Neutrino Mass and Oscillations

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Abstract. This talk will summarize the current experimental understanding of neutrino mass and oscillation parameters, and will discuss prospects for future experiments.

1. Neutrino Mass and Oscillations

Neutrinos are the neutral fermion partners to the charged leptons. They have extremely tiny masses and exclusively weak (plus gravitational) interactions. The properties of neutrinos are interesting not only in that we must fit them into the overall particle physics picture; in addition they give insight into cosmology. For the full story on largest and smallest scales, we need to understand neutrino masses and mixings. New physics beyond the Standard Model may first manifest itself in the neutrino sector[1]. Understanding of neutrino properties also deepens our understanding of astrophysical objects, both mundane and exotic, where neutrinos are significant players in many processes. Neutrino interactions with nuclei are also relevant for understanding of both nuclear and neutrino physics.

A significant focus of recent attention in neutrino physics has been new understanding of neutrino mass and oscillations. Until 1998, it was not known whether neutrinos had any mass at all; although we still do not know the absolute mass scale, we now have insight into neutrino masses via the mixing of different mass states. We assume that the N flavor interaction eigenstates $|\nu_f\rangle$ are distinct from the mass eigenstates $|\nu_i\rangle$, and can be written as a superposition according to

$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^* |\nu_i\rangle,\tag{1}$$

where U_{fi} are the elements of an $N \times N$ unitary mixing matrix. For N = 3 flavors (assumed since only three generations of leptons are known[2]), this mixing matrix is known as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. In this framework, free neutrinos will change flavor content as they propagate. As a simple example, consider the two-flavor case (see for example references [3, 4] for discussions of the assumptions and implications of this simplified quantummechanical treatment):

$$\begin{aligned} |\nu_f\rangle &= \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle \\ |\nu_q\rangle &= -\sin\theta |\nu_1\rangle + \cos\theta |\nu_2\rangle \end{aligned}$$
(2)

The flavor states are rotated versions of the mass states, where the rotation angle θ (the "mixing angle") is a parameter of nature. If you allow a neutrino produced in flavor state $|\nu_f\rangle$

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by a weak interaction to propagate a distance L, $|\nu_i(t)\rangle = e^{-iE_it}|\nu_i(0)\rangle$, then in the relativistic approximation, this can be written $|\nu_i(t)\rangle \sim e^{-im_i^2L/2p}|\nu_i(0)\rangle$, and the probability of neutrino being observed in the original flavor state is $P(\nu_f \to \nu_f) = |\langle \nu_f | \nu_f \rangle|^2$, which works out to

$$P(\nu_f \to \nu_g) = 1 - P(\nu_f \to \nu_f) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_{\nu}),$$
(3)

for L in km and E_{ν} in GeV, and mass in eV. This flavor transition probability depends on two parameters of nature: the mass-squared difference, $\Delta m^2 \equiv m_2^2 - m_1^2$, and the mixing angle θ . Two quantities in this expression depend on the specific parameters of the situation: the energy of the neutrino, E_{ν} , and the distance it travels, L. The wavelength of the oscillation is proportional to $E_{\nu}/\Delta m^2$; the amplitude of the flavor modulation is $\sin^2 2\theta$.

The basic idea of a neutrino oscillation experiment is as follows: neutrinos are allowed to propagate, and their spectrum and flavor composition are measured to the extent possible. The experimental question is: have the flavors changed after propagation? If so, are the flavors and spectrum modified according to equation 3? If the answer to this question is yes, then you have evidence for neutrino oscillation. If all neutrino states have zero mass, Δm^2 is zero, and oscillation is not possible: therefore an observation of energy-dependent flavor change according to equation 3 implies at least one non-zero mass state. One can then fit the observation to oscillation parameters: for a two-flavor oscillation, the traditional parameter space shows Δm^2 on the vertical axis and $\sin^2 2\theta$ on the horizontal axis. In this plane, an experimental setup with large L/E_{ν} gives access to small values of Δm^2 , and small L/E_{ν} gives access to large values. Since a large mixing angle corresponds to large modulation of the signal, large experimental statistics are required to observe a small mixing angle.

Neutrinos interact via charged-current (CC) or neutral-current (NC) interactions. In a charged-current interaction, the neutrino exchanges a W^{\pm} boson with a quark or lepton; the outgoing lepton is of the same flavor as the incoming neutrino. In flavor-blind NC interactions, the neutrino exchanges a Z boson with quarks or leptons. Neutrino oscillation experiments can look for either disappearance or appearance of a given flavor. Since a CC interaction has an energy threshold, if a neutrino oscillates to a flavor for which the required energy is below CC threshold, then the neutrino will effectively disappear. (Although NC interactions will still be present, the observable rate is typically small.) Therefore a loss of observed flux over the neutrino propagation distance, with appropriate energy dependence, can be interpreted as an oscillation. "Appearance" experiments are perhaps more satisfying, but often experimentally challenging: in this case one looks explicitly for a new flavor appearing in a neutrino flux of known flavor. An appearance experiment typically requires experimental capability of tagging lepton flavor in a CC interaction.

