Neutrino Physics with Short Baseline Experiments

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Neutrino physics with low- to medium-energy beams has progressed steadily over the last several years. Neutrino oscillation searches at short baseline (defined as $\lesssim 1$ km) have investigated oscillations with $\Delta m^2 \gtrsim 0.1\mathrm{eV}^2$. One positive signal, from the LSND collaboration, exists and is being tested by the MiniBooNE experiment. Neutrino cross-section measurements are being made by MiniBooNE and K2K, which will be important for reducing systematic errors in present and future oscillation measurements. In the near future, dedicated cross-section experiments will begin operating at Fermilab.

1. Overview

Acclerator-based neutrino experiments at "short" baseline (defined here as $\lesssim 1$ km) probe high-Δm^2 regions of oscillation parameter space, using beams with energies ranging from stopped muon decay ($<$ 53 MeV) to several hundred GeV. In general, these experiments are sensitive to oscillations with $\Delta m^2 \gtrsim 10^{-2}$ eV^2, making them insensitive to the solar and atmospheric mass scales.

These neutrinos are also used as probes of electroweak physics and nucleon structure. Finally, accelerator neutrinos are being used at short baseline to make neutrino interaction cross-section measurements necessary for analyzing long- and short-baseline oscillation data.

2. Oscillations at very high Δm^2

The highest energy neutrino beams have been used in recent years to investigate the possibility of neutrino oscillations at high Δm^2. These have probed primarily $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations at $\Delta m^2 >$ 10 eV^2, with sensitivities as low as $\sin^2 2\theta \sim 10^{-3}$. The tightest limits on $\nu_\mu \to \nu_e$, when measured separately from antineutrinos, come from NuTeV[1] (Fermilab E815) above $\Delta m^2 \sim 30$ eV^2, and from BNL E734[2] and E776[3] at lower Δm^2. The most stringent limits on $\nu_\mu \to \nu_\tau$ appearance at high Δm^2 are from the NOMAD[4] and CHORUS[5] detectors at CERN.

3. The LSND signal

The LSND collaboration has published strong evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations using neutrinos from stopped muon decay[6].

3.1. LSND

LSND used a beam-stop neutrino source at the 800 MeV LAMPF proton accelerator at Los Alamos National Laboratory. The primary source of neutrinos was π^+ and μ^+ decays at rest (DAR) in the target, which yielded ν_μ, $\bar{\nu}_\mu$, and ν_e with energies below 53 MeV. In addition, π^+ and π^- decays in flight (DIF) provided a small flux of higher-energy ν_μ and $\bar{\nu}_\mu$. The $\bar{\nu}_e$ flux was below 10^{-3} of the total DAR rate. The LSND data were collected between 1993

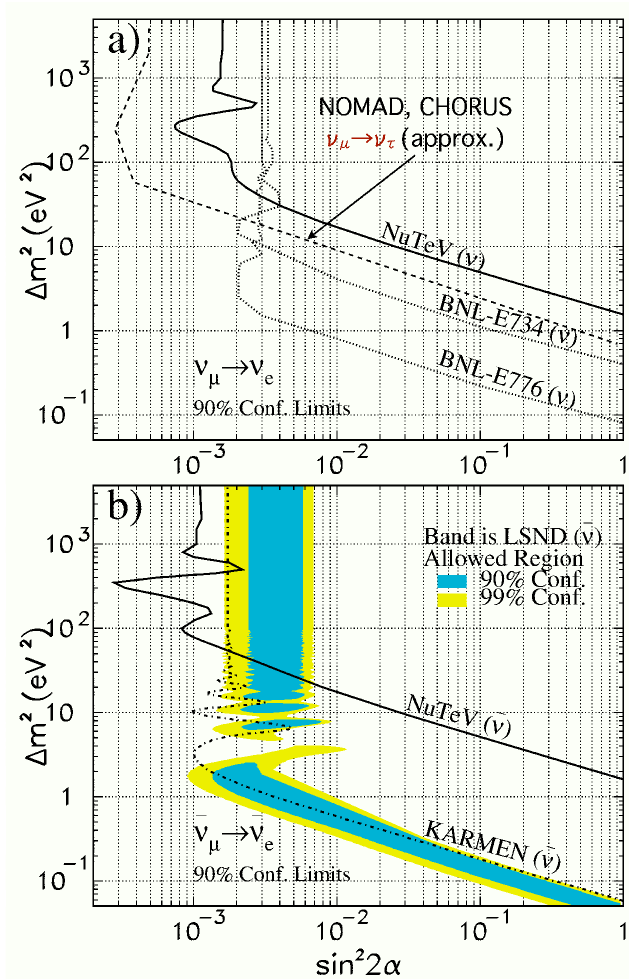

Figure 1: Limits on oscillations of ν_μ (a) and $\bar{\nu}_m u$ (b). All curves represent $\nu_e(\bar{\nu}_e)$ appearance except for NOMAD/CHORUS curve, which is $\nu_\mu \to \nu_\tau$.

