PROCEEDINGS OF SCIENCE

Neutrino Physics - Results

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Recent results of measurements of the properties of massive neutrinos are presented.

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1. What We've Learned Over the Past $\sim$ Decade

Over the past ten years, the evidence for neutrino mass and mixing has gone from suggestive to compelling to convincing. Based on experimental evidence from atmospheric, solar, reactor, and accelerator neutrinos we now believe that neutrinos are created in weak interaction (flavor) eigenstates (ν_e,ν_μ,ν_τ), but that these flavor eigenstates are superpositions of physical or 'propagation' eigenstates (ν_1,ν_2,ν_3). As the neutrinos propagate, the different masses of the physical states leads to interference: a detector far away from the production site may observe flavors not present in the initial beam. To date, the results of all neutrino oscillation experiments are individually well-described by just two-flavor oscillation, which in vacuum yields the familiar survival probability:

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{ij} \sin^2(\frac{1.27\Delta m^2_{ij} L}{E}) \tag{1.1}$$

where α is the flavor of the initial neutrino produced in the weak interaction, and i and j are the indices indicating the propagation states. The Standard Model of course assumes that the physics is actually described by three-flavor mixing, as is found in the quark sector:

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \tag{1.2}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

We have thus added at least seven new independent parameters to the Standard Model: three mixing angles (θ_{12},θ_{23}, and θ_{13}), a phase δ which can lead to CP violation, and of course three new masses. The oscillation experiments can only measure the mass differences shown in Equation 1.1, and therefore we can treat the three new masses as two signed Δm^2s and one global offset.

Measurements with atmospheric neutrinos [1] have taught us that θ_{23} is large, and perhaps maximal (45°). Phenomenologically, this means that a broadband beam which starts out as all ν_μ (for example) will later on average be half ν_τs—not too bad a way to make a lot of tau neutrinos. The mass difference between the second and third mass eigenstates, Δm^2_{23}, is $\sim 2.5\times10^{-3}\text{eV}^2$. We do not yet know the sign of Δm^2_{23}; it could be that the ν_3 is lighter than the ν_2.

Solar neutrino experiments [2, 3] have found that θ_{12} is large, but clearly not maximal: $\theta_{12} \approx 33^\circ$, and that Δm^2_{12} is much smaller than Δm^2_{23}: $\Delta m^2_{12} \approx 8\times10^{-5}\text{eV}^2$. Unlike the atmospheric neutrino sector, we do know the sign of Δm^2_{12}—the ν_2 is heavier than the ν_1.

The third mixing angle, θ_{13}, has not yet been measured. The best limits to date [4] show it to be much smaller than the other two mixing angles: $\theta_{13} < 12^\circ$. The large difference between Δm^2_{23} and Δm^2_{12} also means that $|\Delta m^2_{13}| = |\Delta m^2_{23} - \Delta m^2_{12}| \approx |\Delta m^2_{23}|$. As the only 'small' angle of the three neutrino mixing angles, θ_{13} is particularly important because its size will determine whether Standard Model-like CP violation will be observable by forseeable long-baseline accelerator neutrino experiments.

Figure 1 depicts the current state of our knowledge about the neutrino masses and mixtures. In the 'normal' hierarchy, the ν_3 is assumed to be the heaviest of the three, while in the 'inverted' hierarchy it is the lightest. Our small-mixing bias from the quark sector tends to make us think that the inverted hierarchy is somewhat unnatural: a ν_3 should be mostly ν_τ, and therefore like the

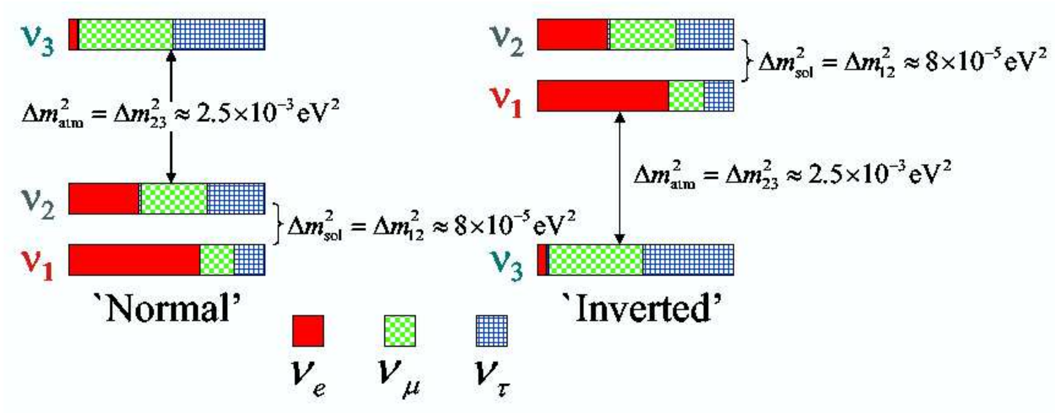

Figure 1: Mass-squared differences and mixing of the neutrinos.

