Progress in determination of neutrino oscillation parameters[†]

B. Ananthanarayan, Chitra Gautham, Aquila Mavalankar, K. Shivaraj, S. Uma Sankar and A. Upadhyay

A press release dated 30 March 2006 from the US laboratory, Fermilab, reported the first results from a new neutrino experiment, MINOS (Main Injector Neutrino Oscillation Search)[1]. The main injector accelerator at Fermilab produces an intense beam of muon neutrinos and directs them at the MINOS detector in the Soudan mine, at a depth of 716 m, in Minnesota, 732 km away. The MINOS experiment expected to observe 177 ± 11 events, but observed only 92, which is 7.5σ away from 177. The probability that random fluctuations are responsible for this shortfall is only part in 10^{10}. Thus the MINOS experiment confirmed that there is a shortfall in the number of muon neutrinos if they are detected a long distance away from their point of production.

Two water Cerenkov detectors, Irvine–Michigan–Brookhaven (IMB)[2] and Kamiokande[3] had first observed this deficit fifteen years ago in muon neutrinos produced in the atmosphere. The interaction rate for downward-going neutrinos, which travel distances of the order of 100 km, was consistent with the expectation but the rate for upward going neutrinos, which travel thousands of kilometres, was only about 60% of the expectation. The field of neutrino physics received a tremendous boost in 1998, when the results of the very large water Cerenkov detector, Super-Kamiokande were announced[4]. These results not only confirmed the deficit of atmospheric muon neutrinos when they travel long distances, but also showed that there are definite correlations between the amount of deficit and the distance travelled and also between the amount of deficit and the neutrino energy. Both the deficit and the correlations can be explained assuming that muon neutrinos, during their long travel, oscillate into another type of neutrino.

However, there are still large uncertainties in the calculation of atmospheric neutrino fluxes. The long-baseline neutrino experiments were planned to find evidence for the spectral distortion caused by oscillations by locating the minimum of the muon neutrino survival probability. The location of this minimum can be used to determine the neutrino oscillation parameters accurately. In Super-Kamiokande, the observed neutrinos have varying energies and also varying pathlengths. Locating the minimum of the survival probability is difficult in Super-Kamiokande because the data sample spans large ranges in energies and pathlengths. The first long-baseline neutrino experiment, called K2K (KEK to Super-Kamiokande 230 km away) in Japan, was a low statistics experiment which confirmed the muon neutrino deficit. It also observed a distortion in the energy spectrum of the muon events, that is consistent with oscillation hypothesis. The number of events in recent MINOS results also is not large and the current accuracy of MINOS is only slightly better than that of K2K. But it is expected that with about 5 years of data collection, they will increase the number of events twenty-fold. This will enable observation of the minimum of survival probability and determination of the neutrino oscillation parameters precisely.

If the MINOS results are interpreted in terms of three flavour neutrino oscillations, they give the following values for neutrino oscillation parameters: $\Delta m_{23}^2 = (3.05^{+0.60}_{-0.55} \pm 0.12) \cdot 10^{-3}$ eV^2, and $\sin^2(2\theta_{23}) = 0.88^{+0.12}_{-0.15} \pm 0.06$. It can be seen from the results presented earlier[1,5] that the MINOS results have already improved the precision in the determination of Δm_{23}^2 but the precision in θ_{23} is still controlled by atmospheric neutrino data.

Here we describe the MINOS experiment in a little more detail. 120 GeV protons are extracted from Fermilab's Tevatron Main Injector at the rate of 10^{13} protons per second and these protons are directed to a fixed graphite target. Pions and kaons are selected from the resultant spray of secondary particles and are focused into a 675 m evacuated decay pipe, where they decay into muons and muon neutrinos. Muons are absorbed by 200 m rock, leaving behind a pure beam of muon neutrinos. The near detector (approx 1 kton) is located 300 m down from the hadron absorber. The far detector is placed in Soudan and is a 5400 ton detector. It was started on 4 March 2005 and it aims to study neutrinos in the energy range 1–30 GeV and to provide a more precise measurement of the mass difference and mixing angle responsible for the disappearance of atmospheric neutrinos (Δm_{23}^2 and θ_{23} mentioned above). The experiment also studies $\nu_\mu \rightarrow \nu_e$ oscillations in the same exposure. The magnetized steel plates used in the detectors allow us to distinguish ν_μ CC events from $\bar{\nu}_\mu$ CC events, and thus to search for CPT violation in atmospheric neutrino oscillations.