More generally, for three flavors, the flavor and masses states are related by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu1}^* & U_{\mu2}^* & U_{\mu3}^* \\ U_{\tau1}^* & U_{\tau2}^* & U_{\tau3}^* \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
(4)

and the oscillation probabilities can be computed straightforwardly[5]:

$$P(\nu_{f} \to \nu_{g}) = \delta_{fg} - 4 \sum_{j>i} \qquad \text{Re}(U_{\text{fi}}^{*} U_{\text{gi}} U_{\text{fj}} U_{\text{gj}}^{*}) \sin^{2}(1.27\Delta m_{\text{ij}}^{2} L/E_{\nu}) \\ \pm 2 \sum_{j>i} \text{Im}(U_{\text{fi}}^{*} U_{\text{gi}} U_{\text{fj}} U_{\text{gj}}^{*}) \sin^{2}(2.54\Delta m_{\text{ij}}^{2} L/E_{\nu}),$$

again for L in km, E_{ν} in GeV, and Δm_{ij}^2 in eV². The negative sign in front of the last term holds for neutrinos and the positive sign holds for antineutrinos. If mass scales are well separated from each other, *i.e.* $|\Delta m_{23}^2| >> |\Delta m_{12}^2|$, then the oscillation "decouples", *i.e.* can be described well by two-flavor oscillations with a single mass-squared difference scale. This situation holds for many real experimental situations.

There are currently two main observed oscillation signals, one occupying each of the "decoupled" regimes. Solar and reactor neutrinos have been observed to oscillate; they will not be covered in detail here because they were addressed in another contribution to this conference. In the next section the oscillation of atmospheric and beam neutrinos will be described in some detail.

2. Atmospheric Neutrino Oscillation Parameter Space

The first unambiguous signal of neutrino oscillation came from study of atmospheric neutrinos. Atmospheric neutrinos are produced in collisions of cosmic rays with atoms in the upper atmosphere. The resulting cascade of hadrons includes such particles as pions and kaons, which decay to neutrinos. The neutrinos have energies ranging from about 0.1 GeV to several hundred GeV and pathlengths from about 10 km (for neutrinos from above) to 13,000 km (for neutrinos from below) when observed near the surface of the Earth. The Super-Kamiokande water Cherenkov experiment in Japan measured a deficit of up-going ν_{μ} with zenith angle and energy dependence consistent with ν_{μ} disappearance oscillation[6], with parameters shown in Fig. 1. Recent work has also been able to more tightly constrain Δm^2 and disfavor some more exotic models for neutrino disappearance by using a high-resolution sample to resolve explicitly the "wiggle" of the oscillation probability[7]; consistency with $\nu_{\mu} \rightarrow \nu_{\tau}$ has also been shown[8, 9]. There is no evidence that the mixing is non-maximal, nor that θ deviates from $\pi/4[10]$.

The next step after atmospheric neutrino oscillation measurements is the "long baseline experiment" to provide an independent confirmation of the atmospheric neutrino oscillation hypothesis using an artificial beam of neutrinos. With ~GeV neutrinos, for an L/E_{ν} suitable for testing the atmospheric Δm^2 parameters, baselines of hundreds of km are needed. The basic method is to create an intense beam of neutrinos by making "artificial cosmic rays": protons are smashed into a target, the resulting charged hadrons are focused forward with a magnetic field, and the boosted pions and kaons are allowed to decay to neutrinos. The neutrino beam characteristics (energy spectrum, flavor composition) are measured to the extent possible at a point near where the neutrinos are produced. The beam then propagates hundreds of km before the neutrinos are measured again.

K2K (KEK to Kamioka) was the first long-baseline neutrino oscillation experiment[11]. It employed a high-purity beam of ν_{μ} of ~1 GeV energy sent 250 km to the Super-K detector. K2K ran from 1999 to 2004, and observed both suppression of ν_{μ} events and spectral distortion consistent with atmospheric neutrino oscillation parameters.

