Status and prospects of neutrino oscillations: terrestrial sources

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Abstract.
By exploring the oscillation mixing angle *vs.* mass difference allowed regions, terrestrial based experiments have advanced our understanding of the ν oscillation solutions proposed by the measurements of neutrinos produced in the sun and in the atmosphere. This paper reviews the contribution of reactor anti-neutrino experiments and of accelerator neutrino experiments to the development of these theories. Selected experiments are briefly described, the results are presented and the impact on our understanding of neutrino oscillations is discussed.

1. Introduction

Since the 1950's, terrestrial neutrino sources have played a major role in the study of neutrino properties with the first direct observation of these elusive particles at a reactor facility, and with the differentiation of muon and electron neutrino flavors at an accelerator facility. An important subset of terrestrial neutrino experiments developed primarily to test the ν flavor oscillation theories proposed to explain the solar neutrino problem, (associated with a deficit of ν_e flux) the atmospheric anomaly, (now associated with a deficit of measured ν_μ flux) and the zenith angle dependence of the measured spectra.

For neutrino flavor oscillation, a mixing matrix links the flavor basis states and the mass eigenstates. The probability for one neutrino flavor to oscillate to a second flavor, assuming two state mixing, is given by

$$P_{\nu_\ell \to \nu_{\ell'}} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right) \tag{1}$$

where θ is the mixing angle between the first and second mass eigenstates, $\Delta m^2 \equiv |m_1^2 - m_2^2|$ is the difference in the square of the masses in units of eV^2, L is the path length traveled in meters, and E is the neutrino energy in MeV. For mixing between three ν states, the 3 by 3 mixing matrix depends on mixing angles, θ_{12}, θ_{13}, and θ_{23}, and the oscillation probability has the same oscillatory dependence on the corresponding mass differences $\Delta m_{12}^2, \Delta m_{13}^2$ and Δm_{32}^2. The importance of the mixing angles extends to symmetry violations in the lepton sector, since CP violation occurs only for $\theta_{ij} = 0$ and $\Delta m_{ij}^2 \neq 0$ for all pairs, i, j.

The ratio, $\frac{L}{E}$ in Equation 1, sets the Δm^2 sensitivity scale. When designing terrestrial source experiments, there may be flexibility to choose the ν energy and flavors, and the detector baseline distance for probing specific two-state mixing.

Terrestrial sources may be shut off to study background contributions or varied under known conditions for detecting a modulated signal. An important, yet obvious, consequence of controlling and characterizing the ν source, is that the spectra calculations and measurements, are independent of the solar and atmospheric models.

Nuclear power fission product decays produce electron anti-neutrinos with low energies, $E_{\bar{\nu}_e} < 10$ MeV. Therefore, the reactor source oscillation experiments involve the detection of only $\bar{\nu}_e$ in a disappearance measurement since the energies are too low to produce leptons in a charged current reaction and the mu and tau antineutrinos are too low in energy to be above the background. Reactor experiments are sensitive to mixing angle $\sin^2 2\theta \approx \sin^2 2\theta_{13}$ and easily achieve sensitivities of $\Delta m^2 \sim 10^{-3}$, with detector distances on the order of 1 km, and with larger distances are capable of reaching the smaller Δm^2 range suggested by solar neutrino measurements. The reactor $\bar{\nu}_e$ source is isotropic. Therefore for good sensitivity, the detector mass must grow with L^2, limiting the practical range of baseline distances.

Accelerator sources can produce muon neutrinos in a wide range of intermediate to high energies on the order of 20 MeV to 30 GeV. These experiments with detectors at different baseline ranges, therefore probe a wide range of mixing angles and the larger mass difference region associated with ν_μ oscillations. Long baseline measurements are primarily sensitive to the $\Delta m^2_{32}, \sin^2 2\theta_{23}$ mixing parameters. A 500 MeV neutrino source can be used to probe $\Delta m^2 \sim 0.1$ with the detector located at a distance of 1 km, and the 100 km range is needed to probe the $\Delta m^2 \sim 10^{-3}$ region. A collimated ν beam allows for reasonable detector sizes even at large distances.