τ itself we might think it is the heaviest of the three. But as can be seen in the figure, the large mixing in the neutrino sector makes none of the three states predominantly ν_τ—the ν_3 is roughly half ν_μ and half ν_τ. The small admixture of ν_e in ν_3 is the result of the size of θ_{13}. In addition to not knowing the arrangement of the masses, we also do not know the overall mass scale—the oscillation experiments tell us only about mass differences. Direct searches looking at tritium beta decay [5] have so only given us upper limits on the mixed sum of the neutrino masses:

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2} < 2.3\mathrm{eV}$$

while cosmological limits, which are somewhat model-dependent, limit the direct sum [6]:

$$\sum_{i=}^{3} m_i < 1.0\mathrm{eV}.$$

2. So What?

Neutrinos have mass—doesn't that just make them more like the rest of the fundamental fermions? Not quite. There are several reasons why neutrino mass and flavor transformation are interesting.

The first is the great gulf that lies between the lightest charged fermion, and the heaviest that the heaviest neutrino could possibly be: almost six orders of magnitude. And if the lightest neutrino has mass far less than 1 eV, then this 'desert' extends almost another two orders of magnitude. Our understanding of mass generation via the Higgs mechanism makes this at least a little suspicious: why should the neutrino couplings to the Higgs be so much smaller than that of the rest of the particles? It raises the question whether there is some additional mechanism responsible for neutrino mass, which tends to give us observable tiny masses. Such a mechanism may likely connect the low energy neutrino world we see with a much higher energy scale which we have yet to explore.

Neutrino mass also requires us to make fundamental changes to the Standard Model Lagrangian. If neutrinos are Dirac particles like the electron, then we must add a mass terms like

$L \sim m_D \overline{\nu_L} \nu_R$. Unlike the electron, however, the right-handed singlet ν_R has no other interactions than those which give the neutrino mass—it is a nearly 'useless' field, existing only because it must be there for neutrinos to be massive. By contrast, the singlet e_R interacts electromagnetically, and the right-handed quarks do so via the strong interaction as well. On the other hand, the absence of neutrino charge means that massive neutrinos can be Majorana particles, in which there are no distinct neutrinos and antineutrinos but only right- and left-handed states. In that case, we would add terms like $L \sim m_M \overline{\nu_R^c} \nu_R$ to the Standard Model Lagrangian. The idea that neutrinos are Majorana particles is particularly exciting because it allows the addition of two new CP-violating phases to the mixing matrix. The 'Majorana CP' phases, along with several other assumptions about the heavier mass scale responsible for the small observed neutrino masses, may explain the origin of the matter/antimatter asymmetry through leptogenesis. The argument which leads to leptogenesis is complex and based on several assumptions (including the idea that neutrinos are Majorana particles), but it currently may be the leading candidate to explain the preponderance of matter over antimatter in our Universe. Perhaps most important in this discussion is the fact that we do not know which hypothesis—Majorana or Dirac—is correct. We do not even have a guiding principle to favor one over the other. With the discovery of neutrino mass, we therefore no longer have a *standard* model per se, but multiple models which can only be distinguished by experiment.

The weak coupling of neutrinos to matter also means that neutrino oscillations are a unique way of searching for new interactions. Neutrino oscillations are fundamentally an interferometric phenomenon, and as such they let us observe tiny things—like the neutrino masses themselves—which otherwise might impossible to see. As an interferometer, neutrino oscillations are sensitive to any flavor non-diagonal process. Perhaps the canonical example is the matter or MSW (Mikeheyev-Smirnov-Wolfenstein [7, 8]) effect. When neutrinos propagate through matter, ν_es couple to electrons via both charged- and neutral-current channels, while the other flavors have only neutral current interactions. We can treat this additional interaction as just the addition of a potential term in the Hamiltonian, so that

$$H = H_f + H_w$$

and

$$\langle \nu_e | H_W | \nu_e \rangle = \sqrt{G_f N_e}$$

where N_e is the number density of electrons in the medium through which the neutrinos pass. The potential term leads to new 'matter eigenstates' which are mixtures of the flavor eigenstates

$$|\nu_{1m}\rangle = \cos\theta_m |\nu_e\rangle - \sin\theta_m |\nu_\mu\rangle \tag{2.1}$$

$$|\nu_{2m}\rangle = \sin\theta_m |\nu_e\rangle + \cos\theta_m |\nu_\mu\rangle \tag{2.2}$$

with mixing angle

$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2} G_F N_e}.$$

We notice that the denominator can be zero for certain values of N_e, and hence not only do we have an interferometer but a resonant interferometer. Any interaction which couples differently to the flavor eigenstates can have the same resonant behavior. Thus by studying neutrino oscillations, we may find other interactions whose coupling may be tiny but whose effects on neutrino oscillations is great.

