Cosmology, Galaxy Formation and Astroparticle Physics
on the pathway to the SKA
Klöckner, H.-R., Rawlings, S., Jarvis, M. & Taylor, A. (eds.)
April 10th-12th 2006, Oxford, United Kingdom

Current and Near-Future Neutrino Experiments

Steve Biller

University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK

Abstract. Experimental neutrino physics has been one of the most rapidly growing and exciting areas of scientific research over the last decade. It is impossible to do justice to the topic in such a brief space, though every reviewer can at least rest safe in the knowledge that anything they say about this field is very transient anyway, since our understanding continues to evolve quickly.

1. Introduction

The richness of neutrino physics has been very significantly enhanced by the discovery of neutrino mass and mixing (*i.e.* the fact that the mass states are not the same as the interaction, or "flavour" states). Neither of these properties are predicted by the Standard Model of particle physics and, thus, provide important insights into what lies beyond. For the most part, the main focus of neutrino physics is now on understanding the details of the Pontecorvo-Maki-Nakagawa-Sakata (or PMNS) matrix, which parameterizes this mixing amongst the 3 active neutrino species. The principle elements of this matrix are the 3 potential mixing angles between the various mass states: θ_{12}, θ_{23} and θ_{13}. In addition, if θ_{13} is non-zero, a CP-violating phase is allowed. There are also other possible phases in the matrix which would be indicative of neutrinos being their own antiparticle ("Majorana" particles), distinguished only by their handedness which, because neutrinos have mass, could be flipped. Taken together, it is possible that the CP-violating and Majorana phases could explain both the smallness of neutrino masses and provide and explanation for the matter-antimatter asymmetry in the universe. Furthermore, the specific values of these phases, plus those of the mixing angles and neutrino masses, provide important clues to the relationship between leptons and quarks, the latter of which are known undergo an analogous mixing between weak and strong eigenstates. Some of the current and near-future experimental efforts associated with determining these various parameters will now be briefly reviewed.

2. Θ_{12}

The whole concept of neutrino mixing and oscillation was first proposed by Pontecorvo in 1957 and, roughly ten years later, offered as an explanation for the discrepancy between the first measurement of the solar neutrino flux by Ray Davis and solar model predictions (Davis 1959). Davis measured contributions mainly from the higher energy ^8B branch of the $p-p$ chain of solar reactions via the transmutation of ^{37}Cl atoms into ^{37}Ar, which were counted using radiochemical techniques, and found about a third of the expected number. This became known as "The Solar Neutrino Problem," though the seriousness and nature of the discrepancy was far from clear initially... neutrino oscillation seemed to be the most fanciful and unlikely solution! The magnitude of the problem became more obvious over the next ~30 years as numerous other experiments (SAGE, GALLEX, Kamokande, SuperKamiokande) (Bahcal & Davis 2000) confirmed the apparent deficit and inputs to the solar model (cross sections and energy transport) were better measured and constrained. In 1986, the Mikheyev-Smirnov-Wolfenstein (MSW) effect was proposed (Mikheyev & Smirnov 1985), in which the passage of neutrinos through matter could greatly enhance the effect of oscillations over a large range of parameter space, thus avoiding "fine-tuning." This made the whole idea of oscillations much more attractive. Still, there was no definitive evidence that this was the explanation until the results of measurements by the SNO experiment was released in the summer of 2000 (Ahmad et al. 2001). The project uses 1000 tonnes of heavy water (D_2O) to allow the measurement of 3 different reactions: the charged-current reaction $\nu_e+d \rightarrow p+p+e^-$, which is only sensitive to electron-neutrinos; the neutral-current reaction $\nu_X + d \rightarrow n + p + \nu_X$, which is equally sensitive to all active neutrino species; and elastic scattering $\nu_{e,X} + e^- \rightarrow \nu_{e,X} + e^-$, which is predominantly sensitive to electron-neutrinos, but has some sensitivity to the other active species. Comparison of these different signatures through different phases of the experiment provides an unambiguous demonstration of flavour-conversion with the extracted parameter values clearly indicating an MSW solution which involving a large mixing angle.

