta}}{\Lambda} \ell_{\alpha L} H C \ell_{\beta L} H + \text{h.c.}, \]

where \( \lambda_{\alpha\beta} = \lambda_{\beta\alpha} \) is a model-dependent coupling, \( \Lambda \) the scale of new physics and \( C \) is the charge conjugation matrix. The Weinberg operator can be UV-completed in a number of ways ranging from loop effects to introducing heavy new degrees of freedom such as sterile neutrinos. However, unlike typical scenarios of leptogenesis, the details of the UV-completion of the dimension five operator need not be specified in this mechanism. We postulate the coupling of the Weinberg operator is functionally dependent upon a SM-singlet scalar, \( \phi \), such that \( \lambda_{\alpha\beta} = \lambda^0_{\alpha\beta} + \lambda^1_{\alpha\beta} \langle \phi \rangle / v_\phi \). Associated to \( \phi \) is a finite temperature scalar potential, which is symmetric under a leptonic flavour symmetry at sufficiently high temperatures. As the temperature of the Universe lowers, the minima at the origin of this potential becomes metastable and a phase transition occurs. As a result, the minima changes from the vacua at the origin to a deeper, true vacua which is stable and non-zero, \( \langle \phi \rangle \). The ensemble expectation value (EEV) of \( \phi \) spontaneously breaks the high-scale flavour symmetry and results in the observed pattern of leptonic masses and mixing. Assuming a first order phase transition, (lepto) bubbles of the leptonically CP-violating broken phase spontaneously nucleate. At a fixed space point within the bubble wall, the coupling \( \lambda \) is time-dependent e.g. \( \lambda(t_1) \neq \lambda(t_2) \) for \( t_1 \neq t_2 \). As a consequence, the lepton asymmetry arises from the non-zero interference of the Weinberg operator at different times.

3 The Closed-Time Path Formalism

We apply the closed-time path (CTP) formalism to calculate the lepton asymmetry. Unlike zero temperature methods, the CTP formalism properly accounts for finite density effects and resolves unitarity issues. The basic building blocks of the CTP formalism are the Green functions and the corresponding self-energy corrections. As we will focus on the self-energy corrections from the
Weinberg operator to the lepton propagators, it is sufficient to present the Higgs ($\Delta$) and lepton ($S$) propagators

\[
\Delta^{T,T}(x_1, x_2) = \langle T[H(x_1)H^*(x_2)] \rangle, \quad \langle T[H(x_1)H^*(x_2)] \rangle,
\]

\[
\Delta^{<, >}(x_1, x_2) = \langle H^*(x_2)H(x_1) \rangle, \quad \langle H(x_1)H^*(x_2) \rangle,
\]

\[
S_{\alpha\beta}^{<, >}(x_1, x_2) = \langle T[\ell_\alpha(x_1)\bar{\ell}_\beta(x_2)] \rangle, \quad \langle T[\ell_\alpha(x_1)\bar{\ell}_\beta(x_2)] \rangle,
\]

where $T$ ($\overline{T}$) denotes time (anti-time) ordering, Greek indices are flavour indices and spinor and electroweak indices have been suppressed. The lepton asymmetry is written in terms of the leptonic Wightman propagators, $S^{<, >}$, such that

\[
n_L(x) = - \frac{1}{2} \sum_\alpha \text{tr} \left\{ \gamma^0 [S^<_\alpha(x, x) + S^>\alpha(x, x)] \right\}.
\]

The Kadanoff-Baym (KB) equations are used to calculate the time evolution of the lepton asymmetry and we follow the conventions of [6, 7] and write this equation as

\[
\text{i} \partial_S^{<,>} - \Sigma^H \odot S^{<,>} - \Sigma^{<, >} \odot S^H = \frac{1}{2} \left[ \Sigma^> \odot S^< + \Sigma^< \odot S^> \right],
\]

(1)

where the symbol $\odot$ presents a convolution, $\Sigma$ is the self-energy of the lepton and $S^H$ ($\Sigma^H$) is Hermitian parts of propagator (self-energy) given by $S^H = S^T - \frac{1}{2} (S^< + S^>)$ ($\Sigma^H = \Sigma^T - \frac{1}{2} (\Sigma^> + \Sigma^<)$). The self-energy contribution ($\Sigma^H S^{<, >}$) and broadening of the on-shell dispersion relation ($\Sigma^{<, >} S^H$) are given on the LHS of Eq. (1). Whilst, the collision term that includes CP-violating source ($\frac{1}{2} (\Sigma^> S^< - \Sigma^< S^>)$) is shown on the RHS [6]. As we focus on the generation of an initial asymmetry, we consider only the collision term.

## 4 Calculating the Lepton Asymmetry

We calculate the lepton asymmetry using similar techniques applied in [8]. The calculation involves application of the KB equation (1) to find the time evolution of the lepton propagator. The self-energy correction is calculated to leading order, in the time-independent flavour basis, as is shown in Fig. 1. The first step is to Fourier transform the Green functions of the Higgs and leptonic propagator respectively

\[
\Delta^\xi(t_1, t_2) = \int d^4r e^{i\xi r} \Delta(x_1, x_2) \quad \text{and} \quad S^\xi(t_1, t_2) = \int d^4r e^{i\xi r} S(x_1, x_2),
\]

where $t_1 = x_1^0$, $t_2 = x_2^0$ and $r = x_1 - x_2$. The lepton asymmetry, at a fixed space point in the bubble wall, is given by

\[
n_L(x) = \int \frac{d^4k}{(2\pi)^4} L_k \text{ with}
\]

\[
L_k \equiv f_{\xi k} - f_{\eta k} = - \int_{t_1}^{t_f} dt_1 \partial_1 \text{tr} \left[ \gamma_0 S_k^>(t_1, t_1) + \gamma_0 S_k^< (t_1, t_1) \right]
\]

\[
- \int_{t_1}^{t_f} dt_1 \int_{t_1}^{t_f} dt_2 \text{tr} \left[ \Sigma_k^>(t_1, t_2) S_k^>(t_2, t_1) - \Sigma_k^<(t_1, t_2) S_k^< (t_2, t_1) \right],
\]

(2)
where \( t_i \) (\( t_f \)) is the initial (final) time and \( \Sigma_{\ell}^\geq(t_1, t_2) \) is the CP-violating two-loop self-energy correction as shown in Fig. 1. Subsequently, (2) may be re-expressed as

\[
L_{\alpha\beta} = \sum_{\gamma\delta} \frac{12}{\Lambda^2} \int_{t_1}^{t_f} dt_1 \int_{t_1}^{t_f} dt_2 \text{Im} \{ \lambda_{\alpha\gamma}(t_1) \lambda_{\beta\delta}(t_2) \} \int_{q,q'} M_{\alpha\beta;\gamma\delta}(t_1, t_2, k, k', q, q') ,
\]

where \( \int_{q,q'} = \int \frac{d^4q}{(2\pi)^4} \frac{d^4q'}{(2\pi)^4} \). The lepton asymmetry has factorised into two parts: one part is a function of the time-dependent couplings, \( \lambda(t) \), which allows for a connection between the lepton asymmetry, the leptonic flavour model and low energy neutrino parameters. The other, \( M_{\alpha\beta;\gamma\delta}(t_1, t_2, k, k', q, q') \), is the finite temperature matrix element which is calculated using CTP Feynman rules (for further details see [8]). For the present calculation, we will ignore the differing thermal widths of the charged lepton propagators and using the limit \( t_i(t_f) \to -\infty(+\infty) \), the total lepton asymmetry \( L_{\ell} \equiv \sum_{\alpha} L_{\ell\alpha\alpha} \) is given by

\[
L_{\ell} = \frac{12}{\Lambda^2} \int_{-\infty}^{+\infty} dt_0 \int_{-\infty}^{+\infty} dt_2 \text{Im} \{ \text{tr} \{ \lambda^*(t_1) \lambda(t_2) \} \} \int_{q,q'} M ,
\]

where the finite temperature matrix element, decomposed in terms of the lepton and Higgs propagators, is expressed as

\[
M = \text{Im} \{ \Delta_{\ell}^\geq(t_1, t_2) \Delta_{\ell}^{\geq}(t_1, t_2) \text{tr} [ S_{\ell}^\geq(t_1, t_2) S_{\ell}^{\geq}(t_1, t_2) P_L] \} .
\]

Throughout we assume the Higgs and leptonic propagators are almost in thermal equilibrium as the scale of the CPPT mechanism is significantly higher than the electroweak scale. The time-varying coupling is functionally dependent upon the EEV of the scalar, \( \phi \). We make an ansatz for the coupling

\[
\lambda(t) = \lambda^0 + \lambda^1 f(t) ,
\]

where \( \lambda^0 \) (\( \lambda^0 + \lambda^1 \)) is the value of the coupling at \( t = -\infty \) (\( t = +\infty \)) and \( f(t) \) varies continuously from 0 to 1. As expected, the lepton asymmetry is not sensitive to the precise functional form of \( f(t) \); it has been shown a tanh and step function produce the same result [5]. Performing a change of integration variables from \( t_1, t_2 \) to \( \tilde{t} = (t_1 + t_2)/2, y = t_1 - t_2 \) and using \( \int_{-\infty}^{+\infty} dt [f(\tilde{t} + y/2) - f(\tilde{t} - y/2)] = y \)

the lepton asymmetry may be written as

\[
L_{\ell} = -\frac{12}{v_H^2} \text{Im} \{ \text{tr} [m_0^\nu m_0^\nu] \} \int_{-\infty}^{+\infty} dy \int_{q,q'} M ,
\]

where \( v_H \) is the Higgs vacuum expectation value and \( m_0^\nu \equiv \lambda^0 v_H^2 / \Lambda \) \( (m_\nu \equiv \lambda^0 + \lambda^1) v_H^2 / \Lambda) \) is the effective neutrino mass matrix before (after) the phase transition. As \( \phi \) only interacts with the leptons and Higgs in the thermal bath, it is reasonable to assume a fast-moving bubble. Consequently, the lepton asymmetry (3) is not dependent upon the bubble properties. Using the calculation of \( M \) (full details given in [5]) the lepton asymmetry can be rewritten as

\[
L_{\ell} = \frac{3 \text{Im} \{ \text{tr} [m_0^\nu m_0^\nu] \} T^2}{(2\pi)^4 v_H^2} F(x_1, x_\gamma) .
\]

\( F(x_1, x_\gamma) \) is a loop factor given by

\[
F(x_1, x_\gamma) = \frac{1}{x_1} \int_0^{+\infty} dx \int_0^{+\infty} x_2 dx_2 \int_{|x_1 - x|}^{x_1 + x} dx_3 \int_{|x_2 + x_3|}^{x_2 + x_3} dx_4 \sum_{n_2, n_3, n_4 = \pm 1} \frac{1}{4n_2 x_1 x_2 x_3} \left[ 1 - \frac{x_1^2 + x_2^2 - x_3^2}{4n_2 x_1 x_2 x_3} \right]
\]

\[
\times \frac{X_{n_2, n_3, n_4} x_1 \sinh X_{n_2, n_3, n_4}}{(X_{n_2, n_3, n_4} + x_3)^2 \cosh x_1 \cosh x_2 \sinh x_3 \sinh x_4} ,
\]

where the four momentum of the leptons and Higgs shown in Fig. 1 are defined as \( k = |k|, k = |k'|, q = |q| \) and correspondingly \( x_1 = k/2T, x_2 = k'/2T, x_3 = q/2T, x_4 = q'/2T \) and \( X_{n_2, n_3, n_4} = x_1 + n_2 x_2 + n_3 x_3 + n_4 x_4 \). The loop factor is dependent upon the lepton energy and the thermal width normalised by the temperature, i.e., \( x_1 \) and \( x_\gamma \) as shown in Fig. 2.
5 Discussion

The lepton asymmetry produced during the CPPT mechanism is partially converted into a final baryon asymmetry via sphaleron processes which are unsuppressed above the electroweak scale. The final baryon asymmetry is roughly given by

$$\eta_B \approx \frac{1}{3} \eta_{B-L}$$

and may be written as

$$n_B^\gamma \approx -\frac{\text{Im} \left\{ \text{tr} \left[ m^0_\nu m^\dagger_\nu \right] \right\}}{8\pi^2 \zeta(3) v_i^4} T^2 F(x_\gamma),$$

where $F(x_\gamma) = \int_0^\infty x_1 dx_1 F(x_1, x_\gamma)$, $n_\gamma = 2\zeta(3) T^3/\pi^2$ and $\zeta(3) = 1.202$. In order to produce a positive baryon to photon ratio, $\text{Im} \left\{ \text{tr} \left[ m^0_\nu m^\dagger_\nu \right] \right\}$ should be negative. It is worth noting the baryon asymmetry is dependent upon three quantities: the self-energy correction to the lepton propagator represented by the loop factor $F(x_1, x_\gamma)$, the effective neutrino mass matrices ($m_\nu$ and $m^0_\nu$) and finally the temperature, $T$, of the phase transition. First, the loop factor is shown as a function of the temperature normalised lepton energy ($x_1$) as shown in Fig. 2. For Standard Model values of the temperature normalised lepton thermal width, $x_\gamma \sim 0.1$, the loop factor provides an $\mathcal{O}(10)$ enhancement to the lepton asymmetry. Second, the lepton asymmetry is crucially reliant on the effective neutrino masses. The structure of $m^0_\nu$ is determined by the particular high-scale flavour symmetry and $m_\nu$ is the neutrino mass matrix which is diagonalised by the PMNS matrix $U^T_{PMNS} m_\nu U_{PMNS} = \text{diag}(m_1, m_2, m_3)$. This establishes a connection between the lepton asymmetry, low-energy neutrino parameters and the flavour symmetry. Finally, in order to estimate the phase transition temperature, we assume $\text{Im} \left\{ \text{tr} \left[ m^0_\nu m^\dagger_\nu \right] \right\}$ is of the same order as $m^2_\nu \sim (0.1\text{eV})^2$ and we have calculated that $F(x_\gamma) \sim \mathcal{O}(100)$, hence the temperature for successful leptogenesis is

$$T \sim 3\sqrt{\eta_B} \frac{v_i^2}{m_\nu}.$$

In order to produce the observed baryon to photon ratio ($\eta_B = (6.19 \pm 0.15) \times 10^{-10}$ [9]) the temperature of the phase transition is approximately $T \sim 10^{11}$ GeV. The energy scale of this mechanism is similar to that of high-scale thermal leptogenesis. However, there are several improvements to this calculation which may lower the temperature. These improvements include accounting for the differing charged lepton thermal widths and calculating the fully time evolved asymmetry.

