# From neutrons to neutrinos: On the trail of solar fusion and terrestrial fission

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In December 2002, the Japan-based Kamioka Liquid scintillator Anti Neutrino Detector (KamLAND) collaboration announced[1] that its measured rate of anti-neutrino fluxes from fission reactions in nuclear reactors was smaller than theoretically expected. In September 2003, The Canada-based Sudbury Neutrino Observatory (SNO) collaboration released its latest data[2] on neutrinos from the sun. They conclude, consistent with their earlier measurement[3], that the measured solar neutrino flux agrees with that expected from fusion reactions in the sun, calculated using standard solar models. Their data also indicate that neutrinos *oscillate* on their way from the sun to the earth. Indeed, both the observed KamLAND deficit and the SNO measurements are consistent with the idea of neutrino oscillations. Along with earlier experiments, they provide compelling evidence for new physics beyond the Standard Model of particle physics.

After briefly describing neutrinos, their sources and their interactions, we will return to the SNO and KamLAND data and explain the extraordinary nature of their results.

*Neutrinos:* There are at least three *flavours* of neutrinos, denoted $\nu$, associated with the three known leptons: electron, muon and tau. Similarly, three flavours of antineutrinos are associated with the anti-leptons. The most common interaction involving neutrinos is neutron beta decay, $n \to p + e + \overline{\nu}_e$, in which an electron antineutrino is produced. In fact, the existence of the neutrino was postulated by Pauli to explain the continuous energy spectrum of the electron in beta decay. Within the Standard Model of particle physics, all neutrinos are considered to be massless and have zero electric charge.

*Neutrino detection:* Matter in both the sun and the earth is electronic in nature in that the atoms contain electrons but no muons or taus. Hence electron neutrinos interact differently with such matter than muon- or tau-neutrinos. For example, charge transfer occurs in the interaction $\nu_e + n \to e^- + p$; hence it is called a charged current (CC) interaction.

A neutral–current (NC) interaction occurs when the neutrino remains unchanged after the interaction. Clearly, any flavour of neutrino can undergo such a scattering in matter. Both $\nu_e$ and $\nu_{\mu,\tau}$ can also elastically scatter (ES)-off electrons, though the latter will have a smaller cross-section.

*Solar neutrinos:* Many eminent scientists, including Eddington, Weizsäcker and Bethe, worked on the problem of the source of energy in the sun. By 1939, it was established[4] that thermonuclear fusion reactions power the sun and the stars. The basic process may be summarized as $p + p + p + p \to {}^4\text{He} + 2e^+ + 2\nu_e +$ 26.7 MeV. Notice that *only* electron-type neutrinos are produced.

The observation of neutrinos from the sun is the only direct experimental evidence for this theory. The enormous importance attached to the detection of solar neutrinos, culminating in the Nobel Prize in 2002 to Davis and Koshiba for 'pioneering contributions to… the detection of cosmic neutrinos', bears out this fact.

The energy released in the process accounts for the luminosity of the sun. From this, we can calculate the solar neutrino flux at the earth to be 70 billion/$\text{cm}^2$/s. However, the neutrino *energy spectrum*, which is crucial for its experimental detection, requires a detailed model for the sun and a knowledge of various thermo-nuclear fusion reactions. Typical Standard Solar Models (SSM) predict that most (99.75%) solar neutrinos are produced when two protons fuse to form the deuteron. These neutrinos have low energies, ranging up to 0.42 MeV.

About 0.01% of the solar neutrinos are produced during the beta decay of $^8$B, which is an intermediate product of the fusion process. These so-called Boron neutrinos have much higher energies, up to 14 MeV. Many of the neutrino detectors that are operational, including the SNO detector, are sensitive only to these neutrinos.

The Boron neutrino flux is sensitive to the various physical processes in the sun and hence is a crucial test of the SSM. It is also a sensitive function of the temperature of the solar core, being proportional to the 25th power of the average core temperature. So, these neutrinos are excellent probes of the processes occurring in the deep solar interior.