These parameter values have been subsequently verified by the KamLAND experiment in Japan (KamLAND Collaboration 2003) for pure vacuum oscillation (i.e. not enhanced by passage through the sun), using terrestrial neutrinos from nuclear reactors at an average baseline of $\sim$ 180 km from a kilotonne, liquid scintillation detector. The detector was built prior to the SNO discovery and the choice of baseline was completely fortuitous, placing them near the peak of the 2nd maximum flux suppression from oscillation to give them a very clear signature.

Taken together, these measurements indicate a mixing angle of $sin^2(2\theta_{12}) = 0.86$ and a difference in the squares of the masses of $\Delta m^2_{21} = 8 \times 10^{-5}\mathrm{eV}^2$. The observation of matter-enhanced oscillation also turns out to provide enough information to determine the ordering of the mass states (*i.e.* that $m_2 > m_1$).

3. Θ_{23}

In fact, the first demonstration that neutrinos had mass and were likely oscillating came from the 1998 measurement of atmospheric neutrinos by the SuperKamiokande (SK) detector (Fukuda et al. 1998). This provided an answer to another long-standing discrepancy known as "The Atmospheric Neutrino Anomaly." When cosmic-rays interact in the atmosphere, copious numbers of pions are produced. The neutral pions decay into photons. However, charged pions decay into a muon plus an anti-muon-neutrino, and the muon subsequently decays into an electron plus an anti-electron-neutrino plus an electron-neutrino. Consequently, one would expect to see about 2 muon-type neutrinos for every electron-type neutrino produced (in reality, this ratio gets altered a bit since the cosmic-ray energy and local geomagnetic field can affect the observed muon decay contribution). However, various experiments throughout the 1980's and 1990's (including IMB, Kamiokande, Sudan and others) found that there were "too few nu-mu" for upward-going events, corresponding to neutrinos produced by interactions on the other side of the earth relative to their detector (Kearns 1999). The SK experiment is a massive water-Cherenkov detector with a volume of roughly 60 kilotonnes. It was therefore able to gather sufficient statistics to not only confirm the effect with high precision, but also to see the dependence of the "disappearance" on both the distance to the interaction point (by looking at events as a function of angle through the earth) and on the neutrino energy. The fact that the muon-neutrino has an "internal clock" which is sensitive to these parameters demonstrates that it must have mass. As the number of electron-neutrinos appears to be unaffected, this would suggest an oscillation between the "second and third" states, defined by a different mixing angle, θ_{23}. Under this hypothesis, the SK results suggest oscillation parameter values of $sin^2(2\theta_{23}) > 0.92$ (perhaps even maximal) and $\Delta m^2_{23} \simeq 2.5 \times 10^{-3}\mathrm{eV}^2$. These values were recently independently confirmed by the MINOS experiment using a terrestrial source, this time from neutrinos produce an the Fermilab accelerator aimed at a tracking calorimeter 730km away in Minnesota (MINOS Collaboration 2006). Their current results provide constraints which are comparable to the SK, but the importance of this experiment is that it will provide substantially better constraints over the course of its operation through the next several years. This will be crucial to not only test theoretical models but to also allow the next phase of neutrino experiments to untangle new effects from measurements which also depend on this mixing.

