PROCEEDINGS OF SCIENCE

Neutrino Physics

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Neutrino physics experienced an explosion of new results around the turn of the century, and is now poised for another leap with a set of new experiments in preparation. The purpose of this article, like the talk it was based on, is to provide a global context to the various neutrino projects and topics discussed at the conference and say a few words about other related projects that might help explain and motivate the interest in them. It is certainly not a global review of neutrino physics (which would require far too much space)! I have not provided references to those experiments/projects discussed at the conference, as you should look at the specific presentations by the real experts to get more information. I have provided a few references for those topics I thought important to discuss which weren't otherwise discussed at the conference.

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1. Introduction

Progress towards understanding the most fundamental constituents and interactions in Nature has been stymied in recent years by the absence of strong experimental guidance on the nature of physics beyond the Standard Model. Strong cosmological evidence for dark matter, which appears to consist of some particle not included in the Standard Model and otherwise totally unknown to science, and for the even-more mysterious dark energy, as well as the observation that the observable universe seems to consist almost exclusively of matter (the so-called baryon asymmetry of the universe, or BAU), all provide experimental proof that physics exists beyond the Standard Model, but are maddeningly unhelpful in figuring out what it is. Of course the structure of the Standard Model itself, a patched-together construct of two individually successful but not-obviously connected theories (the GSW electro-weak theory and QCD, the theory of the strong interaction) cries out for explanation at a deeper level. And then there is the problem of gravity, for which we still have no particle-physics level theory.

Despite this apparently overwhelming evidence for some deeper theoretical construct, the fact remains that the Standard Model is frustratingly successful at predicting the result of most particle physics experiments, and therefore little experimental guidance exists for where we should search for new physics. The one strong failure of the Standard Model to predict the result of a particle physics experiment is in neutrino physics. In the Standard Model of particle physics as originally constructed, neutrinos were massless, existed in only one helicity state (that is, they would always spin in the same direction with respect to their direction of travel), and possessed a conserved flavour quantum number (meaning that a neutrino produced by a weak interaction that produced, say, an electron, would only change into an electron in its subsequent weak interactions). Over the last few decades all these assumptions have been proven wrong by the discovery of the phenomenon of neutrino oscillations, whereby neutrinos of one flavour state are shown to change into another flavour state while propagating. The simplest explanation for neutrino oscillations arises from mass-mediated mixing via the Maki-Nakagawa-Sakata-Pontecorvo, or MNSP, mixing matrix[1]. The matrix connects two different sets of neutrino states:

$$\left|\nu_l\right\rangle = \sum U_{li}\left|\nu_i\right\rangle$$

where the ν_l are the weak eigenstates of the neutrinos, i.e., those states that have well-defined weak interactions (these are the ν_e, ν_μ, and ν_τ that one normally thinks of when talking about neutrinos), the ν_i are the eigenstates of the free particle Hamiltonian, i.e., the states with well-defined masses (just called ν_1,ν_2, and ν_3), and U_{li} is the MNSP mixing matrix. The usual parameterization of the matrix is given by:

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

which contains three mixing angles θ_{ij} and the CP-violating phase δ. Neutrino oscillations take place because neutrinos emitted from a weak interaction in a pure ν_l state propagate as a superposition of the different mass eigenstates. Assuming these have different masses a phase difference builds up between them, creating a different superposition of mass eigenstates at the detector and therefore an admixture of other flavours of neutrino in the beam. The most obvious effect of the CP-violating phase δ is to make the oscillations different for neutrinos and anti-neutrinos. This difference is made harder to observe by another (purely Standard Model) effect called the Mikheev-Smirnov-Wolfenstein (or MSW) effect[2], where the oscillations are affected by the interaction of the neutrinos with the electrons in matter. As matter contains electrons and not anti-electrons, the MSW effect is different for neutrinos and anti-neutrinos, a difference which must be corrected for when looking for real CP violation.

In addition to the three angles and one phase of the MNSP matrix, the other parameters which affect the oscillations are the masses of the ν_i, which determine the wavelength of the oscillations. Oscillations in a vacuum only depend on the difference in the squares of the masses, not their ordering (and the ordering is not obvious *a priori*), however the MSW effect does depend on the mass ordering and therefore matter effects (which appear at higher energies and longer distances between the source and the detector) can help determine the mass ordering. The absolute magnitude of the masses does not affect oscillations, so in order to completely understand neutrino masses and mixings we cannot rely just on oscillation experiments. We must have other experiments which are sensitive to the absolute masses, and we now turn to this subject before returning to neutrino oscillations below.

2. Determining the absolute masses of neutrinos.

The oscillation experiments discussed below give lower limits to the masses of at least two of the mass eigenstates, but they do not give useful upper limits. There are four principle means of measuring (or at least constraining) the absolute masses of neutrinos:

- Neutrinos from Supernovae. If neutrinos have mass, then their speed depends on their energy, and neutrinos emitted from core-collapse supernovae would show dispersion when detected on earth, with the energetic ones arriving first, given by:

  $$\left|\Delta t\right| = \frac{1}{2} L m_\nu^2 \frac{\left|E_1^2 - E_2^2\right|}{E_1^2 E_2^2}$$

  Observations of neutrinos from SN 1987a were used by many authors to provide limits on neutrino mass. Unfortunately, these neutrinos are emitted from a cooling proto-neutron star, giving another reason why the later neutrinos would be lower energy. Mass limits are therefore model dependent, and the PDG derives a best limit from SN 1987a of $m_\nu < 23$ eV[3]. This limit is not competitive with others given below (a recent paper claims a better limit of 5.8 eV[4], still not really competitive), and it is unlikely that future observations of galactic supernovae would make it so (this does not imply that observing supernovae neutrinos should not be a high priority, of course it should, it only means that from them we will learn about supernovae, not neutrino mass).