and 1998. The first data set, collected 1993-1995, used a water target that stopped all hadrons and provided 59% of the DAR data set; the remainder of the data came from a heavy metal target composed mostly of tungsten. The collaboration searched for $\bar{\nu}_e$ appearance using the reaction $\bar{\nu}_e + p \to e^+ + n$ in a 167-ton scintillator-doped mineral oil (CH_2) target/detector. The detector sat 30 m from the target, providing an oscillation scale $L/E \sim 0.6 - 1$ m/MeV. The detector, which was instrumented with 1220 8-inch photomultiplier tubes (PMTs), observed a Cherenkov ring and scintillation light from the positron emitted in the neutrino interaction. An additional handle was the detection of the 2.2 MeV neutron-capture gamma ray from the reaction $n + p \to d + \gamma$. The appropriate delayed coincidence (the neutron capture lifetime in oil is 186 μs) and spatial correlation between the e^+ and γ were studied for DAR $\bar{\nu}_e$ candidates.

In 2001, LSND presented the final oscillation search results, which gave a total $\bar{\nu}_e$ excess above background of $87.9 \pm 22.4 \pm 6.0$ events in the DAR energy range. The dominant background was beam-unrelated events, primarily from cosmic rays. These backgrounds were measured using the 94% of detector livetime when the beam was not on. No significant signal was observed in DIF events; the total $\nu_e/\bar{\nu}_e$ excess above background was $8.1 \pm 12.2 \pm 1.7$ events, consistent with the DAR result. The total events and energy distributions of the DAR and DIF events were used to constrain the oscillation parameter space.

3.2. KARMEN and the joint analysis

Another experiment of similar design, the Karlsruhe-Rutherford Medium Energy Neutrino (KARMEN) experiment at the ISIS facility of the Rutherford Laboratory, also searched for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. KARMEN used a similar beam-stop neutrino source, but with a segmented smaller neutrino target (56 tons). KARMEN's sensitivity was enhanced because the lower beam duty factor (10^{-5}) allowed beam-unrelated events to be removed more effectively with a timing cut. In addition, KARMEN had higher flux because it was closer to the target (18 m versus 30 m). The shorter baseline did, however, reduce KARMEN's sensitivity to low-Δm^2 oscillations compared to LSND. KARMEN's final published result[7], using data collected from 1997 to 2001, reported 15 $\bar{\nu}_e$ oscillation candidates with an expected background of 15.8 ± 0.5 events. This result does not provide evidence for oscillations, and indeed can be used to rule out most of the high-Δm^2 portions of the LSND allowed region. However, an analysis of the combined LSND and KARMEN data sets has found regions of oscillation parameter space (Fig. 2) that fit both experiments' data well[8].

3.3. Physics scenarios including LSND

The LSND data indicate a much larger Δm^2 than atmospheric or solar experiments: $\Delta m^2 \sim 0.1 - 10$ eV^2. This high a Δm^2 is not consistent with a three-neutrino-mass picture when combined with the other known neutrino Δm^2 scales. If there are only three values of m^2, then two Δm^2 must add up to the third, which isn't possible if they are different orders of magnitude. The more common way to account for all the existing oscillation data is to introduce one or more "sterile" neutrino flavors[9]. Other recently proposed exotic physics scenarios include mass-varying neutrinos[10] and a decaying sterile neutrino[11].

3.4. MiniBooNE

MiniBooNE[12] (Experiment 898 at Fermilab) is a short-baseline neutrino oscillation experiment whose main purpose is to test the LSND result. It uses an 8 GeV proton beam from the Fermilab Booster to produce pions, which then decay in flight to produce a nearly pure ν_μ flux at a mineral oil Cherenkov detector 500 m away. The detector uses Cherenkov ring shape information to distinguish charged-current ν_μ from ν_e interactions, searching for an excess of ν_e which would indicate oscillations. The first oscillation result will use data collected from 2002 through 2005, comprising a total of 5.7×10^{20} protons on target.