At this point, it is worth issuing **a word of caution** regarding this whole framework: Formally speaking, oscillation has not been firmly demonstrated in this case as of yet. Both terrestrial and non-terrestrial measurements pertaining to "θ_{23}" only entail the disappearance of muon-neutrinos. By contrast, SNO demonstrated both disappearance of electron-neutrinos and appearance of non-electron-neutrinos for the case of θ_{12}. Also, as a collection, solar neutrino experiments indicate a distortion to the neutrino energy spectrum which is predicted by oscillations. The observation of vacuum as well as matter-enhanced oscillation, further clinches the hypothesis and provides a mass ordering. No such spectral distortion or matter enhancement has yet been demonstrated for θ_{23}. So, for example, there is nothing to prevent the results here from being interpreted instead as neutrino decay to some new particle beast. Or, if it is oscillation, there is no direct information about what it is oscillation into. For instance, the concept of a whole new species of sterile neutrinos (which I prefer to call "neuter-inos") are a popular topic at present. There may even be some hints that this could be the case (see the discussion of MiniBOONE, below). It is worth bearing in mind that, while we may go down a particular path in an attempt to construct a framework from what we have measured so far, such other possibilities remain on the table and must be taken into account when attempting to derive robust constraints from indirect, astrophysical measurements.

4. Θ_{13}

With 3 active flavour eigenstates and 3 related mass eigenstates, there are, in principle, up to 3 independent mixing angles allowed to parameterize this relationship. Having unexpectedly stumbled across two of the neutrino mixings while looking for something else, the third angle, θ_{13}, is somewhat unique in the fact that it is being actively targeted by experimentalists! Indeed, there is now very strong motivation for wanting to know the value of this angle. If non-zero, the PMNS matrix could also then contain an associated CP-violating phase. CP-violation is one of the Sakarov conditions necessary for explaining the matter-antimatter asymmetry of the universe. It is observed via weak mixing amongst the quarks, but the size of the violation appears to be too small to readily explain the asymmetry. If CP-violation within the PMNS matrix turns out to be large, this could well indicate that the birth of the universe proceeded via leptogenesis. In addition, a careful comparison of the mixing parameters constituting the PMNS matrix with those of the CKM matrix (with or without a CP-violating phase) is sure to provide important insights into the relation between quarks and leptons, which could then lead to a much sought-after Grand Unified Theory of particle physics.

Two complementary, experimental approaches are being pursued in this regard. The first involves looking for the apparent disappearance of electron anti-neutrinos produced by nuclear reactors, as with KamLAND, but using a much shorter baseline such that the contribution from θ_{12} oscillation is negligible. As a result, smaller detectors can be used owing to the increased flux. Another substantial advantage of this approach is that, owing to this short baseline and the relatively low energies ($\sim$ 4MeV), the measurement is not sensitive to either matter effects or CP phases. Therefore, it provides an extremely clean probe of θ_{13} alone, which can then be used in conjunction with other approaches to untangle the contributions from these other important effects. The current best limit on θ_{13} comes from the Chooz experiment (Apollonio 1999), which used a detector with a fiducial volume of just 5 tonnes, placed at distance of 1 km from the Chooz reactor in France. Fortuitously, the experiment operated while the reactor itself was still being commissioned, thus providing the project with a large fraction of reactor-off data, which allowed them to directly measure the background levels in the detector. No significant effect was observed within their uncertainties, which were principally limited by knowledge of the primary reactor neutrino flux (known to about 2%). Give our knowledge of the approximate mass splittings from θ_{12} and θ_{23} observations, this yields a constraint of $sin^2(2\theta_{13}) < 0.19$ at the 90% confidence level.

The importance of pursuing an improved reactor experiment with higher sensitivity has been widely recognised as a priority in the overall neutrino programme. Several proposals have been put forward throughout the international community in this regard. At the time of the SKA conference in Oxford, the most advanced and ambitious proposal, based on several independent reviews, was the Braidwood project in Chicago. Sadly, the US Department Of Energy decided to terminate this project in April 2006, days before a scheduled full review to secure initial funding. A large amount of US funding will, instead, be directed towards China and the Daya Bay reactor project. In the UK, our groups at Oxford and Sussex are now working on the effort to make an improved measurement at the Chooz reactor (a project known as "Double Chooz"), along with collaborators from Europe, Brazil, Japan, Russia, as well as some from the US (funded mostly by NSF). Both Double Chooz (The Double Choz Collaboration 2006) and Daya Bay (Wang 2006) will make use of multiple detectors and larger fiducial volumes to reduce uncertainties and improve sensitivity. For Double Chooz, one detector will be at the same 1km site at the original experiment, with a second to be constructed at a distance of 280m from the reactor cores. Comparison of the two will, thus, remove the uncertainty associated with having to model the antineutrino production. This project should be the first to see data, anticipated to start at the far site in 2008, with the second site commissioned in 2010.