*The SNO detector:* The SNO detector is an amazing construction: 1 kiloton of heavy water ($D_2O$) is contained in a transparent, acrylic, spherical shell of diameter 12 m. When a neutrino hits the heavy water, it can produce an energetic electron that passes through the heavy water, generating Cerenkov radiation. This radiation is detected in real time by 9456 photomultiplier tubes (PMT) surrounding the heavy water. These are mounted on a stainless-steel geodesic sphere of diameter 17.8 m, immersed in ultra-pure light water to provide shielding from radioactive contamination from the outside. The entire assembly is placed deep (more than 2 km) underground to shield it from cosmic-ray backgrounds.

Three different types of reactions, CC, NC and ES, can be detected in the SNO detector. In the CC reaction of *only* $\nu_e$ on deuteron, $\nu_e + d \to e^- + p + p$, the final-state electron is detected. The NC reaction of any flavour neutrino on deuteron breaks up the deuteron: $\nu + d \to \nu + p + n$. The NC cross-section is the same for all neutrino flavours. The neutron produced in the reaction is captured within the detector, giving characteristic gamma ray(s) that are detected. The ES cross-section for neutrinos on electrons in the heavy water, $\nu + e \to \nu + e$, is six times smaller for non electron-type neutrino flavours. The scattered electron is detected. All three cross-sections have different angular distributions, so that they can be statistically separated by knowing the instantaneous position of the sun. The energy threshold of SNO is such that only the $^8B$ solar neutrinos can be detected.

Last year, the SNO NC measurement was obtained by absorbing the neutron on the deuteron, giving a monoenergetic

6.25 MeV photon. The neutron-detection efficiency in this channel is only 14%. The new SNO measurement uses 2 tons of salt (NaCl) added into the heavy water, giving a three times larger efficiency for neutron capture. More importantly, neutron capture on chlorine produces multiple gamma rays. These lead to a highly isotropic Cerenkov light, compared to that from CC and ES events with single electrons. This feature allows the NC events to be separated out, so that the NC flux can be measured precisely, *independent of assumptions* on the CC and ES energy spectra. This was not possible earlier.

The SNO result is that the neutrino flux measured in the NC sector is as expected, viz. $\phi(\text{NC, SNO}) = 5.21 \pm 0.47$, compared to the theoretical prediction[5] of $5.05^{+1.0}_{-0.8}$ in units of $10^6/\text{cm}^2/\text{s}$. Since solar neutrinos are purely $\nu_e$, the flux measurements from all channels should have been the same. Instead, the observed fluxes are $1.59 \pm 0.11$ and $2.21 \pm 0.30$ in the same units as above, in the CC and ES channels.

Now, the CC events can only come from $\nu_e$ while the NC events can come from neutrinos of any flavour, with equally weighted contributions due to the equality of the cross-sections. That is, the NC channel counts *all* neutrinos from the sun (excluding possible sterile flavours that do not interact with matter at all). The discrepancy between the NC and CC prediction thus means that $\nu_\mu$ and/or $\nu_\tau$ also contribute to the SNO NC events. This is also consistent with the flux predicted from the ES channel being slightly larger than that from the CC channel.

The logical interpretation of the data is then that the *total* flux of neutrinos from the sun is as predicted, but only about one-third of this flux is $\nu_e$. Since nuclear fusion produces only $\nu_e$, this means that some of these $\nu_e$ have oscillated to other flavours on their journey to the earth. The 'salt-data' of SNO has therefore established the validity of the SSM using neutron detection to establish the solar neutrino flux, *independent of assumptions* on the ES and CC events. In doing so, it has provided evidence for the phenomenon of neutrino oscillations and therefore non-zero neutrino mass.