The above general characteristics of reactor and accelerator ν sources show the complementarity of the two approaches in the mixing angles, $\sin^2 2\theta_{ij}$, and allowed Δm^2 regions that can be probed. Note that considered here are baseline distances less than ~ 500 km for the reactor experiments and intermediate baseline accelerator experiments where matter effects from the Earth are negligible.

For an extensive review of reactor experiments, please refer to the article by Bemporad, Gratta and Vogel[1], and the chapter by F. Boehm in an exhaustive set of articles on neutrino physics collected in one book[2]. In addition, the chapter by D.O. Caldwell provides a detailed review of accelerator based neutrino physics[3].

2. Reactor Neutrino Experiments

Reactor experiments are based on the detection of $\bar{\nu}_e$ from the beta decay of fission products of uranium (^{235}U, ^{238}U) and plutonium (^{239}Pu, ^{241}Pu) isotopes. As can be seen from Equation 1, in a disappearance measurement, the oscillation parameters modify both the total neutrino flux and the energy spectrum detected at distance, L. Note that the oscillation-induced spectral distortion lessens at the limits of the experiment sensitivity to Δm^2 and in the limits of no-oscillation.

The reactor power spectrum (derived from the fuel composition and thermal power history provided by the nuclear power company), the fission rates and the β-decay spectra are used to determine the neutrino spectrum and total yield, about $6 \times 10^{20} \bar{\nu}_e$/s for a 3 GW thermal source. Each of these processes is well known and the neutrino yield can be determined to a few percent or better. Anti-neutrinos above 1.5 MeV are produced primarily in high Q-value, short-lived decays, and track well with the reactor power. These calculations have been validated with the null results from early reactor oscillation experiments (discussed below) at short baselines including multiple baseline comparisons.

The $\bar{\nu}_e$ is detected by inverse beta decay $\bar{\nu}_e + p \to n + e^+$, where coincidence measurements are possible for background reduction. The neutrino energy spectrum is deduced from the positron spectrum, $E_{\bar{\nu}} \approx E_{e^+} + (M_n - M_p) + m_{e^+}$ and has a threshold of 1.8 MeV. The deposited energy of the positron comprises the prompt signal, and the delayed signal comes from the characteristic 2.2 MeV photon emitted in the subsequent capture of the neutron ($n + p \to d + \gamma$). Muon induced spallation neutrons produced in the surrounding rock create the most difficult background signals to discriminate against.

2.1. Early Experiments: Short Baselines

In 1977, scientists at the Institut-Laue-Langevin (ILL) research reactor in France, placed at a distance of 8.7 m from the reactor core, a liquid scintillator positron detector surrounded by ^{3}He proportional counters to detect the neutrons. The measured neutrino spectrum matched the calculated spectrum, excluding the high mass region $\Delta m^2 \geq 0.15$ eV^2 for mixing angles $\sin^2 2\theta > 0.25$.

The detector was moved to Goesgen, Switzerland, and improvements enabled pulse shape discrimination to remove fast neutron background events. With the detector placed sequentially at distances of 38, 46, and 65 m, no evidence for neutrino oscillations was observed with an uncertainty of 6%. The exclusion region was extended to $\Delta m^2 \sim 3 \times 10^{-2}$ eV^2.

In the early 1990's, the 2800 MW reactor at Bugey, France, was the source for detectors located at 15, 40, and 95 m. The identical detectors consisted of prismatic cells of ^{6}Li-loaded liquid scintillator material for short neutron capture times (30 μs). Prompt e^+ events were separated from n capture events (^{6}Li+n $\to^3$H+α) using pulse shape discrimination. No evidence for oscillations was seen with an absolute normalization of 5%, and sensitivity to $\Delta m^2 \sim 10^{-2}$.

Two short-baseline experiments measured deuteron disintegration via the charged current ($\bar{\nu}_e + d \to e^+ + n + n$) and through the neutral current ($\bar{\nu}_e + d \to \bar{\nu}_e + p + n$) interaction. As expected, these experiments showed no indication of oscillations[4, 5].

2.2. CHOOZ and Palo Verde: Intermediate Baselines

The next reactor experiments, CHOOZ and Palo Verde, were designed specifically to probe for ν_e-ν_μ oscillations in the allowed region of $\Delta m^2 \sim 10^{-3}$ suggested by the atmospheric neutrino measurement results at the time of detector construction.