The current state-of-the-art for long baseline disappearance oscillation is the MINOS (Main Injector Neutrino Oscillation Search) experiment in the United States. This experiment makes use of the NuMI beam[12], which sends ν_{μ} over a 735 km baseline from Fermilab to the Soudan mine in Minnesota. The MINOS far detector is quite different from Super-K: it has 5 kton of magnetized iron instrumented with scintillating fibers used to track penetrating particles. MINOS has also observed a ν_{μ} deficit and spectral distortion consistent with parameters describing atmospheric neutrino oscillations. Currently the best resolution on the measurement of the Δm^2 oscillation parameter comes from MINOS[13] (see Fig. 1), although the best $\sin^2 2\theta$ constraint is still that from the Super-K atmospheric neutrino analysis.

Another long-baseline project is CNGS (CERN Neutrinos to Gran Sasso) in Europe[14], with a 730 km baseline. This project involves a higher energy ν_{μ} beam, with peak energy around 15-20 GeV. For CNGS the goal is to observe τ appearance explicitly. In order to observe CC ν_{τ} interactions, the ν_{τ} must have at least 3.5 GeV of energy in the lab frame. The CNGS far detectors at Gran Sasso National Laboratory in Italy are also optimized for τ appearance:



Figure 1. Allowed parameters in atmospheric neutrino parameter space from MINOS and Super-K, from reference [13].

one needs a very fine-grained tracking detector in order to resolve the outgoing topology of a τ decay. The experimental signature is a kink of only millimeter scale. The OPERA experiment at Gran Sasso[15] is a lead/emulsion sandwich with active scintillator strip planes, along with a magnetic spectrometer. OPERA has observed its first ν_{τ} candidate[16]. In five years of running, for current best-fit atmospheric oscillation parameters OPERA expects about 10 τ -decay signal events with a background of less than one event. The other fine-grained tracker operating for CNGS at Gran Sasso is the ICARUS experiment[17], a 600 ton liquid argon time projection chamber.

3. Three-Flavor Oscillations and Next Generation Experiments

There are currently two firm signals of neutrino oscillation. First, "atmospheric" oscillation described by $\nu_{\mu} \rightarrow \nu_{\tau}$ at parameters $\Delta m^2 = 2 \times 10^{-3} \text{ eV}^2$, and near-maximal $\sin^2 2\theta$, first seen in atmospheric neutrinos, was later confirmed by beam experiments. Second, solar neutrino $\nu_e \rightarrow \nu_{\mu,\tau}$ disappearance described by parameters $\Delta m^2 = 8 \times 10^{-4} \text{ eV}^2$, and large mixing angle, $\tan^2 \theta = 0.5$, has been confirmed with reactor neutrinos. We have two mass-squared differences and two mixing angles: by convention the masses in the solar mixing are m_1 and m_2 , so that the solar Δm^2 is $\Delta m_{12}^2 = m_1^2 - m_2^2$. The atmospheric mixing is then between mass states m_2 and m_3 , and the atmospheric Δm^2 is $\Delta m_{23}^2 = m_2^2 - m_3^2$ (the sign is unknown).

Our model of neutrino mixing requires a 3×3 mixing matrix, and the oscillation is described by a total of six parameters, of which four are known. Three mixing angles and a CP-violating phase are present in the MNS matrix: only two of the mixing angles are known. The mixing matrix can be written out as a product of three "Euler-like" rotations:

$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
(5)

where "s" represents sine of the mixing angle and "c" represents cosine. The "1-2" matrix describes "solar" mixing; the "2-3" matrix describes "atmospheric" mixing. The third angle, θ_{13} ,



Figure 2. Schematic of normal and inverted hierarchies, under the assumption of three neutrino flavors, with mass states represented by horizontal bars. The mass-squared values are indicated by the vertical dimension, and possible flavor composition is indicated by the horizontal divisions (ν_e on the left, ν_{μ} in the middle, and ν_{τ} on the right).

is still unknown, although it is known to be small. The CP-violating phase δ is also unknown.¹ Another unknown is the absolute mass scale, since oscillation measurements inform us only on mass *differences*. Although two of the mass-squared differences are known, we do not know how the three masses are arranged: there could be two light ones and a heavy one (the "normal" hierarchy) or two heavy ones and a light one (the "inverted" hierarchy): see Fig. 2.