There is one further reason why the results of the neutrino sector are worthy of attention. In addition to the observations of oscillations in the solar and atmospheric sectors, the LSND short-baseline accelerator experiment also sees a strong oscillation signal—roughly a 4σ result for the appearance of $\overline{\nu_e}$s using $\overline{\nu_\mu}$s produced by stopped πs [9]. What is particularly interesting about this result is that the energy and baseline of the experiment correspond to a Δm^2 much larger than either Δm^2_{12} or Δm^2_{23}—we thus cannot 'fit' the oscillation into the already-known pattern of neutrino masses. Given the restriction that there are only 3 light, active neutrino flavors, we must conclude that either the oscillation seen by LSND involves a fourth, non-interacting (sterile) neutrino, that something even more exotic is going on, or that LSND's observation is the result of something which has nothing to do with neutrino physics.

3. Today's Experimental Goals

The exploration of the new neutrino sector has several well-defined goals, partly driven by the need to fill in the unknowns of the model, and part by the expectation that the neutrino sector, which has already brought us surprises, may likely bring us more.

3.1 Measure the Mixing Parameters

The continued measurement of the known mixing parameters: θ_{12}, θ_{23}, Δm^2_{12} and Δm^2_{23} is needed if we are ultimately going to be able to search for new physics in the neutrino sector through precision measurement. More importantly, we would like measurements of the two remaining unknowns, the angle θ_{13} and the Dirac CP phase δ. As discussed above, we have yet to observe any direct evidence of three-flavor mixing, in which all three mass eigenstates participate. To do so, we need θ_{13} to be large enough—greater than about 2°. A value of θ_{13} this big or bigger also allows us to observe CP violation with accelerator beams by measuring the asymmetry:

$$A_{\rm CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})}.$$

θ_{13} is important here because at the 'atmospheric' baseline (which is what accelerator experiments typically run at) it controls the appearance of ν_e's in a ν_μ beam.

3.2 Test the Oscillation Model

The model of neutrino flavor transformation is based in large part on our extensive knowledge of mixing in the quark sector. Nevertheless, it is nothing more than a model, and has yet to be tested in any kind of detail. The model has many testable predictions and assumptions: the L/E dependence of the neutrino survival probability in vacuum, the changes to the survival probability when neutrinos propagate through matter, the universality of the parameters (phase, angles, and Δm^2's), and unitarity.

3.3 Resolve the Mass 'Hierarchy'

As discussed above, we do not yet know whether the ν_3 is heavier or lighter than the other two neutrino states. The sign of the mass hierarchy has important implications for the prospects of observing the Majorana nature of neutrinos through the detection of neutrinoless double-beta decay.

3.4 Determine the Magnitude of at Least One m_ν

A measurement of one neutrino mass, along with the Δm^2's we already know (and the sign of the mass hierarchy), would give us the entire neutrino mass spectrum. The absolute scale of neutrino mass would also give us insights into the role neutrinos played in the early Universe.

3.5 Demonstrate the Majorana or Dirac Hypothesis

As discussed in Section 2, perhaps the single most important question in neutrino physics is whether neutrinos are Dirac or Majorana particles. Without knowing which, we do not have a complete Standard Model.

3.6 Resolve the LSND Anomaly

If the LSND results are correct, they very likely point to completely new neutrino physics. Determining whether this is true is a very high priority—it could open up a whole new realm of particle physics accessible at even low energies.

3.7 Use Neutrinos as Astrophysical Probes

Like photons, neutrinos can travel directly to us over great distances. But unlike photons, they are almost unaffected by the interstellar medium, or even the envelope of matter in which they are produced. We have already seen that with our new understanding of neutrino oscillations we can now determine that the Standard Solar Model is correct—a start on the road toward using neutrinos as astrophysical tools.

3.8 Look for the Unknown

We have been surprised many times by neutrinos, and we need to bear in mind that we have only begun to understand them in any details. We should continue to be open to unexpected physics as we begin looking more carefully.