The Palo Verde detector was built 12 m underground, about 32 meter-water-equivalent (mwe), and was located either 0.89 km or 0.75 km from three generating reactor cores that comprise the Palo Verde Nuclear Generating Station in Arizona, USA. The CHOOZ neutrino experiment was conveniently constructed in an existing underground cavity (300 mwe) at a distance of 1.11 km and 0.998 km from the two reactor cores of the Électricité de France power station located in the Ardennes.

Both experiments consist of gadolinium loaded liquid scintillator, and are based on a coincidence measurement of a prompt e$^+$ and annihilation $\gamma\gamma$ signal and delayed n capture in Gd producing a cascade of γ-rays with a total energy of 8 MeV. The detector design for each experiment was dictated by the background suppression needs resulting in different detector construction. Analysis methods included flux and spectra comparisons for full and reduced power ranges at the different generating stations and taking into account the different source distances.

CHOOZ and Palo Verde saw no evidence for ν oscillations. The ratio of the number of expected $\bar{\nu}_e$ to the number detected was reported as 1.01 ± 0.04 for the CHOOZ experiment[6] and 1.04 ± 0.08 for the Palo Verde experiment[7]. These results indicate that atmospheric neutrino oscillations are primarily ν_μ to ν_τ and not ν_μ to ν_e in the range $\Delta m^2 > 10^{-3}$. This is consistent with the subsequent results from SuperK[8]. In addition, the CHOOZ result puts an important stringent upper limit of $\sin^2\theta_{13} < 0.1$ at 90% confidence level in the large Δm^2 region[6].

2.3. KamLAND: Long Baselines

The Kamioka mine site (where both the Kamiokande and Super Kamiokande experiments were constructed) is strategically located 140 to 200 km away from over 16 reactors in Japan and Korea. With an average baseline distance of 190 km, the Kamioka Liquid scintillator Anti-Neutrino Detector, KamLAND is the first terrestrial ν experiment to be sensitive to an allowed region including the Large Mixing Angle (LMA) oscillation solution ($\Delta m^2 \sim 10^{-5}$ eV^2) suggested by solar ν experiments[9].

KamLAND positioned at 2700 mwe, is a 1 kton liquid scintillator viewed by 1879 photomultiplier tubes (PMTs) surrounded by a water Čerenkov veto detector viewed with 225 PMTs. The usual e^+n coincidence signal is detected in the liquid scintillator with n background suppression from fiducial volume cuts and cuts based on μ events. For experimental details, please see the KamLAND paper in these proceedings[10]. For a no-oscillation result, the excluded region will eliminate the LMA solution from further consideration. If KamLAND observes a deficit of antineutrinos, then (assuming CPT invariance) this important result will provide the most stringent restraints in the Δm^2 allowed region for $\nu_e \to \nu_x$ oscillations.

2.4. Next generation

If KamLAND fails to see oscillations at the LMA mass limits, then another round of experiments will be needed to study the high range of the Large Mixing Angle region. Such a reactor experiment has been proposed in Germany. The Heilebron experiment would strategically be located in a salt mine (480-640 mwe) near several reactors with distances about 10-20 km. The detector would be a 100 - 1000 kton scintillator depending on the sensitivity needed[11]. In addition, the upper range of Δm^2 could be reached with very long baseline experiments (see below).

3. Accelerator Neutrino Experiments

Accelerator neutrinos originate from the decay of pions and kaons produced in the bombardment of a fixed target with high-energy protons. The beam is primarily $\nu_\mu + \bar{\nu}_\mu$ with a small percentage of $\nu_e + \bar{\nu}_e$. Each flavor is generated with a different average energy.

Accelerator experiments focus primarily on the disappearance of ν_μ or the appearance of ν_τ, and thus are well suited for atmospheric neutrino oscillation studies. Disappearance studies of ν_e is very difficult since less than 1% of the neutrinos produced are electron neutrinos. This neutrino beam contribution must be understood in order to study $\nu_\mu \to \nu_e$ appearance in very sensitive measurements. Essentially no electron antineutrinos are produced, so that $\bar{\nu}_e$ appearance can readily be studied. For ν_μ disappearance experiments, a near detector calibrates the neutrino beam with intensity and ν spectra measurements. Meson detectors are used to monitor the beam. Beam simulations to characterize the ν source is sufficient for ν_τ appearance measurements, and a near detector is not required. Note that the threshold for τ production is 3 GeV, and therefore ν_τ appearance can only be studied at the higher energy accelerator facilities.