The aim of future neutrino experiments is to hunt down these unknowns. The next promising quarry for neutrino oscillation experiments is the unknown mixing angle θ_{13} . The best knowledge so far about the value of θ_{13} comes from the Chooz reactor experiment[18]. The Chooz detector comprised 5 tons of gadolinium-loaded scintillator and was located ~1 km from two nuclear reactors. Chooz looked for spectral distortion of the positron spectrum from inverse beta decay. No significant distortion was observed, and hence a limit was set on the disappearance oscillation parameters for the Δm^2 greater than about 10^{-3} eV², range, down to $\sin^2 2\theta$ of about 0.1. Interpreted in a three-flavor context, this corresponds to a limit of about 0.05 on $\sin^2 \theta_{13}$ in the known Δm^2 range. Information from atmospheric neutrinos is consistent with this limit. If θ_{13} is non-zero, one expects a small enhancement of upward-going electron neutrinos in the 5 to 10 GeV energy range, due to resonant enhancement as the neutrinos traverse matter in the Earth. The Super-K three-flavor atmospheric neutrino analysis[10] shows no significant enhancement of upward-going high-energy ν_e events, consistent with $\theta_{13} = 0$. MINOS also has a ν_e appearance search result[19].

There are two approaches to learning the value of θ_{13} , which are complementary. First, reactor experiments can perform $\bar{\nu}_e$ disappearance experiments, *i.e.* look for spectral distortion of MeV neutrinos. Second, one can look for a tiny appearance of electron neutrinos in a beam of GeV muon neutrinos. Vigorous experimental efforts are in progress for both reactor and beam approaches.

The disappearance probability for $\bar{\nu}_e$ is given by $P(\bar{\nu}_e \rightarrow \nu_x) \sim \sin^2 2\theta_{13} \sin^2(\Delta m_{13}^2 L/4E_{\nu})$. At reactor neutrino energies, the oscillation length is a few kilometers. Since the expected modulation is proportional to $\sin^2 2\theta_{13}$, which is known to be small, systematic uncertainties of less than 1% are required. To achieve this level of uncertainty, next-generation reactor neutrino experiments employ both near and far detectors, to cancel systematic uncertainties in the ratio between oscillated and unoscillated fluxes to the extent possible. Three new reactor experiments will have results within several years: these are Double Chooz located at the Chooz nuclear power station in France[20], the Daya Bay experiment in China[21], and RENO at Yonggwang in Korea[22].

¹ There are also "Majorana phases", which do not affect oscillation probabilities.

Alternatively, one may look for an appearance signal of ν_e in a GeV ν_{μ} beam on a fewhundred km distance scale. The ν_e appearance probability is approximated by $P(\nu_{\mu} \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{23}^2 L}{4E_{\nu}}\right)$, where E_{ν} is the energy of the neutrino; this expression holds in vacuum for $\Delta m_{23}^2 >> \Delta m_{12}^2$, and $E_{\nu} \sim L\Delta m_{23}^2$, $\delta = 0$. The oscillation is driven by the "atmospheric" Δm^2 ; from the known limit on θ_{13} , the appearance amplitude cannot be more than about 7%. Therefore good statistics and a clean sample are both needed to observe an appearance signal of non-zero θ_{13} . For a baseline of ~300 km, the first oscillation maximum is at around 600 MeV. Two next-generation long baseline oscillation experiments, T2K and NO ν A, will improve their sensitivity to oscillations via clever configuration of beam and detector: they will site their detectors slightly off beam axis. According to two-body decay kinematics, at locations few degrees off beam-axis, neutrino energy becomes relatively independent of pion energy. The neutrino spectrum is then more sharply peaked, which allows enhanced flux at the oscillation maximum and reduction of backgrounds from off-peak tails of the spectrum.

The T2K experiment[23] is the first off-axis long-baseline neutrino oscillation experiment, employing a high-intensity beam from the J-PARC facility in Tokai (designed eventually to achieve 750 kW beam power) sent to the 22.5 kton fiducial mass Super-Kamiokande (Super-K) water Cherenkov detector 295 km away in Kamioka. The experiment also includes a number of detectors deployed near the neutrino source for beam characterization. T2K construction is complete, and near and far detectors were running well at the time of this presentation. First neutrino events were observed in February 2010. The eventual aim of the T2K experiment, for running of 750 kW times (5×10^7 s), is for a sensitivity to $\sin^2 2\theta_{13}$ between $2 - 15 \times 10^{-3}$ (depending on δ and the mass hierarchy) at the current best measured value of Δm_{23}^2 . See Fig. 3.



Figure 3. T2K sensitivity to θ_{13} at the 90% confidence level as a function of δ_{CP} . Beam is assumed to be running at 750 kW for 5 years, using the 22.5 kton fiducial volume SK detector. 5%, 10% and 20% systematic error fractions are plotted. The following oscillation parameters are assumed: $\sin^2 2\theta_{12} = 0.8704$, $\sin^2 2\theta_{23} = 1.0$, $\Delta m_{12}^2 = 7.6 \times 10^{-5} \text{eV}^2$, $\Delta m_{23}^2 = 2.4 \times 10^{-3} \text{eV}^2$, normal hierarchy.