We also briefly recall the results from K2K. This is a long-baseline experiment where the neutrinos are produced in KEK using a proton synchroton which accelerates protons to an energy of 12 GeV. These protons strike an aluminum target and produce pions which then decay into muons and neutrinos. A detector in KEK first detects the neutrino flux before the neutrinos travel 250 km to the Super-Kamiokande, where they are detected by the Cerenkov principle in 50,000 tons of water. In the absence of neutrino oscillations, there were supposed to be $158.1^{+9.2}_{-8.6}$ events, but only 112 were observed[6].

Neutrinos are elementary particles, which are neutral counterparts of the charged leptons, namely the electron, the muon and the τ-lepton, all of which participate in weak interactions. Determination of neutrino properties remains notoriously difficult from the point of view of experiments, and their precise determination remains one of the great challenges and goals of elementary particle physics research today. At the moment, there is no information of even the values of their individual masses, which are today bounded by experiments as follows[7]: $m_1 < 3$ eV, $m_2 < 190$ keV, $m_3 < 18.2$ MeV. It is worth noting here that the direct detection of the ν_τ was reported[8] for the first time only as recently as 2000 by the Fermilab DONUT (Direct Observation of Nu Tau, E872) experiment. This experiment used protons accelerated by the Tevatron to produce a ν_τ beam and an active emulsion detector.

We note here that the subject of neutrino physics is considered so important

---

[†]In Memoriam: John N. Bahcall (1934–2005), Raymond Davis Jr. (1914–2006).

at the present time that the American Physical Society has commissioned a multi-divisional study whose reports are now available to the public on the internet[9]. In particular, several working groups were formed, on solar and atmospheric experiments, reactor experiments, neutrino factory and beta beam experiments, neutrinoless double-beta decay and direct search experiments, neutrino astrophysics and cosmology, and on theory.

The presence of neutrino oscillations implies existence of distinct and nonvanishing masses for the two heavier flavours. In particular, there are now three masses m_1, m_2 and m_3 and three angles that 'mix' the neutrino flavours denoted by θ_{12}, θ_{23} and θ_{13}. (This last parameter has not been experimentally determined so far. A reactor neutrino experiment, CHOOZ, which measured the survival probability of electron anti-neutrinos from a nuclear power reactor in France, observed no deficit[10] and set the bound $\sin^2\theta_{13} < 0.05$.) In addition, neutrinos may also be Majorana particles, i.e. they are neutral fermions which are their own antiparticles. In that case there would also be the possibility of lepton number violation in nature by two units, $\Delta L = 2$, which, for example, is the basis of the neutrinoless double-beta decay experiment. The matrix that describes the neutrino mixing is called the PMNS matrix, named after Pontecorvo, Maki, Nakagawa and Sakata, the authors who first described it. In form, it is similar to its counterpart in the quark sector, namely the CKM matrix named after Cabibbo, Kobayashi and Maskawa[11]. However, the angles in the CKM matrix are all well measured and all three of them are small (less than 12°) whereas two of the three mixing angles in the neutrino sector are larger than 30°, showing that the patterns of mixing in quark and lepton sectors are different. Note that the CKM matrix has a non-zero phase δ which leads to CP violation in the decays of K and B mesons and is well determined from the experimental measurement of CP-violating observables. CP violation may also occur in neutrino oscillations if the PMNS matrix contains a non-zero phase. Such a non-zero phase is possible in the mixing of three neutrinos (as it is in the case of three quarks). Such a phase leads to the prediction that the oscillation probabilities for neutrinos and anti-neutrinos are unequal. One can establish CP violation in the neutrino sector by studying $\nu_\alpha \rightarrow$ ν_β and $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$, where α and β are neutrino flavours. CPT violation in the neutrino sector can be established if one can show that the survival probabilities $P(\nu_\alpha \rightarrow \nu_\alpha)$ and $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha)$ are unequal.