The ν flavors are identified through the charged current (CC) interaction, namely with the capture of a neutrino producing the lepton partner, ℓ, and a residual nucleus ($\nu_l + N \to l + N'$). The long baseline experiments may include detecting neutral current (NC) reactions for overall rate comparisons, and CC to NC event ratio differences between near and far detectors.

3.1. CHORUS and NOMAD: Intermediate Baselines

The Neutrino Oscillation MAgnetic Detector, NOMAD, and the CERN Hybrid Oscillation Research apparatUS, CHORUS, were designed to search for $\nu_\mu \to \nu_\tau$ oscillations, and take advantage of neutrinos produced at the CERN proton synchrotron which accelerates protons onto a Be target. The neutrino beam is primarily ν_μ with an average energy of 24 GeV with about 6% $\bar{\nu}_\mu$ at an average energy of 19 GeV. One detector is positioned just downstream of the other in the same experimental hall located approximately 600 m from the neutrino source. These experiments are therefore sensitive to the large $\Delta m^2_{\mu\tau}$ region.

In NOMAD, the identification of τ^- production is through the kinematic criteria that requires identifying the leptonic or hadronic decay particles, measuring their momentum, and analyzing the transverse momentum. For momentum analysis, the 2.7 ton fiducial volume ν target region is located within a uniform magnetic field (0.4 T) perpendicular to the beam axis creating a particle drift chamber.

The CHORUS detector, which contains 770 kg of emulsion, identifies τ events through the identification of kinks in the particle tracks produced by the τ^- decay to a negative hadron, electron or muon. To reduce background events, the track kink must satisfy specific distance and energy criteria depending on the leptonic or hadronic decay of the τ^-. Alternating layers of scintillating fiber trackers initially identify vertex and track positions to be studied in the emulsion sheets. A hadron spectrometer with fiber trackers measures track momenta. The energy is measured with a lead scintillating fiber calorimeter.

Both experiments failed to see oscillations ν_μ to ν_τ. CHORUS and NOMAD provide consistent null results in the large Δm^2 region, and with 90% confidence level (CL), put an upper limit on the oscillation probability of $P_{\mu\tau} < 3 \times 10^{-4}$ and exclude $\nu_\mu \to \nu_\tau$ mixing down to $\sin^2 2\theta \sim 10^{-4}$ with similar limits for $\nu_e \to \nu_\tau$ mixing[12]. These limits reinforce the small Δm^2, ν_μ to ν_τ oscillation explanation of the atmospheric anomaly.

3.2. LSND and KARMEN: $\bar{\nu}_e$ Appearance

The Liquid Scintillator Neutrino Detector, LSND, and the KArlsruhe-Rutherford Medium Energy Neutrino, KARMEN, experiments are designed to detect the appearance of $\bar{\nu}_e$ from $\bar{\nu}_\mu$ beams ($< E_\nu > \sim 35$ MeV) produced in the beam stop of intermediate-energy (800 MeV) proton accelerators. The protons are accelerated onto a water or lead target at the Los Alamos Meson Facility for LSND, and onto a Ta + D_2O target at the ISIS spallation facility at the Rutherford Appelton Laboratory for

KARMEN. Pions, produced in the target, decay in flight into muons, $\pi^+ \to \mu^+ + \nu_\mu$, and the muons subsequently decay at rest, $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$. Both experiments measured $\bar{\nu}_e$ production from the coincidence signal from the inverse beta decay reaction, $\bar{\nu}_e + p \to e^+ + n$, observed in liquid scintillator material.

The LSND detector located 30 m and 12° off-axis from the target, consisted of 167 tons of mineral oil with a diluted scintillator that allowed the detection of both scintillation and Čerenkov light. In contrast, KARMEN was located 18 m and 90° off-axis from the target and consisted of 56 tons of Gd loaded scintillator segmented into 512 modules. These designs resulted in different sensitivities to Δm^2, methods of background suppression, position and energy resolutions, and detector efficiencies.