Another off-axis neutrino beam θ_{13} search, NO ν A, is planned in the United States[24]. For this program, the Fermilab NuMI beam will be upgraded from 400 to 700 kW, and a 15 kton scintillating tracking detector at an 810 km baseline will be constructed. NO ν A's goal sensitivity to θ_{13} is better than 0.01; precision measurements of the 2-3 mixing parameters will also be possible.

4. CP Violation and Next-Next Generation Experiments

While the current cohort of oscillation experiments is pursuing a measurement of θ_{13} , the longterm goal is to observe CP violation in the lepton sector. CP violation can be parameterized by δ in the MNS mixing matrix, and information may be extracted from measurements of the transition probabilities for neutrinos and antineutrinos, *e.g.* $\nu_{\mu} \rightarrow \nu_{e}$ and $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ [25]. However extraction of information about δ from these observables is not completely straightforward, because transition rates depend on all of the MNS parameters; furthermore, matter effects come into play. One needs precision measurements of all parameters, and multiple measurements, if possible including both neutrinos and antineutrinos, to resolve all ambiguities (see *e.g.* [26, 27, 28]). Matter effects in particular can be considered both a help and a hindrance: they cause a matter-dependent asymmetry in transition rates between neutrinos and antineutrinos, which can mask CP violation. However the sign of the modification depends on the hierarchy: therefore one may in principle use long baseline oscillation measurements to distinguish between normal and inverted hierarchies.

With the next set of experiments, there is some hope of resolving the mass hierarchy if parameters are favorable. With its longer baseline through matter, NO ν A by itself has some sensitivity, and this improves in combination with T2K[29]. Beyond NO ν A and T2K, next-phase high-intensity beam programs are under serious consideration in the U.S., Japan and Europe.

For the next phase of T2K, the J-PARC beam will first be upgraded to 1.66 MW, and perhaps eventually 4 MW will be achieved. The vision for a next-generation far detector is Hyper-Kamiokande[30], a new 0.5 Mton water detector at Kamioka, possibly in combination with a second detector at a 1000-1250 km baseline in Korea (the "T2KK experiment")[31]. Intermediate locations are under consideration as well: a candidate site is Okinoshima Island at 660 km from J-PARC. This program could also include different detector technology, such as liquid argon[32].

Future "superbeam" projects are in the works in the United States as well. At Fermilab, one possibility is to upgrade NuMI for a narrow-band off-axis beam: the Long Baseline Neutrino Experiment (LBNE) experiment aims to use a 700 kW beam[33] with a potential far detector site at the Deep Underground Science and Engineering Laboratory in South Dakota, 1300 km away. Also under serious consideration at Fermilab for the farther future is "Project X", which includes a new high-intensity neutrino beam making use of an 8 GeV LINAC frontend, the Recycler and an upgraded Main Injector. "Project X" includes in addition facilities for diverse other physics programs[34]. There are two leading possibilities for the detector technology for a next-generation long-baseline neutrino detector: water Cherenkov and liquid argon time projection chamber (TPC). Water Cherenkov detectors like Super-K have very well-understood technology and employ very inexpensive target material; however they have intrinsically imperfect tracking (since final state particles from a neutrino interaction may be below Cherenkov threshold and invisible), making event reconstruction and background rejection more difficult. In contrast, liquid argon TPC technologies offer much superior tracking capabilities, efficiency and background rejection; however they are unproven at very large scales. In both cases, there exists also a rich physics program of non-accelerator particle physics, e.g. baryon number violation searches, and astrophysical (atmospheric, solar, supernova) neutrino searches, provided the detector is at sufficient depth. At this time, the U.S. community is entertaining both options. If resources are sufficient, both kinds of detectors will provide complementary information. Discussion of future megadetectors and beams has also been lively in Europe[35]. Another interesting proposed project is at the Indian Neutrino Observatory (INO)[36], to be located in southern India (6560 km from J-PARC).

Other future ideas for neutrino physics include neutrino factories (muon storage rings in which decaying muons produce very high fluxes of well-understood neutrinos)[37], "beta beams"[38] (radioactive ions in a storage ring decay to either neutrinos or antineutrinos) and cyclotron-based stopped-pion sources [39].

5. Two Sets of Parentheses

The previous discussion was all based on the validity of the three-flavor oscillation picture. However, there are currently a few outstanding experimental anomalies pointing to physics outside of this standard picture. So here I will open and close two sets of parentheses.