There are several major differences between MiniBooNE and LSND, which should assure that systematic errors are independent. First, MiniBooNE operates at an energy and oscillation baseline over an order of magnitude greater than LSND: $E_\nu \sim 500 - 1000$ MeV, compared to $30 - 53$ MeV at LSND. The baseline $L = 500$ m, versus 30 m at LSND. L/E remains similar, ensuring that the oscillation sensitivity is maximized in the same region of parameter space as LSND. MiniBooNE uses the quasielestic neutrino scattering reaction $\nu_e {}^{12}\mathrm{C} \to e^- X$ with the leading lepton's Cherenkov ring reconstructed, rather than LSND's antineutrino interaction with a hydrogen nucleus followed by neutron capture. Finally, MiniBooNE's eventual goal is a factor of ten higher statistics than LSND had.

Backgrounds to the oscillation analysis include intrinsic electron neutrinos in the beam and misidentification of ν_μ events. Intrinsic ν_e result mostly from tertiary decays of μ^+ in the decay pipe, with smaller but still significant contributions from three-body decays of K^+ and K^0_L.

The intrinsic ν_e from muon decays are constrained well by analyzing ν_μ quasielastic interactions in the MiniBooNE detector, as these originate from the same π^+ as the muons.

The oscillation analysis is blind: all Monte Carlo and analysis tuning is performed using samples from

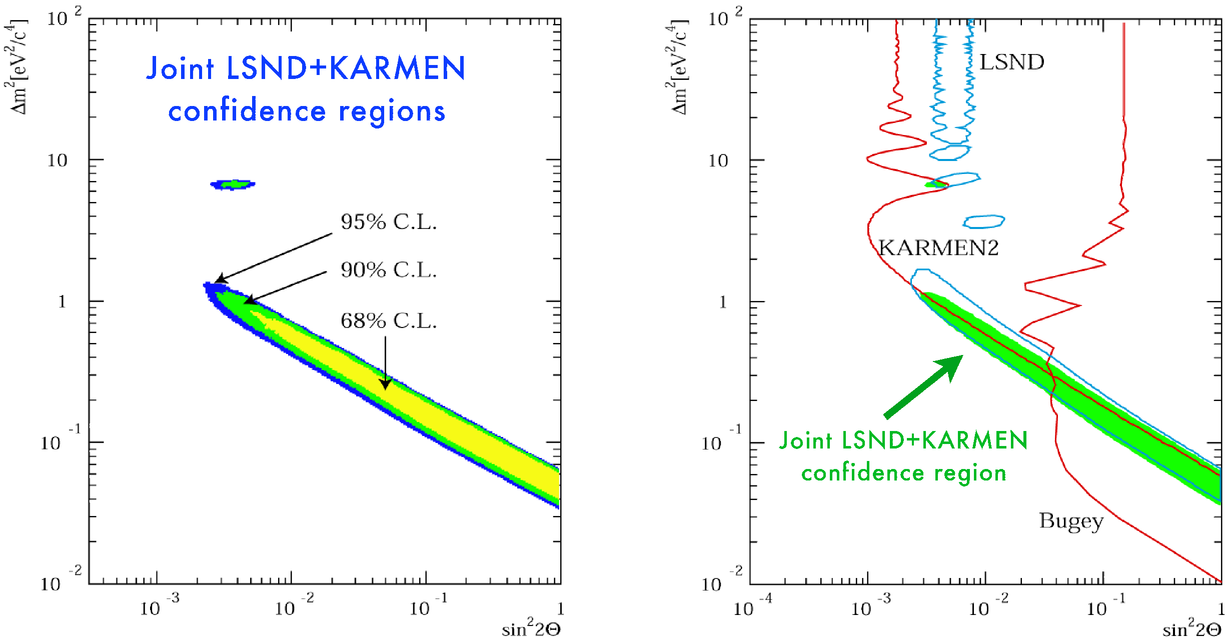

Figure 2: Left: Confidence regions from the joint LSND-KARMEN analysis. Right: LSND-KARMEN region superimposed over confidence region from LSND decay-at-rest data and 90% confidence exclusion regions from KARMEN2 and Bugey.

which electron neutrino candidates have been removed. The only exception to this is for events from the NuMI beam, which can be viewed at a large off-axis angle by MiniBooNE. NuMI's flux has a large kaon fraction, resulting in a high ν_e rate at this large angle and therefore a flux that is useful for cross-checking MiniBooNE's particle identification.

The oscillation analysis is in its final stages as of late 2006.

