Direct neutrino mass measurements

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Abstract. Direct neutrino mass measurements are based on high precision spectroscopy studies close to the kinematic end-point of low-energy ß-emitters such as ^{3}H and ^{187}Re. Relying only on energy-momentum conservation in ß-decay, they offer the *only* model-independent method to measure the absolute ν-mass scale with sub-eV sensitivity. The two most sensitive detection principles, electrostatic retarding spectrometers and microbolometers, are complementary to each other, and two experiments are currently being prepared to explore ν-masses down to m(ν) = 200 meV. ß-spectroscopy will thus allow to constrain the role of neutrino hot dark matter in structure formation, as well as to explore the parameter region of ν-mass scenarios with quasi-degenerate pattern. The MARE project will investigate the ß-decay of ^{187}Re with bolometers based on metallic Re and $AgReO_4$ in a two-staged approach: in a phase-I set-up a sensitivity of m(ν) = 2 eV is expected, forming the basis for a later sub-eV phase-II. The Karlsruhe Tritium Neutrino (KATRIN) experiment is currently being set-up on the site of Tritium Laboratory at KIT. The experiment will combine an ultra-luminous windowless gaseous tritium source with a high resolution electrostatic spectrometer and offer an unprecedented precision in ß-decay studies, pushing this technique to its technological limits. First KATRIN measurements with ^{3}H after successful system integration are expected for mid-2012. This contribution gives a status report and outlook for both experiments and discusses the impact of direct ν-mass experiments on astroparticle physics.

1. Neutrino masses in astroparticle physics

In the last decade, the observations of flavour oscillations of solar and atmospheric neutrinos, as well as of reactor and accelerator ν´s at long baseline, have provided compelling evidence for massive neutrinos and yielded the first direct evidence for novel physics beyond the Standard Model. However, ν-oscillation experiments are sensitive only to the differences of the squared ν-mass values Δm_{ij}^2. The absolute mass scale of neutrinos can be investigated by: a) high precision measurements of ß-decay kinematics, providing information on the effective electron neutrino mass $m(\nu_e)$ [1], b) searches for neutrinoless double ß-decay 0νßß, yielding results for the effective Majorana ν-mass $m_{ßß}$ [2], and c) cosmological observations of large scale structures (CMB and galaxy redshift surveys), allowing to deduce likelihood values for the sum of neutrino masses Σm_i in the framework of the ΛCMD ´concordance´ model [3-6].

As neutrinos are lighter by more than a factor of 10^5 than all other elementary fermions, the mass generating mechanism in the ν-sector is most likely fundamentally different from the quark and charged lepton sector. A particularly attractive model for light ν-masses is provided by the see-saw mechanism, however, there are many alternative scenarios. All models lead to three generic **ν**-mass patterns:

a hierarchical pattern with $m_1 \ll m_2 \ll m_3$, an inverted hierarchy with $m_1, m_2 \gg m_3$ and, finally, a quasi-degenerate case with $m_1 \approx m_2 \approx m_3$.
The fundamental mass scale m(ν) is also of great interest for cosmology, as relic neutrinos from the Big Bang participate as hot dark matter in the shaping of large scale structures in the universe via their free streaming. In the past years many analyses have been performed to deduce a value for the sum of ν-masses Σm_i using different combinations of cosmological parameters. The resulting upper limits spread from $\Sigma m_i < 0.19$ eV–1.9 eV (95% C.L.). Most recently, in an analysis incorporating the WMAP 5 year data set, an upper limit $\Sigma m_i < 0.63$ eV has been obtained [3]. However, these cosmological results are strongly model-dependent. In particular, as has been pointed out by Hannestad [4], there is a degeneracy between the ν-mass parameter Σm_i and the dark energy equation of state w (w=P/ρc^2). A combined analysis of cosmological data and results from direct ν-mass experiments [5,6] could thus break this degeneracy. As shown in [4], a non-zero value for $m(\nu_e)$ from an experiment like KATRIN would indicate a dark energy equation of state value $w < -1$, thereby contributing to corroborate models with a time-dependent energy density of dark energy (e.g. scenarios with quintessence).

