Direct Observation of Neutrino Oscillations at the Sudbury Neutrino Observatory

B Ananthanarayan and Ritesh K Singh

A brief description of the path-breaking evidence for the observation of neutrino oscillations at the Sudbury Neutrino Observatory is presented and the experimental principles and theory thereof are briefly discussed.

The Sudbury Neutrino Observatory (SNO), located in Canada, has recently announced evidence for the direct observation of oscillation of neutrino flavors [1]. The observations indicate that during the flight from the interior of the Sun to the Earth, the neutrinos produced as electron-type neutrinos change their flavor. Neutrinos are fundamental particles that come in three types (flavors): electron, muon and tau denoted by ν_e, ν_μ and ν_τ, respectively. Electron type (anti-) neutrinos are produced, for instance, in radioactive decays of certain heavy nuclei, and are also produced copiously in stars during the process of nucleosynthesis. It may be recalled that there is a long-standing problem, called the 'solar neutrino problem', associated with the shortfall in the number of neutrinos observed on the Earth as compared to the number expected from calculations based on the standard solar model and the standard model of elementary particle physics. The solar models happen to be very stringently constrained and the flux of neutrinos produced in the Sun is known with practically no uncertainty, due to extreme sensitivity of the flux to the values of the parameters going into the solar model. As a result, it has been long believed that any solution to the problem must come from the elementary particle physics sector, such as the oscillation of flavors, or the possible interaction of the neutrinos with the solar magnetic fields which might significantly scatter away the neutrinos that were directed towards the Earth. A flavor oscillation necessarily implies that the neutrinos are massive particles and this was first pointed out a long time ago by the Italian born Soviet scientist Bruno Pontecorvo. Whereas there are constraints on the masses of the electron-, muon- and tau-type neutrinos ($m_{\nu_e} \leq 2.8$ weV/c^2, $m_{\nu_\mu} \leq 170$ keV/c^2 and $m_{\nu_\tau} \leq 18.2$ MeV/c^2), the oscillation can, in principle probe differences of the squares of the masses and the probability of conversion from one flavor into another depends on the path length between production and observation, and on the kinetic energy of the neutrino that is being observed. The observation from SNO definitively shows that the electron type neutrino oscillates into an admixture of the other two flavors. The SNO collaboration also reports a possible day-night effect [2], in that there seems to be some indication that the probability of conversion of the electrons depends on the path length which depends on whether the observation is made during the day or during the night.

The experiment is based on the principle of detecting interactions of neutrinos with matter in an ingenious manner, heavy water is used as the medium in which the interactions take place and in which the reaction products are detected. This differs from earlier measurements at Kamiokande and the super-Kamiokande experiments, which used normal water and from those based on radiochemical measurements, which used interactions of the neutrinos with nuclei of chlorine in carbon tetrachloride or with gallium nuclei. For completeness, we note that the solar neutrino problem was first established by the historic chlorine experiment of Ray Davis at the Homestake Mine in South Dakota, USA, which employs the following reaction to detect neutrinos

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e^-$$

The Gallium experiments use the reaction

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-.$$

The neutrinos that are observed at SNO are produced in the core of the Sun. The reaction is as follows.

$$^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be} + e^+ + \nu_e.$$

The kinetic energy of the neutrinos produced in this reaction could vary from as little as a fraction of an MeV to approximately 15 MeV. These neutrinos interact with the water molecules in a variety of ways. The normal water detector detects this neutrino from its elastic scattering (ES) with the electrons in the water molecules. The ES measurements are predominantly sensitive to the electron type flavor only. The measurements of super-Kamiokande had established from the event rates they observed, a shortfall in the expected event rate, consistent with the earlier radiochemical measurements which had led to the classical solar neutrino problem. These observations were based on the charged current (CC) reactions. The full electroweak theory of Glashow, Salam and Weinberg has established that the theory also has, in addition to the conventional electromagnetic interaction, what is called the neutral current (NC) interactions. All the interactions arise from the exchange of (virtual) intermediate vector bosons, the CC interactions from $W^{\pm}$, the NC interactions arise from a neutral boson called Z^0, just as the electromagnetic interactions arise from the photon. Here we note that the main principle in both the normal and heavy water detectors for the observation of the scattered electron in the ES or the produced electron in the CC reaction is that of the detection of Cerenkov light produced by the ultra-relativistic electron during its motion with its velocity exceeding that of light in the medium (water). The Cerenkov light is detected by photomultiplier tubes at the boundary of containers. Note that the water has to be of extraordinary purity in order to prevent attenuation of the light during its travel from the electron source to the detector. The measurements of the ES and CC reaction rates by the SNO collaboration were reported earlier [3], which further confirmed the solar neutrino problem.