The first set concerns the Liquid Scintillator Neutrino Detector (LSND) at Los Alamos[40], a 167 ton scintillator experiment (making use of both scintillation and Cherenkov signal in the scintillator) located 30 m away from a stopped-pion source of neutrinos. In 1996, LSND reported[41] an excess of $\bar{\nu}_e$ candidate events over their expected background, which they interpreted as a two-flavor oscillation. The final published analysis from 2001[42] reports an excess corresponding to $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ oscillation parameters in the range Δm^2 of 0.2-10 eV² and $\sin^2 2\theta$ between 10^{-3} and 4×10^{-2} . Another stopped-pion neutrino source experiment, KARMEN (Karlsruhe Rutherford Medium Energy Neutrino Experiment) with 56 tons of scintillator located 17.5 m from the ISIS neutrino source at Rutherford-Appleton Laboratory did not observe an excess, ruling out most, but not all, of the LSND allowed oscillation space[43].

The MiniBooNE experiment at Fermilab was designed to test the LSND oscillation hypothesis with the same L/E_{ν} , but higher baseline (~500 m) and energy ~ 1 GeV. MiniBooNE makes use of neutrinos from the FNAL Booster along with a dedicated horn and decay pipe, creating a beam of primarily ν_{μ} with a spectrum peaking around 700 MeV. The detector contains 1 kton of scintillator, and employs primarily Cherenkov radiation for event reconstruction. In April 2007, MiniBooNE reported first oscillation results [44]. MiniBooNE observed no evidence of an energydependent excess of ν_e in a sample of events with reconstructed neutrino energy above 475 MeV, which is in the energy range where one would expect to see an excess if the $\nu_{\mu} \rightarrow \nu_{e}$ oscillation driven by LSND $\bar{\nu}_e$ appearance parameters were taking place. The MiniBooNE results lead to exclusion of essentially all of the allowed LSND parameters under the assumption that neutrinos and antineutrinos oscillate in the same way: reference [45] examines compatibility. However, a new anomaly has turned up: the MiniBooNE collaboration observed an excess of e-like events at energies below 475 MeV, and this anomaly persists despite exhaustive checks of systematic effects[46]. Further MiniBooNE running with a beam of $\bar{\nu}_{\mu}$ presents even more puzzles: at the time of this presentation, the antineutrino beam data showed a $1.3\sigma \bar{\nu}_e$ excess at low energy, but a more significant excess for E > 475 MeV, consistent with the LSND appearance signal [47, 48]. MiniBooNE $\bar{\nu}$ running will continue to gather more statistics to try to resolve the anomaly, and the MicroBooNE liquid argon experiment [49] will take further data in the same beam.

The second set of parentheses encloses a potentially interesting anomaly from MINOS, still with rather low statistics so far. Because of its magnetic field, MINOS can distinguish neutrinos from antineutrinos event by event. The two-flavor 2-3 disappearance oscillation parameters measured using antineutrinos are marginally inconsistent with those measured using neutrinos[50]: such a difference could be indicative of CPT violation, or other exotic effect. A statistical study using Super-K's atmospheric neutrino sample[51] (for which no event-by-event ν vs. $\bar{\nu}$ separation is possible) shows no hint for any difference; however the data are not able to rule out the MINOS $\nu/\bar{\nu}$ difference. MINOS will continue to acquire $\bar{\nu}$ data.

6. Neutrino Absolute Mass

The question of absolute neutrino mass, as well as that of whether the neutrino is its own antiparticle, can be addressed by searches for neutrinoless double beta decay. However because this topic was covered in a separate contribution to this conference, it will not be covered here.

The most direct way of probing the question of absolute neutrino mass scale is from kinematic experiments. In nuclear beta decay, $n \to p + \bar{\nu}_e + e^-$, the total energy in the three-body final state must include the rest-mass energy of the neutrino. The endpoint energy of the electron spectrum will therefore be reduced by this energy, and the electron spectrum near the endpoint will be distorted with respect to the expectation for a zero-mass neutrino; very high resolution energy measurement is required to observe this distortion, given the tiny mass of the neutrino. Two main experimental approaches are spectrometers and bolometers. In the spectrometer approach, the β source (typically tritium, which has an 18.6 keV endpoint) is distinct from the detector and the electron energies are measured by various techniques. In the bolometer approach, the source is the detector material, and electron energies are measured via temperature increase of the detector. Existing bolometer designs are based on ${}^{187}\text{Re} \rightarrow {}^{187}\text{Os} + e^{-} + \bar{\nu}_{e}$, which has a 2.5 keV endpoint[52]. The current best direct kinematic limits on the absolute neutrino mass scale of about 2 eV/c^2 come from Mainz[53] and Troitsk spectrometers[54], neither of which has observed a distortion consistent with a finite-mass neutrino, and the results are now limited by systematic uncertainties. The current best bolometer limits are in the range of 15 eV[57]. The next-generation kinematic neutrino mass search, aiming for sub-eV sensitivity, is KATRIN, a spectrometer located at Karslruhe in Germany [56]. The next-generation bolometer is MARE [57]. A novel idea is "Project-8" [58] to use detection of cyclotron radiation of tritium decay electrons. Next-generation kinematic experiments aim for eventual sensitivity of about $0.2 \text{ eV}/\text{c}^2$.