The second approach involves the use of higher energy neutrinos resulting from the decay of charged pions produced in particle accelerators. In this case, the signal would be the appearance of electron-type neutrinos from a muon-neutrino beam due to θ_{13} oscillations. Two such efforts are underway here: NOvA (Ayres et al. 2005) in the US and T2K in Japan (Nishikawa et al. 2003). For T2K, the detector to be used for this will be SuperKamiokande, which is situated 300km from the beam facility under construction in Tokai. It is the combination of this baseline and the higher energies that make such measurements potentially sensitive to CP and matter effects and is why both this and the reactor approach to the problem are required. This project involves a large, international collaboration with a substantial contribution from the UK. This UK effort will actually be focused on the construction of a near detector to better understand the initial neutrino beam, in much the same way as for the reactor projects. T2K is scheduled to turn on sometime in 2009.

5. $\Theta_{??}$

In fact, another possible oscillation phenomenon had been reported in 1995 by the LSND collaboration (Aguilar et at. 2001), indicative of anti-muon to anti-electron neutrino transitions at the LAMPF facility in Los Alamos. However, the parameters derived from this observation do not fit into the nice framework previously described, and the measurement has been widely regarded as an experimental anomaly. The MiniBOONE project at Fermilab (Church et al.) has been designed to provide an independent, clear measurement which would either confirm or refute the observation. It began taking data in September of 2002 and has been carefully analysing the data under a blindness scheme to avoid inadvertent bias to the final result, one way or another. The project is due (in fact, overdue) to "open the box" on the blindness scheme and release final results anytime now. It is generally assumed that this will be a null result. However, if this turns out not to be the case, the focus of the field will shift significantly and the future neutrino programme could look very different.

6. Mass and Majorana

Beyond the mixing angles and CP phase, there is also the question of Majorana phases in the PMNS matrix as well as what the absolute neutrino mass values are (since oscillations only determine the mass differences). A direct approach to testing the absolute mass scale involves a high-precision measurement of the beta-decay endpoint of tritium. Tritium is the simplest isotope which undergoes beta-decay, with a spectrum that can be accurately predicted theoretically. Given that neutrinos have mass, the endpoint of the observed electron spectrum should fall short of the full decay energy by an amount which reflects this minimum energy carried away by the mixed mass state of the electron anti-neutrino. The most robust limit on the lightest neutrino mass is < 2.2eV, set by the Mainz group using this technique. The KATRIN experiment (KATRIN collaboration 2001), due to begin taking data next year, is expected to reach a sensitivity which is an order of magnitude better than this. The huge spectrometer built for this project is probably the largest that can be practically constructed, so this likely represents the limit of what can be achieved by this technique.

It should also be noted here that some cosmologically derived bounds are already up to a factor of 2-3 better than the current mass limit, though still not what KATRIN should achieve. However, these are predicated not only on certain cosmological assumptions, but also on an assumed neutrino framework which, itself, is still a target of scrutiny for such measurements. On the other hand, as direct measurements pin down this framework and better determine fundamental parameter values, their impact on constraining some aspects of the cosmological models may become significant.