- Other kinematic limits. The most model-independent measurements of neutrino masses arise from kinematics. Over the years many limits were placed on the masses of the different flavour states by looking at the momenta of other particles emitted in decays which produce neutrinos, however the measurements of mass differences by oscillation experiments described below mean that only one of these is currently competitive – the measurement of the effective mass of the electron anti-neutrino derived from measurements of the energy spectra of electrons emitted in the β decay of tritium. While this method is not as sensitive as either of the two methods discussed next, it is much more robust to model uncertainties, and it yields a strong upper limit to the absolute mass of neutrinos: $m_\nu < 2$ eV (95% c.l.)[5]. More discussion will be given in section 2.1.

- Neutrinoless double-beta decay ($0\nu\beta\beta$)[6]. A number of nuclei are stable against ordinary β decay, but unstable against double-β decay. In the Standard Model this can only happen by two simultaneous ordinary β decays, with the emission of two anti-neutrinos (called $2\nu\beta\beta$). The anti-neutrinos will both be right-handed, however if neutrinos have mass there will be an admixture of the left-handed state. That would permit the right-handed anti-neutrino emitted from one decay to be absorbed as a left-handed neutrino by the neutron from the other decay – provided there is no difference between neutrinos and anti-neutrinos other than their helicity. Such neutrinos are called Majorana neutrinos, and their existence is favoured by a strong theoretical prejudice. The resulting decay would emit no neutrinos, providing an excellent experimental signature of two electrons emitted with summed energy equal to the endpoint energy of the decay, and searches for such a signature have produced the most sensitive limits on Majorana masses (as discussed in more detail in section 2.2).

- Limits from cosmology[7]. Neutrinos left over from the Big Bang are the second most numerous particles in the universe (after photons), so if they have even a small mass could have cosmological consequences. Data from both particle physics (the combination of the absolute mass limit from tritium beta decay and oscillation results) and cosmology (the existence of structure on intermediate distance scales) rule out neutrinos as the major component of the dark matter, however it is still possible that massive neutrinos provide some fraction of the missing matter. In our standard cosmology the structure (the clumpiness of matter into galaxies, clusters of galaxies, and so forth) we see in the universe today is caused by the collapse under gravity of tiny density fluctuations in the early universe. Given the known mass limits, neutrinos are relativistic in the early universe, and hence don't clump, and therefore tend to wash out structure. The observation of structure hence provides a limit to the mass of neutrinos. The good thing about such limits is that they apply to the sum of all neutrino masses (including the ones hard to produce in terrestrial experiments), the bad thing is that anything else that affects structure formation is covariant at some level with neutrino mass, and therefore such mass limits depend on our understanding of cosmological models. This will be discussed in section 2.3.

2.1 Limits from β decay.

Tritium has traditionally been the nucleus of choice for looking for neutrino mass effects in β decay. Tritium is a superallowed decay (minimizing distortions of the electron spectrum from nuclear physics effects), has a low endpoint energy of 18.6 keV (which increases the fraction of decays which are interesting, i.e., where the electron is emitted very near the endpoint, although the fraction is still incredibly small), is the lowest Z so minimizes distortions to the spectrum from atomic physics effects, and has a half-life which is long enough to simplify experimental design but short enough to give a decent specific activity to the source. The measurement is simple in principle – if the neutrinos emitted in the decays have an effective mass of m_ν, where:

$$m_\nu^2 = \sum_{i=1}^{3} \left| U_{ei}^2 \right| m_i^2$$

then the electron spectrum falls to zero a distance of $m_\nu c^2$ below the nominal endpoint energy E_0 with a characteristic shape distortion. The effect, however, is tiny (for massless neutrinos only one in 5×10^{12} of all tritium decays would have an electron within 1 eV of the endpoint), and there are many other distorting effects (experimental resolution, energy loss, atomic final state effects, nuclear shape corrections, etc.) which change the spectrum and are therefore covariant (at some level) with the neutrino mass. Between the pioneering measurements of Langer and Moffat[8] in the 1950's and the gargantuan KATRIN experiment described by Fraenkle in this volume the story has been one of steadily increasing the size of the apparatus to get more rate while improving the resolution and eliminating or measuring the other confounding effects. The field exploded in interest after the positive claims of Lyubimov in 1980[9] leading to a very large number of projects being started, few of which produced final results. As time has gone on, and the extremely difficult nature of the experiments appreciated, the number of projects has gotten smaller as the projects themselves have gotten bigger. The need to reduce or eliminate backscattering of the electrons from and energy loss in the source has caused the steady replacement of solid sources by gaseous ones, while the need for high resolution and high acceptance for electrons near the endpoint while not observing the great majority of the electrons which occur at lower energies has led to the adoption of the MAC-E hybrid magnetic-electrostatic spectrometer. KATRIN has just begun operations, and expects to eventually reach sensitivity to effective neutrino masses of the order of 200 meV.

The KATRIN collaboration consists of pretty much all of the world's experts in this area, and probably represents the culmination of this type of experiment (further improvements using this type of apparatus require the physical scaling of the apparatus, and anyone who thinks that a bigger MAC-E filter could be built is invited to consider Figure 1). The only current alternative for measuring β decay spectra with useful accuracy are attempts to build cryogenic bolometers with the source internal to the detector. The MARE collaboration[10] is trying to build bolometers to measure the decay of ^{187}Re, which has an endpoint energy of only 2.47 keV. These efforts face two very significant hurdles. First, since all decays are measured (and the detectors are not inherently fast), there is great difficulty getting enough events to see any events at all near the endpoint without ending up being dominated by pileup. This requires highly segmented detectors. The second problem is resolution, as the effects of non-zero neutrino mass only extend a few times m_ν below the endpoint, so poor would wash out any usefully measurable effect. If these two problems could be conquered there would then be issues with the rather complex shape of the rhenium spectrum and possible issues with tails on the high side of the energy resolution function causing events to leak upwards from the huge peak of low-energy decays. While published results are currently orders of magnitude away from the interesting region, these are small-scale experiments in a not mature technology so there is certainly good reason to pursue this approach.