6 Conclusion

CPPT is a completely new and novel mechanism that could simultaneously explain the observed baryon asymmetry and the pattern of mixing in the lepton sector. Unlike conventional scenarios of leptogenesis, which specify a particular neutrino mass generation mechanism, CPPT allows for relative model independence as the new physics responsible for neutrino masses has already been integrated out before the CP-violating phase transition occurs. There are several interesting aspects of the our mechanism that could be further explored. These include studying this mechanism in the context of a particular flavour model and predicting the associated gravitational wave spectra.

References


Radiative decay of heavy neutrinos at MiniBooNE and MicroBooNE

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The MiniBooNE experiment reported results from the analysis of $\nu_e$ and $\bar{\nu}_e$ appearance searches, which showed an excess of signal-like events at low reconstructed neutrino energies with respect to the expected background. A proposed explanation for this anomaly is based on the existence of a heavy ($\sim 50$ MeV) sterile neutrino. These $\nu_h$ would be produced by $\nu_\mu$ electromagnetic and neutral current interactions. A fraction of them decays radiatively inside the detector. The emitted photon is misidentified as an electron or positron in MiniBooNE. We have investigated the $\nu_h$ production by coherent and incoherent electroweak interactions at the MiniBooNE and MicroBooNE targets, CH$_2$ and Ar, respectively. Studying the $\nu_h$ propagation inside the detector, we obtain the energy and angular distributions of emitted photons for a choice of model parameters. The distinctive shape and total number of photon events from this mechanism at MicroBooNE makes its experimental investigation possible.

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The paradigm of three mixing flavors of neutrinos emerges from oscillation
experiments with solar, atmospheric, reactor and accelerator neutrinos in which
the square-mass differences and mixing angles have been determined with ever
growing precision. Nevertheless, a number of anomalies that challenge this picture has
been observed. One of them, reported by MiniBooNE, has found an excess of electron-like
events over the predicted background in both $\nu$ and $\bar{\nu}$ modes [1, 2]. The excess is
concentrated at $200 < E_{QE}^\nu < 475$ MeV, where $E_{QE}^\nu$ is the neutrino energy reconstructed
assuming a charged-current quasielastic (CCQE) nature of the events.

Existing analyses struggle to accommodate this result together with world oscilla-
tion data, even in presence of one or more families of sterile neutrinos [3], pointing at
an explanation that does not invoke oscillations. It was suggested that an underesti-
imated background from photons emitted in neutral current (NC) interactions could
account for the excess [4]. Indeed, the MiniBooNE detector does not distinguish be-
tween electrons and single photons. However, studies considering nuclear effects and
acceptance corrections [5, 6], obtain a number of photon-induced electron-like events
which is consistent with the MiniBooNE estimate.

Gninenko proposed that additional photons could originate in the weak production
of a heavy ($m_h \approx 50$ MeV) sterile neutrino slightly mixed with muon neutrinos,
followed by its radiative decay [7] In Ref. [8] it was pointed out that the $\nu_h$ could also
be electromagnetically produced, alleviating tensions in the original proposal with
other data such as those from radiative muon capture measured at TRIUMF.

We have revisited the scenario presented in Ref. [8]. We compute coherent and
incoherent $\nu_h$ production using present understanding of electromagnetic (EM) and
weak interactions on nucleons and nuclei. For a more detailed analysis, we compare
to the MiniBooNE excess of events in the originally measured electron energy and
angle [9] (being the photon ones in our case) rather than in $E_{QE}^\nu$. We also take into
account the experimental efficiency correction available from Ref. [9].

Further insight on the nature of the MiniBooNE anomaly should be brought by
the currently running MicroBooNE experiment, capable of distinguishing between
electrons and photons. We have also computed the number of photon events from $\nu_h$
for the target (Argon) and geometry of the MicroBooNE detector.

We have studied $\nu_h$ EM and weak production in the following processes

$$\nu_\mu, \bar{\nu}_\mu (k) + N(p) \rightarrow \nu_h, \bar{\nu}_h (k') + N(p') , \quad (1)$$

$$\nu_\mu, \bar{\nu}_\mu (k) + A(p) \rightarrow \nu_h, \bar{\nu}_h (k') + A(p') , \quad (2)$$

$$\nu_\mu, \bar{\nu}_\mu (k) + A(p) \rightarrow \nu_h, \bar{\nu}_h (k') + X(p') . \quad (3)$$

Reaction (2) is coherent while (3) is incoherent; excited states $X$ include any number
of knocked out nucleons but no meson production. The considered targets are $N = p$
and $A = ^{12}$C for MiniBooNE (CH$_2$),and $A = ^{40}$Ar for MicroBooNE.
In the EM case, following Ref. [8], we have adopted the effective interaction
\[ L_{\text{eff}} = \frac{1}{2} \mu_{tr}^i \left[ \overline{\nu}_h \sigma_{\mu\nu} (1 - \gamma_5) \nu_i + \overline{\nu}_i \sigma_{\mu\nu} (1 + \gamma_5) \nu_h \right] \partial^\mu A^\nu, \quad (4) \]
in terms of a real transition coupling \( \mu_{tr} \); \( \nu_h \) is assumed to be a Dirac fermion of mass \( m_h \). For all the reactions under consideration, the EM amplitude can be cast as
\[ M_{\text{EM}} = \frac{e \mu_{tr}^\mu}{2(q^2 + i\epsilon)} \overline{u}(k') \sigma^\mu (1 - \gamma_5) u(k) \langle Y(p')|J_{\mu}^{\text{EM}}|N(p) \rangle, \quad (5) \]
where \( q = k - k' = p' - p \). EM current \( \langle Y(p')|J_{\mu}^{\text{EM}}|N(p) \rangle \), with \( Y = p, A, X \), is the same probed in the corresponding electron-nucleus elastic scattering processes. For the nucleon, it is given in terms of electric and magnetic form factors (FF), for which we have adopted standard dipole parametrizations. For coherent scattering [2], the current is proportional to the nuclear FF, obtained as the Fourier transform of the empirical charge density distribution. Finally, for the incoherent reaction we take into account particle-hole excitations in infinite nuclear matter, adapted to finite nuclei using the local density approximation.

In the weak case, the neutrino vertex has the same structure as in the Standard model, so that the amplitude
\[ M_{w} = -U_{\mu h} G_F \sqrt{2} \overline{u}(k') \gamma^\mu (1 - \gamma_5) u(k) \langle Y(p')|J_{\mu}^{\text{w}}|N(p) \rangle \]
reduces to the one for neutrino nucleus NC scattering in the limit of mixing \( U_{\mu h} \rightarrow 1 \) and \( m_h \rightarrow 0 \). With the weak hadronic current \( \langle Y(p')|J_{\mu}^{\text{w}}|N(p) \rangle \) we have proceeded as with the EM current. As usual, vector FF are related to the EM ones; for the axial FF we have adopted the conventional dipole parametrization with \( M_A = 1 \text{ GeV} \).

Our results for the integrated cross sections (cs) on protons and \( ^{12}\text{C} \), obtained with \( m_h = 50 \text{ MeV} \), \( \mu_{tr}^\mu = 2.4 \times 10^{-9} \mu_B \), and \( |U_{\mu h}|^2 = 0.003 \) [8], are given in Fig 1. The EM cs on \( ^{12}\text{C} \) is dominated by the coherent mechanism while the incoherent one is suppressed by Pauli blocking at low \( q^2 \), where the amplitude is enhanced by the photon propagator [Eq. (5)]. On the contrary, the incoherent reaction is the largest contribution to the weak cs. Similar features are observed for \( ^{40}\text{Ar} \) target and also for antineutrino beams.

We have then investigated the \( \nu_h \) propagation, followed by their radiative decay inside the detector, and obtained the photon energy and angular distributions. We have taken advantage of the fact that, as pointed out in Ref. [8], the beam energies are large compared to \( m_h \) and only an insignificant amount of the electromagnetically (weakly) produced heavy neutrinos have the spin against (aligned with) its momentum. Radiative decay photons are emitted predominantly in the direction opposite to the \( \nu_h \) spin. The \( \nu_h \) lifetime in its rest frame \( \tau = 5 \times 10^{-9} \text{ seconds} \) [8].
Figure 1: Integrated cross sections for $\nu_h$ production in $\nu_\mu$-nucleus scattering by EM (left) and weak (right) interactions as a function of the incident neutrino energy.

The resulting event distributions at the MiniBooNE detector for $N_{\text{POT}} = 6.46 \times 10^{20}$ ($N_{\text{POT}} = 11.27 \times 10^{20}$) in neutrino (antineutrino) modes are shown in Fig. 2. Fluxes have been taken from Ref. [10]. To compare to the measured excess of events, the detection efficiency [9] has to be taken into account. Being energy dependent and low (at most 14%), its impact on the number of events is significant. The contribution from the two protons in the target, coherent and incoherent scattering on $^{12}$C are separately shown. The number of low energy events is underestimated in $\nu$-mode, while the agreement is good in $\overline{\nu}$-mode. The predominantly EM coherent contribution is strongly forward peaked. This leads to a very narrow angular distribution not

Figure 2: Photon events from radiative decay of $\nu_h$, $\overline{\nu}_h$ at the MiniBooNE detector in neutrino mode (top) and antineutrino mode (bottom). Theoretical results obtained with the $\nu_h$ properties of Ref. [8] are compared to the MiniBooNE excess [9].
observed in the experiment. This result is in line with the findings of Ref. [11].

The agreement can be improved by fitting the parameters in the allowed range. These results will be reported elsewhere [12]. The radiative decay hypothesis can be tested at MicroBooNE. Our predictions for the photon distributions at this detector with the flux in $\nu$-mode [13] and $N_{\text{pot}} = 6.6 \times 10^{20}$ are displayed in Fig. 3. The shape and number of events appears distinctive from those of conventional mechanisms.

Figure 3: Photon events from radiative decay of $\nu_h$ at MicroBooNE in neutrino mode predicted with the $\nu_h$ properties of Ref. [8].

References

Measuring the Leptonic Dirac CP Phase with TNT2K

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I describe how the TNT2K (Tokai and Toyama to Kamioka) configuration with a muon decay at rest (μDAR) add-on to T2(H)K can achieve better measurement of the leptonic Dirac CP phase $\delta_D$. It has five-fold advantages of high efficiency, smaller CP uncertainty, absence of degeneracy, as well as guaranteeing CP sensitivity against non-unitary mixing (NUM) and non-standard interaction (NSI). In comparison to the flux upgrade with T2K-II, the detector upgrade with T2HK, and the baseline upgrade with T2HKK, TNT2K is a totally different concept with spectrum upgrade to solve the intrinsic problems in current and next generations of CP measurement experiments. With a single $\mu$DAR source, TNT2K is much cheaper and technically much easier than the DAE$\delta$ALUS proposal. The latter needs three sources that cannot run simultaneously and consequently requires much higher fluxes. The single $\mu$DAR source at TNT2K also allows a single near detector ($\mu$Near) to fully utilize the neutrino flux for the purpose of constraining NUM, but this is impossible at DAE$\delta$ALUS with three spatially separated sources.

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1 The Intrinsic Problems in CP Measurement

Both T2K and NOνA measure $\delta_D$ by observing the $\nu_\mu \rightarrow \nu_e$ oscillation. To maximize event rate, the neutrino energy and baseline are matched to put oscillation at the first peak, reducing the oscillation probability to have only $\sin \delta_D$ dependence,

$$P_{\nu_\mu \rightarrow \nu_e} \approx 4s_\alpha^2 c_\gamma^2 s_r^2 + 8c_\alpha s_\delta c_r s_s \sin \phi_{21} \sin \delta_D,$$

where $(\theta_a, \theta_r, \theta_s) \equiv (\theta_{23}, \theta_{13}, \theta_{12}), (c_x, s_x) \equiv (\cos \theta_x, \sin \theta_x)$, and $\phi_{ij} \equiv \delta m_{ij}^2 L/4E_\nu$. The feature of only $\sin \delta_D$ dependence causes several intrinsic problems. First, the CP term has opposite sign in the neutrino and anti-neutrino modes. With relative suppression by $c_s s_s \sin \phi_{21}/s_r \approx 1/5$, the CP term can be easily smeared by the uncertainty of $s_a^2$ in the first term of (1). Fortunately, we can extract $\sin \delta_D$ from the difference $P_{\nu_\mu \rightarrow \nu_e} - P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$ by measuring both neutrino and anti-neutrino modes. To gather comparable event rates, the anti-neutrino mode needs much more time than the neutrino mode due to smaller cross section, $\sigma_{\bar{\nu}} < \sigma_{\nu}$. Roughly speaking, the anti-neutrino mode requires at least $2/3$ of run time. This significantly reduces the event rates, leading to efficiency problem. Secondly, extracting $\sin \delta_D$ cannot uniquely determine $\delta_D$, with degeneracy between $\delta_D$ and $\pi - \delta_D$. Thirdly, the CP uncertainty is proportional to $|1/\cos \delta_D|$ with only $\sin \delta_D$ dependence. The recent global fits with preference for maximal CP $\delta_D \approx -\pi/2$ is not good news for precision measurement.