We now turn to the solar neutrino problem which has been discussed earlier[12]. This problem also is resolved by postulating neutrino oscillations. To recall briefly the salient features of this problem, the measured fluxes of solar neutrinos at the radio chemical experiments at Homestake (associated with Raymond Davis Jr.), SAGE, Gallex and GNO experiments were significantly lower than those predicted by the standard solar model (SSM, associated with John N. Bahcall). The experiment at Homestake was based on the capture of neutrinos by chlorine nuclei, while those at the other three were based on the capture of neutrinos by gallium nuclei. That there was a solar neutrino problem was also confirmed by Kamiokande and Super-Kamiokande experiments, which detected solar neutrinos in *real time* by observing neutrino-electron scattering. According to standard electroweak model (SEM), the sun should emit only electron neutrinos which can be detected on earth through their charged current (CC) interactions. In such an interaction, the electron neutrino exchanges charge with another particle and produces an electron. The observed deficit of solar neutrinos, compared to the predictions of SSM is explained by assuming that electron neutrinos are oscillating into muon/tau neutrinos. These neutrinos cannot be observed in the above detectors because their CC interactions produce a muon/tau in their final states. The low energies of solar neutrinos preclude the production of these heavy mass particles. Thus observed fluxes were lower than the predicted fluxes.

This raises the question: Is it possible to observe the muon/tau neutrino fraction in the solar neutrinos reaching the earth? It is possible to observe them through their neutral current (NC) interactions. In an NC interaction, a neutrino of a given flavour retains its identity and exchanges only energy with the other participating particle. If heavy water is used as a target, then a neutrino interacting with a deuteron will break it up and the resultant neutron can be detected. Sudbury Neutrino Observatory (SNO) used this technique to measure the NC interaction rates of solar neutrinos. According to

SEM, the NC interaction rates of all three types of neutrinos, with any given particle, are the same. Thus, if the electron neutrinos emitted by the sun are changing into muon/tau neutrinos, then the NC interaction rate should be consistent with the predictions of SSM. The first results[13] of SNO, announced in 2001, definitely established that the NC interaction rates of solar neutrinos are indeed in accordance with SSM predictions. SNO independently measured the CC interaction rate of electron neutrinos also, by detecting the final-state electrons. These measurements are consistent with the previous measurements and show that there is indeed a shortfall of electron neutrinos from the sun as they arrive on earth. Detection of the neutron in SNO is subject to various uncertainties. Therefore, SNO decided to use three different techniques to detect the neutron. In the first phase, they used the heavy water itself to detect the neutron. In the recently concluded second phase, salt was added to the heavy water to improve the neutron detection efficiency[14]. In the current third phase, the salt is withdrawn and ^{3}He proportional counters added which detect neutrons through the reaction $n + {}^3\text{He} \rightarrow p + {}^3\text{H}$. This will assist in reducing the error in the measurement of the NC reactions rates.

The combined results of all the solar neutrino experiments require that the resolution of the solar neutrino problem is through neutrino oscillations with a large mixing angle (LMA) modified by the MSW (Mikheyev–Smirnov–Wolfenstein) mechanism. Recalling briefly here, the MSW effect results from the enhancement of the flavour oscillation of ν_e generated in various nuclear reactions in the solar interior to ν_μ/ν_τ, due to their interaction with the dense solar interior. The mechanism turns out to be efficient for the energy range of the detected neutrinos and is known as 'resonance conversion'. The final determination of solar neutrino oscillation parameters are: $\Delta m_{12}^2 = 8^{+0.6}_{-0.4} \cdot 10^{-5}$ eV^2, $\theta_{12} = (33.9^{+2.4}_{-2.2})°$. It may be noted that results coming from the BOREXINO experiment, which seeks to measure the intensity of the monochromatic 861 keV neutrino line, could play an important role in constraining solar models and neutrino oscillation models. An ambitious project based on the 1976 proposal of R. S. Raghavan that is being planned is the LENS (Low Energy Neutrino Spectroscopy) experiment, which is based on a

radiochemical reaction involving indium targets and can also measure low-energy neutrinos produced in the solar proton–proton cycle in real time.