Figure 1 The KATRIN Spectrometer is moved to the laboratory.

2.2 Limits from 0νββ decay.

Searches for 0νββ decay have yielded the most sensitive laboratory limits on neutrino mass, although of course they are only sensitive to Majorana masses. One very significant problem is that while it is relatively straightforward to convert an observed event rate (or the lack of one) into a value for the lifetime of the relevant nucleus for 0νββ decay, turning this into a limit on neutrino mass is much more problematic. The first problem arises because the "mass", m_{ee}, that enters into 0νββ decay is given by:

$$m_{ee} = \left| \sum_k U_{ek}^2 m_k \right| = \left| \sum_k U_{ek}^2 e^{i\alpha_{ek}} m_k \right|$$

where the α_{ek} are two (potentially) CP-violating phases that enter specifically for Majorana neutrinos. Thus a measurement of (or limit on) m_{ee} can only be turned into a measurement of the m_k that can be compared to results from oscillation experiments if all the other parameters are known, which they aren't. The values of U_{ek} can, in principle, be measured by the oscillation experiments discussed below, however the values of the Majorana phases are more problematic. If CP is conserved in this sector then these are limited to ±1, however even in that case there can be cancellations. If CP is not conserved then even more complex combinations are possible. Perhaps an even bigger problem arises because m_{ee} can only be derived from measurements of the lifetime if you know the matrix element, $|\Sigma M_{if}|^2$, which requires some knowledge of the microphysics of the nuclear structure in the virtual intermediate states. These matrix elements are not directly measureable, and must be calculated. Calculations have historically shown significant disagreement, and while recent results are in closer agreement (although whether this is because they are more correct or just represents intellectual phase-locking is hard to say), it is hard to see how we would be confident that they were known to better than a factor of two in the near term[11] (with a corresponding uncertainty in m_{ee}). This is particularly unfortunate, because the Majorana phases mentioned above would be even more interesting to measure than the phase δ in the MNSP matrix, and the only experimental access to the Majorana phases would come from a comparison of neutrino masses measured by kinematics or astrophysics to those seen in 0νββ decay, which would require a knowledge of the matrix elements to an accuracy sufficient to demonstrate a disagreement between the two arising from partial cancellations in m_{ee}. If 0νββ decay ever were observed there would hopefully be a substantial theoretical assault to reduce the uncertainties in our knowledge of $|\Sigma M_{if}|^2$ (and increase our confidence in their quantification).

There are two basic experimental variants in the search for 0νββ decay. In the first, the nuclei being checked for ββ decay are placed in a thin source with detectors on either side to look for the emission of two electrons with the correct summed energy. In the second, the nuclei are actually incorporated into the detector. Each method has its advantages and disadvantages. The first method allows both electrons to be tracked and identified as electrons, suppressing many backgrounds and providing confirmation of their origin in ββ decay by the observation of their angular distributions and energy spectra. At least in experiments performed so far (and planned for the near future), the second method has the advantage of allowing much better energy resolution and larger source masses, with the possibility of scaling to much larger source masses. So far the battle between the two techniques would have to be considered as roughly a draw. The separated source-detector technique allowed the first observations of the Standard Model-allowed 2νββ decay mode (which requires neither neutrino mass nor Majorana neutrinos) in the pioneering experiments of Elliott et al.[12], and the best measurements of this mode are still being made by this method (see the article about the NEMO 3 experiment by

Beillet-Kovalenko in this volume). However the lumped source-detector method has yielded the best limits on 0νββ decay (see the articles on Germanium experiments by Brugnera and on CUORICINO/CUORE by Guardincerri). There are plans for upgrades to all these experiments, but if 0νββ decay continues to elude us after the next round of experiments (like the Super NEMO, GERDA, and CUORE experiments discussed in the other articles in this volume mentioned above), it would appear that the better energy resolution (which is necessary to discriminate against the high-energy tail from the 2νββ decay mode) and larger source masses (which will be necessary just to get any events) of the second technique will win out in the longer term. In the longest term it would be good to combine the tracking of the first method with the energy resolution and source size of the second, which may require the development of entirely new types of detectors (such as those pursued by the COBRA collaboration[13], which was not discussed in Kracow).

2.3 Limits from astrophysics.

As mentioned above the interpretation of observed structure in the distribution of galaxies in the cosmos is sensitive to neutrino mass. However one has to be very careful in moving from a clear sensitivity of an observational distribution to one input parameter to a statement that observations of that distribution are a good way to measure that parameter. Most scientists, for instance, believe that the mean surface temperature of the earth is highly sensitive to the carbon dioxide content of the atmosphere, however that does not mean that measurements of the mean surface temperature of the earth would be a good way to determine the level of atmospheric carbon dioxide. Difficulties arise when the models connecting the parameter to the distribution are potentially complex and have many other covariant parameters. The confidence one assigns to cosmological limits (or measurements) of neutrino mass depends strongly on how much confidence you assign to the idea that the universe can be accurately described by a model with only a handful of parameters (less than 10 in most current models), and that one can handle the systematic uncertainties that arise when combining the very different data sets used to constrain structure on different scales (no one data set constrains structure over a wide enough range of scales to make a sensitive determination of neutrino mass). One of the most troublesome parameters is the bias (the extent to which the luminous matter which we see traces the distribution of the dark matter which we don't), a topic discussed at the conference by Pollo (see the paper in these proceedings). There were no talks on cosmological neutrino mass itself, however there are recent papers with a tabulations of limits[14,15]. These limits are derived in a standard model where the energy density of the universe is dominated by a combination of cold dark matter and a cosmological constant (a ΛCDM model) applied to various data sets with slightly different assumptions, with the resulting 95% c.l. limits (for the sum of all three neutrino masses) varying from 0.17 eV to 2.4 eV. However other papers relaxing some of the assumptions[16] or using other data sets[17] actually claim evidence for non-zero neutrino mass, so the final answer is not yet in.