These three problems are intrinsic problems for accelerator-based experiments, including T2K, NOνA, and the future DUNE. In addition, T2K-II and T2HK have exactly the same configuration and hence the same problems. The baseline upgrade T2HK seems to have better chance. However, it needs to sit at the second oscillation peak to maximize event rate, still leading to the same problems.

2 CP Measurement at TNT2K

TNT2K is designed for better CP measurement by supplementing T2K (T2HK) with a $\mu$DAR source [1] close to SK (HK). This requires a cyclotron to produce the $\mu$DAR neutrino flux by accelerating proton to hit target, producing charged pions which decay through the chain $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow (e^+ + \nu_e + \bar{\nu}_\mu) + \nu_\mu$. The $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel can be measured via inverse beta decay, $\bar{\nu}_e + p \rightarrow e^+ + n$, with double coincidence. Then T2(H)K can devote all time to the neutrino mode while $\mu$Kam, $\mu$SK ($\equiv \mu$DAR+SK) or $\mu$HK ($\equiv \mu$DAR+HK), measures the anti-neutrino mode. With much larger flux and shorter baseline, $\mu$Kam can collect much more anti-neutrino events than T2(H)K. This combination can significantly improve the efficiency by a factor of 3 (4) in the neutrino (anti-neutrino) mode [2].

<table>
<thead>
<tr>
<th>$\delta_D^{true} = -90^\circ$</th>
<th>T2K</th>
<th>$\mu$SK</th>
<th>T2K+$\mu$SK</th>
<th>$\nu$T2K+$\mu$SK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event Numbers</td>
<td>$114\nu + 56\bar{\nu}$</td>
<td>$212\bar{\nu}$</td>
<td>$57\nu + 268\bar{\nu}$</td>
<td>$342\nu + 212\bar{\nu}$</td>
</tr>
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</table>
The $\overline{\nu}_\mu$ flux is produced from $\mu^+$ decay at rest with a wide and flat spectrum across the interested energy range, $30 \text{ MeV} \lesssim E_\nu \lesssim 55 \text{ MeV}$. Using the decomposition formalism [3] in the propagation basis in Fig. 1, we can clearly see vanishing $\cos \delta_D$. The $\nu$ term at the J-PARC spectrum peak, $E_\nu \approx 600 \text{ MeV}$, in contrast to comparable $\cos \delta_D$ and $\sin \delta_D$ terms across the $\mu$DAR energy range, allowing TNT2K to avoid degeneracy and large uncertainty problems with the help of $\cos \delta_D$ dependence. Fig. 2 shows how CP uncertainty depends on baseline with optimal distance around 23 km [1].

Figure 1: The decomposed coefficients of $P_{\mu e}$ and $\overline{P}_{\mu e}$ at T2(H)K and $\mu S(H)K$.

Figure 2: The baseline dependence of CP sensitivity at TNT2K without or with HK.

3 Non-Unitary Mixing

If heavy neutrino exists and mix with light neutrinos, the usual 3 $\times$ 3 light neutrino mixing matrix becomes non-unitary,

$$N = N^{NP}U = \begin{pmatrix} 
\alpha_{11} & 0 & 0 \\
0 & \alpha_{22} & 0 \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{pmatrix} U. \quad (2)$$
For $\mu \to e$ transition, the phase in $\alpha_{21} \equiv |\alpha_{21}|e^{-i\phi}$ can fake CP effect,

$$P_{\mu e}^{NP} = \alpha_{11}^2 \left\{ \alpha_{22}^2 \left[ c_a^2 |S_{12}|^2 + s_a^2 |S_{13}|^2 \right] + 2c_a s_a (\cos \delta_D R - \sin \delta_D I) (S_{12}' S_{13}'\ast) \right\} + |\alpha_{21}|^2 P_{ee} \nonumber$$

$$+ 2\alpha_{22} |\alpha_{21}| \left[ c_a (c_\phi R - s_\phi I) (S_{11}' S_{12}'\ast) + s_a (c_\phi + s_\phi I) (S_{11}' S_{13}'\ast) \right].$$

(3)

In addition to $(\cos \delta_D, \sin \delta_D)$, four extra CP terms $(c_\phi, s_\phi)$ and $(c_\phi + s_\phi, s_\phi + c_\phi)$ appear. The CP sensitivity at T2(H)K can be significantly reduced. The TNT2K configuration can partially improve the situation due to the presence of $\cos \delta_D$ dependence. Further adding a near detector close to the $\mu$DAR source can fully restore the CP sensitivity by measuring the zero-distance effect, $P_{\mu e}^{NP}|_{L \to 0} \to |\alpha_{21}|^2$, to constrain the size $|\alpha_{21}|$ of the extra CP term [4].

4 Non-Standard Interaction

The CP effect can also be faked by NSI. Since NSI enters oscillation as matter potential, its effect is proportional to the neutrino energy which is unfortunately not small at T2K and NOνA. As show in the first subplot of Fig. 4, the CP sensitivity at T2K $\Delta \chi^2 \approx 15$ can be significantly reduced by a factor of 5. In contrast, the neutrino energy of the $\mu$DAR flux is smaller than T2K by a factor of 10 and feels negligible effect from NSI, see the second subplot of Fig. 4. While T2K measures both the genuine CP $\delta_D$ and NSI, $\mu$DAR focuses on $\delta_D$. As shown in the last two subplots in Fig. 4, TNT2K can measure $\delta_D$ and NSI simultaneously, hence guaranteeing the CP sensitivity against NSI [2].

5 Comparison with DAE$\delta$ALUS

Requiring only one cyclotron, TNT2K can run with duty factor close to 100%, in contrast to the 25% $\sim$ 30% of DAE$\delta$ALUS. The later needs 3 $\mu$DAR sources but they cannot run simultaneously. Otherwise, it is impossible to tell from which source the neutrinos come from and how long they have traveled. To achieve the same $\mu$DAR
event rate as TNT2K, DAE\$ALUS demands much higher flux which is inversely proportional to duty factor and hence more advanced technology. In addition, the $\mu$Near detector for constraining NUM can use the full $\mu$DAR flux at TNT2K but this is impossible at DAE\$ALUS with distributed sources. Comparing with DAE\$ALUS, TNT2K is cheaper with only one cyclotron, technically easier with lower flux, and physically has more potential.

References


Towards a complete $\Delta(27) \times SO(10)$ SUSY GUT

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I discuss a renormalisable model based on $\Delta(27)$ family symmetry with an $SO(10)$ grand unified theory (GUT) with spontaneous geometrical $CP$ violation. The symmetries are broken close to the GUT breaking scale, yielding the minimal supersymmetric standard model. Low-scale Yukawa structure is dictated by the coupling of matter to $\Delta(27)$ antitriplets $\bar{\phi}$ whose vacuum expectation values are aligned in the CSD3 directions by the superpotential. Light physical Majorana neutrinos masses emerge from the seesaw mechanism within $SO(10)$. The model predicts a normal neutrino mass hierarchy with the best-fit lightest neutrino mass $m_1 \sim 0.3$ meV, $CP$-violating oscillation phase $\delta^l \approx 280^\circ$ and the remaining neutrino parameters all within $1\sigma$ of their best-fit experimental values.

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1 Introduction

It is well established that the Standard Model (SM) remains incomplete while it fails to explain why neutrinos have mass. Small Dirac masses may be added by hand, but this gives no insight into the Yukawa couplings of fermions to Higgs (where a majority of free parameters in the SM originate), or the extreme hierarchies in the fermion mass spectrum, ranging from neutrino masses of $\mathcal{O}(\text{meV})$ to a top mass of $\mathcal{O}(100)\,\text{GeV}$. Understanding this, and flavour mixing among quarks and leptons, constitutes the flavour puzzle. Other open problems unanswered by the SM include the sources of CP violation (CPV), as well as the origin of three distinct gauge forces, and why they appear to be equal at very high energy scales.

An approach to solving these puzzles is to combine a Grand Unified Theory (GUT) with a family symmetry which controls the structure of the Yukawa couplings. In the highly attractive class of models based on $SO(10)$ [1], three right-handed neutrinos are predicted and neutrino mass is therefore inevitable via the seesaw mechanism.

In this paper I summarise a recently proposed model [2], renormalisable at the GUT scale, capable of addressing all the above problems, based on $\Delta(27) \times SO(10)$.

2 Features of the model

All SM fermions (and their superpartners) are gathered in a single superfield $\Psi$, an $SO(10)$ spinor that is a triplet under $\Delta(27)$, and couples to (gauge singlet) antitriplet flavons $\phi$. The vacuum expectation values (VEVs) of these flavons are aligned in particular directions in flavour space, known as the CSD3 alignment, which dictate the Yukawa structure at the low scale.

Large lepton mixing is accounted for by the seesaw mechanism [3, 4] with constrained sequential dominance (CSD) [5]. The basic goal of the flavour sector in these models is to couple matter to flavons $\bar{\phi}_{\text{atm}}$, $\bar{\phi}_{\text{sol}}$ and $\bar{\phi}_{\text{dec}}$, whose VEVs are aligned in the CSD3 direction [6], i.e. where

$$
\bar{\phi}_{\text{atm}} = v_{\text{atm}} \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}, \quad \bar{\phi}_{\text{sol}} = v_{\text{sol}} \begin{pmatrix} 1 \\ 3 \\ 1 \end{pmatrix}, \quad \bar{\phi}_{\text{dec}} = v_{\text{dec}} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix},
$$

which has been previously shown to be a very promising and predictive setup for understanding lepton masses [7].

Since $SO(10)$ constrains the Dirac couplings of leptons and quarks to be equal (or nearly so), it is non-trivial that the successful scheme in the lepton sector will translate to success in the quark sector. Remarkably we find that we can attain good fits to data for quark and lepton masses, mixings and phases.

Interactions between the flavons and additional non-trivial singlets of $\Delta(27)$ give rise to CPV phases, which fixes all phases in the lepton mass matrices, and leads to
a novel form of spontaneous geometrical CPV (for a partial list of available literature on geometrical CPV, see Ref. 6 in [2]).

The model has many other attractive features, including the use of only the lower dimensional “named” representations of $SO(10)$, i.e. the singlet, fundamental, spinor or adjoint representations. $SO(10)$ is broken via $SU(5)$ with doublet-triplet (DT) splitting achieved by a version of the Dimopoulos-Wilczek (DW) mechanism [8]. We find that the MSSM $\mu$ term can naturally be $O(\text{TeV})$, and confirm that proton decay is highly suppressed.

The family symmetries are broken close to the GUT breaking scale to yield the minimal supersymmetric standard model (MSSM). The model is realistic in the sense that it provides a successful (and natural) description of the quark and lepton (including neutrino) mass and mixing spectra.

### 3 Field content and mass matrices

The most important superfields in the model [2] are given in table 1. It includes the MSSM matter superfield $\Psi$, various Higgs fields that break $SO(10)$, $SU(5)$ and electroweak gauge symmetries, and flavons $\phi_i$ that produce the phenomenologically successful form of the quark and lepton mass matrices. It also includes the singlet $\xi$, which acquires a VEV below the GUT scale, $\langle \xi \rangle \lesssim 0.1 M_{\text{GUT}}$ and ultimately controls the hierarchies present in the model. CP is conserved at the high scale and spontaneously broken by flavons, while GUT and flavour singlets $Z, Z''$ break $Z_4^R$ $R$-symmetry to regular $R$-parity [9].

<table>
<thead>
<tr>
<th>Field</th>
<th>$\Delta(27)$</th>
<th>$SO(10)$</th>
<th>$Z_4^R$</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Psi$</td>
<td>3</td>
<td>16</td>
<td>1</td>
<td>Contains SM fermions</td>
</tr>
<tr>
<td>$H_{u,d}^{10}$</td>
<td>1</td>
<td>10</td>
<td>0</td>
<td>Break electroweak symmetry</td>
</tr>
<tr>
<td>$H_{16,\overline{16}}$</td>
<td>1</td>
<td>16, $\overline{16}$</td>
<td>0</td>
<td>Break $SO(10)$</td>
</tr>
<tr>
<td>$H_{45}$</td>
<td>1</td>
<td>45</td>
<td>0</td>
<td>Breaks $SU(5)$</td>
</tr>
<tr>
<td>$H_{DW}$</td>
<td>1</td>
<td>45</td>
<td>2</td>
<td>Gives DT splitting via DW mechanism</td>
</tr>
<tr>
<td>$\overline{\phi}_i$</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>Produces CSD3 mass matrices</td>
</tr>
<tr>
<td>$\xi$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Gives mass hierarchies, $\mu$ term</td>
</tr>
<tr>
<td>$Z, Z''$</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>Break $Z_4^R \rightarrow Z_2^R$ ($R$-parity)</td>
</tr>
<tr>
<td>$A_i$</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>Aligns triplet flavons $\overline{\phi}_i$</td>
</tr>
<tr>
<td>$O_{ij}$</td>
<td>$1_{ij}$</td>
<td>1</td>
<td>2</td>
<td>Aligns triplet flavons $\overline{\phi}_i$</td>
</tr>
</tbody>
</table>

Table 1: Core superfields of the model and their representations under the symmetries.