In order to establish the validity of the conclusions from the SNO observations, viz. the resolution of the solar neutrino problem through the LMA–MSW solution, the KamLAND experiment (Kamioka Liquid scintillator Anti-Neutrino Detector) was set up in Toyama, Japan in 2002. The detector is surrounded by 53 Japanese commercial power reactors (180 km away), which produce $\bar{\nu}_e$. The neutrinos are detected using the Cerenkov principle in 1000 tons of mineral oil, benzene and fluorescent chemicals. Without neutrino oscillation, the experiment was expected to observe 86.6 ± 5.6 events. However, only 54 events were observed. This confirmed the picture of LMA oscillations in vacuum[15].

Finally, the presence of non-vanishing masses for the neutrinos is likely to hold the key to our understanding of not just the properties of elementary particles, but also to the entire history of the universe. As a result, it is important to demonstrate neutrino oscillations in several different settings, and to independently measure mass square differences. That is why the results of MINOS and the future experiments T2K (under construction) and NOVA and INO (in planning stages) are important. Note that the above experiments, which detect neutrino oscillations, can only give information on neutrino mass differences but not on the mass of the lightest neutrino. This information is expected to come from tritium beta decay experiments[16] and double-beta decay experiments[17].

We recall here the results from a somewhat controversial experiment known as LSND (Liquid Scintillator Neutrino Detector)[18]. The experiment observed excesses of events for both the $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ oscillation searches. If confirmed, the results of LSND experiment imply that there is a mass-squared difference of about 0.1 eV^2 between two neutrino mass eigenstates. This conclusion, inevitably leads to the prediction that there should be a fourth light neutrino, because we cannot have three mass-squared differences of three different orders of magnitude with just three neutrinos. The fourth neutrino must be sterile (essentially non-interacting) because results of the LEP experiments have shown that there are only three light neutrinos

with the standard interactions[19]. Mini-BooNE (Mini Booster Neutrino Experiment)[20] experiment at Fermilab has been taking data and it can confirm or rule out the LSND result. It consists of a 1 GeV neutrino beam from pion decay and a single, 800-ton mineral oil (12-m diameter sphere) detector. The MiniBooNE detector is located 500 m downstream of the neutrino source. The MiniBooNE results are expected to be announced in a year's time.

We now discuss experiments whose goal is neutrino astronomy, identifying astrophysical sources of neutrinos which include medium energy (about 100 MeV) sources within our galaxy like supernovae and the sun and high energy (a few GeV and greater) extragalactic sources like exploding stars, gamma ray bursts, black holes and neutron stars. Some of these experiments also try to detect neutrino oscillations.

It may be recalled that the field of supernovae neutrino physics was born with the detection of the neutrinos from the supernova 1987A by IMB[21] and Kamiokande-II (ref. 22). Some of the current neutrino experiments, Super-kamiokande and SNO, are capable of observing supernova neutrinos. There are various plans to improve the current ones or design new experiments to enhance the detection capabilities of supernova neutrinos. Study of signals from supernova neutrinos in different types of detectors is an important topic in neutrino physics today[23,24].

Neutrino telescopes can be located under water. DUMAND (Deep Underwater Muon And Neutrino Detector) and Baikal were among the first to explore the unchartered waters. The former was located offshore Hawaii in the Pacific Ocean, while the latter was located in Lake Baikal, Siberia. The next is NESTOR (Neutrino Extended Submarine Telescope With Oceonographic Research) located offshore Greece, in the Mediterranean Sea, which detects neutrinos in the TeV range. It determined the cosmic ray muon flux as a function of the zenith angle and the energy spectrum and composition of primary cosmic rays. Future experiments include ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) located offshore France and NEMO (NEutrino Mediterranean Observatory) offshore Sicily. ANTARES is a step towards a cubic kilometre telescope in the Mediterranean Sea. ANTARES and NEMO

are designed to detect high-energy neutrinos in the TeV to PeV range.