The remarkable advantage of the heavy water detector is its capability to observe the

NC interactions as well, in addition to observing the CC interactions. It must be mentioned that the construction of the SNO experiment was directly inspired by an important paper by the late Herb Chen [4]. The crucial property of the heavy water detector arises from the fact that the deuterium nucleus has a remarkably small binding energy of 2.225 MeV. This may be contrasted with the typical binding energies of 8-9 MeV/nucleon for most nuclei. As a result, the kinetic energy of the neutrinos is sufficiently large so as to induce the following reactions:

$$\nu_e + {}^2\mathrm{D} \rightarrow e^- + 2p \qquad \text{(CC)}$$
$$\nu_l + {}^2\mathrm{D} \rightarrow \nu_l + p + n,\ l = \nu, \mu, \tau \qquad \text{(NC)}$$

The reason why the CC reaction above is sensitive only to the electron-type neutrino is that kinetic energy of the neutrinos produced in the boron reaction is sufficient only to produce electrons (m_e=0.511 MeV/c^2), in accordance with Einstein's mass-energy equivalence, whereas the muons and the tau-leptons are too massive to be produced in this reaction (m_μ=105.7 MeV/c^2, m_τ=1777 MeV/c^2). The NC reaction does not have this kinematic constraint and is therefore sensitive to all flavors. The combination of the small binding energy of the deuterium nucleus with the NC reaction is capable of producing a characteristic signal which can be detected when the deuterium nucleus is shattered and the neutron is liberated. Nevertheless, the heavy water detector observed the CC reaction and the ES reaction rates by 2001, but had to wait until 2002 to observe the NC. The latter required that ultra-pure common salt (NaCl) be introduced into the heavy water so that the neutrons produced in the NC reactions could be absorbed by the Cl nuclei and then produce a characteristic 8.6 MeV gamma ray signal. Otherwise neutrons were detected by characteristic 6.25 MeV gamma ray when they get absorbed by deuterium in heavy water. The neutron absorption probability in heavy water is about 25% which increased to 85% by addition of ultra-pure NaCl. This was achieved and the results were subsequently reported in [1]. The final numbers quoted therein translate to 2/3 of the electron-type neutrinos oscillating into muon and tau type flavors. Furthermore, the observation of a non-vanishing day night effect shows that there may be some regeneration of the electron type neutrino flux in the passage of the neutrinos from the Sun through the Earth. Such an effect, known as the Mikheyev–Smirnov–Wolfenstein effect, has been studied in the past and is now likely to be constrained quite effectively, or alternative vacuum oscillation scenarios are likely to be constrained as well. For a recent discussion of the impact of the SNO measurements on theoretical scenarios, we refer to [5].

It must be mentioned again that the advantages of the heavy water also leads to the possibility of large backgrounds. In fact, the SNO experiment is located deep underground in nickel mines in Canada, and the heavy water which is stored in a large acrylic container is also surrounded by jackets containing normal water in order to absorb radiation from the surrounding rock and also from cosmic ray sources which could easily generate spurious signals which serve as a background.

In conclusion, we note that the remarkable experiment at SNO based on the deep insights of Chen has resolved the solar neutrino problem in favor of a solution arising from neutrino oscillations, rather than from unknown inadequacies of the standard solar model. The SNO collaboration is expected to improve its statistics and bring down uncertainties in their measurements and will pave the way to confirming and constraining theoretical scenarios which account for neutrino oscillations.