The flavour structure for quark and lepton matrices is determined by the CSD3 framework, where the fermions couple to flavons that acquire VEVs like in Eq. [1]
More precisely, its implementation can be understood as follows: at the renormalisable level, $\Psi$, $\bar{\phi}_i$ and $H$ couple to $SO(10)$ spinor superfields $\chi_i$, which act as messengers. Integrating these out produces Yukawa-like terms

$$\lambda \Psi \Psi H \bar{\phi}_j \frac{\xi^n}{M_{\chi}^{n+2}},$$

where $\lambda$ are $O(1)$ couplings, $n$ are integer powers, and $M_{\chi} \gtrsim M_{\text{GUT}}$. The presence of different such terms with different powers of $\xi$ establishes a hierarchy between elements of the fermion mass matrices, and consequently a natural explanation for the large range of fermion masses. $\xi$ is also responsible for generating a $\mu$ term that can be $O(\text{TeV})$. After $SO(10)$ is broken, all but two of the Higgs doublets and all triplets contained in $H^u_{10}$ and $H^d_{16,16}$ must be very heavy, while exactly two doublets, $H_{u,d}$, are light. Constructing the effective mass matrix for Higgs doublets, it has one light eigenvalue with $\mu \sim \langle \xi \rangle^8 / M_{\text{GUT}}^8 \ll M_{\text{GUT}}$.

Guided by $SO(10)$ unification, ultimately all mass matrices take the same generic form:

$$m^f = m^f_1 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m^f_2 \begin{pmatrix} 1 & 3 & 1 \\ 3 & 9 & 3 \\ 1 & 3 & 1 \end{pmatrix} + m^f_3 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

where $m^f_3$ are complex numbers. An exception is the term $\Psi \Psi H^u_{10} \bar{\phi}_{\text{sol}} \bar{\phi}_{\text{dec}}$, which is allowed by the symmetries and messengers, giving an additional contribution to $m^u$ like

$$m^u_4 \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 3 \\ 1 & 3 & 2 \end{pmatrix}.$$  

It does not affect neutrino physics. As the matrix in Eq. 3 is a sum over rank-1 matrices, we find that also the neutrino mass matrix after seesaw always retains this form. A proof is given in [10], which also discusses leptogenesis in this model.

This matrix structure can successfully accommodate all quark and lepton masses and mixing angles, and is predictive in the lepton sector. It predicts a Normal Hierarchy with best fit parameters

$$\theta_{12} = 33.1^\circ, \quad \delta_{\text{CP}} = 280^\circ, \quad m_1 = 0.32 \text{ meV},$$

$$\theta_{13} = 8.55^\circ, \quad \alpha_{21} = 264^\circ, \quad m_2 = 8.64 \text{ meV},$$

$$\theta_{23} = 40.8^\circ, \quad \alpha_{31} = 323^\circ, \quad m_3 = 49.7 \text{ meV}.$$  

Once lepton masses are fitted, the PMNS matrix is completely fixed with no freedom, including the Dirac phase $\delta_{\text{CP}}$, which is a prediction of the model and not fitted. It agrees well with the current experimental hints.
4 Conclusion

This is one of few flavour $SO(10)$ models with realistic fits to both quark and lepton data, and the most complete, as it is renormalisable and accounts for gauge coupling unification, the $\mu$ term, DT splitting, and (lack of) proton decay. It is predictive in the lepton sector, and may be probed by precise measurements of PMNS parameters, particularly $\delta_{CP}$, and ruled out by observation of an Inverse Hierarchy, or non-observation of SUSY.

References


The main physics goal of the SNO+ experiment is the search for neutrinoless double-beta decay ($0\nu\beta\beta$), a rare process which if detected, will prove the Majorana nature of neutrinos and provide information on the absolute scale of the neutrino mass. Additional physics goals include the study of solar neutrinos, anti-neutrinos from nuclear reactors and the Earth’s natural radioactivity as well as Supernovae neutrinos. Located in the SNOLAB (Canada) deep underground laboratory, it will re-use the SNO detector. A short phase with the detector completely filled with water has started at the beginning of 2017, before running the detector with scintillator. This paper describes in details the SNO+ sensitivity to $0\nu\beta\beta$ decays, as well as the other physics goals. Crucial to these large volume liquid scintillator experiments, is the ability to constraint the low-energy background from radioactive decays. Methods to mitigate those are also presented.

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1 The SNO+ experiment

The SNO+ experiment uses the SNO ∼9300 photo-multipliers (PMTs). The detector was upgraded with a new hold-down ropes systems, new data-acquisition and read-out systems, and modifications of its water plant. New scintillation and tellurium purification plants are also being completed at present. The detector is constituted of a geodesic steel structure of 17 m diameter which supports the PMTs. Inside, a spherical acrylic vessel of 6 m radius holds the media. The acrylic vessel is shielded by 7 kt of pure water which fills the entire cavern, additional rock shields composed of norite and granite/gabbro are surrounding the detector located 2 km underground in SNOLAB (Canada). SNO+ will have several experimental phases: a water phase, a scintillator phase with 780 tons of liquid scintillator and a scintillator loaded phase with 1.33 tons of $^{130}\text{Te}$ (0.5% $^{nat}\text{Te}$). The detector is equipped with a set of different calibration systems which are composed of deployable radioactive sources (provide an estimation of the reconstruction efficiency and the systematics uncertainties) and optical systems (measure the PMTs response and media properties such as the attenuation and scattering coefficients). See [1, 2, 3, 4] for more detailed information.

2 The SNO+ Physics

2.1 Neutrinoless double-beta decay with $^{130}\text{Te}$

Two neutrinos double-beta decay ($2\nu\beta\beta$) is a very rare process that is permitted for 35 known natural isotopes. It was experimentally observed in 11 of them. Neutrinoless double-beta decay ($0\nu\beta\beta$) can occur if neutrinos have a mass and they are their own anti-particles (Majorana neutrinos). The effective Majorana mass corresponds to $< m_{\beta\beta} > = |\sum m_i \times U_{ei}^2|$ [5], where $m_i$ is the mass of the neutrino eigenstate i and $U_{ei}$ the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix elements ($i = 1, 2, 3$). The $0\nu\beta\beta$ decay rate can be written as follows:

$$\Gamma_{0\nu\beta\beta} = ln(2) \cdot (T_{1/2}^{0\nu\beta\beta})^{-1} = ln(2) \cdot G_{0\nu\beta\beta}^{0\nu\beta\beta}(Q_{\beta\beta}, Z) \cdot g_A^4 \cdot |M_{0\nu\beta\beta}|^2 \cdot \frac{< m_{\beta\beta} >^2}{m_e^2}$$

where $G_{0\nu\beta\beta}$ is the phase-space factor and $M_{0\nu\beta\beta}$ the Nuclear Matrix Elements (NME), both have values depending on the isotope chosen [6]. The limit on the isotope half-life can be described as:

$$T_{1/2}^{0\nu\beta\beta} = \frac{N \cdot ln(2)}{n_{\sigma}} \cdot \frac{f(\delta_e) \cdot t}{\sqrt{(b \cdot M + c) \cdot \delta E \cdot t}}$$

with N corresponding to the total number of isotope nuclei, $n_\sigma$ the number of standard deviation, $f(\delta_e)$ the energy window acceptance fraction, t the time, M the isotope mass.
in kg, $\delta E$ the energy window in keV, $b$ the background counts in $(\text{keV.kg.yr})^{-1}$ and $c$ the backgrounds counts in $(\text{keV.yr})^{-1}$. Background $b$ (e.g. U/Th) scales with the isotope quantity whereas $c$ is independent of the isotope (e.g. solar $^8\text{B}$). $^{130}\text{Te}$ has been chosen by the SNO+ collaboration for the following properties: its high natural abundance (34.08%), its $2\nu\beta\beta$ long half-life ($7.0 \times 10^{20}$ yr) and the absence of inherent absorption lines. However, its energy end-point $Q_{\beta\beta} = 2.527$ MeV, which requires a very detailed knowledge of the backgrounds falling in the Region of Interest (ROI).

The $0\nu\beta\beta$ half-life as a function of the effective Majorana neutrino mass for different isotopes is given in Figure 1.

![Figure 1: $0\nu\beta\beta$ half-life and effective Majorana mass sensitivity for different isotopes and NME values.](image)

2.2 Backgrounds mitigation

A novel technique for loading the scintillator cocktail (LAB+PPO) uses Te-Diol, which will provide a light yield of 390 hits/MeV. The spectrum of an hypothetic $0\nu\beta\beta$ signal for a effective Majorana mass of 200 meV and backgrounds for 5 years of data-taking with 0.5% $^{nat}\text{Te}$ loading and a FV cut $R = 3.5$ m is given in Figure 2 (left). The expected sensitivities for the $0\nu\beta\beta$ half-life $T_{1/2}^{0\nu\beta\beta}$ is $> 0.8 \times 10^{26}$ yr (1.96$\times 10^{26}$ yr) for 1 year (5 years) data-taking. The background budget can be found in Figure 2 (right) representing 13.4 counts/yr in FV and ROI. The $2\nu\beta\beta$ background is irreducible but will be constrained by using an asymmetric, $[\mu - 0.5\sigma, \mu + 1.5\sigma]$, ROI, however the energy resolution is limited. Background from ($\alpha$,n) will be rejected using coincidence-based cuts with an expected efficiency $> 99.6\%$ (90\%) for the prompt (delayed) signal. External $\gamma$ backgrounds will be identified using FV and PMTs time distribution cuts.

For the U and Th chain, the dominant background from $^{214}\text{BiPo}$ and $^{212}\text{BiPo}$ decays

*The values $G^{0\nu\beta\beta} = 3.69 \times 10^{-14}$ yr$^{-1}$, $g_A = 1.269$ and $M^{0\nu\beta\beta} = 4.03$ (IBM-2) have been used.
will be rejected using coincidence-based cuts with 100% rejection power for events in separate triggers. Purification techniques and long term underground storage will help eliminate backgrounds from cosmogenics. Finally the continuous background from elastically scattered electron from the solar $^8$B interaction will be normalized using published data.

### 2.3 Other physics

In addition to the search for $0\nu\beta\beta$ decays, SNO+ has several other physics goals described below. Anti-neutrinos coming from nearby nuclear reactors will be measured (see Figure 3, left) in the pure and Te-loaded liquid scintillator phases. The neutron delayed capture ($2.2\text{ MeV} \gamma$) from the inverse-beta-decay (IBD) reaction is used to tag such events. The expected precision to the neutrino oscillation parameter $\Delta m^2_{12}$ is $0.2 \times 10^{-5} \text{ eV}^2$ for 7 years of data-taking, similar to the precision obtained by KamLAND [7]. Detection of Solar neutrinos is done by recording the recoil electron signal from the neutrino elastic (ES) scattering in the pure scintillator phase (see Figure 3, right). The expected precision on the different fluxes is of 7.1% for $^8B$, 3.3% for $^7Be$, 8.9% for pep and 15% for CNO for 1 year data. Neutrinos from Supernovae located...
in the vicinity of 10 kpc (see Figure 4, left) can be detected in all phases of the SNO+ experiment. A search for invisible modes such as the neutron decay from $^{16}$O into

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{neutrino_spectra}
\caption{Neutrino energy spectra from a Supernova explosion \cite{8} in the $\nu$-p ES channel (left) and nucleon decay spectra with a FV cut R = 5.5 m (right).}
\end{figure}

$3\nu$ with emission of several $\gamma$s \cite{9} will be performed in the water phase (see Figure 4, right). The expected limit on the neutron and proton lifetimes for 6 months of data is $\tau_n \geq 1.25 \times 10^{30}$ yr and $\tau_p \geq 1.38 \times 10^{30}$ yr.

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Baby MIND: A magnetised spectrometer for the WAGASCI experiment


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The WAGASCI experiment being built at the J-PARC neutrino beam line will measure the difference in cross sections from neutrinos interacting with a water and scintillator targets, in order to constrain neutrino cross sections, essential for the T2K neutrino oscillation measurements. A prototype Magnetised Iron Neutrino Detector (MIND), called Baby MIND, is being constructed at CERN to act as a magnetic spectrometer behind the main WAGASCI target to be able to measure the charge and momentum of the outgoing muon from neutrino charged current interactions.

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1 Introduction

The prototype Magnetized Iron Neutrino Detector (Baby MIND) \cite{1} is currently being built at CERN, where it will be fully characterized at a charged particle beam line. Once the detector has been characterised, the plan is to integrate it into the WAGASCI, WAter Grid And SCIntillator, (T59) experiment \cite{2, 3} in Japan to improve measurements of the ratio of neutrino interaction cross sections on water and carbon. To this end, it will provide charge identification and momentum measurements for muons resulting from neutrino interactions in the WAGASCI neutrino targets located upstream. The purpose of this experiment is to constrain the main non-cancelling systematic uncertainty for the neutrino oscillation analysis at T2K \cite{4}.

2 WAGASCI and Baby MIND layout

WAGASCI consists of a segmented target of water and scintillator cells, where the cross section can be measured in both media simultaneously. The WAGASCI experiment requires some form of magnetic spectrometer to measure momentum and charge identification of the outgoing muons from charged current interactions. The Baby MIND detector consists of 33 magnetised metal plates and 18 scintillator modules that measure the position of hits along the spectrometer and the curvature of the track in the magnetic field. Two muon range detectors (MRD) are placed at either side of the WAGASCI target to measure escaping particles.

Figure 1 shows a layout of the WAGASCI detector, with the main target at the centre, Baby MIND at the end and the two side-MRDs. Figure 2 shows a more detailed side view of the Baby MIND detector, with the alternating magnetised iron plates and scintillator planes shown. Each scintillator module consists of four planes of polystyrene-based extruded scintillator bars, two of the planes are oriented along the horizontal direction, with bars 30 mm wide, and two of the planes are oriented along the vertical direction, with bars 210 mm wide. Each bar contains Kuraray wavelength-shifting fibres of diameter 1.0 mm to collect the light and transport it at either end to Hamamatsu S12571-025C Multi-pixel Photon Counters (MPPC).