The new generation of neutrino experiments also includes the Antarctic Muon and Neutrino Detector Array (AMANDA) built to detect extra-solar sources of neutrinos. The photomultiplier tube array located between 1500 and 2000 m of Antarctic ice detects neutrinos coming through the earth from the northern sky using the Cerenkov principle. The depth of the array effectively blocks atmospheric neutrinos. Compared to underground detectors like Super-Kamiokande, AMANDA is capable of looking at higher energy neutrinos (>50 GeV). AMANDA demonstrated the viability of a neutrino telescope in ice and in 2005 was officially incorporated into its successor ICECUBE. It will encompass a cubic kilometre of ice and will be completed in 2010–11. IceCube will be able to explore the PeV (10^{15} eV) energy region. Detection of cosmic neutrino beams would open the opportunity to study neutrino oscillations over megaparsec baselines.

There is a proposal to build a neutrino observatory in India called India-based Neutrino Observatory (INO) which is likely to be built in the Nilgiris. It is a 50 kiloton detector consisting of magnetized iron sheets interspersed with active detector elements. It can detect muons produced by atmospheric muon neutrinos and can determine their charge, energy and direction accurately. This will enable the detector to measure the atmospheric mass-squared difference very accurately (to about 10%)[25]. In addition, it can also determine the mass-hierarchy of neutrino mass eigenstates[26] and the deviation from maximality of θ_{23} if the CHOOZ mixing angle θ_{13} is large enough[27].

We conclude with a remark on the constraints that the present-day neutrino experiments and the future experiments will place on theoretical models for neutrino masses and mixings. One of the spectacular possibilities is that of 'grand unification' of the standard model interactions, viz. the strong and electro-weak interactions. Such models are often based on larger 'gauge groups' into which the gauge symmetries of the standard model would fit. Notable among these is $SO(10)$ unification, which would naturally accommodate a right-handed neutrino, and would also admit both Dirac and Majorana masses for neutrinos. In this event, the well-known 'see-saw' mechanism could generate the observed spectrum of

masses[28,29]. There are many models today which predict and accommodate the observed masses and mixings. The forthcoming experimental results will help in discriminating among these models.

Update: After this article was written, in a press release dated 7 August 2006 from Fermilab[30], it has been reported that the MINOS collaboration has analysed data representing 37 increase compared to the results presented at the end of March 2006. In the absence of neutrino oscillations, they would have expected to observe 336 ± 14 muon neutrinos, but instead they recorded 215 muon neutrino events, thereby confirming their previous results with the best fit for $\Delta m_{23}^2 = 2.74_{-0.26}^{+0.44} \cdot 10^{-3}$ eV^2.