4. Recent Results from the Solar Sector

4.1 The Sudbury Neutrino Observatory

The Sudbury Neutrino Observatory (SNO) is a heavy water (D_2O) Cherenkov detector, located $\sim$2 km underground in INCO, Ltd.'s Creighton Mine. SNO's primary aim is the observation of solar neutrino flavor transformation through the inclusive appearance of ^{8}B solar neutrinos: the number of ν_e's detected through charged-current (CC) interactions is compared to the count of all flavors through neutral-current (NC) interactions. Specifically, SNO observes neutrinos three ways:

$$\nu_x + e^- \rightarrow \nu_x + e^- \qquad \text{(ES)}$$
$$\nu_e + d \rightarrow p + p + e^- \qquad \text{(CC)}$$
$$\nu_x + d \rightarrow p + n + \nu_x \qquad \text{(NC).}$$

The elastic scattering (ES) reaction proceeds through both charged-current and neutral-current channels.

SNO is run in three phases, each of which differs in its sensitivity to the NC reaction. In Phase I, the detector was run in its simplest configuration, with no loading of the D_2O target. The neutrons in this phase were detected via their capture on deuterons and the subsequent release of a 6.25 MeV γ-ray. Although the neutron detection efficiency was low ($\sim$14%) the advantage was a very simple detector and consequently a 'clean' measurement. In Phase II, 2 tons of NaCl were added to the D_2O volume. The added Cl provided a much higher capture efficiency—more than three times higher—as well as an improved ability to distinguish the Cherenkov light created by CC- and ES-generated electrons from that generated by the neutron capture. The discrimination was the result of the fact that the neutron capture on Cl produces multiple γ-rays, and hence the detector hit pattern was noticeably more isotropic than that expected for a single Cherenkov electron. Phase III, which is proceeding now and will last until January 2007, the NaCl has been removed and an array of discrete ^{3}He proportional counters have been added, making SNO a hybrid detector. The ^{3}He counters have a high neutron capture efficiency, but most importantly they provide event-by-event NC and CC/ES separation.

Figure 2 summarizes the results for the measurement of the neutrino fluxes for SNO's first two phases, compared to previous solar neutrino experiments and the predictions of the Standard Solar Model (here normalized to 1.0 for all energies). We can see that there is a clear excess of events measured with the NC reaction over the other two, and that the prediction of the Standard Solar Model for the ^{8}B solar flux is in excellent agreement with the measurements of both Phase I and Phase II. The most recent flux results from SNO [2], which are based on the full 391-day data set with NaCl added to the heavy water, are:

$$\Phi_{CC} = 1.68^{+0.06}_{-0.06}(\text{stat})^{+0.08}_{-0.09}(\text{syst}) \qquad (4.1)$$
$$\Phi_{ES} = 2.35^{+0.22}_{-0.22}(\text{stat})^{+0.15}_{-0.15}(\text{syst}) \qquad (4.2)$$
$$\Phi_{NC} = 4.94^{+0.21}_{-0.21}(\text{stat})^{+0.38}_{-0.34}(\text{syst}) \qquad (4.3)$$
$$(4.4)$$

in units of $10^6 \nu \text{cm}^{-2}\text{s}^{-1}$. In extracting the three signals from the data for these results, no assumptions have been made about distortions to the ^{8}B neutrino spectrum—the advantage of the NaCl is that it allows separation of the neutron and electron signals without using energy spectrum information. For comparison, the Standard Solar Model prediction [10] for the total solar ^{8}B neutrino flux in the same units is

$$\Phi_{^8\text{B}} = 5.82 \pm 1.34. \qquad (4.5)$$

As discussed in the previous section, the new neutrino model makes other predictions for solar neutrinos besides the suppression of the ν_e flux. At high energies, we expect the survival probability to be suppressed due to the MSW effect, but at low energies we should be dominated