Suggested Reading

[1] Q R Ahmad and others, [SNO Collaboration], *Phys. Rev. Lett.*, Vol. 89, p.011301, 2002.

[2] Q R Ahmad and others, [SNO Collaboration], *Phys. Rev. Lett.*, Vol. 89, p.011302, 2002.

[3] Q RAhmad and others, [SNO Collaboration], *Phys. Rev. Lett.*, Vol. 87, p.071301, 2001.

[4] H H Chen, *Phys. Rev. Lett.*, Vol. 55, p.1534, 1985.

[5] J N Bahcall, M C Gonzalez-Garcia and C Pena-Garay, arXiv:hep-ph/0204314.

For articles in *Resonance* of related interestes, see

[1] S M Chitre, *Resonance*, Vol. 7, No. 8, p. 67, 2002.

[2] R Ananthakrishnan, *Resonance*, Vol. 4, No. 4, p. 12, 1999.

B Ananthanarayan and Ritesh K Singh, Centre for Theoretical Studies, Indian Institute of Science, Bangalore 560 012, India. Email:anant@cts.iisc.ernet.in

Of Studies

Studies serve for Delight, for Ornament, and for Ability. Their Chief Use for Delight, is in Privateness and Retiring; For Ornament, is in Discourse; And for ability, is in the Judgement and Disposition of Business. For Expert Men can Execute, and perhaps Judge of particulars, one by one; But the general Counsels, and the Plots, and Marshalling of Affairs, come best from those that are Learned. To spend too much Time in Studies, is Sloth; To use them too much for Ornament, is Affectation: To make Judgement wholly by their Rules is the Humour of a Scholar. They perfect Nature, and are perfected by Experience: For Natural Abilities, are like Natural Plants, that need Proyning by Study: And Studies themselves, do give forth Directions too much at large, except they be bounded in by experience. Crafty Men Contemn Studies; Simple Men Admire them; And Wise Men Use them: For they teach not their own use; But that is a Wisdom without them, and above them, won by Observation. Read not to Contradict, and Confute: Nor to Believe and Take for granted; Nor to Find Talk and Discourse; But to weigh and Consider. Some Bookes are to be Tasted, Others to be Swallowed, and some Few to be Chewed and Digested: That is, some Bookes are to be read only in Parts; Others to be read but not Curiously; And some Few to be read wholly, and with Diligence and Attention. Some Bookes also may be read by Deputy, and Extracts made of them by Others; But that would be, only in the less important Arguments, and the Meaner Sort of Bookes; else distilled Bookes, are like Common distilled Waters, Flashy Things. Reading maketh a Full Man; Conference a Ready Man; and Writing an Exact Man. And therefore, If a Man Write little, he had need have a Great memory; If he Confer little, he had need have a Present Wit; And if he Read little, he had need have much Cunning, to seem to know that, he doth not. Histories make Men Wise; Poetry Witty; The Mathematics Subtile; Natural Philosophy deep; Moral Grave; Logick and Rhetorick Able to Contend. Abeunt Studia in Mores. Nay there is no Stond or Impediment in the Wit, but may be wrought out by Fit Studies: Like as Diseases of the Body, may have Appropriate Exercises. Bowling is good for the Stone and Reines; Shooting for the Lungs and Breast; Gentle Walking for the Stomach; Riding for the Head; and the like. So if a Man's Wit be Wandering, let him Study the Mathematics; For in Demonstrations, if his Wit be called away never so little, he must begin again: If his Wit be not Apt to distinguish or find differences, let him Study the Schoole-men; For they are Cymini sectores. If he be not Apt to beat over Matters, and to call up one Thing, to Prove and Illustrate another, let him Study the Lawyer's Cases: So every Defect of the Mind, may have a Special Receipt.

Francis Bacon, The Essays, 1601