LSND observed $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillations in the large Δm^2 region where the small $\sin^2 2\theta < 0.1$ region is not ruled out by reactor results. The LSND signal above background is quoted as $87.9 \pm 22.4 \pm 6.0$ events with an oscillation probability of $(0.264 \pm 0.067 \pm 0.045)\%$[13]. KARMEN2 (data from 1997-2001) measured 15 events with an expected background of 15.8 ± 0.5 events: no oscillation evidence. KARMEN provides the most stringent constraints on the LSND results, with a limit on the LSND range to $0.3\text{eV}^2 < \Delta m^2 < 2\text{eV}^2$[14]. A joint detailed statistical analysis of original data shows incompatibility of the two measurements each at the 60%CL for an overall 36% CL and areas of statistical compatibility only at $\Delta m^2 < 1$ eV^2[15].

This is the only positive oscillation result for accelerator experiments, and implies a third Δm^2 range that is different from the solar and atmospheric values. To accommodate this additional mass difference range, a number of theories have been developed including the postulation of a fourth but sterile neutrino flavor, ν_s, so that the 3 weak interacting ν flavor constraint set by the width of the Z boson is satisfied.

3.3. K2K and MINOS: Long Baselines

A wide-band ν beam with energy $1 - 2$ GeV from the proton synchrotron at KEK, in Japan, is directed at SuperK, at a distance of 250 km and with a beam aiming accuracy of about 1 mrad. In this KEK to Kamioka (K2K) experiment, SuperK serves as the far detector in a ν_μ disappearance measurement. Assuming a $\Delta m^2 = 5 \times 10^{-3}$ eV^2, a 1 GeV neutrino would be near the first minimum after traveling a distance of 250 km. For 10^{20} protons on target at KEK, the rate is $\sim$200 events at SuperK and the expected background is 5 atmospheric events/day. The near detector at 300 m is a 1 kton water Čerenkov detector with the same PMT arrangement (40% coverage) as SuperK, followed by a scintillating fiber detector for tracking, a lead glass array for tagging electromagnetic showers and a μ range detector to measure energy and momentum of muons from CC ν_μ events.

The K2K data recorded so far measured 56 events with an expected number for the case of no-oscillations of 80 events; results inconsistent with no-oscillations at 99% CL. The best fit to the measured spectrum gives $\Delta m^2 = 2.7 \times 10^{-3}$ eV^2 with $\sin^2 2\theta = 1$, and is consistent with the SuperK atmospheric results[16].

MINOS, the Main Injector Neutrino Oscillation Search, far detector currently under development will be located at the Soudan mine, 730 km from FermiLab, where the Neutrinos at the Main Injector (NuMI) beam is produced. With a two-horn system to focus the mesons into the decay region, and variable proton target locations, NuMI is expected to vary the neutrino energy with an average of $< E_\nu >= 3, 6, 12$ GeV. The far detector is based on light-tight modules of alternating steel plates and scintillator strips forming a 5.4 kton fiducial volume monitored with PMTs. The near detector located 300 m from the end of the NuMI meson decay tunnel, is a 930 ton fiducial volume scintillator tracking calorimeter segmented like the far detector for high-statistics measurements of the ν beam including energy spectra and ν_e contamination. NuMI expects 120 GeV protons on target by 2004 with MINOS taking data by 2005.

If the atmospheric mass difference squared is indeed in the range, $\Delta m^2_{atmos} \approx (2.0 - 5.0) \times 10^{-3}$ eV^2, then the MINOS experiment will determine the value with an estimated uncertainty of 10% for 10 kton-years of data. With the long baseline and $|\Delta m^2_{21}| << |\Delta m^2_{32}|$, MINOS will put a more stringent limit on the allowed range for Δm^2_{32} and $\sin^2 2\theta_{23}$. In addition, the comparison of the CC to NC event ratio in the near and far detectors may be sensitive to $\nu_\mu \to \nu_s$ mixing, providing another existence test of sterile neutrinos.