Clearly the best situation would be if neutrino masses could be determined by terrestrial experiments, which would allow the cosmological data to be used to constrain cosmological physics which cannot even in principle be measured on earth. However if neutrinos are Dirac particles it is hard to see what terrestrial measurement would ever be able to achieve absolute mass sensitivity significantly better than KATRIN, as is claimed for future (and even some current) cosmological determinations. We therefore may have to rely on cosmological determinations. In that situation it will become even more important that the model dependencies and systematics of these determinations be rigorously quantified. Recent papers show that progress is being made in this direction, however there is still quite a gap between the level of systematic rigor which the community requires in an experiment such as KATRIN and that displayed in the cosmological papers. For instance it is routine to hear commentators look over a list of limits as displayed in arXiv:0809.1095v1 and say the "best" limit is the smallest one, i.e., $\Sigma m_\nu < 0.17$ eV, when a particle physicist would conclude that if all the models were reasonable and all the data sets valid, the "best" limit on neutrino mass would be the most conservative, or 2.4 eV.

3. Neutrino mixing and oscillations.

The MNSP matrix is analogous to the CKM matrix which parameterizes mixing in the quark sector (the MNSP matrix actually predates it). The importance which we attach to the CKM matrix can be seen in the huge number of experiments over the years which have been done to measure its parameters, the (at least) four Nobel Prizes arising from it, and the vast array of theoretical papers exploring its significance and attempting to explain its values. The MNSP matrix is just as interesting, and for the same reasons – its parameters are either fundamental constants of nature, or (more likely) the consequence of exactly the kind of beyond-the-Standard-Model physics which we are desperate to probe (see the talks by Feruglio, Malinsky, and Hernández). In addition, CP violation in the MNSP matrix may be related (in an unfortunately model-dependent way, see the talk by Molinaro) to physics at higher scales that could give rise (via a mechanism called leptogenesis) to the observed baryon asymmetry of the universe, one of those mysteries left unexplained by the Standard Model. To completely constrain the MNSP matrix you would need to measure all three angles, the phase, and the masses (which ought to be three mass parameters, but turns out experimentally to be five parameters – two mass squared differences, their signs, and the overall mass scale discussed above). Of course to test the model you would like to overconstrain these parameters with multiple distinct measurements of each one. Of these numbers we have measured two of the angles, the two mass squared differences and the sign of one of them, leaving only limits for the third angle and the mass scale and no information at all about the sign of the other mass squared difference and the phase (see Fig 2). We therefore need experiments targeted on the so-far unobserved effects of those unknown parameters, all of which except the mass scale are measurable using neutrino oscillations. Let me now go through some of the different types of neutrino oscillation experiments which were discussed at the conference and comment on where we are and what the future might hold.

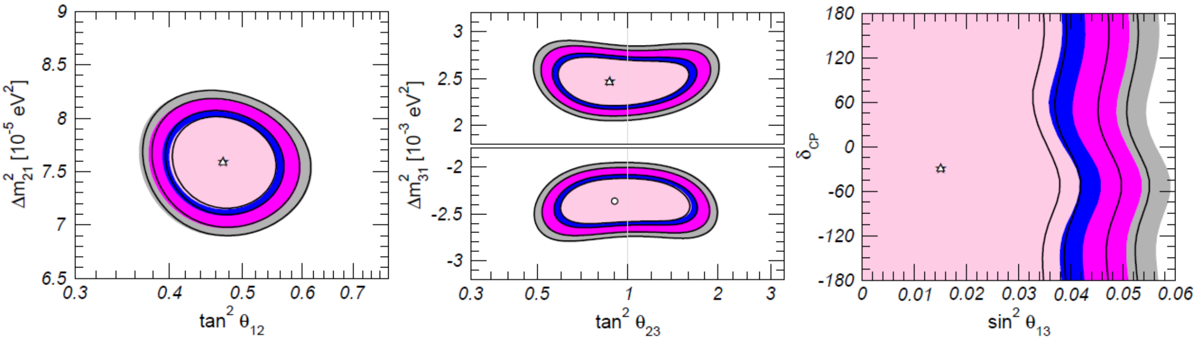

Figure 2 Limits on neutrino mixing parameters derived from a global fit to the available data (adapted from Figure 9 in ref. 18).

3.1 Solar and Atmospheric Neutrinos.

The furthest plot to the left in Figure 2 quantifies the output of the many decades of experimental work on solar neutrinos, starting with the pioneering Homestake ^{37}Cl experiment[19] and the first observations of neutrino-electron scattering in Kamiokande[20], moving through the

SAGE[21] and GALLEX/GNO[22] ^{71}Ga radiochemical experiments, the even more precise measurements of neutrino-electron scattering in Super Kamiokande[23], and then the separate measurements of the ν_e and total ν fluxes in the SNO experiment[24]. That might seem like a lot of experiments for that one plot (and in reality only the x-axis of the plot is due to solar neutrinos, as the constraints on the y-axis arise from the KamLAND experiment to be discussed in the next section), however it was the observed deficit in the Homestake experiment which launched the field of neutrino oscillation measurements, the Kamiokande experiment which showed that the deficit seen at Homestake was real, and the gallium experiments which removed any credible astrophysical explanation and left neutrino oscillations as Occam's choice. Meanwhile the IMB[33] and Kamiokande[34] experiments gave indications of a similar problem in atmospheric neutrinos, further measurements of which by the Super Kamiokande experiment[35] derived the first clear demonstration of neutrino mass with a zenith-angle dependent disappearance of muon neutrinos that indicated near maximal mixing. The SNO experiment then gave the first demonstration of neutrino flavour change (one of the key predictions of neutrino oscillations), setting the stage for the KamLAND[25] experiment to finally apply the coup de grace to models other than neutrino oscillations.