1. http://www.fnal.gov/pub/presspass/press_releases/minos 3-30-06.html
2. Casper, D. *et al*. [IMB collaboration], *Phys. Rev. Lett*., 1991, **66**, 2561.
3. Hirata, K. *et al*. [Kamiokande collaboration], *Phys. Lett. B*, 1992, **280**, 146.
4. Fukuda, Y. *et al*. [Super-Kamiokande collaboration], *Phys. Rev. Lett*., 1998, **81**, 1562; *Phys. Rev. Lett.*, 1999, **82**, 2644.
5. Schwetz, T., hep-ph/0606060.
6. Ahn, M. *et al*. [K2K collaboration], hep-ex/0606032.
7. Eidelman, S. *et al*., *Phys. Lett. B*, 2004, **492**, 442.
8. Kodama, K. *et al*. [DONUT collaboration], *Phys. Lett. B*, 2001, **504**, 218.
9. http://www.aps.org/neutrino
10. Apollonio, M. *et al*. [CHOOZ collaboration], *Phys. Lett. B*, 1999, **466**, 415.
11. Eidelman, S. *et al*., *Phys. Lett. B*, 2004, **492**, 130.
12. Ananthanarayan, B. and Singh, R. K., *Curr. Sci*., 2002, **83**, 553; Indumathi, D., *Curr. Sci.*, 2003, **85**, 1662.
13. Ahmad, Q. R. *et al*. [SNO collaboration], *Phys. Rev. Lett*., 2001, **87**, 071301 [arXiv:nucl-ex/0106015]; *Phys. Rev. Lett*., 2002, **89**, 011301 [arXiv:nucl-ex/0204008]; *Phys. Rev. Lett*., 2002, **89**, 011302 [arXiv:nuclex/0204009].
14. SNO collaboration: Aharmim, B. *et al*., *Phys. Rev. C*, 2005, **72**, 055502, see also Bandyopadhyay, A., Choubey, S., Goswami, S., Petcov, S. T. and Roy, D. P., *Phys. Lett. B*, 2004, **583**, 134.
15. Eguchi, K. *et al*. [KamLAND collaboration], *Phys. Rev. Lett*., 2003, **90**, 021802; Araki, T. *et al*. [KamLAND collaboration], *Phys. Rev. Lett*., 2005, **94**, 081801.
16. Kraus, C. *et al*., *Eur. Phys. J. C*, 2005, **40**, 447.
17. Bilenky, S. M., hep-ph/0509098.
18. Aguilar, A. *et al*., *Phys. Rev. D*, 2001, **64**, 112007.
19. *Phys. Lett. B*, 1992, **276**, 247 (LEP collaborations), hep-ex/0412015.
20. Ray, H. L. for MiniBoone collaboration, hep-ex/0411022.
21. Bratton, C. B. *et al*. [IMB collaboration], *Phys. Rev. D*, 1988, **37**, 3361.
22. Hirata, K. *et al*. [KAMIOKANDE-II collaboration], *Phys. Rev. Lett.*, 1987, **58**, 1490.
23. Dighe, A. S. and Yu. Smirnov, A., *Phys. Rev. D*, 2000, **62**, 033007.
24. Datta, G., Indumathi, D., Murthy, M. V. N. and Rajasekaran, G., *Phys. Rev. D*, 2000, **62**, 093014; *Phys. Rev. D*, 2001, **64**, 073011.
25. http://www.imsc.res.in/~ino
26. Gandhi, R. *et al*., *Phys. Rev. Lett*., 2005, **94**, 051801; *Phys. Rev. D*, 2006, **78**, 053001.
27. Choubey, S. and Roy, P., *Phys. Rev. D*, 2006, **73**, 013006.
28. Minkowski, P., *Phys. Lett. B*, 1977, **67**, 421.
29. Gell-Mann, M., Ramond, P. and Slansky, R., *Supergravity* (eds van Nieuwenhuizen *et al*.), North Holland, Amsterdam, 1980, p. 315; Yanagida, T., In Proceedings of the Workshop on the Unified Theory and the Baryon Number in the Universe (eds Sawada and Sugamoto, A.), KEK, Tsukuba, Japan, 1979, p. 95; Glashow, S. L., The Future of Elementary Particle Physics, In Proceedings of the 1979 Cargèse Summer Institute on Quarks and Leptons (eds Lévy, M. *et al.*), Plenum Press, New York, 1980, p. 687; Mohapatra, R. N. and Senjanovic, G., *Phys. Rev. Lett*., 1980, **44**, 912.
30. http://www.fnal.gov/pub/today/archive_2006/today06-08-07.html

B. Ananthanarayan*, K. Shivaraj and A. Upadhyay are in the Centre for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India; Chitra Gautham is in the Madras Christian College, Tambaram, Chennai 600 059, India; Aquila Mavalankar is in the St. Stephen's College, New Delhi 110 007, India; S. Uma Sankar is in the Department of Physics, Indian Institute of Technology, Mumbai 400 076, India
*e-mail: anant@cts.iisc.ernet.in