3 Electronics test beam

During June-July 2016 a test beam was performed to characterise the readout system, data acquisition (DAQ) and electronics to be used in the Baby MIND detector. The test beam was at the T9 beam of the East Area, operating at the Proton Synchrotron (PS) at CERN. A Totally Active Scintillation Detector (TASD) constructed under the AIDA project (Advanced European Infrastructures for Detectors at Accelerators) was used to test the readout system, electronics, DAQ and reconstruction software.
For the test beam, twelve planes, consisting of 16 scintillator bars $10 \times 10 \times 1000 \text{ mm}^3$, read out on both sides by S12571-025C Hamamatsu MPPCs along alternating $x$ and $y$ directions were instrumented (a total of 384 MPPCs). The beam consisted of muons and pions from $\sim 200 \text{ MeV}/c$ up to $10 \text{ GeV}/c$. Figure 3 shows a schematic of the TASD and figure 4 shows the evolution of the beam profile as measured by the TASD during the test beam and reconstructed with the SaRoMan software.

The electronic readout consists of custom-made Front End Boards (FEB). Each FEB consists of three 32 channels CITIROC ASICs. Each channel has a 12-bits ADC reading out at 40 Mega-samples per second per channel. The data processing is carried out by an Altera ARIA5 FPGA that controls the 400 MHz timing. The slow control readout is carried out with a USB3 or a Gigabit RJ45 chain and there is also an externally propagated Trigger signal.
4 Baby MIND software

The software suite used for the Baby MIND detector is the Simulation And Reconstruction Of Muons And Neutrinos (SaRoMaN) software. SaRoMaN can handle simulated single particle data from GEANT4 [5], simulated neutrino data from GENIE [6] as well as real beam data. The digitisation software converts $x$ and $y$ bar hits into three-dimensional space points and performs event building from the data acquisition. The generic detector model is handled using GDML (Geometry Description Markup Language) files [7], allowing to utilize the same geometry in both the simulation and the reconstruction. The reconstruction software uses RecPack, a Kalman filter fitting package used to improve trajectory fits by using preliminary fitting parameters and a geometry description to improve the trajectory parameters [8].

Figure 5 shows the current reconstruction efficiency, using simulated data in Baby MIND, defined as the number of reconstructed tracks from the number of muons in the simulation. For a single muon pencil beam parallel to the detector axis, the efficiency is more than 95% for full range (0.2-6 GeV/c). Figure 6 shows the current charge identification efficiency, which is defined as the number of tracks with the correctly assigned charge out of all the reconstructed trajectories. For a single muon pencil beam parallel to the detector axis, the efficiency is more than 90% in the expected full reconstructible momentum range (0.2-6 GeV/c).

![Simulations 2016](image1)

![Simulations 2016](image2)

Figure 5: Reconstruction efficiency for a single muon pencil beam.

Figure 6: Charge identification efficiency for a single muon pencil beam.

5 Outlook

The construction of the Baby MIND detector is ongoing and taking place at CERN. The magnetised steel plates are being assembled at CERN and the scintillator bars
with wavelength shifting fibres are being constructed by INR Moscow. The detector construction and testing schedule is as follows:

- The full Baby MIND detector will be finalised in May 2017;
- A test beam will be carried out in June 2017 to characterise the full Baby MIND detector;
- Shipping of the Baby MIND detector to Tokai, Japan in July 2017;

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Trigger for the SoLid Reactor Antineutrino Experiment

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SoLid, located at SCK-CEN in Mol, Belgium, is a reactor antineutrino experiment at a very short baseline of 5.5 – 10m aiming at the search for sterile neutrinos and for high precision measurement of the neutrino energy spectrum of Uranium-235. It uses a novel approach using Lithium-6 sheets and PVT cubes as scintillators for tagging the Inverse Beta-Decay products (neutron and positron). Being located overground and close to the BR2 research reactor, the experiment faces a large amount of backgrounds. Efficient real-time background and noise rejection is essential in order to increase the signal-background ratio for precise oscillation measurement and decrease data production to a rate which can be handled by the online software. Therefore, a reliable distinction between the neutrons and background signals is crucial. This can be performed online with a dedicated firmware trigger. A peak counting algorithm and an algorithm measuring time over threshold have been identified as performing well both in terms of efficiency and fake rate, and have been implemented onto FPGA.

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1for the SoLid collaboration
1 Introduction

SoLid is a short-baseline reactor antineutrino experiment. It probes the deficit from the electron antineutrino ($\bar{\nu}_e$) prediction yield measured by various reactor antineutrino expriments – known as the reactor antineutrino anomaly [1] – in close proximity (5.5m . . . 10m) from the reactor core. An observation of an oscillation in the antineutrino energy spectrum at close distance measured independenty of the predictions, relative measurements at different distances, could provide evidence for the existence of sterile neutrinos, the sterile flavour state being an addition flavour to the three flavours commonly known ($\nu_e$, $\nu_\mu$ and $\nu_\tau$) that does not interact weakly.

The experiment is located at the BR2 reactor at SCK•CEN in Mol, Belgium. BR2 is a tank-type material research reactor fuelled by Uranium-235 with a power range of up to 100MW and a core diameter of only 50cm, which makes it an almost point-like neutrino source. The SoLid detector, depicted in Figure 1a, consists of 5 modules, or 50 planes that each contain 256 ($5 \times 5 \times 5$)cm cubes consisting of PVT and a layer of $^6$LiF : ZnS(Ag). The detector uses 1.6t of active material.

![Diagram](attachment:image.png)

(a) The SoLid 1.6t-detector, consisting of 50 planes.

![Diagram](attachment:image.png)

(b) Interaction of $n$ and $e^+$ in the detector cube. Source: [2].

Figure 1

1.1 Detector Technology

SoLid’s neutrino detection is based on Inverse Beta-Decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$  

(1)
The two IBD products – the positron ($e^+$) and the neutron ($n$) – are captured by two different materials in the cube. The positron is absorbed within $\mathcal{O}(10^{-8})$ s by the PVT and is emitted as a short ($\mathcal{O}(10^{-7})$ s), intense light pulse $^2[3]$. The neutron however undergoes thermalisation while being scattered through the material before being caught by the $^6\text{LiF} : \text{ZnS(Ag)}$ sheets by the process

$$n + ^6\text{Li} \rightarrow ^3\text{H} + \alpha + 4.78\text{MeV}.$$ (2)

Both $^3\text{H}$ and the $\alpha$-particle contain sufficient energy to excite the electrons in the ZnS crystals. Scintillation light is emitted by de-excitation of these electrons over a longer period of $\mathcal{O}(10^{-6})$ s, an order of magnitude higher than the positron’s signal length. The positron and neutron signals hence are clearly distinct by their latency, amplitude and decay time. IBD capture by the cube is sketched in Figure 1b.

1.2 Read-out System

Wavelength-shifting fibres guide the light from the PVT cubes to Silicon Photomultipliers (SiPMs). 64 SiPMs are read out per plane. The SiPM signal are shaped and filtered by an analogue board and then sent to the digital board that includes the FPGA. The read-out electronics is placed on side of the frame containing the cubes. The boards are custom-made to serve the needs of the SoLid experiment $^4$.

1.3 Firmware

The SoLid FPGA firmware is responsible for buffering the data, triggering on it, and for communication with other planes as well as with the data acquisition device. Also, it has the slow-control for the SiPMs integrated in its functionality. The firmware is based on the IPbus protocol, a gigabit Ethernet-based reliable high-performance protocol designed for particle physics experiments $^5$ $^6$. A medium-density device – the XILINX Artix 7-200T FPGA – is used. The ionising radiation being faced is about the same as normal background levels as the increase in neutron and gamma flux by the reactor is compensated for by water and containment shielding.

2 Trigger

SoLid faces a large amount of background signals due to it being an overground experiment in proximity to the reactor core. This requires the read-out system – or namely the trigger part – to reject as many background signals as possible. The extent to which this rejection has to take place is dependent on data generation by the digital board and on the data handling capacity by the online software. A summary of data rates and reduction factors is given in Table 1. It is the task of the trigger
to provide efficient, yet pure data reduction. The positron signal – due to its high amplitude and briefness – is fairly easy to distinguish; a threshold trigger is used. In contrast, the neutron trigger is more complex, as its signals usually do not reach high amplitudes. Using solely the positron trigger – that has low purity – would increase data rate up to a point at which it cannot be handled by the online software, which is the reason why triggering properly on the neutrons is necessary for detector read-out.

2.1 Algorithm Evaluation

Test data have been used for evaluation of different neutron trigger algorithms, or features. The test setup uses an $^{241}$AmBe $\alpha$-particle source, located $\sim 3$cm from a PVT cube connected to two SiPMs and a photomultiplier tube that is used for acquiring the reference signal.

An overall comparison of features has been used to reduce the number of potential features by short-listing those that perform well, i.e. that yield high efficiency, high purity and low fake rate simultaneously. High efficiency, or true positive rate, correlates with how many IBD physics events are caught. High purity, or positive predictive value, correlates with contamination of IBD events with backgrounds. And a low fake rate, or false positive rate, means that few non-IBD events are acquired. The results on the efficiency-fake rate plane are shown in figure 2.

A variety of trigger algorithms have been evaluated. Of these, the following three have been performing well on test data:

**Number-of-Peaks** The Number-of-Peaks feature counts the number of maxima above a certain threshold $\theta$ within a time window. An example is shown in figure 3.

The threshold is set in order that pure noise-induced maxima are not considered. The reasoning behind this algorithm is that each time the $^6$LiF : ZnS(Ag)-layer is emitting a photon, a peak on the input signal occurs. It may be expressed in discrete space as a function of the discrete signal within a limited time window $X$:

$$g(X) = \left| \{t | \forall t : X[t] > \theta \wedge X[t-1] \geq X[t-2] \wedge X[t] < X[t-1] \} \right|.$$ (3)
Figure 2: Summarising ROC curve of different features in terms of efficiency and fake rate (= false positive rate), with the Number-of-Peaks algorithm performing best on the test data set.

In other words, the cardinality – i.e. the number of elements – $|.|$ of the set $\{\cdot\}$ of points that are a maximum above a certain threshold forms the feature.

**Time-over-Threshold** The Time-over-Threshold measures the number of samples (i.e. length of time) a signal is above a certain threshold $\theta$. It is expressed as a a function of a discrete signal $X$ within a time window of sample length $m$ as

$$g(X) = \sum_{t=1}^{m} \delta[t] \land \delta[t] = \begin{cases} 1, & \text{if } X[t] > \theta, \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

**Integral-over-Amplitude** The Integral-over-Amplitude (or Integral/maximum Amplitude) divides the integral of a signal by division by maximum amplitude:

$$g(X) = \frac{\sum_{t=1}^{m} X[t]}{\max X}. \quad (5)$$

### 2.2 Feature Tuning

Many features have free parameters, such as the threshold $\theta$ in the Number-of-Peaks (Equation 3) and Time-over-Threshold (Equation 4) algorithms. These parameters
have to be tuned for the optimum value. This can be achieved by sweeping the free parameter $\theta$ [7], as shown in Figure 4a.

2.3 Correlation Analysis

The features examined are correlated to a very high degree (Pearson’s $r > 0.8$), except the Integral-over-Amplitude that cannot be implemented, as shown in section 2.4. This indicates that redundant information would be obtained when using more than one feature. It can be concluded that no significant increase of performance can be expected when using more than one feature. Therefore a single threshold trigger on the feature output value is used, and other machine learning algorithms considered such as the perceptron and the feed-forward neural network have been discarded.

2.4 Implementation

As 64 channel triggers plus the other firmware elements have to be synthesised on a single FPGA, hardware resources are strictly limited. Implementation of algorithms and their synthesis has been undertaken for the Time-over-Threshold, Number-of-Peaks (with and without time veto) and Integral-over-Amplitude features, as well as for the Integral feature.

The Integral, Time-over-Threshold, Number-of-Peaks features rely on comparators, sums and differences only that can be easily implemented as adder-subtractors into digital logic [8]. However, the Integral-over-Amplitude algorithm contains a division, an operation that is resource-intense on the FPGA. The usage of hard-
(a) Surface plot for Time-over-Threshold feature tuning. Threshold is swept from 0 to 4.5PA with a mountain visible in the range of 0.5PA, indicating the optimum value.

(b) Hardware usage of different feature extraction algorithms versus efficiency at a 20% purity level and on the usual window size of 256 samples (1 sample ≈ 20ns). The red line indicates hardware resource availability per channel.

Figure 4

ware resources is compared in Figure 4b. It can be seen that the Integral-over-Amplitude algorithm exceeds the hardware limit by far. Therefore, implementation into the firmware has been made for the Number-of-Peaks algorithm and the Time-over-Threshold feature extraction method.

3 Conclusion

According to the findings, the most suitable trigger has been implemented, that are now the Number-of-Peaks and the Time-over-Threshold feature extraction algorithms and a threshold trigger on the feature extraction output value. These algorithms have been implemented and synthesised into firmware, and embedded into the IPbus framework. The trigger performance evaluation was carried out relative to the test data, and conditions at the reactor are not known at the moment. Therefore the decision on the trigger algorithm relies on the assumption that the best performing algorithms on the test environment also perform well on the reactor site. However this might be wrong if background signals are qualitatively different from the test signals. This can be considered unlikely though, as the same detection scheme underlies both setups. The actual background rate determines at which efficiency level the trigger can operate. The tuning of the parameters for the trigger is performed at calibration. Calibration will aim not only for highest efficiency, but also for uniformity along the different channels. As trigger efficiency directly propagates to detector efficiency,
optimal trigger calibration is essential for the quality of the experiment.