The only report in Kracow from these areas was Misiaszek's report on results from Borexino. Borexino measures the low-energy ^{7}Be neutrinos, which is particularly interesting because of their ability to explore matter effects in solar neutrino oscillations. Note that the left hand plot in Figure 2, which comes mainly from solar and reactor experiments, has only a single solution for $\tan^2\theta_{12}$, while the centre plot from atmospheric and long-baseline experiments is almost symmetric around $\tan^2\theta_{23}=1$. That is because the sign of the mass-squared difference (which corresponds to whether θ is greater or less than 45°) is only known if matter effects are observed, which is true for solar neutrinos but not (so far) for atmospheric or long-baseline neutrinos. The solution implied by solar and reactor measurements requires a matter-enhanced oscillation for the higher-energy solar neutrinos, with a vacuum oscillation for the lower-energy neutrinos (which see a smaller suppression). The ^{7}Be neutrinos observed by Borexino sit on the transition between the two, and therefore provide a nice test of the model. So far the observations have slightly too large errors to really demonstrate the transition, however with more work on calibrations reductions in the systematics should allow Borexino to provide a strong test of the MSW solution for solar neutrinos.

3.2 Reactor Experiments

Reactor neutrino oscillation experiments have a long history, however for many years they only provided limits on oscillation parameters as they failed to see any sign of disappearance of the $\bar{\nu}_e$ from reactors. When solar neutrino results clearly indicated a large value for the solar mixing angle it became clear that oscillations should be visible on a terrestrial baseline of order a hundred kilometres, but only a huge detector could observe reactor anti-neutrinos at such a distance. This led to the construction of the one kiloton KamLAND detector in the old Kamiokande cavern, whose observations of neutrino disappearance (combined with earlier solar and atmospheric results) finally eliminated all credible alternative models to neutrino oscillations, as well as making a precise determination of the 1-2 mass splitting. Meanwhile the Chooz[26] and Palo Verde[27] reactor experiments had been built on a much smaller baseline to look for the large suppression which would have been seen if the atmospheric neutrino anomaly was due to $\nu_\mu \rightarrow \nu_e$ oscillations. The lack of a visible suppression in the Chooz experiment eliminated this possibility (meaning that the atmospheric oscillations must be primarily $\nu_\mu \rightarrow \nu_\tau$), and their further analysis also put a limit on sub-leading oscillations due to the third mixing angle θ_{13} (this is, in fact, the main source of the limits on the size of θ_{13} shown in the right-hand plot on Fig. 2).

So what is the role for reactor experiments now? As explained by Palomeres for Double Chooz and Pec for Daya Bay, there are plans for several even more ambitious experiments being rapidly built around the world (the under-construction RENO experiment was not discussed at Kracow, and there are others being considered). These experiments are aimed at seeing the sub-leading oscillations that are sensitive to the value of θ_{13}, and thus need to be more accurate than their predecessors. The accomplish this by building two (or more) detectors, a near detector to effectively monitor reactor power and provide a normalization for cross-sections and detector efficiencies, and a similar (but usually larger) far detector to observe the neutrinos themselves. The proponents of these experiments enthusiastically claim that they will work on a highly accelerated schedule, with first results within the next few years. Personally I believe that the difficulties in achieving the extremely ambitious goals for systematic precision will mean that real results will take somewhat longer (the goals for understanding the relative energy scale, efficiencies, and backgrounds of the two detectors are significantly better than 1%, which is extremely difficult to demonstrate even for two ostensibly identical detectors). However the value of these experiment are such that the effort, and any wait for results, is well worth it. These experiments measure anti-neutrino disappearance, which has no CP violation even in principle, and are on such a short baseline and at such low energies that matter effects are effectively zero. While the inability to see effects due to δ or the mass heirarchy might seem a weakness, it is (for the next round of experiments) in fact a strength as it means that the degeneracies and covariances (explained below) that plague long-baseline accelerator experiments are absent and reactor experiments give a clean measurement of θ_{13} (provided, of course, that those systematics are properly accounted for). Comparing these measurements to long-baseline accelerator experiments can then help to resolve the degeneracies[28], provided that the true value of θ_{13} lies within the sensitivity of the next generation of experiments ($\sin^2 2\theta_{13} \geq \sim 0.01$).

3.3 Long-Baseline Accelerator Neutrinos

The detection of neutrino from accelerators has a long history, dating back to the Nobel-prize winning confirmation of the existence of a distinct muon neutrino by Lederman, Schwartz and Steinberger[29], the confirmation of parity violation by Garwin, Lederman, and Weinrich[30], the invention of the horn magnet (which increases the flux of neutrinos in a conventional neutrino beam by focussing the pions forward) by Simon van der Meer at CERN in 1961, leading to the stunning demonstration of the existence of the weak neutral current by the Gargamelle collaboration in 1973[31] for which the collaboration was so appropriately rewarded with the EPS HEPP Prize at the conference. Accelerator neutrinos have also been extensively used to study the structure of nuclei and nucleons, but our subject here is the neutrino itself so we will pass over those experiments.

The first long-baseline (>10 km) accelerator neutrino experiments were motivated by the anamolous atmospheric neutrino results from Kamiokande. Were these oscillations, and if so, were they $\nu_\mu \rightarrow \nu_e$ or were they $\nu_\mu \rightarrow \nu_\tau$? As mentioned above, the Chooz experiment ruled out $\nu_\mu \rightarrow \nu_e$, but it wasn't until the K2K experiment[32] observed the disappearance of ν_μ from a conventional neutrino beam that there was supporting evidence for the effect itself. K2K contained all the elements of a typical long-baseline neutrino oscillation experiment based on a conventional neutrino beam. Protons from the 12-GeV synchrotron at KEK were collided with a target to produce pions, which were sign-selected and focussed forward by a horn magnet into a decay volume where they produced muon neutrinos via the decay $\pi \rightarrow \mu + \nu_\mu$. Dense material then ranges out the muons before they can decay and contaminate the beam (although of course some do decay first). Pion and muon monitors and a set of near detectors enabled the experimenters to determine the neutrino flux before oscillations. The beam then propagated 250 km across Japan to the Super Kamiokande experiment, where the remaining flux and energy spectrum of the neutrinos was determined by looking at muons created by charged-current neutrino interactions in the detector. The experiment convincingly demonstrated that muon neutrinos were disappearing, as predicted based on the atmospheric results, but the statistics were too small to make precision measurements of the oscillation parameters.