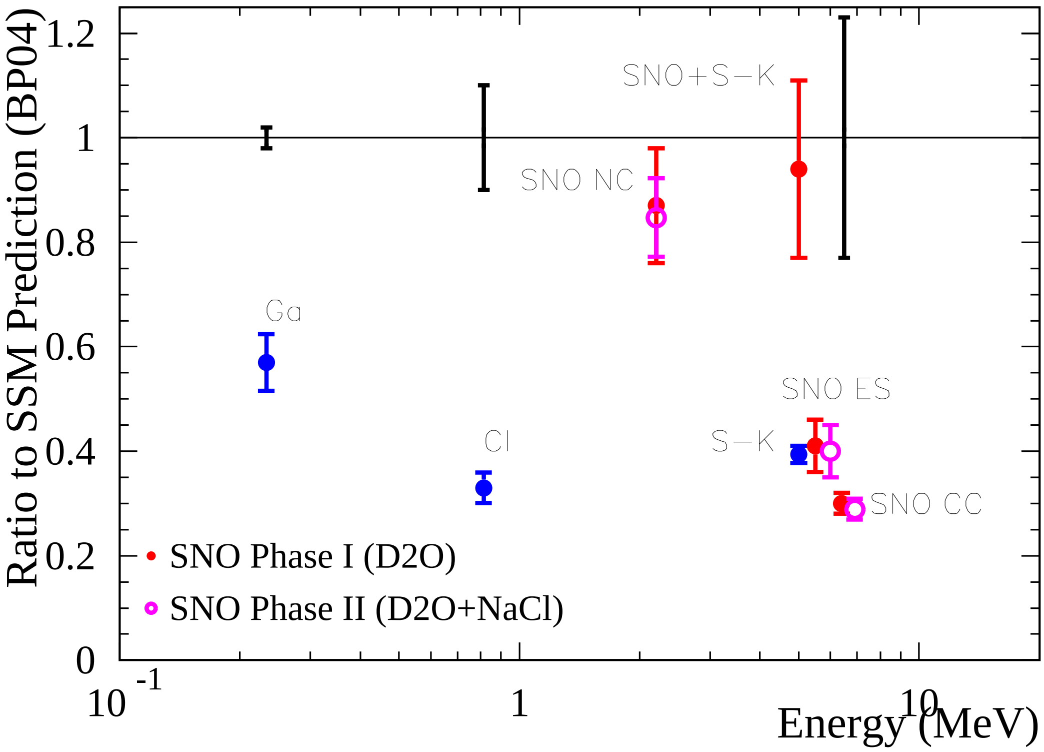

Figure 2: Solar neutrino flux measurements relative to Standard Solar Model predictions.

by simple vacuum oscillations. There should therefore be a 'transition region' between the matter-dominated and vacuum-dominated regimes, which occurs somewhere between 1-5 MeV, where we should see the survival probability rise from its high energy value of about 0.3 to a value above 0.5. In addition, for some values of the mixing parameters, we may see an effective regneration of the ν_e flux at night, when the neutrinos pass through the Earth on their way to SNO. The most recent results from SNO show neither of these two effects—the spectrum above an effective kinetic energy threshold of $T_{\rm eff} = 5.5$ MeV is consistent with an undistorted ^{8}B shape and the Day/Night asymmetry,

$$A_{ND} = \frac{2\phi_N - \phi_D}{\phi_N + \phi_D}$$

is consistent with zero.

SNO has also recently published its first search for periodicities in the solar neutrino flux [11]. There have been claims of periodic signals in the Super-Kamiokande data sets [12], though these have been contradicted by studies done by the Super-Kamiokande Collaboration [13]. SNO's new search uses both binned and unbinned methods to search frequencies in the range 1/day to 1/10 years, and sees no evidence of a period signal. A check for the the effects of the Earth's orbital eccentricity produces a signal just 1.7σ above flat.

4.2 Super-Kamiokande

Super-Kamiokande (Super-K) is a 50kT water Cherenkov detector, which observes solar neutrinos through the elastic scattering reaction. Beginning in December 2002, Super-K has been running with a much lower photocathode coverage ($\sim$ 19%) than their nominal 40% coverage, due to an accident which destroyed roughly half the PMTs. The lower coverage has required them to raise their energy threshold from a total electron energy of 5.0 MeV to 7.0 MeV. With a 622-day data set, the Super-K II preliminary measured ^{8}B flux is

$$\Phi_{ES} = 2.36^{\pm 0.06}(\text{stat})^{+0.16}_{-0.15}(\text{syst}) \tag{4.6}$$

in units of $10^6 \nu \text{cm}^{-2}\text{s}^{-1}$ [14]. This flux is in excellent agreement with the lower threshold 1496-day measurement from S-K I [15],

$$\Phi_{ES} = 2.35^{\pm 0.02}(\text{stat})^{\pm 0.08}(\text{syst}). \tag{4.7}$$

(4.8)

The Day/Night asymmetry measurement by Super-K II is also in agreement with the Super-K I results. Their new asymmetry measurement is

$$A_{DN} = 0.014 \pm 0.049(\text{stat.})^{+0.024}_{-0.025}(\text{sys.})$$

and is also consistent with zero asymmetry [14].

Super-K's latest spectral measurement shows no noticeable distortion of the ^{8}B spectrum [14], though at the higher threshold they have somewhat reduced sensitivity to the MSW expectations. However, the work done to understand the detector and backgrounds in the current configuration has opened the possibility of lowering the energy threshold in the future.

4.3 All Solar Data

The combination of all solar neutrino data, including the Chlorine and Gallium experiments, the SNO and Super-Kamiokande spectra and Day/Night measurements, have provided restrictive limits on our knowledge of the mixing parameters, in particular on the mixing angle θ_{12}. Based on the solar experiments alone, the best fit values are $\Delta m^2_{12} = 6.5^{+4.4}_{-2.3} \times 10^{-5}$ and $\tan^2 2\theta_{12} = 0.45^{+0.09}_{-0.08}$ [2].