The hunt for sterile neutrinos in the very-short baseline range has started, and SoLid is about to start its first large-scale physics run. In the case the reactor anomaly cannot be reconfirmed, SoLid’s purpose might not be fulfilled, but the results would fit nicely not only with the three-flavour neutrino oscillation model, but also with recent results from accelerator- and atmospheric-based neutrino experiments. In case SoLid, in line with other very short-baseline experiments, does find a deficit, a theorist might hope for a systematic simulation error in calculating reactor neutrino flux to give sufficient explanation — if not, he or she has to seriously consider an update of the neutrino model currently most favoured, from having three to having four or even more neutrino flavour states by adding sterile neutrinos.

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References

Commissioning of ELLIE for SNO+

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SNO+ is a neutrinoless double beta decay and low energy neutrino experiment located in Sudbury, Canada. To improve our understanding of the detector energy resolution and systematics, calibration systems have been developed to continuously monitor the optical properties of the detector, such as: absorption, re-emission, scattering and timing.

A part of this in-situ optical calibration system is the Embedded LED/Laser Light Injection Entity (ELLIE). It consists of three subsystems: AMELLIE, SMELLIE, TELLIE. The attenuation module (AMELLIE) is designed to monitor the total optical attenuation, whereas the optical scattering over a wavelength range of 375nm – 700nm will be characterized by the scattering module (SMELLIE). The timing module (TELLIE) aims to measure the timing characteristics of the photomultiplier tubes.

We present the planned commissioning of these three systems, the running of which began early 2017.

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# Introduction to SNO+

SNO+ is a general purpose neutrino detector based 2 km below surface at SNOLAB with the main aim of searching for neutrinoless double beta decay in $^{130}\text{Te}$ [1]. The detector is a 6 m radius acrylic vessel (AV) filled with detection medium, suspended in a 40 m tall cavern filled with ultra-pure water (UPW). The AV is surrounded by $\sim 9300$ photomultiplier tubes (PMTs) on a 9 m radius PMT support structure (PSUP) [2].

There are three phases of detection medium: UPW, pure scintillator and Te loaded scintillator. Currently the AV and cavity are filled with UPW and data taking for the water phase has begun, as has commissioning of the calibration systems [3].

## ELLIE

The Embedded Laser/LED Light Injection Entity (ELLIE) is part of the in-situ optical calibration system for SNO+. It provides continuous monitoring and aims to improve the understanding of detector energy resolution and systematics. It consists of three subsystems: the Attenuation Module (AMELLIE), the Scattering Module (SMELLIE) and the Timing Module (TELLIE).

All of these involve optical fibres mounted on the PSUP, connected either to lasers or LEDs pointed such that the beam passes through the AV, and hence the detection medium, as shown in Figure 1. These fibres are mounted external to the AV to meet stringent radioactivity requirements.

![Figure 1: A schematic of the SNO+ detector [4] with example SMELLIE (yellow) and TELLIE (green) beams overlaid.](image-url)
3 AMELLIE

AMELLIE is designed to monitor the attenuation in scintillator, using 8 narrow angle fibres at four injection points, connected to LEDs of two wavelengths. Changes in beam intensity will relate to changing scintillator properties over time.

In the water phase of the experiment, there are several calibrations to complete, including measurements of angular distributions of beams as these are an input to simulation and intensity scans in order to calibrate intensity of light to number of photons as seen in the detector.

![Figure 2: Analysis of an simulated AMELLIE beam. Using PMT timing and position information, the direct beam can be identified (red area bottom left). Reflections from other components such as the AV and PMT concentrators can be associated with other features in this plot.](image)

4 TELLIE

TELLIE measures the timing characteristics of the PMTs with 92 light injection points on the PSUP connected to LEDs of 505 nm wavelength. Light is injected with a wide angle, providing full coverage of the PMT array. Therefore, each channel can be used to calibrate timing and gain of the PMTs in its beamspot. By reducing the intensity of light such that each PMT sees a single photoelectron, it is possible to measure the timewalk of the PMTs.

Additionally, by using light reflected by the AV, it is possible to determine the AV position. From simulation studies, the expected resolution on this measurement is less than 1 cm.
TELLIE has already been fully commissioned. Each channel has been calibrated using a desktop PMT. The three main calibrations of TELLIE are: light output corresponding to each intensity setting; PIN measurement against light output (the PIN reading is a measurement of light intensity made by an internal system); delay between each channel and the trigger out signal.

Figure 3: Plot of the intensity calibration results for an example channel, with error bars scaled up by a factor of ten for visibility. Parameter IPW sets the intensity of the TELLIE channel. For single photoelectron calibrations, the intensity is set to 1000 photons. The PIN reading saturates at 65536 as it is stored as a 16-bit number and has been calibrated to be sensitive down to low light levels where detector calibration will happen.

5 SMELLIE

SMELLIE is designed to measure and characterise the scattering properties of the detection medium. It consists of 15 collimated fibres at five locations on the PSUP. These are connected to five lasers: four fixed wavelength dye laser heads (375 nm, 405 nm, 445 nm and 495 nm) and one supercontinuum laser (allows wavelengths between 400 – 700 nm with a bandwidth down to 10 nm). SMELLIE has a monitoring PMT unit (MPU) which is used to measure the intensity of each laser pulse before it enters the detector. This allows for a pulse by pulse correction to the optical intensity of the beam, knowledge of which is relied upon in the analysis technique to determine scattering length.

Water phase is particularly useful for calibration as the scattering properties of water are already well understood. Therefore, there are several calibrations to complete.
before scintillator is put into the AV. Firstly, the electronics settings of the monitoring system, consisting of the MPU, but also a spectrometer for the supercontinuum laser, need to be optimised. Fibre installation position and angle needs to be confirmed. Then, a map needs to be created of laser intensity settings against wavelength against number of photons entering the detector, for each fibre. This allows the system to be operated with a ‘multi-hit’ correctable region, discussed further in [6]. Also, detailed measurements of beam profiles, as seen in the detector must be made, as these are an input to the analysis. These calibrations are currently underway.

Figure 4: Map of PMTs during SMELLIE laser pulses while the detector was partially filled. The direct beamspot is cut in half due to the water level (middle); a reflection from the AV can be seen (bottom right). Colour represents the number of hits, which is proportional to the optical intensity. Only a fraction of PMTs were operating at high voltage in this commissioning run, taken in 2016.

References


The Hyper-Kamiokande Experiment: Overview & Status

JOST MIGENDA FOR THE HYPER-KAMIOKANDE PROTO-COLLABORATION

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The Hyper-Kamiokande (HK) experiment centres around a proposed next-generation underground water Cherenkov detector that will be nearly 20 times larger than the highly successful Super-Kamiokande experiment and use significantly improved photodetectors with the same 40% photo-coverage.

HK will increase existing sensitivity to proton decay by an order of magnitude, and it will study neutrinos from various sources, including atmospheric neutrinos, solar neutrinos, and supernova neutrinos. In addition to operating as a standalone experiment, HK will serve as the far detector of a long-baseline neutrino experiment using the upgraded J-PARC neutrino beam, enhancing searches for lepton-sector CP violation.

This poster presents recent developments and the current status of the experiment. It provides an overview of the project, including ongoing R&D efforts and upgrades to both the beam and the near detector suite. The expected physics reach, showcased in the recently published design report, will also be featured.

[Nb: This contribution to the NuPhys2016 proceedings focuses on photosensor development and supernova neutrinos. Other physics topics, including neutrino oscillations and nucleon decay, are discussed in a separate contribution to these proceedings.]

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1 Introduction

Hyper-Kamiokande (HK, [1]) is a proposed next-generation water Cherenkov detector, whose broad physics programme covers many areas of particle and astroparticle physics. It will increase existing sensitivity to nucleon decay by an order of magnitude, and it will study neutrinos from various sources, including atmospheric neutrinos, solar neutrinos, supernova neutrinos and annihilating dark matter. In addition to operating as a standalone experiment, HK will serve as the far detector of a long-baseline neutrino experiment (T2HK) using the upgraded J-PARC neutrino beam, enhancing searches for lepton-sector CP violation and enabling precision measurements of several other neutrino oscillation parameters.

In section 2, we give an overview over the experiment. We discuss photosensor development in section 3 and the expected physics reach in the area of supernova neutrinos in section 4. Other physics topics, in particular neutrino oscillations and nucleon decay, are discussed in a separate contribution to these proceedings [2].

2 The Hyper-Kamiokande Experiment

2.1 Overview

Figure 1: Drawing of the Hyper-Kamiokande detector and infrastructure.
HK is based on the proven technology of (Super-)Kamiokande. Its much higher
detector volume and additional improvements in key areas like photosensors and
near/intermediate detectors make it a straightforward yet powerful extension of the

The detector will be located about 8 km south of Super-Kamiokande (SK) in
the Tochibora mine with an overburden of 1750 m.w.e. As shown in fig. 1 it will
consist of two cylindrical tanks (each 60 m high and 74 m in diameter) and have a
total (fiducial) mass of 0.52 (0.37) Mton, making it 10 (17) times larger than its
predecessor. It will use 40,000 photomultiplier tubes (PMTs) per tank to reach the
same 40% photocoverage, and benefit from newly designed high-efficiency PMTs.

2.2 Recent Progress

The HK proto-collaboration was formed in January 2015 and has since grown to about
300 people from 73 institutions and 15 countries. In 2016, a design report presenting
an optimized detector design was published [1].

Construction for the first tank is expected to start in 2018, with data-taking
starting in 2026. In September 2016, the T2K collaboration published a proposal for
an extended run of their experiment [3], which would enable a seamless transition
to T2HK. An upgrade of the J-PARC beamline to 750 kW power is already ongoing,
while additional upgrades to reach 1.3 MW are planned before the start of HK.

In the baseline design described in the design report, the second tank would get
constructed next to the first one and start data-taking in 2032. As an alternative, the
possibility of building the second tank in Korea was explored in a white paper pub-
lished in November 2016 [4]. At a longer baseline of 1000–1300 km, that tank would
be able to observe the second oscillation maximum, where the effect of a non-zero $\delta_{CP}$
would be increased. The proposed detector locations offer a higher overburden (and
thus lower spallation backgrounds) than the Japanese HK site, which would increase
sensitivity to low-energy physics like solar or supernova relic neutrinos.

3 Photosensor Development

A new 50 cm PMT model, the Hamamatsu R12860-HQE, was developed for HK. It is
based on Hamamatsu’s R3600 PMT used in SK, but includes a box-and-line dynode
and several other improvements. As a result, this new model offers better timing
resolution and a detection efficiency that is two times as high due to improvements to
both quantum efficiency and collection efficiency (see fig. 2). Work to reduce the dark
noise rate and design new PMT covers for pressure resistance is currently ongoing.

In addition to this baseline design, R&D on alternative photosensor options like
hybrid photo-detectors, LAPPDs and multi-PMT modules is ongoing.
Figure 2: Single p.e. transit time (left) and relative detection efficiency (right) in the HQE B&L PMT developed for HK (blue) and the PMT used in SK (black).

4 Supernova Neutrinos

4.1 Galactic Supernova

For a galactic supernova at a fiducial distance of 10 kpc, HK will detect $O(10^5)$ neutrinos within about 10 s. This high event rate enables HK to resolve fast time variations of the event rate, which could give us information on properties of the progenitor (like its rotation) or on details of the supernova explosion mechanism like the roles of turbulence, convection and the standing accretion shock instability, SASI, on which there is significant disagreement between different computer simulations [5].

4.2 Supernovae in Neighbouring Galaxies

Due to its large volume, HK would be sensitive to supernova bursts in nearby galaxies as well, observing $O(5000)$ events from a SN1987a-like supernova in the Large Magellanic Cloud or $O(20)$ events from a supernova in the Andromeda galaxy.

Using strict timing coincidence with an external trigger, like a gravitational wave signal in LIGO or the nearby KAGRA, HK could even be sensitive to single supernova neutrino events. For supernovae at up to 4 Mpc distance, which are expected to happen every 3–4 years on average, HK has a 50% or greater chance of detecting at least one event (see fig. 3).

4.3 Supernova Relic Neutrinos

The total neutrino flux from all remote supernovae in the history of the universe is known as supernova relic neutrinos (SRN). While these neutrinos cannot be traced back to a specific supernova, they deliver information on the average spectrum of
supernova neutrinos and could enable a first measurement of the rate of failed (optically dark) supernovae, which are the origin of stellar mass black holes. The SRN measurement is therefore complementary to observations of nearby supernovae.

At HK, SRN are observable in an energy window of 16–30 MeV shown in fig. 3 which is bounded by cosmic-ray induced spallation backgrounds at lower energies and invisible muon background from atmospheric neutrinos at higher energies. Within 10 years, about 100 SRN events are expected at HK, corresponding to an observation of SRN with $4.8\sigma$ significance.

References


[2] See contribution by M. Yokoyama in these proceedings.


Baby MIND is a magnetized iron neutrino detector, with novel design features, and is planned to serve as a downstream magnetized muon spectrometer for the WAGASCI experiment on the T2K neutrino beam line in Japan. One of the main goals of this experiment is to reduce systematic uncertainties relevant to CP-violation searches, by measuring the neutrino contamination in the anti-neutrino beam mode of T2K. Baby MIND is currently being constructed at CERN, and is planned to be operational in Japan in October 2017.

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1 Introduction

The Baby MIND experiment as the downstream MRD of the J-PARC T59 experiment (WAGASCI) [1], was approved by the CERN Research Board in December 2015 [2]. The WAGASCI experiment, with a novel detector arrangement which creates arrays of small cubic cells whose walls are made from plastic scintillators, provides better acceptance compared to a classical layout of successive X and Y planes scintillator bars. The adoption of WAGASCI units for upgrades to the T2K ND280 near detector is being considered, motivated by the need to reduce systematics due to nuclear effects in water, one of the dominant systematic uncertainties in the T2K neutrino oscillation analyses, and of direct relevance to the HyperK project [3].