*Neutrino oscillations:* The theory of neutrino oscillations was proposed as early as 1958 by Pontecorvo[6]. Neutrinos of different flavours can mix with one another. Then, the propagating neutrino mass eigenstates are not the same as the flavour eigenstates that interact with matter. The mixing is described by a unitary matrix that rotates mass eigenstates to flavour eigenstates. The parameters of mixing are thus mixing angles and phases. Apart from flavour mixing, a condition for neutrino flavour oscillations to occur is that at least some of the neutrinos are massive; hence there is now evidence to believe that neutrinos have a mass. The nature and extent of the mixing, and hence the observed flux, is determined by these parameters. In the case of simple two-flavour mixing, for example, one mixing angle $\theta$ and one mass squared difference $\delta \equiv m_2^2 - m_1^2$ are the relevant parameters.

*Reactor neutrinos:* In power reactors, heavy elements such as uranium ($^{235,238}$U) and plutonium ($^{239,241}$Pu) undergo thermal neutron-induced fission to lighter nuclei, releasing energy in the process. The mixture of fuels used at different reactors and the energy produced vary widely. However, all of them produce *only* electron antineutrinos from the beta decay of the fission fragments, with a typical energy spectrum extending to about 10 MeV. The flux and energy spectrum of the antineutrinos at the source are known to good accuracy, based on the power produced by the reactor.

*The KamLAND detector:* This detector is also spherical. It is a balloon of diameter 13 m, made of 135 μm thick transparent nylon, supported by ropes. It is filled with 1 kiloton of liquid scintillator (LS) and placed in a buffer oil inside a 19 m diameter spherical steel containment vessel to shield it from external radiation. It is also placed about 1 km underground to cut out cosmic ray background.

The aim of KamLAND is to detect electron antineutrinos from several tens of power reactors in Japan, on the average about 180 km away. The distance implies that given typical reactor neutrino energies, KamLAND will be sensitive to the *same* mixing angle as the solar neutrinos are. Neutrino interactions inside the LS produce Cerenkov radiation, with a lower threshold so that electron antineutrinos down to 1.8 MeV can be detected, in contrast to the SNO detector. This is made possible by the use of LS instead of heavy water. The radiation is detected by 1325 PMTs mounted on the inner surface of the containment vessel. Electron antineutrinos interact with protons in the LS to produce positrons and neutrons. The positron is detected as a prompt signal, while the neutron is absorbed on protons to give a 2.2 MeV delayed photon. The delayed coincidence measurement of positron and neutron removes virtually all possible backgrounds. Furthermore, the energy spectrum of the prompt signal, $E_{\text{prompt}}$, is closely related to the original antineutrino spectrum.

Above $E_{\text{prompt}} = 2.6$ MeV, KamLAND observes 54 events with a single possible background event, while 86.8 events were expected during the detection period. There is a clear deficit, especially in the low prompt-energy region. This can be attributed to neutrino oscillations.

A two-flavour analysis of just the SNO data allows a large set of mixing parameters, including the so-called small mixing angle (SMA) solution to the solar neutrino problem with $\theta \sim 1°$. On combining the SNO and KamLAND data, a small region of allowed mixing parameter space is clearly demarcated. The best-fit parameters, including the SNO, KamLAND and other experiments are $\delta = 7.1 \times 10^{-5}\ \text{eV}^2$ and $\theta = 32.5°$, with errors on the parameters of roughly 10%. Maximal mixing with $\theta = 45°$ is disfavoured at 5.4 standard deviations, so also the SMA solution.

Interestingly, antineutrinos from $^{238}$U and $^{232}$Th decays contribute to the KamLAND signal up to $E_{\text{prompt}} = 2.49$ MeV. Since the abundances of these elements in the earth are not well known, a cut of $E_{\text{prompt}} > 2.6$ MeV was applied in the analysis. On lowering the threshold to 0.9 MeV, the oscillation best-fit parameters remain the same. Using a particular model of geo-neutrinos[7], a prediction of 4(5) geo-antineutrinos from U(Th) was obtained, which corresponds to 40 TW radiogenic heat generation in the earth. The low-energy data of KamLAND thus open up the prospect of studying the distribution of U and Th in the crust and mantle of the earth.