It is unfortunate that this best-fit point is one of the very few places in the entire $(\Delta m^2_{12}, \theta_{12})$ plane in which neither of the two explicit signatures of the MSW effect—a low-energy rise in survival probability and a Day/Night asymmetry—would be seen by current experiments. To see one of these effects, either significant additional statistics need to be taken, the energy threshold of the ^{8}B experiments needs to be lowered, or a new spectrally-sensitive low energy solar experiment will have to be built.

4.4 KamLAND: Back to the Vacuum

The best-fit values for the mixing parameters based on solar neutrino data are derived under the hypothesis that the MSW effect is responsible for the measured neutrino survival probabilities at the high energy end of the solar neutrino spectrum. If this hypothesis is correct, and the oscillation model is an accurate description of neutrino flavor transformation, then the same parameters predict that the vacuum survival probability for neutrinos of reactor energies $E \sim 4$MeV should have an oscillation length of $\sim$ 100km.

	Reactor	Solar
Energy	2-10 MeV	0.1-15 MeV
Baseline	$\sim$ 150 km	1.5×10^6km
MSW	No	Yes
ν	$\overline{\nu_e}$	ν_e

Table 1: Comparison of the solar neutrino regime with the intermediate-baseline reactor antineutrino regime explored by KamLAND.

The KamLAND experiment, located in the same Kamioka mine as Super-Kamiokande, was built to be sensitive to exactly this intermediate-baseline vacuum oscillation. KamLAND is a liquid scintillator detector, and its location places it at the appropriate average distance from Japan's many nuclear reactor sites to see a substantial disappearance signal.

The first measurements from KamLAND [16] showed the expected disappearance signature with a significance of 99.998%, and the most recent KamLAND results [3] also show the energy spectrum distortion expected for vacuum oscillations. The combination of both rate and spectral shape information has a significance for oscillations at the 99.999995% C.L., and there is even a fairly convincing indication that they can see the expected L/E oscillatory behavior—the data show a rise from a minimum to a maximum and back to a minimum, but they do not yet have the sensitivty to see the full oscillation wavelength.

The KamLAND results are therefore the first precision test of the Standard Model modified to include neutrino oscillations. Few if any other models of neutrino flavor transformation would expect the exact same parameters to describe the measurements by both solar experiments and terrestrial reactor experiments. Table 4.4 compares the relevant differences between the two physical regimes studied by these experiments.

The mixing parameters measured by KamLAND alone [3] are $\Delta m^2_{12} = 7.9 \times 10^{-5}\text{eV}^2$ and $\tan^2\theta = 0.46$.

4.5 Solar Sector Summary

Including the KamLAND results, and assuming CPT invariance so that the antineutrinos of KamLAND and the solar neutrinos have the same mixing parameters, the best fit values become restrictive [2]: $\Delta m^2_{12} = 7.9^{+0.6}_{-0.5} \times 10^{-5}\text{eV}^2$, and $\tan^2\theta = 0.40^{+0.10}_{-0.07}$. Maximal mixing in the solar neutrino sector is thus excluded at greater than the 5σ level.

5. Recent Results from the Atmospheric Sector

5.1 Super-Kamiokande

Super-Kamiokande observes the oscillations of atmospheric neutrinos primarily by looking at the zenith angle ($\cos\theta_z$) dependence of the detected flux of ν_μs in several bins of E_{lepton}, the energy of the outgoing lepton produced when the neutrinos interact within or outside the detector. The energy bins are defined in part by the event topology. 'Fully contained' events, in which the neutrino interacts within the detector and the produced lepton ranges out without leaving, correspond to neutrino energies around 1 GeV. 'Partially contained' events where the lepton leaves the detector and 'stopping muons' in which the interaction occurs outside the detector but the resultant muon ranges out inside the fiducial volume, correspond to neutrino energies of roughly 10 GeV. 'Through-going' muons, which are due to neutrino interactions in the rock surrounding the detector and which produce muons which travel across and back out of the detector, correspond to the highest energies, above about 100 GeV. Super-K also divides the data set into μ-like and e-like events based upon the characteristic of the observed Cherenkov cone.

Super-K's results therefore span orders of magnitude in energy and a large range of baselines (from short-baseline downward-going events to very long baseline upward-going events). Their results agree with great precision with the expectations of the oscillation of ν_μs into ν_τs, over the entire range of observations [1]. The data from 627 days of Super-K II, with the reduced photocathode coverage, are consistent with the results of the 1489-day Super-K I data set [14].