2. Experimental techniques in ß-spectroscopy

Following Fermi´s theory of ß-decay, and incorporating in addition the ´effective electron neutrino´ mass $m(\nu_e)$, the energy spectrum dN/dE of ß-decay is given by:

$$\frac{dN}{dE} = C \cdot p \cdot (E+m_e) \cdot (E_0\text{-}E) \cdot \sqrt{(E_0 - E)^2 - m(\nu_e)^2} \cdot F(E,Z) \cdot \Theta(E_0\text{-}E\text{-}m(\nu_e)) \quad \text{with } m^2(\nu_e) = \sum_{i=1}^{3} |U_{ei}^2| m_i^2$$

where $C \sim (G_F)^2 \cdot \cos^2\Theta_c \cdot |M|^2$, E_0 denotes the end-point energy, p and E the electron momentum and kinetic energy, F(E,Z) the Fermi function and $\Theta(E_0\text{-}E\text{-}m(\nu_e))$ the step function. The non-zero ν-mass $m(\nu_e)$, formed by the *incoherent* sum of the neutrino mass eigenvalues, then leads to a tiny distortion close to the ß-endpoint energy E_0, where neutrinos are non-relativistic, and their energy-momentum relation can be measured kinematically (note that the experimental energy resolution $\Delta E \approx (\Delta m^2)^{1/2}$).
A high sensitivity direct ν-mass experiment requires a ß-emitting isotope with: a) short half life $t_{1/2}$ to ensure high luminosity, b) low end-point energy E_0 to maximise the number $\tilde{N}$ of decay events close to the endpoint E_0 ($\tilde{N} \sim 1/E_0^3$), c) simple configuration of the electron shell, so that final state effects can be calculated precisely, and d) superallowed/allowed ß-transition, so that the nuclear matrix element has no energy dependence. In addition, the ß-decaying isotope should be available in a high isotopic abundance. There are only two isotopes meeting these demands: ^{3}H and ^{187}Re. Their properties are listed and compared in table 1.

Table 1. Comparison of the ß-decay isotopes ^{3}H & ^{187}Re and their corresponding ß-source parameters

	$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$	$^{187}Re \rightarrow {}^{187}Os + e^- + \bar{\nu}_e$
half life $t_{1/2}$	12.3 years	43.2 Gyears
end-point energy E_0	18.57 keV	2.47 keV
decay mode	super-allowed	unique first forbidden
electron shell	simple (H-like)	complex
ß-source	gaseous / quench-condensed	metallic Re / dielectric $AgReO_4$
total ß-activity	high: ~10^{11} ß/s	low: < 10^5 s^{-1}
detector specific ß-rate	4.7 Ci s^{-1} injection (KATRIN)	~ 1 Bq / mg Re (MARE)
systematic effects	electron scattering in ß-source	surface / solid state effects

The main advantage of ^{187}Re is its very low endpoint energy E_0, however, the rather low intrinsic decay probability requires a rather large target mass to achieve a good statistics close to the endpoint. The main driver for the long list of tritium ß-decay experiments over the past decades [7] has been the very high decay rate and simple atomic structure of molecular tritium.

The very high intrinsic decay rate of ^{3}H allows making use of *thin* targets, which can be read out by high resolution electrostatic spectrometer techniques for precision ß-spectroscopy, whereas the low activity of ^{187}Re implies massive *thick* ß-decay targets, which require a calorimetric technique to measure the ß-spectrum. The two generic techniques used in ß-spectroscopy are compared in table 2.

Table 2. Comparison of techniques in ß-spectroscopy: calorimeters and spectrometers

	electrostatic spectrometer	**cryogenic micro-bolometer**
detector response	kinetic energy of ß-electron	entire energy
ß-energy interval	narrow interval at E_0	entire spectrum
ß-spectroscopy	integral spectrum	differential spectrum
experimental set-up	integral design	modular design (arrays)
energy resolution	ΔE = 0.93 eV (100%)	ΔE > 5-10 eV (FWHM)
systematic effects	HV fluctuations, scattering	energy calibration, surface effects

The major advantage of the calorimetric approach is the fact that the entire energy of the ß-decay electron and the daughter molecule is sampled. Also, the use of micro-bolometers allows the construction of very large detector arrays, which can be expanded and up-scaled. However, the energy resolution of ΔE=5 eV, which is the ambitious aim for the next generation of micro-calorimeters, is an order of magnitude larger than the energy resolution of the next-generation of spectrometers. Spectrometers, on the other hand, allow focusing on a very narrow energy range below E_0, which can be investigated with a very sharp energy resolution. As spectrometers only measure the kinetic energy of ß-decay electrons, the nuclear recoil energy as well as molecular excitations have to be calculated by quantum-chemical methods, which, however, are extremely precise and in mutual agreement.
Finally, the different systematic effects of both techniques, which mainly result from using thick or thin ß-emitters, render spectrometer and calorimeter techniques complementary to each other.