One challenge to be addressed by the Baby MIND collaboration is that of obtaining high charge identification efficiencies for $\mu^+$ and $\mu^-$ down to 400 MeV/c. Magnetized iron neutrino detectors are limited by multiple scattering in the iron, and their use is overlooked for applications requiring good charge ID efficiencies below 1 GeV/c. By optimising the distance between the first magnet modules, rendered possible by the magnet design, our simulations show high charge identification efficiencies of 97% down to 500 MeV/c, and capabilities for charge identification down to 300 MeV/c.

2 Baby MIND Detector design

The design and construction of the Baby MIND detector was very much constrained by the need to operate the detector both at CERN and in Japan on a relatively short timescale, and also the installation limitations in Japan via a narrow shaft (Figure 1), which in particular has driven the new magnetization scheme of the detector. Baby MIND is built from sheets of iron interleaved with detector modules as shown in Figure 2 but unlike traditional layouts for magnetized iron neutrino detectors (e.g.MINOS) which tend to be monolithic blocks with a unique pitch between consecutive steel

Figure 1: (Left) Sketch of WAGASCI detector, side MRDs and Baby MIND, (Right) Baby MIND installation in ND280 pit.
Figure 2: One possible Baby MIND layout, with muons incident from the left. Scintillator modules are referenced d0 to d17, magnet modules are referenced s1 to s33.

segments and large conductor coils threaded around the whole magnet volume, the Baby MIND iron segments are all individually magnetized, allowing for far greater flexibility in the setting of the pitch between segments, and in the allowable geometries that these detectors can take. This is of relevance for neutrino experiments that might consider muon spectrometers based on magnetized iron surrounding an active detector volume such as plastic scintillator, water cherenkov, liquid argon.

3 Detector hardware construction

The different detector hardware components and systems are listed below:

- Magnet module.
- Scintillator detector module.
- Cable bundles.
- Front-end electronics module.
- DAQ system.
- Mechanics support systems.

The general approach of the collaboration is to ensure documentation and traceability of components and systems. A construction database has been written to store parameters relevant to the detector hardware such as detector geometrical configurations, serial numbers of components and test data. The majority of systems have undergone prototype validation before launching the production phases. Assembly and qualification procedures are drafted for each system. Integration procedures ensure the correct handling of interfaces during systems integration phases.
3.1 Magnet modules status

The magnetization scheme for Baby MIND was designed at CERN[4]. Construction of the magnet modules was completed there by February 2017. The magnet modules are made from ARMCO steel sheets with two horizontal slits machined in the center and are wrapped by aluminium coil in a sewing pattern, Figure 3. This design allows the magnetic flux to be very uniform in the central tracking region, and contains the return flux in the side planes. The required horizontal magnetic field of 1.5 T can be reached for a current of 140 A and a dissipation power of 350 W per module.

3.2 Scintillator modules status

The scintillator modules with dimensions of $2 \times 3 \text{ m}^2$ contain 95 horizontal bars and 16 vertical bars each. The bars are extruded scintillators with wavelength shifting fiber and custom photosensor connectors manufactured under the responsibility of INR [5]. One completed scintillator module is shown in Figure 3. A total of 18 standard detector modules will be used in Baby MIND final layout, interleaved with magnet modules. The final position of these modules with respect to magnet modules is not frozen yet and is subject to changes depending on different performance priorities. The production of all the units is scheduled to be finished for the end of April 2017.

3.3 Electronics and DAQ system

The Baby MIND electronic readout scheme has been published in ref [6]. The Front End Board for the experiment was developed by the University of Geneva based on the CITIROC ASIC. The readout system includes two additional ancillary boards, the Backplane and the Master Clock Board (MCB). The readout system architecture is shown in Figure 4. After the extensive validation tests of the FEBv1 during beam tests at the T9 beamline at CERN with 1 to 10 GeV/c muons in summer 2016, FEBv2 was developed, integrating layout changes dictated by cabling considerations and with additional features for daisy chaining and synchronisation of multiple boards. The DAQ PCs are connected by USB3 links to the first FEB in a group of 6 FEBs that are daisy chained using RJ45 links.
4 Outlook

The collaboration is currently focused on completion of the detector construction and preparation for the upcoming beam tests at the T9 beamline at CERN in May and June 2017. After full characterization, the detector will be shipped to Japan in July 2017. The installation and commissioning of the detector in J-PARC will take place in September 2017 in order to be ready for beam at J-PARC in October 2017.

References


Status of the SuperNEMO $0\nu\beta\beta$ experiment

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SuperNEMO is an ultra-low-background tracker-calorimeter experiment designed to look for the neutrinoless double-beta decay of various isotopes. We present the current state of the experiment’s Demonstrator Module, which is currently being installed and commissioned at the LSM in France.

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\[1\text{On behalf of the SuperNEMO collaboration}\]
1 Introduction

Double-beta decay ($2\nu\beta\beta$), in which two neutrons decay simultaneously inside a nucleus, ejecting two electrons and 2 electron antineutrinos, has been observed in several isotopes. However, if neutrinos are Majorana particles, it should be possible for a double-beta decay to occur with no neutrinos in the final state. These $0\nu\beta\beta$ events can be distinguished from $2\nu\beta\beta$ decays by summing the energies of the two beta electrons: for $0\nu\beta\beta$, the electrons will carry the full decay energy $Q_{\beta\beta}$, while for $2\nu\beta\beta$ events, the summed electron energies will form a continuum up to $Q_{\beta\beta}$.

SuperNEMO [1] has been designed to study double-beta decays, and in particular, to look for $0\nu\beta\beta$ decays, which have never been observed. It builds on the design principles of its predecessor, NEMO-3 [2], with an ultra-low-background tracker-calorimeter architecture, allowing us both to measure electron energies and to fully reconstruct particle tracks to identify $\beta\beta$ events.

![Figure 1: Expanded diagram of the SuperNEMO Demonstrator showing (from left to right) calorimeter wall, tracker, source foil frame, tracker, calorimeter wall.](image)

The SuperNEMO Demonstrator Module (figure 1) has a layered design, with foils of $\beta\beta$ emitter sandwiched between tracker modules, surrounded by calorimeter walls. Initially, the source isotope will be 7kg of $^{82}\text{Se}$, mixed in a PVA base to create thin foils, suspended from the source foil frame. The modular design allows us to change these foils to study other isotopes.

The tracker, constructed in four C-shaped sections, consists of 2034 3-metre long drift cells operating in Geiger mode, arranged in rows of nine cells on each side of the source foil. Each cell comprises a central anode wire surrounded by 12 field-shaping wires, with copper cathode end caps at either end. When a charged particle crosses the cell, the anode signal timing tells us the distance from the anode wire, while the relative timings of the cathode signals give a position along the wire, allowing three-dimensional reconstruction.

The two calorimeter walls, situated outside the tracker, consist of 520 optical modules; 8-inch radiopure PMTs coupled to polystyrene scintillator blocks wrapped in teflon and mylar, with individual iron shielding. Lower-resolution optical modules
around the edges of the tracker (giving a total of 712 modules) offer $4\pi$ acceptance.

In its initial running period of 2.5 years, the Demonstrator Module will have a sensitivity to the $0\nu\beta\beta$ half-life of $T_{1/2}^{0\nu\beta\beta} > 6.5 \times 10^{24}$ years, corresponding to a Majorana neutrino mass $\langle m_\nu \rangle < 200 - 400$ meV. A proposed 20-module full SuperNEMO detector with an exposure of 500 kg years (5 years, 100 kg of $^{82}$Se) would improve our sensitivity to $T_{1/2}^{0\nu\beta\beta} > 10^{26}$ years ($\langle m_\nu \rangle < 50 - 100$ meV).

2 Tracker and calorimeter installation at LSM

![Figure 2: Installation of the Demonstrator Module at LSM](image)

(a) The back side of one of the main calorimeter walls (b) A final row of cells is inserted as two tracker C-sections are coupled

The optical modules have all been built, and in 2016, the two outer calorimeter walls (figure 2a) were assembled at the Laboratoire Souterrain de Modane (LSM), in the Fréjus road tunnel in France. The four C-shaped tracker sections were constructed and commissioned in the UK, and by December 2016, all four had been shipped to LSM. The first two C-sections have been joined together (figure 2b) and coupled to the first calorimeter wall, forming half of the Demonstrator Module. In situ commissioning of this half detector commenced in February 2017. In the following months, the source frame will be shipped to LSM and installed in the middle of the detector, allowing the full Demonstrator Module to be coupled together and commissioned.

3 Radon mitigation strategy

One of the largest backgrounds is due to radon, as $\beta$ decays of its daughter isotope $^{214}$Bi can mimic $0\nu\beta\beta$ events in our detector. To protect against this, stringent radiopurity requirements are imposed both on materials used in and around the detector, and on the gas in the tracking chamber. To measure the activity of detector components, we leave them in an emanation chamber (figure 3a) for two weeks, then measure
the activity with an electrostatic detector similar to [3]. To reach SuperNEMO’s target sensitivity, the radon activity in the tracker gas must be below 0.15 mBq/m$^3$. As our electrostatic detector is only sensitive to 1 mBq/m$^3$, we flow tracker gas through a Radon Concentration Line (RnCL) [4], capturing any radon in a carbon trap. Measuring the activity of the concentrated gas from the trap lets us calculate tracker activities as low as 10 $\mu$Bq/m$^3$. Our measurements indicate that, in order to meet the 0.15 mBq/m$^3$ requirement, we need to flow gas through the Demonstrator Module tracker at the reasonable rate of 2 m$^3$/hour.

4 Gas system automation

The tracker is filled with a mixture of 95% helium, 4% ethanol, and 1% argon. The gas system (figure 4) includes mass flow controllers and a pair of ethanol bubblers used to adjust the gas fractions. A RaspberryPi connected to the slow control system tracks the pressure and temperature in the bubblers and the gas flow rate, and provides alarms and real-time monitoring via a user interface.
(a) Simulated 0νββ event. Circles show drift radii; colours indicate timing. (b) 2 reconstructed electrons, showing tracker drift radii and calorimeter hits.

Figure 5: Simulated 0νββ events in the SuperNEMO event viewer

5 Software and analysis

SuperNEMO’s simulation and reconstruction software have been used to perform sensitivity studies, confirming initial predictions, and to evaluate the effects of potential sources of background contamination. The event display (figure 5), which visualises and displays information about simulated and reconstructed calorimeter hits, has allowed us to study how signal and background events will present themselves in the detector, enabling us to improve our event selection.

6 Conclusion

SuperNEMO’s Demonstrator Module is currently being installed and commissioned at LSM, and will begin taking data in 2017. A stringent radon mitigation strategy gives us ultra low backgrounds, with a projected Majorana mass sensitivity of 200-400 meV in 2.5 years of running.

ACKNOWLEDGEMENTS

References

SNO+ Commissioning Status

Billy Liggins on behalf of the SNO+ collaboration

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SNO+ inherits much of its infrastructure from the Noble prize winning SNO detector. However due to the two orders of magnitude increase in light output in liquid scintillator many upgrades have been made. Details of these upgrades and their commissioning status are presented, along with an update on the current status of SNO+.

PRESENTED AT

1 SNO+

SNO+ is a general purpose neutrino detector which will search for neutrinoless double beta decay ($0\nu\beta\beta$) in 1.3 T of $^{130}$Te loaded in 780 kT of LABPPO $^{[1]}$. SNO+ is situated at SNOLAB in Sudbury, Ontario, Canada. SNOLAB is 2 km (6000 m.w.e) below ground in shaft 9 of the active Creighton Nickel mine. At this depth cosmogenic backgrounds are reduced, with the total muon flux less than $10^{-9}$ cm$^{-2}$ s$^{-1}$. SNO+ uses the same 6 m radius acrylic vessel (AV) as SNO and is observed by the same $\sim 9300$ 8 inch Hamamatsu R1408 photomultiplier tubes providing a coverage of 54%. The detector is housed in a cavity filled with ultra pure water. While commissioning the detector for $0\nu\beta\beta$ phase SNO+ will be sensitive to invisible nucleon decay and solar axions during the initial water phase. During the second phase, with a detector full of scintillator, SNO+ will search for low energy solar neutrinos as well as Geo and reactor anti-neutrinos. SNO+ could also be sensitive to a galactic supernova event. A substantial amount of work has been done to transform the detector from a heavy water based detector to a liquid scintillator detector.

2 Detector and Processing Plant Upgrades

2.1 Hold Down Ropes

As the LABPPO is less dense than water, the AV will experience a significant buoyant force during scintillator fill. A hold down rope system was designed and installed in 2012 and has been tested at various points throughout commissioning. Testing was achieved by filling the cavity to a level above that of the AV fill level thus manufacturing a buoyant force. The ropes system was found to work as expected under an upward force of 1260 kN.

2.2 Scintillator Plant

A new processing plant had been constructed to achieve the purity of scintillator needed to ensure the low backgrounds required, $>10^{-17}$ g/g$_{LAB}$. Many tasks have been undertaken and completed; Helium leak checking, cleaning and passivation, fire suppression system installation, pipe insulation and water commissioning. The plant is currently being commissioned with 40 tonnes of LABPPO.

2.3 Cover Gas

The nitrogen cover gas that existed on SNO, has been upgraded to satisfy the cleanliness requirements for low background. The cover gas seals the detector from high levels of Radon gas in the mine air. The system also adjusts for pressure differentials.
between the detector and the mine. The upgrades were installed and commissioned in 2014.