Another way of addressing the question of absolute neutrino masses is to look on cosmological scales: the field of observational cosmology now has a wealth of data. Non-zero neutrino mass affects galaxy formation, and overall there are a host of other effects on cosmological observables. Global fits to the data– large scale structure, high Z supernovae, cosmic microwave background, and Lyman α forest measurements – yield limits on the sum of the three neutrino masses of less than about 0.3-0.6 eV, although specific results depend on assumptions. Future cosmological measurements will further constrain the absolute mass scale. Reference [59] is a recent review.

7. Summary

Overall, the field of experimental neutrino physics has experienced tremendous progress over the last decade and a half. Beyond a doubt, neutrinos have mass and mix. In both the atmospheric and solar neutrino oscillation sectors, we are entering a precision measurement regime. The next quest on the horizon is first to measure a non-zero value of the third mixing angle, θ_{13} . Following that measurement, from oscillation experiments we may learn about the mass hierarchy and CP violation in the lepton sector. New beam and reactor experiments to accomplish these goals will soon have results, and future phases of these experiments, as well as ambitious next-next generation experiments are in the planning stages. There are good prospects for pushing down sensitivity to absolute neutrino mass to sub-eV levels, and information from cosmological observations will also improve. The next decade will surely bring further exciting progress in neutrino physics.

References

- [1] Mohapatra R N et al. 2007 Rept. Prog. Phys. 70 1757–1867 (Preprint hep-ph/0510213)
- [2] Amsler C et al. (Particle Data Group) 2008 Phys. Lett. B667 523
- [3] Cohen A G, Glashow S L and Ligeti Z 2008 ArXiv:0810.4602 (*Preprint* 0810.4602)
- [4] Kayser B 1981 Phys. Rev. D24 110
- [5] Amsler C et al. (Particle Data Group) 2008 Phys. Lett. B667
- [6] Ashie Y et al. (Super-Kamiokande) 2005 Phys. Rev. D71 112005 (Preprint hep-ex/0501064)
- [7] Ashie Y et al. (Super-Kamiokande) 2004 Phys. Rev. Lett. 93 101801 (Preprint hep-ex/0404034)
- [8] Fukuda S et al. (Super-Kamiokande) 2000 Phys. Rev. Lett. 85 3999-4003 (Preprint hep-ex/0009001)
- [9] Abe K et al. (Super-Kamiokande) 2006 Phys. Rev. Lett. 97 171801 (Preprint hep-ex/0607059)
- [10] Wendell R et al. (Kamiokande) 2010 Phys. Rev. D81 092004 (Preprint 1002.3471)
- [11] Ahn S H et al. (K2K) 2001 Phys. Lett. B511 178-184 (Preprint hep-ex/0103001)