Another experimental approach has the potential to explore even smaller neutrino mass scales, bringing it in range of the known Δm_{21} splitting, should neutrinos turn out to be Majorana particles. The latter is, in itself, a question of tremendous interest in the field that could have important consequences for our understanding of the matter-antimatter asymmetry and Grand Unification. The method stems from the phenomenon of double-beta-decay, in which the process of beta-decay can simultaneously occur twice, as a single quantum mechanical event, within particular nuclei. Normally, each beta-decay would produce a single electron antineutrino via the process $n \rightarrow p+e^{-}+\bar{\nu_e}$. However, if the neutrinos are Majorana in nature, the fact that they are massive allows one, in principle, to boost to a reference frame in which their spin appears to reverse, thus turning them into anti-neutrino, or visa versa. As such, there is a probability (which depends on the value of the neutrino mass) for a virtual process to occur during this quantum event whereby the anti-neutrino produced by one of the beta-decays appears as a neutrino, and is effectively "swallowed" by the second beta-decay reaction instead of emitting an anti-neutrino itself. Consequently, the signature for this process would be the production of two electrons with the full decay energy as no neutrinos would be produced. Experiments which search for this require excellent energy resolution and background rejection in detectors with a large mass (approaching 1 tonne) and utilising carefully selected isotopes. Several solid state detectors are being pursued, including EXO, MAJORANA, CUORE, and COBRA (the latter being a UK-led effort) (Zuber 2006). SuperNEMO plans to use thin foils of source material embedded in gas TPCs to identify electron tracks (Barabash et al. 2006). SNO+ is also investigating the possibility of using Nd-loaded scintillator to perform a search using the a modified SNO detector (SNO+ Collaboration 2004). These projects all face significant technical challenges to improve sensitivity and understand backgrounds, but it is recognised as an extremely important area for future neutrino research.

7. Conclusion

The past decade has seen very substantial advances in neutrino physics. What was once considered to be a bit of an obscure area of study is now very much mainstream, with a richness that promises key insights into Grand Unification and the birth of the universe. This richness is, for the most part, embodied in the PMNS matrix, whose elements specify neutrino mixing, CP violation and the possible Majorana nature of neutrinos. However, it is important to recognise that this framework may not be the complete picture. There are still a number of questions which remain unanswered and hypotheses yet to be confirmed. Neutrinos have a history of throwing up surprises, and there may yet be more to follow.

References

Aguilar, A., et al., (LSND Collaboration), 2001, Phys. Rev., D64, 112007 (hep-ex/0104.049)

Ahmad, Q. R., et al. (SNO collaboration), 2001, Phys. Rev. Lett., 87, 071

Apollonio, M., et al. (CHOOZ Collaboration), 1999, Phys. Lett. B, 466, 415

Ayres, D., et al. (The NOvA Collaboration), 2005, (hep-ex/0503053)

Bahcall, J. N. and Davis, R. Jr., 200, PASP, 112, 429

Barabash, A. S. for the NEMO Collaboration, 2006, J.Phys.Conf.Ser., 39, 347

Church, E. ,et al., (BooNE Collaboration), FERMILAB-PROPOSAL-0898.

Davis, R., 1959, Bull. Am. Phys. Soc. (Washington meeting)

Fukuda, S., et al. (Super-Kamiokande Collaboration), 1998, Phys. Rev. Lett., 81, 1562

The KamLAND Collaboration, 2003, Phys. Rev. Lett., 90, 021802, (hep-ex/0212021)

The KATRIN collaboration, 2001, (hep-ex/0109033)

Kearns, E., 1999, Nucl. Phys. Proc. Suppl., 70, 315, (hep-ex/9803007)

Mikheyev, S. P. & Smirnov, A.Yu., 1985, Yad. Fiz., 42, 1441

The MINOS Collaboration, 2006, Phys. Rev. Lett., 97, 1918011 , (hep-ex/0607088)

Nishikawa, K., et al. (T2K Collaboration), 2003, KEK Report

Pontecorvo, B., J., 1957, Exp. Theor. Phys., 33, 549 (1958, Sov. Phys. JETP 6, 429)

SNO+ Collaboration, Letter of interest submitted 12 April 2004

The Double Choz Collaboration, 2006, (hep-ex/0606025)

Wang, Yifang, talk given at ICHEP06, Moscow, July, 2006

Zuber,K., 2006, Acta Phys.Polon., B37, 1905