2.4 Universal Interface

A new universal interface (UI) was designed and installed in late 2016. The UI controls access to within the detector allowing the deployment of various calibration sources, see §5.2. The UI also includes various level sensors and veto PMTs.

3 Electronic Updates

With the increased light output of liquid scintillator, the SNO+ electronics have been upgraded to deal with the increase in current and trigger rate. New XL3 readout cards can deal with the expected trigger rates, while also providing ethernet communication with the front end boards. The MTC/A+ trigger cards can handle the increase in PMT hits, as well as providing better baseline stability and monitoring. The ability to introduce reprogrammable trigger logic has also been added. The CAEN v1720 digitizer aids in instrumental background reduction through outputting the triggered waveforms on each event. An additional trigger utility board, TUBii, adds an extensive suite of tools tying many parts of the experiment together. TUBii is built around a MicroZed development board containing a Zynq chip running a FPGA alongside a Linux processing system. Features include synchronisation of calibration systems with detector readout, extra trigger ports and detector wide timing verification. TUBii also introduces on the fly programmable trigger logic. The full electronics system (with upgrades) has been testing and commissioned in all phases to date.

4 Data Acquisition Upgrades

The data acquisition system (DAQ) has undergone a complete overhaul, which saw improvements in decoupling data flow from detector controls (ORCA). Taking this modular approach provides improved detector control and stability. Stress tests have taken place on various occasions throughout air and partial water fill phases. The detector control GUI provides both user and expert operation modes, giving increased confidence in detector output. Online monitoring tools have been developed capable of displaying data at 20 kHz. These tools offer the possibility of monitoring the detector from anywhere in the world, added to a potential remote shifter’s tool box. An extensive alarm server with accompanying GUI, which monitors both short and long time changes has been implemented. Improved detector readout during ramping the detector to high voltage has been implemented, providing a responsive GUI allowing controllers to check for abnormalities channel to channel. The detector state is
committed to a database on a run by run bases, allowing for individual run reproducibility during offline analyses. Grid based processing and storage channels have been updated accounting for the increased trigger rate. The full DAQ has been stress tested in various “mock data challenges” which have helped in finding potential bottle necks and speed ups.

5 Calibration

5.1 In situ sources

The Embedded LED/Laser Light Injection Entity (ELLIE) is a new multi purpose optical calibration system. It consists of three sub systems, AMELLIE, SMELLIE and TELLIE. AMELLIE will measure attenuation in scintillator, thus monitoring scintillator quality, and is due to come online for scintillator phase. SMELLIE uses a super continuum laser to measure the scattering length of the detecting medium. SMELLIE will run across all phases of data taking and at the time of writing is currently being commissioned. TELLIE uses high frequency LEDs to measure the timing response of the PMTs and was fully commissioned in the spring of 2017. For more details on the in situ calibration in SNO+ see [2].

5.2 Deployed sources

Substantial effort has gone into updating the deployed calibration sources from SNO ready for the SNO+ scintillator phase. Due to the increased cleanliness requirements new deployment mechanisms have been developed, machined and shipped to SNO-LAB. A new “laserball” reducing the self shadowing angle from 30° to 7° has also been designed and constructed.

6 Current Status

SNO+ is currently in operational mode currently undergoing water calibration. The detector electronics were switched on in early 2017 and have been are functioning and stable. Water fill is due to finish in late spring 2017, however the water level has been above the PMTs for some time allowing for calibration to take place. Both in situ and deployed source calibration is on going.

7 Outlook

With calibration complete SNO+ will search for invisible nucleon decay as well as characterising the state of the detector. Scintillator fill is scheduled to commence in
August 2017 and to be completed by the end of the year. The Scintillator phase will build upon the work done in the previous phase and assess the background levels present in the detector, optical studies will also take place. Reactor and Geo anti-neutrino studies will be undertaken and background level permitting low energy Solar signals will be measured. With the background studies complete, loading with $^{130}\text{Te}$ will begin, thus commencing the $0\nu\beta\beta$ phase. This is scheduled for early 2018.

References


Light Sterile Neutrinos at $\nu$STORM: Decoherence and CP violation

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Light sterile neutrino oscillations can be partially or completely washed out at short-baseline experiments due to the breaking of neutrino production coherence. In this work we address this issue in sterile searches at $\nu$STORM, an experimental proposal for a beam of neutrinos from the decay of stored muons. We work with 3+1 and 3+2 models, the latter introducing CP violation at short-baselines. We find that decoherence effects are only relevant for sterile masses above $\Delta m^2 \gtrsim 10 \text{ eV}^2$, and that, even in that regime, we are able to place strong appearance bounds in such clean environments. In addition, the novel signatures of CP violation in the parameter space of interest can be identified with a significance of up to $\gtrsim 3\sigma$.

PRESENTED AT

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$^1$Work supported by CNPq - Brazil.
$^2$Poster presenter.
1 Introduction

The three neutrino paradigm is challenged by a few experimental anomalies at short-baselines, prompting experimental efforts to search for light sterile neutrinos. In this work we evaluate the capabilities of νSTORM [1, 2] in bounding the active-sterile mixing in models with one (3+1 model) and two (3+2 model) sterile neutrinos with $\Delta m^2$ in the range of $10^{-1} - 10^3$ eV$^2$. This mass range realises the interesting scenario where oscillations could occur at the far or already at the near detector. The large masses considered can also break the condition for the coherent production of neutrino mass eigenstates, a question we address via the wave-packet formalism of [3]. In addition, the 3+2 model allows for new CP violating phases to become relevant at short-baselines. The sensitivity of νSTORM to these novel CP violation signals for some of the 3+2 model parameter space is then evaluated.

Particularly important to this study is the fact that νSTORM offers an environment with low backgrounds and well-controlled systematics. The neutrino beam is obtained from the decay of 5 GeV pions and 3.8 GeV muons, where muons from pion decays are stored and circulate in a race-track like storage ring. Beam monitoring devices would then drastically lower flux normalisation uncertainties, providing ideal conditions to measure neutrino-nucleus cross sections in an energy range of interest to future long-baseline experiments [4]. Moreover, it allows appearance searches, for instance, to be made in a beam with very little contamination.

2 Short-Baseline Oscillations with Decoherence

The finite size of the neutrino source can break the coherence of the neutrino mass eigenstates at production, leading to suppressed oscillations [3]. These effects can be taken into account by summing the quantum mechanical amplitude for neutrino production coherently over the finite source. With the assumption of point-like parent particles this approach has been shown to be equivalent to the usual averaging of the probability over the decay pipeline [3]. Whilst in the plane-wave approximation the oscillation phase is given by $I_{kj} = \exp (-i \Delta m^2_{kj} L/2E)$, it can be shown that, ignoring the detector size, the coherent summation of the amplitude modifies it to

$$I_{kj} = \frac{1}{1 - e^{-\Delta r/\xi}} \frac{1}{1 - i\xi} \left[ 1 - e^{-\Delta r/\xi} e^{i\Delta r} \right] e^{-i\Delta},$$  

where $\Delta = \Delta m^2_{kj} L/2E$, $\Delta r = \Delta m^2_{kj} \ell_p/2E$ and $\xi = \Delta m^2_{kj} \ell_{dec}/2E$. The size of the production region is then dictated by the parent particle decay length $\ell_{dec}$ and the pipeline length $\ell_p$. Note how the plane-wave expression is recovered when $\ell_p$ vanishes.

The 3+1 oscillation in the short-baseline regime (taking $\Delta m^2_{31}$ and $\Delta m^2_{21}$ to zero) is effectively a two neutrino one and the appearance formula, for instance, reads

$$P^{3+1}_{\nu_{\alpha} \rightarrow \nu_{\beta}} = 2 |U_{\alpha 4}|^2 |U_{\beta 4}|^2 (1 - \Re (I_{41})),$$  

(2)
where $\mathbb{R}$ stand for the real part. With two light steriles, the short-baseline oscillation is effectively a three neutrino one, allowing for CP violation effects to appear in an appearance channel. The interference terms carry the effective CP phase parametrized by $\eta = \operatorname{arg} (U^*_{\alpha 5} U_{\beta 5} U^*_{\alpha 4} U_{\beta 4})$. The 3+2 appearance probability is then

$$P^{3+2}_{\nu_\alpha \rightarrow \nu_\beta} = 2 |U_{\alpha 4}|^2 |U_{\beta 4}|^2 (1 - \Re (I_{41})) + 2 |U_{\alpha 5}|^2 |U_{\beta 5}|^2 (1 - \Re (I_{51}))$$

$$+ 2 |U_{\alpha 4} U_{\beta 4} U_{\alpha 5} U_{\beta 5}| \Re \left( e^{i \eta} (1 - I_{41}^* - I_{51} - I_{54}) \right).$$

### 3 Experimental Sensitivities

In this section we discuss our simulation, and then present our results for $\nu_e \rightarrow \nu_\mu$ appearance and $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance. We use GLoBES [5] and assume a 1.3 kt iron-scintillator far detector (FD) at 2 km, considered in [2], and a 200 tonne version of the same detector at 50 m as a near detector (ND). These have been implemented via migration matrices [6]. In trying to be as comprehensive as possible in our simulation we use the full near and far detector datasets when performing our $\chi^2$ analysis, i.e. $\chi^2_{\text{tot}} = \chi^2_{\text{ND}} + \chi^2_{\text{FD}}$. This allows us to avoid the near-to-far ratio approach and is necessary for large mass steriles, as their oscillations might impact the near detector. If that is the case, the oscillations are expected to be washed out due to the breaking of the localisation condition ($\delta x_S \ll L_{\text{osc}}$, where $\delta x_S$ is the size of the source), leading to production decoherence. The first straight section of the ring where pions are injected and muons subsequently produced is assumed to be $\ell_p = 180$ m long, which determines the maximum size of the neutrino production region.

![Figure 1: Appearance (left) and disappearance (right) sensitivity curves at 99% C.L. for $\nu$STORM. The brown (cyan) curve assumes only a single near (far) detector, and does not take decoherence into account. The solid (dashed) purple curve assumes the presence of both detectors with (without) decoherence.](image)

Finally, for our systematics we include 0.5% flux normalisation uncertainties correlated between near and far detectors, and 0.5% for each detector specific uncertainties.
Bin dependent cross section times efficiency uncertainties are taken to be 20% with overall background normalisation uncertainties at the level of 35%.

We show our results for the 3+1 model using the phenomenological parameters $\sin 2\theta_{\alpha \beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$ in figure 1. It highlights the interplay between the near and the far detectors. For low $\Delta m^2$ the near detector is not affected by oscillations and can safely measure cross sections and the flux normalisation, whilst the far detector measures the oscillation parameters. The detector roles are swapped for larger $\Delta m^2$, however, where oscillations now are washed out at the far detector, but could occur at the near detector depending on how strong the decoherence effects are. These considerations have been explored in the literature before in the context of VLENF [7] and are pivotal here. Moreover, the appearance bounds are particularly interesting at large masses. In such a regime the ND, which benefits from high statistics, would be probing flavour transitions in the $\nu_e \rightarrow \nu_\mu$ channel with very low backgrounds.

The results for the 3+2 model are shown in figure 2 for specific choices of the model parameters. Note that the presence of two oscillation frequencies spoils the independence of the near and far detectors. If $\Delta m^2_{41}$ is in the $\mathcal{O}(1)$ eV$^2$ region and $\Delta m^2_{51}$ is around $\mathcal{O}(10^2)$ eV$^2$, then both near and far detectors are affected by oscillations (washed-out oscillations in the case of the ND) and the systematics cannot be safely measured at any detector. This effect is very relevant for disappearance, but not as much for appearance, which is mostly background limited.

Figure 2: Sensitivity of $\nu$STORM to 3+2 oscillation parameters for an appearance (left) and disappearance (center) experiment keeping $\Delta m^2_{41}$ fixed. Dashed lines show the statistical limit and solid ones include systematics. On the right we bound products of mixing matrix elements combining appearance and disappearance. We restrict ourselves to part of the parameter space as indicated in each plot.

A measurement of the 3+2 model parameters assuming CP conservation is expected to have uncertainties between 10% and 20% for the following choice of true parameters: $\Delta m^2_{41} = 0.47$ eV$^2$, $\Delta m^2_{51} = 0.87$ eV$^2$, $|U_{e4}| = 0.13$, $|U_{e5}| = 0.14$, $|U_{\mu 4}| = 0.15$ and $|U_{\mu 5}| = 0.13$. Using this fact, we evaluate the sensitivity of $\nu$STORM to the effective CP phase $\eta$ with the same choice of true parameters, later increasing $\Delta m^2_{51}$ by three times its value. Our results are shown in figure 3 using a single polarity
run (collecting \(\pi^+\)'s and storing \(\mu^+\)'s) and splitting the runtime of \(\nu\)STORM in two opposite polarities.

![Figure 3](image.png)

Figure 3: The sensitivity of \(\nu\)STORM to the CP violating phase \(\eta\) when giving all other parameters errors of 10% (solid) and 20% (dashed). We take \(\Delta m^2_{51} = 0.87\) eV\(^2\) on the left, using a three times as large value on the right. In cyan we show the single polarity run and in purple the run with split polarities.

### 4 Conclusions

The low backgrounds and low systematics at a facility like \(\nu\)STORM provide an ideal way to constrain the existence of light sterile neutrinos. We have shown that decoherence effects are small and that appearance bounds can be very robust, applying to sterile masses much above the few eV. A second light sterile neutrino can spoil the interplay between near and far detectors and weaken the disappearance bounds dramatically, but it reinforces the strength of appearance searches. Finally, the effective CP violation in the 3+2 model can be seen at \(\nu\)STORM at more than 3\(\sigma\) for some parts of the parameter space if it is maximal.

### References