The need to look at zenith-angle distributions is driven in part by the fact that the direction of the produced outgoing lepton from the neutrino interactions is not necessarily co-linear with the neutrino direction. Nevertheless, a selected set of events is fairly co-linear, and has the additional advantage of also carrying much of the energy of the incident neutrino. With this selected set, Super-K has been able to make a plot of the effective survival probability (data/prediction) in terms of L/E for ν_μs. Their preliminary results show the 'dip' at the expected first minimum of the oscillation pattern, and at the 3σ level this rules out more exotic transformation scenarios such as neutrino decoherence or neutrino decay [17]. With the data set of Super-K II, the oscillation dip is still present, albeit with somewhat more limited statistics [14].

With the success of the 'L/E' analysis, Super-K has now gone on to include a more global fit in L/E to all of their data, effectively using more information than in their previous fits for the mixing parameters. The preliminary results of the new analysis significantly narrow the allowed regions of the mixing parameters, with the best fit value of $\Delta m^2 = 2.5\times10^{-3}\text{eV}^2$, and $\sin^2 2\theta = 1.0$. The 68% C.L. contour in Δm^2 extends from roughly $2.2\times10^{-3}\text{eV}^2$ to $2.8\times10^{-3}\text{eV}^2$, and in $\sin^2 2\theta$ down to just above 0.95.

5.2 K2K

The K2K experiment is the first long-baseline neutrino oscillation experiment. The beam, created at the KEK laboratory in Japan, is aimed at the Super-Kamiokande detector in Kamioka, ~ 250 km away. To make a disappearance measurement, the beam, its energy spectrum, and the neutrino cross sections need to be known very well. K2K accomplished this normalization measurement with a near detector which combined several technologies: a water Cherenkov detector to help measure the cross sections and interaction topologies that would be seen in the far detector (Super-K), as well as more finely-grained detectors such as a lead glass calorimeter and a muon rangefinder. K2K's observations were 107 single-ring μ-like beam events in the far detector, with an expectation of 149.7 based on the near detector measurements and modeled extrapolation to the far detector. The hypothesis of no oscillation is excluded at better than the 4σ level, with the best fit $\Delta m^2 = 2.8\times10^{-3}\text{eV}^2$ and $\sin^2 2\theta = 1.0$. These results are all in excellent agreement with the mixing parameter measurements of Super-Kamiokande using atmospheric neutrinos.

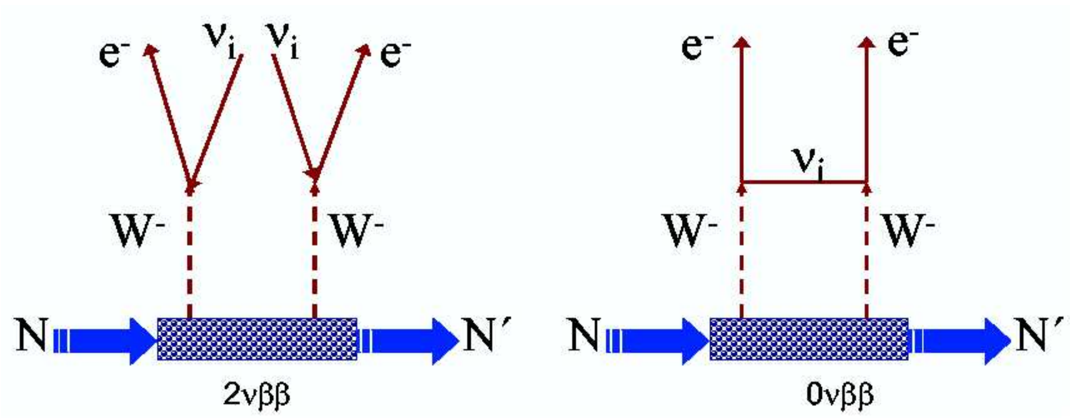

Figure 3: $2\nu\beta\beta$ and $0\nu\beta\beta$ decay.

6. Checking the LSND Anomaly

The mystery of the LSND results is now being investigated by the MiniBooNE experiment at Fermilab. MiniBooNE looks at the appearance of ν_e's in a ν_μ beam. The ν_μs are created by in-flight decay of πs produced by protons from Fermilab's booster ring. The detector is a mineral oil Cherenkov detector (with some scintillation light). The analysis is being done blindly, but they have begun looking at cross section measurements, such as production of π^0s through resonant Δ production, as well as the coherent production of π^0s off of carbon in the MiniBooNE detector's mineral oil. They are hoping to have first results sometime in the Spring of 2006.