- [12] Anderson K et al. FERMILAB-DESIGN-1998-01
- [13] Adamson P et al. (The MINOS) 2011 (Preprint 1103.0340)
- [14] Sirri G 2007 Nucl. Phys. Proc. Suppl. 172 149–151
- [15] Rosa G (OPERA) 2008 J. Phys. Conf. Ser. 136 022015
- [16] Agafonova N et al. (OPERA) 2010 Phys. Lett. B691 138–145 (Preprint 1006.1623)
- [17] Amerio S et al. (ICARUS) 2004 Nucl. Instrum. Meth. A527 329-410
- [18] Apollonio M et al. (CHOOZ) 1999 Phys. Lett. B466 415-430 (Preprint hep-ex/9907037)
- [19] Adamson P et al. (The MINOS) 2010 Phys. Rev. D82 051102 (Preprint 1006.0996)
- [20] Ardellier F et al. (Double Chooz) 2006 ArXiv:hep-ex/0606025 (Preprint hep-ex/0606025)
- [21] Wang W (Daya Bay) 2010 AIP Conf. Proc. 1222 494-497 (Preprint 0910.4605)
- [22] Ahn J K et al. (RENO) 2010 (Preprint 1003.1391)
- [23] Itow Y et al. (The T2K) 2001 ArXiv:hep-ex/0106019 (Preprint hep-ex/0106019)
- [24] Ayres D S et al. (NOvA) 2004 ArXiv:hep-ex/0503053 (Preprint hep-ex/0503053)
- [25] Minakata H and Nunokawa H 1997 Phys. Lett. B413 369–377 (Preprint hep-ph/9706281)
- [26] Minakata H and Nunokawa H 1998 Phys. Rev. D57 4403-4417 (Preprint hep-ph/9705208)
- [27] Minakata H, Nunokawa H and Parke S J 2002 Phys. Lett. B537 249-255 (Preprint hep-ph/0204171)
- [28] Burguet-Castell J, Gavela M B, Gomez-Cadenas J J, Hernandez P and Mena O 2001 Nucl. Phys. B608 301–318 (Preprint hep-ph/0103258)
- [29] Mena O, Nunokawa H and Parke S J 2007 Phys. Rev. D75 033002 (Preprint hep-ph/0609011)
- [30] Nakamura K 2003 Int. J. Mod. Phys. A18 4053-4063
- [31] Kajita T 2008 J. Phys. Conf. Ser. 136 022020
- [32] Hasegawa T Talk at Neutrino 2010, Athens, Greece
- [33] Bass M et al. 2010 A study of the physics potential of the long-baseline neutrino experiment project with an extensive set of beam, near detector and far detector configurations http://www.int.washington.edu/ PROGRAMS/10-2b/LBNEPhysicsReport.pdf.
- [34] Appel J et al. 2008 Physics with a high intensity proton source at fermilab http://www.fnal.gov/ directorate/Longrange/Steering_Public/P5/GoldenBook-2008-02-03.pdf.
- [35] Rubbia A (LAGUNA) 2010 Acta Phys. Polon. B41 1727-1732
- [36] Datar V M (INO) 2008 J. Phys. Conf. Ser. 136 022016
- [37] Gomez-Cadenas J J 2008 J. Phys. Conf. Ser. 136 022023
- [38] Zucchelli P 2002 Phys. Lett. B532 166-172
- [39] Conrad J M and Shaevitz M H 2010 Phys. Rev. Lett. 104 141802 (Preprint 0912.4079)
- [40] Athanassopoulos C et al. (LSND) 1997 Nucl. Instrum. Meth. A388 149–172 (Preprint nucl-ex/9605002)
- [41] Athanassopoulos C et al. (LSND) 1996 Phys. Rev. Lett. 77 3082-3085 (Preprint nucl-ex/9605003)
- [42] Aguilar A et al. (LSND) 2001 Phys. Rev. D64 112007 (Preprint hep-ex/0104049)
- [43] Church E D, Eitel K, Mills G B and Steidl M 2002 Phys. Rev. D66 013001 (Preprint hep-ex/0203023)
- [44] Aguilar-Arevalo A A et al. (The MiniBooNE) 2007 Phys. Rev. Lett. 98 231801 (Preprint 0704.1500)
- [45] Aguilar-Arevalo A A et al. (MiniBooNE) 2008 Phys. Rev. D78 012007 (Preprint 0805.1764)
- [46] Aguilar-Arevalo A A et al. (MiniBooNE) 2008 ArXiv:0812.2243 (Preprint 0812.2243)
- [47] de Water R V Talk at Neutrino 2010, Athens, Greece
- [48] Aguilar-Arevalo A A et al. (The MiniBooNE) 2010 Phys. Rev. Lett. 105 181801 (Preprint 1007.1150)
- [49] Antonello M (ArgoNeuT and MicroBooNE) 2010 AIP Conf. Proc. 1222 257-261
- [50] Vahle P Talk at Neutrino 2010, Athens, Greece
- [51] Takeuchi Y Talk at Neutrino 2010, Athens, Greece
- [52] Arnaboldi C et al. 2003 Phys. Rev. Lett. 91 161802
- [53] Bonn J et al. 2001 Nucl. Phys. Proc. Suppl. 91 273-279
- [54] Lobashev V M et al. 2001 Nucl. Phys. Proc. Suppl. 91 280-286
- [55] Doe P Talk at Neutrino 2006, Santa Fe, NM
- [56] Osipowicz A et al. (KATRIN) 2001 ArXiv:hep-ex/0109033 (Preprint hep-ex/0109033)
- [57] Nucciotti A and Collaboration f t M 2010 (Preprint 1012.2290)
- [58] Monreal B and Formaggio J A 2009 Phys. Rev. D80 051301 (Preprint 0904.2860)
- [59] Lesgourgues J and Pastor S 2006 Phys. Rept. 429 307-379 (Preprint astro-ph/0603494)