3. MARE

The Microcalorimeter Array for a Rhenium Experiment (MARE) [8] is based on the experiences gained in the previous MANU and MIBETA experiments, which have been pioneering the use of micro-calorimeters in the investigation of the ß-spectrum of ^{187}Re, using either metallic Re (MANU) or $AgReO_4$ (MIBETA) as substrate. Figure 1 (a) shows the principle of a calorimeter for the silver perrhenate absorber of the Milan group with phonon (heat) signal read-out by a semiconductor thermistor.

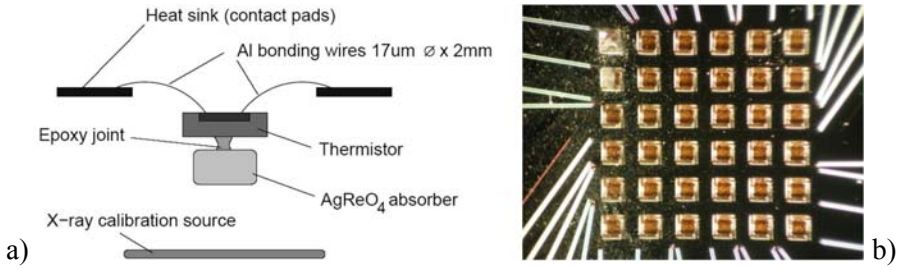

Figure 1. a) principle of an $AgReO_4$ bolometer, b) 6×6 $AgReO_4$ pixel array from the Milano group

In 2004 a sensitivity of $m(\nu_e) < 15$ eV for an array of 10 micro-calorimeters was reached, based on an ensemble of 6.2×10^6 ß-decays. The MARE project will improve this sensitivity in a staged approach, at each of two stages significantly up-scaling the previous statistics while also using improved detectors. In a first intermediate phase (MARE-I) the goal is to collect ~7×10^9 ß-decays in 3 years, thereby improving the present experimental sensitivity by an order of magnitude to reach the benchmark parameter $m(\nu_e) \sim 2$ eV [9] set by the Mainz and Troitsk experiments [7,10]. MARE-I will use both me-

tallic superconducting Re absorbers, as well as dielectric silver perrhenates (m = 0.5 mg, T = 85 mK). In the latter case, a first 6 × 6 pixel array is already operational with an energy resolution ΔE = 34 eV, see figure 1 (b). The cryostat, which is presently under construction, will house a total of 288 bolometers (4 × 72). In a second large-scale phase (MARE-II), a further increase in statistics to ~10^{14} ß-decays is envisioned with a corresponding sensitivity m(ν_e) = 0.2 eV. Before a MARE-II phase can be launched however, substantial R&D efforts to develop new detectors will have to be completed successfully. A very promising technology is the magnetic micro-calorimeter with a paramagnetic sensor, where a temperature change δT in the absorber results in a change δM of the sensor magnetism. The MARE-II design sensitivity would require operation of a multiplexed pixel array with a total of up to ~50.000 micro-bolometers in several cryostats with a measuring time of about 5-10 years [8,9].