In summary, the SNO experiment has precisely determined the total active boron solar neutrino flux. This agrees with the SSMs. The SNO and KamLAND experiments indicate that neutrinos and antineutrinos oscillate and so have non-zero mass; such a signal for new physics will necessitate modification of the Standard Model of particle physics.

A combined analysis of the SNO and KamLAND data constrains some of the oscillation parameters. Unambiguous proof of neutrino oscillations needs to be obtained by observing regeneration of neutrino species rather than just depletion of spectra. Other questions remain. For example, is CP violated in the leptonic sector? This may help explain the baryon asymmetry in the universe. Are neutrinos Dirac or Majorana particles? Is there room for a sterile neutrino? What is the origin of the neutrino (and perhaps other fermion) masses? What role does a massive neutrino play in cosmology?

Recall that the neutrino is a *neutral* fermion, i.e. it is possible that it is its own antiparticle. Such particles are called Majorana particles. All other known fermions (quarks and charged leptons such as electrons) are Dirac particles, as they have a non-zero charge which is opposite for the corresponding anti-particle. The mass term that can be written in a Lagrangian that defines a massive neutrino will be different for a Dirac and Majorana particle. In particular, having a Majorana mass term allows for the possibility of neutrino-less double beta decay. This is not possible with a Dirac neutrino. Furthermore, the mixing matrix for Majorana particles will have more CP-violating phases. Finally, the Majorana mass matrix allows, through the see-saw mechanism, a natural framework to explain why the neutrinos have such a small mass, by invoking a large mass-scale. Such an access to very high-scale physics (near what is known as the grand unification scale) through the measurement of a small neutrino mass, is what makes the Majorana possibility an exciting one. This explains the great interest in looking for neutrino-less double beta decay.

Clearly, the implications of existing results in neutrino physics extend beyond particle physics, all the way from geophysics to cosmology. Many experiments around the world, including possibly an India-based detector, will try, over the next decade or more, to pin down the precise values of the oscillation parameters. This may help gain a better theoretical understanding of neutrino masses and mixings, and of the fundamental nature of this particle.


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## OPINION

# Digital and information divides: Initiatives for change

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I wish to submit a couple of notions for discussion by the readership. These briefly are:

- We could effectively use the digital and information technology revolution in education and science and technological research to realize our dormant potential in these areas to a fuller extent, and
- Provide open access to empirical data on the Internet to promote capturing a larger proportion of the mind-resources nationally and globally leading to the generation of creative and innovative knowledge efficiently.

Today we often hear of digital divide afflicting particularly the developing nations. This refers to the computer education of the youth. We have to recognize that related to the digital divide there is also another divide – the information divide. We are in the information age. The driving elixir of progress is information, be it education, creative knowledge or innovation.

Back in the fifties, Prime Minister Nehru in a visionary move, established a series of laboratories and educational institutions as incubators for producing resources required for the real progress of the nation. True, a lot has been achieved by the nation. Today perhaps we have the largest force of scientists and technologists in the world. But can it not be said that we could do better in terms of our contribution to the 'new knowledge'? If so let the areas where improvements are needed be identified and efforts be made accordingly.

The curse of the digital and information divides is not only afflicting the realm of the education of the youth but it appears to be equally serious with some of the generation that is at the helm of affairs dealing with the management of our nation's science, technology and education policies and programs.

People make investments in science so as to better understand the workings of nature and to take advantage of the same in improving human life. Historically the progress of science has occurred in two ways. First, like in the evolution of species there are scientific revolutions[1] fuelled by new ideas or discoveries that disturb the equilibrium or the existing paradigms. During the equilibrium periods science hibernates just exploring within the ruling paradigms. Most of the time it just produces a replication of what was largely known or done earlier. The other avenue of revolution is via the progress of scientific tools[2]. The advent of computers and the Internet no doubt has provided new and powerful tools to science, as indeed they have also opened up the opportunity for tapping of the mind resour-