4. Non-oscillation physics

4.1. Deep inelastic scattering

Neutrino deep inelastic scattering has in the recent past been used for studies of electroweak and nucleon structure physics. NuTeV (FNAL E815) is the most recent and likely to be the last of these studies. Recent results from NuTeV include a measurement[13] of the electroweak mixing angle $\sin^2\theta_W = 0.2277 \pm 0.0013_{\rm stat} \pm 0.0009_{\rm syst}$, a value three standard deviations above the standard model prediction. While several nonperturbative QCD effects (in particular the possibility of isospin violation in the nucleon and asymmetry in the strange sea) could affect this result at the $\lesssim 1\sigma$ level, no standard model effect has fully explained the experimental result. Unfortunately, no high-energy neutrino beams are now operating or under development, so it is unlikely that a new experiment will test this result in the foreseeable future. (A collaboration has proposed to perform a neutrino-based measurement of $\sin^2\theta_W$ at the Braidwood reactor, using a new method[14]. Sensitivity comparable to NuTeV may be achieved, albeit at lower Q^2.)

NuTeV has also recently published precise measurements[15] of the muon neutrino and antineutrino cross-sections in the energy range $30 < E < 340$ GeV, along with fits to the structure functions $F_2(x, Q^2)$ and $xF_3(x, Q^2)$. Full cross-section tables have been made available at Ref.[16].

4.2. Neutrino interactions at the GeV scale

Short-baseline neutrino experiments have recently made some significant measurements of neutrino cross-sections on nuclear targets. These measurements are important for testing nuclear models, and are critical for understanding the large data sets being produced in current and future oscillation experiments.

At the MiniBooNE flux (which is very similar to T2K, and overlaps with the somewhat higher-energy K2K flux), the largest cross-section process is charged current quasielastic scattering (CCQE),

$$\nu_\mu n \to \mu^- p.$$

This process, which is the primary detection mode for oscillation searches, represents $\sim 40\%$ of the total interaction rate.

Charged current pion production (labeled CCπ^+) via a nucleon resonance,

$$\nu_\mu N \to \mu^- \Delta \to \mu^- \pi^+ N',$$

represents about a quarter of the total event rate. The recoil nucleons are generally undetected, so these events are difficult to distinguish from a similar final state that can be achieved by scattering coherently off a nucleus:

$$\nu_\mu A \to \mu^- \pi^+ A.$$

Neutral pion production can occur in charged-current scattering through a resonance (CCπ^0), or in either resonant or coherent neutral-current scattering (NCπ^0, with no charged lepton in the final state). The NCπ^0 processes, expected to be about 7% of the total event rate at MiniBooNE, are of particular interest to electron neutrino appearance searches because of the potential for the π^0 to be misidentified as an electron.

Coherent and resonant π^+ and π^0 production have been modeled by Rein and Sehgal[17], and these results are used by all the major neutrino collaborations for Monte Carlo modeling of these processes. At energies in the 1 GeV range, these models have only been tested in the past on proton and deuterium targets. K2K and MiniBooNE are now producing the first tests of these models on nuclear targets and, therefore, the first searches for coherent pion production.

K2K has measured the q^2 distribution of CCπ^+ production using the SciBar fine-grained scintillation detector at K2K's near detector site[18]. The q^2 distribution can be used to distinguish statistically the coherent and resonant fractions, and is therefore a test of the Rein-Sehgal model. That model predicted a coherent π^+ cross-section ratio to all charged-current ν_μ for the K2K flux of 2.67%. The K2K data fit (Fig. 3) to the q^2 distribution, however, showed no evidence for coherent events: the final sample contained 113 events with a background estimate of 111. This results in an upper limit of the cross-section ratio of

$$\frac{\sigma(\text{Coherent } \nu_\mu A \to \mu^- \pi^+ A)}{\sigma(\nu_\mu \text{A} \to \mu^- \text{X})} < 0.6\%$$

at 90% confidence level, a significant disagreement from the Rein-Sehgal prediction. MiniBooNE has studied the CCπ^+ process on carbon and, while the results are still preliminary, the angular distribution of leading muons shows a deficit at the extremely forward angles where coherent scattering is expected. However, both K2K and MiniBooNE have observed neutral current π^0 production cross-sections that show clear evidence for coherent scattering near the expected levels.

In a new paper, Rein and Sehgal [19] have proposed that the deficit in charged-current coherent pion production may be due to a destructive interference between axial vector and pseudoscalar amplitudes when the nonzero muon mass is accounted for. Since the muon mass does not appear in the neutral current process, the suppression does not occur and coherent scattering should appear at about the naïvely expected rate.