4. KATRIN

The Karlsruhe Tritium Neutrino (KATRIN) is an international direct ν-mass experiment which is currently being set up at the Tritium Laboratory Karlsruhe (TLK) by an international collaboration. KATRIN has been designed for a reference ν-mass sensitivity m(ν_e) = 200 meV (90% C.L.) and will push the MAC-E-filter technique, where ß-decay electrons from a windowless gaseous tritium source are adiabatically guided to a system of electrostatic retarding spectrometers for energy analysis, to the technological limits [11,12]. The 70 m long reference set-up is shown in figure 2 and comprises the major beam line elements WGTS (windowless gaseous tritium source), DPS2-F (differential pumping section), CPS (cryogenic pumping section), the electrostatic pre- and main spectrometer, and the focal plane detector (not shown is a separate beam line for monitoring the HV fluctuations of the retarding voltage in the ppm range). The figure also shows the distribution of the magnetic field strength B along the beam axis, which is typically in the range from 3.6 - 5.6 T in the source and transport section, while dropping to very low values in the spectrometer section ($B_{min} = 3 \times 10^{-4}$ T in the analysing plane of the main spectrometer) to transform cyclotron motion into longitudinal motion in order to allow an integral energy measurement by an electrostatic retarding field. Special emphasis has been put on the electromagnetic layout of the experiment with regard to the a) adiabatic transport of ß-decay electrons over more than 70 m b) alignment of the flux tube relative to the beam pipes c) minimisation of background (no trapping of ß-decay particles in Penning traps, suppression of cosmic background in the spectrometers and the focal plane detector) as well as on the control of systematic uncertainties such as electron energy losses in the source, HV fluctuations, and source properties.

At present, all major components are currently either being manufactured by industrial partners (WGTS, DPS2-F, CPS, detector and pinch magnets) or are already on-site (pre- and main spectrometer, cryoplant TCF50 and cryogenic transfer lines) and are being commissioned. The new KATRIN experimental halls adjacent to the TLK (including extensive infrastructure facilities) are finished since the end of 2007 and operational.

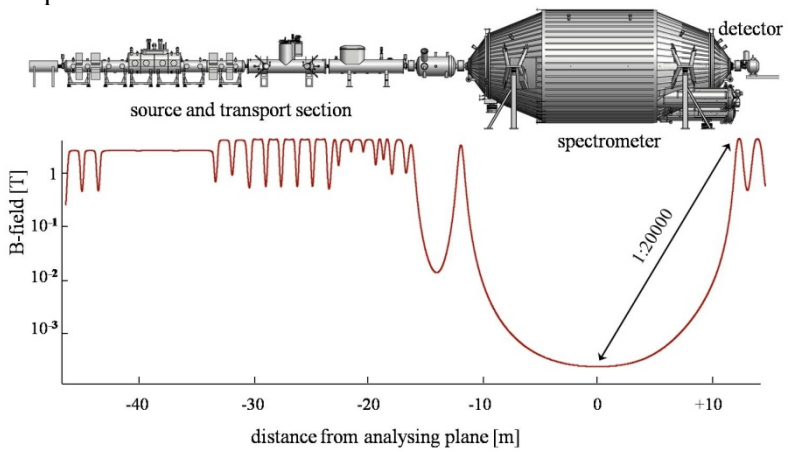

Figure 2. Distribution of the magnetic field strength B in the ~70 m long KATRIN set-up

4.1. Source and Transport System STS

The STS comprises the tritium bearing beam elements WGTS, DPS2-F and CPS, as well as the associated tritium loops together with the extensive infrastructure required for operating the entire system in a closed tritium cycle (T_2 throughput is 40 g/day). The design parameters of this system, which has been optimised for maximum ß-luminosity and minimised systematic effects, are shown in table 3:

Table 3. Design parameters of the WGTS of KATRIN and required precision for long-term operation

	design value	**Precision**
Luminosity	1.7×10^{11} Bq	
injection rate	5×10^{19} mol / s	± 0.1 %
column density ρd	5×10^{17} mol / cm^2	± 0.1 %
tritium purity	>95 %	
magnetic field	3.6 T	± 2 %