7. Neutrinoless Double-Beta Decay

To date, the only known viable way of determining whether neutrinos are Majorana particles or not is to look for lepton-number violating processes in nuclear β-decay. For some even-even nuclei, a 'double-beta' decay can occur, with the simultaneous decay of two neutrons:

$$^A_ZN \rightarrow e^- + \overline{\nu_e} + e^- + \overline{\nu_e} + ^A_{Z+2}N$$

If neutrinos are Majorana particles, then as shown in Figure 3 *neutrinoless* double-beta decay $0\nu\beta\beta$ is also possible:

$$^A_ZN \rightarrow e^- + e^- + ^A_{Z+2}N.$$

The rate of $0\nu\beta\beta$ depends on phase space, the neutrino mass, and the nuclear matrix element. While the phase space term is relatively easy to calculate, the matrix element is very difficult, and subject to many uncertainties. Under the assumption that $0\nu\beta\beta$ proceeds due to massive Majorana neutrinos (and not some more exotic scenario), the neutrino mass upon which the rate depends is a mixed average of the known neutrinos:

$$m_\nu = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{2i\phi_1} m_3|U_{e3}|^2 e^{2i\phi_2}|$$

where ϕ_1 and ϕ_2 are the Majorana CP violating phases. We know the lowest bound on the heaviest neutrino from the atmospheric neutrino measurements: $m \geq \sqrt{\Delta m^2_{23}} \approx 50$meV, which would correspond to a $0\nu\beta\beta$ half-life of $T_{1/2} \sim 10^{27}$ years. Unfortunately, for the normal hierarchy the heaviest neutrino is ν_3 and it happens to have the smallest admixture, $|U_{e3}|^2 \sim \sin^2\theta_{13}$. To see a signal in the next generation of $0\nu\beta\beta$ experiments, we therefore hope that either the hierarchy is inverted (making ν_2 the heaviest) or that the masses are nearly degenerate. Of course, even in this case, the Majorana phases can conspire to suppress a signal.

$0\nu\beta\beta$ experiments are extremely difficult: they require large masses in order to have an appreciable signal rate, but at the same time must reduce radioactive backgrounds to extraordinarily low levels. They need excellent energy resolution in order to resolve the 0ν signal from the 2ν 'background'. In addition, to avoid theoretical uncertainties associated with calculations of the nuclear matrix element, several different nuclear species need to be used and to overcome systematic uncertainties associated with the detectors, several different technologies.

To date, there has been one claim of a $0\nu\beta\beta$ signal [18], corresponding to an effective neutrino mass of ~ 0.4 eV, but the result has yet to be confirmed.

7.1 NEMO 3

The NEMO 3 experiment, located in Frejus at a depth of 4800 meters water equivalent, is most like a standard high energy physics detector. NEMO relies heavily on tracking to dramatically reduce backgrounds associated with radioactivity, and scintillator calorimetry to provide their energy measurement. To overcome uncertainties associated with the nuclear matrix element and other systematics, they also use several different isotopes. Their most recent results [19] using 6.914 kg of ^{100}Mo and 0.932 kg of ^{82}Se show no evidence of a $0\nu\beta\beta$ signal. The limit they place on the half life for ^{100}Mo is $T_{1/2}(0\nu\beta\beta) > 4.6\times10^{23}$years with a corresponding limit on the effective neutrino mass of $m_\nu < 0.66-2.81$eV, depending on the nuclear matrix element. The ^{100}Mo limit is rouhgly an order of magnitude better than previous limits with the same nuclear species. Their limits from the ^{82}Se measurement are $T_{1/2}(0\nu\beta\beta) > 1.0\times10^{23}$years and $m_\nu < 1.75-4.86$eV, more than an order of magnitude improvement over previous ^{82}Se measurements.

7.2 CUORE

The CUORE experiment uses a very different detector, concentrating on energy resolution as the primary way of separating signal from background. The CUORE detector uses an array of bolometers with energy resolution which approaches 5 keV, built out of TeO_2 crystals which are naturally low in radioactivity. Segmentation of the array also helps in background rejection, and the depth in the Gran Sasso laboratory avoids cosmics. Their initial results, using a smaller array ('CUORICINO') than the planned final version show no evidence of a signal, corresponding to a limit on the half life of $T_{1/2}(0\nu\beta\beta) > 1.8\times10^{24}$years at the 90%C.L. [20]. In neutrino mass, the limit is $m_\nu < 0.2-1.1$eV, which can be compared to the expectation from the claim of Ref. [18] of 0.5 eV. For the same matrix element as was used in Ref. [18], the neutrino mass limit derived from the half-life limit is $m_\nu < 0.4$eV.

8. Summary

The physics of massive, mixed neutrinos is clearly moving from the discovery phase to an era of precision measurement. We are only now beginning to test the model in any detail. In addition, the advances in double-beta decay are beginning to push into interesting territory. Perhaps most importantly, we need to keep in mind that it is likely neutrinos will continue to surprise us.

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