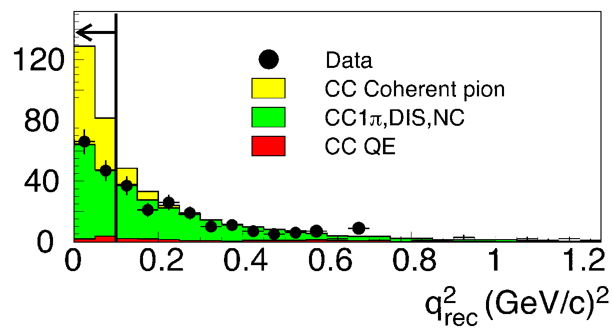

Figure 3: Reconstructed q^2 for charged-current pion candidates in the K2K coherent scattering search sample.

Another preliminary measurement recently released by MiniBooNE is the neutrino energy dependence of the ratio of the CCπ^+ to CCQE cross-sections. The CCπ^+ events are readily identified in the MiniBooNE detector by their final state: the pion and muon each leave stopped-μ decay electron signatures after the primary event. The pion is generally below Cherenkov threshold, so the muon ring can be reconstructed cleanly. By using the measured lepton energy and angle relative to the beam direction, a neutrino energy is calculated assuming a missing Δ^{++} mass. This yields $\sim 20\%$ resolution on E_ν for CCπ^+ events. Normalization quasielastic events are reconstructed similarly, with an assumed proton recoil. The resolution on E_ν is $\sim 10\%$ for the CCQE sample. The measured cross-section ratio is shown in Fig. 4. As expected, the relative contribution of pion production rises from the kinematic threshold, to a level comparable to CCQE for neutrinos above 1 GeV. Systematic errors are dominant at present, and are due primarily to energy scale and photon scattering and extinction models in the mineral oil. MiniBooNE expects these errors to be reduced substantially as modeling of the detector optics is improved.

4.3. Cross-sections in the near future

We can expect future investigations of the above-mentioned processes (and the CCπ^0 and NCπ^0 processes) from MiniBooNE in the near future.

Around the beginning of 2006, the Booster Neutrino Beam was reconfigured to reverse the current in the focusing horn in order to focus antineutrinos for Experiment 944, which is using the MiniBooNE detector to study antineutrino interactions. The goal of E944 is to accumulate a total of 2×10^{20} protons on target and generate a data set of 50,000 antineu-

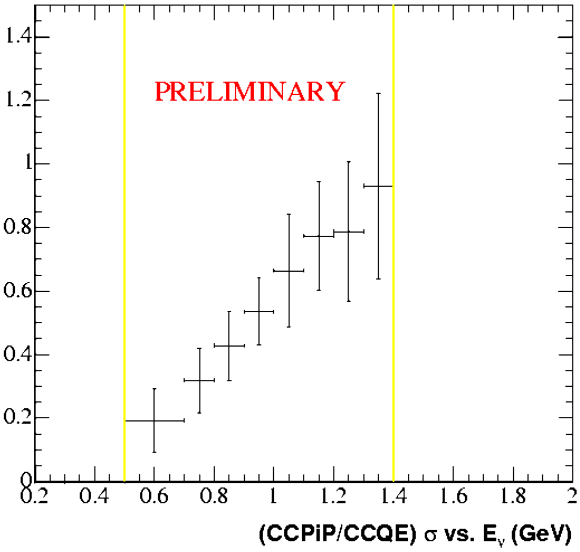

Figure 4: MiniBooNE preliminary measurement of ratio $\sigma(\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + \pi^+ + X)/\sigma(\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + Y)$, where Y represents a final state with no pions. Errors are predominantly systematic.

trino events. This will represent the first study of antineutrino cross-sections between 0.1 and 1 GeV, and pioneering measurements of quasielastic scattering and resonance production scattering can be expected. Data taking is scheduled to continue through spring 2007.

In addition, the K2K SciBar has been relocated to Fermilab for use in the BooNE beamline as Fermilab E954 (SciBooNE) [20]. The experimental facility for SciBooNE is under construction at present, and the experiment will operate beginning in 2007. In the medium-term future, we can expect major improvement in neutrino interaction physics when the MINERνA (E938)[21] experiment at Fermilab and the near detectors at the newly constructed JPARC neutrino beam (T2K)[22] are commissioned later this decade.

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