What are the remaining targets for long-baseline experiments? The assumption that the atmospheric oscillations are mainly $\nu_\mu \rightarrow \nu_\tau$ is the only one consistent with all the existing data, but other than some statistically not-yet-compelling indications in Super Kamiokande, nobody has ever actually seen the appearance of a ν_τ in a ν_μ beam. That is the target of the OPERA experiment, described by Pessard, which is looking for the appearance of ν_τ in the CNGS conventional neutrino beam from CERN to Gran Sasso with a large hybrid electronic-emulsion detector. The experiment is now running and as of this writing we are awaiting the first events from ν_τ appearance. Meanwhile the MINOS experiment (from which Evans gave results) has been measuring ν_μ disappearance from the NUMI neutrino beam fired from Fermilab to a 5.4 kT iron tracking calorimeter in the Soudan mine in upstate Minnesota. MINOS has confirmed the disappearance of ν_μ and has already improved our knowledge of the 2-3 mass splitting (which is reflected in the center plot of Figure 2), and with further statistics should also improve our knowledge of θ_{23}. They are now running with the horn currents reversed to look at the oscillations of anti-neutrinos, an area where there is very little existing data.

Next-generation experiments have two main targets – to improve our measurements of θ_{23} by looking at ν_μ disappearance, and to look for sub-leading oscillations that would give rise to ν_e appearance as a way to measure θ_{13} with a conventional neutrino beam. The first of these goals is an important part of our quest to understand the underlying mechanism that generates the MNSP matrix. The CKM matrix in the quark sector is approximately diagonal, with the mixings all "small", and this originally led people to expect that the MNSP matrix would be similar. In fact the MNSP matrix looks completely different, with one angle (θ_{13}) small, one (θ_{23}) near maximal, and one (θ_{12}) intermediate. In order to try to understand that we need to know of the apparent symmetries ($\theta_{13} = 0$ and $\theta_{23} = 45°$) are real or if in fact the three angles just look like three random numbers drawn in the interval from 0° to 45° (which is still a possible interpretation given the significant uncertainties in the existing measurements of the angles). This will require much more accurate measurements of θ_{23} to see if it remains consistent with maximal mixing.

The same reasoning applies to measuring deviations of θ_{13} from zero, however an even stronger motivation for that measurement arises from the desire to measure the other unknowns – the sign of the mass heirarchy and the value of the CP-violating phase δ. The need for a measurement of θ_{13} can be seen by examining the probability for ν_e appearance in a ν_μ beam arising from sub-leading effects (I got this formula from some long-mislaid report, and it has been cut and pasted so many times I have lost track of the original source – my apologies to those authors!):

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\ \left(1 - 2S_{13}^2\right)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E}\ \frac{aL}{4E}\ \left(1 - 2S_{13}^2\right)
\end{aligned}
$$

where the c_{ij} and s_{ij} are the cosines and sines of the angles in the MNSP matrix, L is the distance form the source to the detector, E the neutrino energy, and a is a constant arising from the matter effects (this formula is valid in the approximation of constant matter density). This formula is a bit dense, but quite a bit can be understood about future neutrino projects by staring at it. First, there is only one term that doesn't contain $\sin\theta_{13}$ (the first term in the next-to-the-bottom line), which is the term that leads to solar neutrino oscillations, but it is unobservable for an experiment using terrestrial neutrinos in the near term. Obviously if θ_{13} is too close to zero all the other terms, which include the phase δ and the matter effects we need to resolve the mass heirarchy, will be unobservable. In fact for neutrino energies ~ 1 GeV (with resulting baselines of ~few hundred kilometres) the matter effects are small and only the very first term and the two terms containing δ are significant. Given the current limit on $\sin^2 2\theta_{13}$ of about 0.14, the first term actually dominates for now and we are still doing what looks essentially like a two-neutrino oscillation experiment looking for a small appearance ν_e in a ν_μ beam. One thing that must always be kept in mind is that there are multiple unknowns in this formula (a, δ, θ_{13}) and other parameters which are only known with errors (the other angles and mass splittings), so if you make one measurement of this probability (for one species of neutrino at one baseline and one energy, for instance) you will be plagued by covariances and degenerate solutions. We will therefore need multiple experiments in order to come to a unique set of measured parameters.

Existing experiments have already looked for this appearance, however K2K had insufficient statistical sensitivity to challenge the Chooz limit. MINOS has seen a mildly intriguing 1.5 sigma excess of events, however this is on a background which is not small because of the coarse nature of the calorimeter (which was optimized for measuring muons for the disappearance measurement, which was the dominant physics topic at the time it was designed). The backgrounds fall into the same categories for all long-baseline ν_e appearance experiments. Firstly, there are the intrinsic ν_e in the beam which arise from kaons produced in the target and by the decay of the muons before they are ranged out. These can be minimized by good beam design, and distinguished from ν_e arising from oscillations by their energy spectrum. Then there are various backgrounds that arise from the ν_μ beam itself. It is possible, of course, to mistake a muon for an electron, which produces a background directly, however this is small in most experiments. A far more insidious background arises from neutral current (NC) interactions of the beam (oscillated or not, as NC interactions do not discriminate between flavours). The most dangerous of the NC interactions is the production of a single π^0, which decays to two gammas. If one of the gammas is missed or overlaps with the other in the detector, the resulting event looks very much like the single electromagnetic shower arising from a ν_e. Some detectors also suffer background from neutral particles produced by beam interactions in the rock surrounding the detector, however these backgrounds get smaller with higher energies and larger detectors. The design of new experiments is strongly tied to minimizing these backgrounds, as the systematic uncertainty in them tends to dominate the error budget for long running times.