3.4. Next generation projects

The Booster Neutrino Experiments (BooNE) are underway at FermiLab where an 8 GeV proton beam produces a $\nu_\mu + \bar{\nu}_\mu$ beam with energy ranging from 300 MeV to 1.5 GeV. The set of BooNE experiments, starting with MiniBooNE, are designed to test the same allowed mass region as LSND. The detector, located 440 m from the source, is a Čerenkov detector with 776 tons of mineral oil viewed by 1275 PMTs. This experiment looks at the appearance of both ν_e and $\bar{\nu}_e$ from ν_μ and $\bar{\nu}_\mu$, respectively, requiring a Monte Carlo analysis to determine the expected ν flux. In 2 years of data for 10^{21} protons on target, MiniBooNE expects 10^5 ν_μ CC events and the LSND oscillation predicts 1000 $\nu_\mu \to \nu_e$ events out of an expected 3500 electron like events in the detector[17]. As of autumn 2002, MiniBooNE has begun taking data.

Two experiments under development are optimized to study $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ appearance from the CERN to Gran Sasso (CNGS) neutrino beam source located 730 km away with an average ν energy of 17 GeV, and with a 2% ν_μ and 0.8% $(\nu_e + \bar{\nu}_e)$ contamination. To achieve a mass difference sensitivity of 10^{-3} eV^2, which translates to a position sensitivity of 1 μm, the Oscillation Project with Emulsion-tRacking Apparatus (OPERA) detects τ decays by identifying track kinks in a massive target (2 kton) of alternating layers of Fe and Pb plates and thin emulsion sheets in which the emulsion area is more than 300 times that of CHORUS. If OPERA fails to see τ events, the region for $\nu_\mu - \nu_\tau$ mixing with $\Delta m^2 < 1.2 \times 10^{-3}$ eV^2 at maximal mixing and $\sin^2 2\theta < 5.7 \times 10^{-3}$ at large Δm^2 will be excluded at 90% CL[18].

The second CNGS experiment, ICARUS (Imaging Cosmic and Rare Underground Signals) a 3 kton detector with a liquid Argon time projection chamber, will measure τ appearance in the complementary method using kinematic criteria. With fiducial volume cuts, particle momentum and energy cuts, ICARUS will reach the same sensitivity as OPERA for $\nu_\mu - \nu_\tau$. With 1 mm resolution and good particle identification including electrons, ICARUS is expected to reach a sensitivity of $\sin^2 2\theta_{13} > 2 \times 10^{-2}$[18], reducing the limits set by CHOOZ. Completion of the CNGS beam and detectors is planned for 2006.

4. What's next?

The next set of terrestrial source experiments will require new ν beams and detectors to improve the sensitivity to Δm^2_{23} and θ_{23} and in a ν_e appearance measurement, to $\sin^2 \theta_{13}$. In addition, new measurements may be sensitive to CP violation, or to the sign of Δm^2 which will shed light on the mass hierarchy of the ν mass states.

The JHF2K project under construction, will direct a ν beam ($< E >\sim 0.5$ GeV) from the JAERI accelerator in Tokai, Japan, initially to the SuperK detector located $\sim$300 km away in Kamioka, and in the second phase, at the next generation large scale (1 Mton) detector (HyperK) in Japan[20]. Several superbeams as upgrades to current US accelerators have been proposed[21]. New liquid argon based ν detectors are being considered as part of a 100-1000 km baseline detector system using a proposed superbeam neutrino source at the Brookhaven National Laboratory in New York[22]. Accelerating β unstable radioactive isotopes to high energies has been proposed to produce an intense low-energy ν_e beam[19]. These and other proposals for detector and accelerator developments based on superbeams and neutrino factories form the basis of the NuFACT02 conference and the topics of these proceedings.

5. Summary

So far, the terrestrial neutrino oscillation experiments have confirmed and complemented the solar neutrino results, ν_e oscillates to ν_μ and ν_τ with $\Delta m^2 \approx 10^{-5}$ to 10^{-4} eV^2[9], and the atmospheric neutrino results that ν_μ oscillates to ν_τ with large $\Delta m^2 \approx 10^{-3}$eV^2 [8]. The reactor measurements and the intermediate baseline accelerator results are consistent with the neutrino oscillation solutions and have put important limits on the allowed regions of Δm^2 *vs.* $\sin^2 2\theta$. KamLAND will provide the next reactor experiment result, and with sensitivity to the favored LMA solution, will either complete or extend the solar neutrino puzzle. Soon, MiniBooNE will confirm or refute the LSND large Δm^2 oscillation results and provide insights into the existence of a third mixing mass region. In the following years, the long baseline experiments will help define the lepton mixing matrix elements and contribute to the determination of the (as yet unknown) mass hierarchy.

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