The WGT is a 16 m long complex cryostat with more than 50 sub-assembly groups, 12 cryogenic circuits and 6 working fluids and more than 500 sensors (temperature sensors, flow meters, heaters, and Hall probes). High purity molecular tritium will be injected through capillaries at the centre of the 90 mm diameter stainless steel beam tube and diffuse to both ends, where turbomolecular pumps (TMPs) pump out the T_2 molecules for re-injection, while electrons from the $\sim 10^{-9}$ fraction of ß-decaying tritium molecules are adiabatically guided along the beam axis. The cryogenic circuit is the most complex part of the WGTS, as it has to maintain the beam tube temperature at 27 K with exceptional precision: the long-term stability (over 1h) and homogeneity (over 10m) has to be kept at the level of 10^{-3}, so that the tritium column density is stabilised at the reference value with the same precision (see table 3). After completion of the on-going assembly of the so-called ´WGTS demonstrator´ in autumn 2009, the cryogenic system will be tested at TLK to validate the beam tube cooling concept (2-phase boiling Neon at p = 1 atm) as well as the mechanical integrity and functionality of the sub-assembly groups. Then, the 12 m WGTS demonstrator will be partly disassembled again, before the final WGTS assembly (including the 7 s.c. magnets) is finished in early 2011.

The subsequent tritium pumping system has to reduce the tritium flow from the WGTS injection rate of 1.8 mbar ℓ/s by 14 orders of magnitude to guarantee a tritium partial pressure in the spectrometer section of less than 10^{-20} mbar, which is equivalent to a background rate < 1 mHz from tritium decaying in the spectrometer volume. Reducing the tritium flow to $<10^{-14}$ mbar ℓ/s can only be achieved by combining active differential pumping by TMPs with subsequent passive cryogenic traps, where hydrogen isotopomers are frozen onto ultra-cold surfaces. This combined system has to operate under stable conditions with a high duty cycle in a fail-safe mode. There are two separate beam line elements currently being manufactured for this task: the DPS2-F cryostat, equipped with 4 TMPs for differential pumping and the CPS cryostat, where the remaining tritium molecules will be trapped onto 3K cold beam tube elements covered by argon snow.

The first element, the 6.6 m long DPS2-F cryostat is presently near completion at an industrial manufacturer and will be delivered to TLK in mid-2009. Subsequently, the magnet and cryogenic performance of this first on-site source element will be tested in parallel with its flow reduction characteristics. The latter tests will be important to validate the MC codes that have been developed to calculate TMP pumping efficiencies in rarefied gas flows.

Over the past two years major efforts were targeted at the design and the specification of the cryogenic trap CPS. Following an extensive test programme on the tritium retention properties of condensed argon snow in the 3-5 K temperature range with the TRAP (Tritium Argon Frost Pump) facility at TLK, important benchmark parameters for the specification of the CPS cryostat could be obtained. TRAP has been instrumental in demonstrating and verifying the CPS concept, and in gaining experience in the preparation and long-term operation of argon frost traps, including the subsequent regeneration of the system by flushing with warm He-gas at the end of a measuring cycle. Since May 2008 the CPS cryostat is being manufactured with an estimated delivery date in early autumn 2010.

4.2. Spectrometer and Detector System SDS

This section consists of a pre-spectrometer acting as pre-filter to reject low-energy electrons, a high resolution main spectrometer for precision energy analysis of ß-decay electrons around the tritium ß-endpoint energy at 18.6 keV, and a segmented detector (Si-PIN-array) to count the transmitted electrons. Also this system is technologically very challenging, exemplified by the requirement to maintain excellent ultra high vacuum (UHV) conditions at a stable level in very large volumes (1240 m^3) over long periods of time. In addition, extensive works have been performed over the past years to optimise the SDS electromagnetic layout with its strong gradients of both the magnetic guiding field (0.3 mT – 6 T) and the electrostatic retarding/post-accelerating fields (-18.6 kV…+35 kV).

The pre-spectrometer was the first major beam line element to arrive on-site. Since 2004, extensive vacuum tests have verified the UHV concept, consisting of cascaded TMPs in combination with low-activity non-evaporable getter (NEG) strips. An important first result was the measurement of the outgassing rate of the electropolished stainless steel inner surface, where the specified value of 1×10^{-12} mbar ℓ cm^{-2} s^{-1} was reached already at room temperature, rendering the rather cost-intensive cooling of the spectrometer vessels to -20°C obsolete. In doing so, the extensive cleanliness methods (electropolishing, pickling) and the strict material selection rules were verified as well. After bake-out to 250°C and separate activation of the NEG strips, the pre-spectrometer has routinely been operated under stable UHV conditions with $p < 10^{-11}$ mbar. Subsequently, it has been used as an important test bed to validate the novel electromagnetic layout of the KATRIN spectrometers, where the vessel walls are on HV and an inner electrode system precisely defines the retarding potential. The still on-going measurement programme has resulted in a substantially improved design of the inner electrode parts operated close to ground potential, leading to a minimised storage of particles in Penning traps.