The designs of the two new experiments long-baseline experiments (T2K, discussed in these proceedings by Sakashita, and NOvA) are therefore strongly affected by the need to minimize these backgrounds. Both have adopted an off-axis beam design, where the neutrino beam is carefully designed to miss the detector by a few degrees. This might seem like a bad idea, and certainly the total neutrino flux is smaller off-axis. However by a quirk of the kinematics of pion decay the energy spectrum of neutrinos at an off-axis position gets concentrated on a single energy (where the flux at that particular energy is actually higher than on-axis). If the angle is selected such that the peak energy is at the maximum of the oscillation this enhances the signal, while at the same time surpressing the backgrounds that would arise from NC interactions of the higher energy neutrinos (which are mostly absent in an off-axis beam).

T2K was built to take advantage of one existing facility (Super Kamiokande) and one facility which was already planned (the new J-PARC accelerator facility in Tokai on the east coast of Japan). As part of T2K a neutrino beamline which is designed to produce the most intense neutrino beam ever built has been added to J-PARC (see the talk by Sakashita). Super Kamiokande, which has been equipped with all-new electronics and DAQ to further improve its ability to detect neutrinos, is almost the ideal detector in this energy range because of its incredible effective granularity and huge size. Super Kamiokande detects neutrinos by observing Cerenkov light emitted by charged particles resulting from neutrino interactions in an array of over ten thousand photomultiplier tubes (PMTs). Each PMT hit which is recorded corresponds to only about a millimeter of particle track, meaning that the 50 thousand ton mass of Super Kamiokande is instrumented with an effective granularity of a millimeter. However, there is a catch. The hit doesn't tell you which millimeter of track the light came from, so you must reconstruct the events based on timing and the hit pattern. For very simple events with just a few charged particles, this reconstruction is relatively straightforward. For more complex events it is very difficult, and hence water Cerenkov detectors are only useful for neutrinos up to a few GeV at most. Luckily the distance from Tokai to Kamioka and the known mass-squared difference for atmospheric neutrino oscillations puts the peak oscillation energy at 600-700 MeV, which is pretty much the ideal energy for a water Cerenkov. Super Kamiokande is thus very good at distinguishing muons from electrons from the problematic π^0s. That leaves the question of the near detectors. A water Cerenkov detector would not work as the near detector on the J-PARC site (for a number of reasons), so two more complex near detectors which will make detailed measurements of the beam properties but also of the interactions of neutrinos at these energies (where the cross sections are very poorly known, as I will come back to below). As for this writing T2K has just begun operating, and first results are hoped for within a year.

The NOvA detector[36] is placed at an off-axis position in the NUMI neutrino beam (which will be upgraded to a power of 400 kW as part of the project) built for MINOS, and uses a huge (15,000 ton) liquid scintillator tracking calorimeter as the far detector. The calorimeter is built of an array of plastic tubes with a rectangular cross-section arranged in planes and filled with liquid scintillator. Readout is by a long wavelength-shifting fiber which loops through the volume so that both ends of the fiber come out of the same end of the tube where they are read out with an avalanche photo-diodes (APD). NOvA is almost completely active (only the thin plastic tubes are not), from which it derives the excellent event reconstruction capability necessary to discriminate against NC backgrounds. Civil construction has commenced at the Ash River far detector site (810 km from Fermilab) and the full installation is scheduled to be completed in 2014. T2K and NOvA have similar sensitivity to θ_{13} (about an order of magnitude below the existing limits). Because of its longer baseline and higher energy NOvA is more sensitive to matter effects, and there is about a 50% chance that (if appearance is seen) the combination of NOvA with T2K and/or reactor experiments could allow the mass heierarchy to be determined.

3.4 MiniBooNE and LSND

The above picture of neutrino oscillations is nicely consistent with a very wide range of experiments, but there is one exception – LSND[37]. On the one hand, this should give confidence, because as a witty scientist once remarked (I think it was Eddington, but I can't find the quote) that anything which is consistent with all experimental data must be wrong, because you know for a fact that at least some of the experimental data must be wrong. So the failure of LSND to conform to the standard 3-neutrino oscillation pictures saves us from Eddington's worry. On the other hand, a single inconsistent result is sometimes the signpost to new physics, so it was necessary to produce an experimental test. LSND claimed to see a small excess of $\bar{\nu}_e$ in a mixed-flavour neutrino beam from stopped pion decay, which they interpreted as evidence for neutrino oscillations with a much larger Δm^2 than found for solar or atmospheric oscillations. The KARMEN experiment[38], with similar sensitivity, saw no effect, but two experiments of similar sensitivity can never rule one another out (as one could always be the beneficiary and the other the victim of a statistical fluctuation). This led to the construction of the MiniBooNE experiment, described in these proceeding in the paper by Osmanov. MiniBooNE saw no evidence for two-neutrino oscillations consistent with the original LSND interpretation, but this was no real surprise as the only way to have such oscillations would be for either the solar or atmospheric observations to completely wrong (as three neutrinos only have two independent mass splittings, which are taken up by the solar and atmospheric oscillations, leaving no room for the LSND claim). It is probably unnecessary to point out that in both the case of solar/reactor and atmospheric/long baseline oscillations their are many overlapping experiments in support. The high-statistics results of MiniBooNE are with neutrinos, however, while the LSND excess is with anti-neutrinos (MiniBooNE has anti-neutrino results as well, which also show no effect, but they do not have sufficient statistical significance to rule out the LSND claim). So as of the time of this writing there are still speculations that oscillations to sterile neutrinos (to evade the results from solar and atmospheric) which violate CPT (to evade the MiniBooNE results) explain the LSND result. The mystery is deepened by the observation in MiniBooNE of an unexplained excess of events at low energy in the neutrino sample (but not the anti-neutrino sample) which is inconsistent with LSND oscillations but also inconsistent with the predictions of the MiniBooNE Monte Carlo. My own feeling is that science consists of that which can be reproduced, which is especially true in neutrino physics. All neutrino experiments are hard, and the history of the field is littered with exciting results which didn't survive experimental test (many of which have never been explained). Given the negative results from KARMEN and MiniBooNE I think the balance of probability between, on the one hand, the LSND result arising from an experimental artifact, and on the other hand, sterile neutrinos which violate CPT, would lie pretty strongly with the former. However one should certainly keep this puzzle in mind when considering new physics scenarios (as, for instance, the idea of Non-Standard Neutrino Interactions, or NSI, discussed at the conference by Miranda).