The design and the manufacture of the large main spectrometer has benefited substantially from the experiences gained with the pre-spectrometer. After the order for the manufacture was placed at the end of 2004, the spectrometer was designed and manufactured during a 1.5 year period by an industrial partner. After the spectrometer was successfully leak tested in August 2006, it was transported over a period of two months from Deggendorf (Bavaria) to Forschungszentrum Karlsruhe in an 8800 km long sea-going voyage around Europe (Danube, Black Sea, Mediterranean, Atlantic Ocean, North Sea, and Rhine). The final 7 km required a very high precision to manoeuvre the spectrometer through a neighbouring small village (see figure 3 a). After steam blasting and further pickling, the spectrometer was lifted into the spectrometer hall. Equipped with a thermal insulation, the vessel was then baked-out at 350°C by an oil-based heating/cooling system. At room temperature, a hydrogen-dominated outgassing rate of 1.2×10^{-12} mbar ℓ cm^{-2} s^{-1} was measured, and, using a total of 6 TMPs, the specified pressure for 1% of the final pumping capacity of 1×10^{-9} mbar was reached. Shortly thereafter, the spectrometer was successfully undergoing an initial HV micro-discharge test up to 45 kV.

At present, the major focus of the spectrometer commissioning works is on the installation of the inner electrode system, which will completely cover the 690 m^2 inner surface. The two layer electrode system will comprise more than 23,000 stainless steel wires integrated in 250 frames. The main tasks of this system will be the suppression of cosmic muon induced background by a factor 10-100 and the maintenance of a stable HV. It will also provide the option to operate the spectrometer in dipole mode to eject stored particles in between short-term measuring periods. A significant part of the 250 wire modules has already been manufactured at Münster University (see figure 3c). As not a single wire is allowed to break during spectrometer bake-out periods, extensive QA measures on wire integrity have been implemented. Since March 2008, a stainless steel mounting system inside the spectrometer is operational, allowing safe access to any point inside the spectrometer (see figure 3 b). The system has already been used for the laser tracker calibration of the inner spectrometer geometry to guarantee a wire mounting precision of 100 µm. Access to the spectrometer inner volume is provided by a 100 m^2 clean room (class 100.000) at the rear part of the spectrometer. The installation of the inner electrode system will start in mid-2009 and will be completed by early 2010, allowing first dedicated electromagnetic tests of the main spectrometer (transmission function, storage of particles in Penning traps) in early summer 2010, immediately after UHV reconditioning.

Figure 3. a) final 7 km of the main spectrometer transport b) mounting system c) wire electrode unit

The ß-decay electrons transmitted through the spectrometer section are detected by a segmented Si-PIN diode array. At present, three 148-pixel detectors have been tested at room temperature meeting the specifications. All materials used in construction have been radioassayed for low-level operation in the 1 mHz range. The calibration, veto and shield systems of the detector are currently being integrated into the detector system. The pre-amplifier electronics and hardware DAQ system are being used to test the detector thoroughly until the end of 2009. The on-line DAQ programme ORCA, supplied by UW Seattle, is ready for operation and in use at the pre-spectrometer. The detector and pinch magnets will be delivered in mid-2009, so that the entire detector system can be thoroughly tested before being shipped to Karlsruhe in mid-2010.
In 2011 all major beam elements of KATRIN will be on-site. Then, following the commissioning of the single components and the subsequent system integration, the long-term data taking with the KATRIN set-up will start in the third quarter of 2012. After initial calibration and monitoring data have been taken with a gaseous ^{83m}Kr source and a high intensity scanning electron gun, high-quality neutrino data will be gathered in several tritium scanning cycles per year, each one lasting about 2 months. The neutrino mass sensitivity of the experiment will initially rise very quickly, so that already after the first tritium cycle a sub-eV ν-mass sensitivity will be reached. In addition, the high quality KATRIN spectroscopic data will allow investigating further interesting astroparticle physics topics such as the search for non V-A interactions or a potential violation of Lorentz invariance [11].

5. References

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