3.5 Cross sections Measurements

The tedious job of measuring exclusive cross sections for various obscure neutrino interactions ($\sigma(\nu_\mu p \rightarrow \mu^- n \pi^+ \pi^+)$ anyone?) may not seem like the most exciting bit of physics, but the reliability of the precision long-baseline experiments of the future absolutely relies upon it.

Prior to the current round of experiments, the knowledge of neutrino cross sections in the relevant few hundred MeV to few GeV range was truly appalling[39], with factor of two uncertainties in some of the most important (like the cross section for single π^0 production) and factors of 100 between models and measurements for some others (like the one listed above). Most of this data came from old bubble chamber experiments which had been hand-scanned and events numbered in the tens or hundreds. The current generation of experiments – both the near detectors or neutrino detectors themselves (such as MiniBooNE) and dedicated neutrino cross-section experiments like SciBooNE[40] (the K2K SciBar detector deployed in the MiniBooNE neutrino beam) are creating significant new data sets and have resolved some issues while raising others (it seems impossible to find a consistent value for the effective axial mass MA which parameterizes the key charged-current quasi-elastic cross section, while coherent production of π^0s is inconsistent between charged and neutral currents). More and better data will be required to sort this out, as well as new analyses (such as the one presented by Graczyk). New data on cross sections which will be one of the main jobs of the near detectors for T2K and NOvA as well as dedicated experiments like the MINERvA experiment at Fermilab (discussed by Osmanov). In a similar vein it is also worth noting the importance of hadron production experiments like NA61 at CERN (discussed by Palczewski in a poster at the conference) for understanding neutrino beams and hence interpreting oscillation results.

3.6 The Future

Within a few (5?) years we should have results from the current round of experiments – T2K, NOvA, Double Chooz, and Daya Bay. It should then be clear whether $\sin^2 2\theta_{13}$ is “large”, i.e., greater than about 0.01, or not. The significance of this for determining the phase δ can be seen from the oscillation formulat above. The leading term depends on $\sin^2\theta_{13}$, while the two terms containing δ depend on $\sin\theta_{13}$. Thus as the value of θ_{13} is reduced the fractional effects of non-zero δ actually get bigger, but at the same time the total number of events falls. In the case of a conventional neutrino beam (either an off-axis beam such as that for T2K or NOvA, or an on-axis broad-band beam such as is being considered for the Project X to DUSEL programme at Fermilab) that means the effect gets bigger but the number of events shrinks, and for $\sin^2 2\theta_{13}$ smaller than about 0.01 the events just shrink into the background and CP violation becomes unmeasureable. However if $\sin^2 2\theta_{13}$ is bigger than 0.01 there are events to play with, and it would be possible to search for CP violation in an upgraded experiment based on a conventional neutrino beam. The Project X/DUSEL is one such programme under active development (discussed by Prebys at the conference), where a broad-band on-axis beam is used to allow the oscillation pattern to be observed for two oscillation maxima (which allows the degenerate solutions to be distinguished). Another idea is to build a large detector on the island of Okinoshima of the west coast of Japan (which lies nearly on-axis for the T2K beam) and perform a similar measurement there. There is also interest in a next-generation experiment in Europe, where various design studies are considering the possibilities.

The situation becomes more difficult if $\sin^2 2\theta_{13}$ is smaller than 0.01, as discussed at the conference by Edgecock. The ultimate facility for neutrino oscillations would probably be a Neutrino Factory (as discussed by Blondel), where an extremely intense mixed-flavour neutrino beam would be derived from the decay of muons which were collected from pion decays and re-accelerated with a dedicated accelerator. The sensitivity of a Neutrino Factory to θ_{13} is as much as a factor of a 1000 beyond the present experiments, and it can perform useful searches for CP violation down to $\sin^2 2\theta_{13} \approx 10^{-4}$. In my view, if the current round of experiments don’t see evidence for $\theta_{13} > 0$ the best thing to do would be to proceed as quickly as possible to a Neutrino Factory, as other possibilities do not extend our current sensitivity by enough. However many feel that funding agencies will not be willing to leap into the unknown with the extremely technically challenging (and therefore expensive) Neutrino Factory without first trying another less ambitious step, and they may well be right (I am always aware that each “step” requires at least a decade, and I don’t have that many decades left, so I am probably biased!). What is certain is that we need a great deal more work on the technical aspects of these future facilities, so projects like MICE (which tests the ionization cooling which would be critical to a Neutrino Factory, and was discussed the conference by Bonesini) and MERIT (which tests an idea for making the required high-power target) must be strongly supported by the community. And no matter what project we engage in it will require a new generation of ultra-large detectors which will (hopefully) be much more capable than the ones we have now. Studying those is the purpose of the LAGUNA project, discussed here by Kisiel, and we certainly need more people involved in the effort to push new detector technologies.

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