Resolving the solar neutrino problem:

Evidence for massive neutrinos in the Sudbury Neutrino Observatory

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The solar neutrino problem

For more than 30 years, experiments have detected neutrinos produced in the thermonuclear fusion reactions which power the Sun. These reactions fuse protons into helium and release neutrinos with an energy of up to 15 MeV. Data from these solar neutrino experiments were found to be incompatible with the predictions of solar models. More precisely, the flux of neutrinos detected on Earth was less than expected, and the relative intensities of the sources of neutrinos in the sun was incompatible with those predicted by solar models. By the mid-1990's the data were beginning to suggest that one could not even in principle adjust solar models sufficiently to account for the effects. Novel properties of neutrinos seemed to be called for. With the recent measurements of the Sudbury Neutrino Observatory (SNO), it has finally become possible to test the solar model predictions and the particle properties of neutrinos independently.

Solar models that simulate the interior of the Sun and explain stellar evolution have been developed using experimental and theoretical inputs from nuclear physics, astrophysics, and particle physics. These models are based on the assumption of light element fusion in the Sun. As more and more astrophysical data have become available, solar models were tested through a variety of observables and found to be successful in many respects.

A variety of hypotheses that require new particle physics have been postulated to explain the discrepancy between the solar model expectations and the apparent deficit of solar neutrinos detected on Earth. In the Standard Model, neutrinos belong to the family of leptons. Neutrinos were believed to be massless particles with three distinct flavors (electron, muon, and tau) depending on the weak interaction process that created them. One flavor could not transform into another. All three types of neutrinos have been directly detected experimentally, the tau neutrino only in the last year. In the light element fusion processes in the Sun, only electron type neutrinos are created.

As early as 1969, Bruno Pontecorvo proposed that neutrinos might oscillate between the electron and muon flavor states (the only ones known then). Like the K^0–$\bar{K}^0$ mixing phenomenon, neutrino oscillations are a quantum effect. Oscillations can occur if the physical neutrinos are actually particles with different masses but not unique flavors. Neutrino mass and flavor mixing are not features of the Standard Model of particle physics. In quantum mechanics, an initially pure flavor (e.g. electron) can change as neutrinos propagate because the mass components that made up that pure flavor get out of phase. The probability for neutrino oscillations to occur may even be enhanced in the Sun in an energy-dependent and resonant manner as neutrinos emerge from the dense core of the Sun. This effect of matter-enhanced neutrino oscillations was suggested by Mikheyev, Smirnov, and Wolfenstein (MSW) and is one of the most promising explanations of the solar neutrino problem.

The measurements at the Sudbury Neutrino Observatory (SNO) show that the neutrino flux produced in the $^8B \rightarrow 2(^4He) + e^+ + \nu_e$ beta decay reaction in the Sun contains a significant non-electron type component when measured on Earth [1]. This measurement is the first strong indication for the oscillation of solar neutrinos! This in itself is evidence that neutrinos have mass. Together with the oscillation signature in atmospheric neutrino studies, these results are strong evidence for physics beyond the Standard Model. It is also interesting that most theories that attempt to unify the description of all forces between elementary particles already permit non-zero neutrino masses. As for the cosmological implications, the measurements of SNO, combined with the results from other experiments, set an upper limit on the total mass of electron, muon, and taus neutrinos in the Universe.

The Sudbury Neutrino Observatory

Located 2 km underground in an active nickel mine in Sudbury, Ontario, the Sudbury Neutrino Observatory is an imaging water Cherenkov detector specifically designed to study the properties of solar neutrinos. It consists of a spherical acrylic tank filled with 1000 tonnes of heavy water and surrounded by 7000 tonnes of light water to shield it from backgrounds (Figure 1). The choice of D_2O as a target material makes the SNO detector unique in comparison with other solar neutrino detectors. It allows SNO to measure both the total flux of solar neutrinos as well as the electron-type component of the neutrino flux produced in the Sun. Almost 10,000 photomultiplier tubes (PMT) are used to record flashes of Cherenkov light from the heavy water.

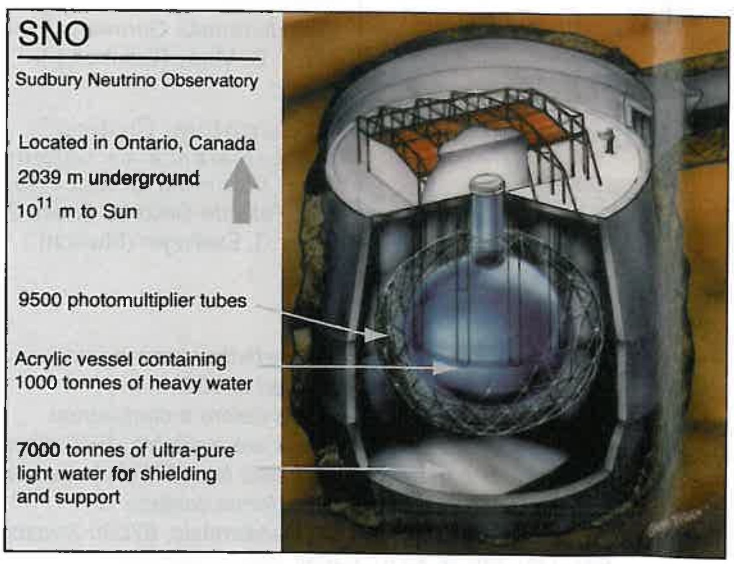


Fig. 1: Artist's conception of the Sudbury Neutrino Observatory. Shown are the acrylic vessel, the photomultiplier support structure, the water-filled cavity, and the deck of the detector where the electronic resides.

Solar neutrinos from the decay of ^8B are detected via the charged-current reaction on deuterium (ν_e+d→p+p+e^-) and by elastic scattering off electrons (ν_x+e^-→ν_x+e^-). The charged-current reaction is sensitive exclusively to ν_e while the elastic-scattering reaction also has a small sensitivity to ν_μ and ν_τ. Neutrinos also interact through the neutral-current reaction (ν_x+d→p+ν+e^-) which dissociates the deuterium and liberates a neutron that quickly thermalizes in the heavy water. Both the charged-current and elastic scattering interaction rates have been measured at SNO. The determination of the neutral-current interaction rate is under way and results will be reported in the near future.

Measurement of charged-current interactions of ^8B neutrinos

The data reported by the SNO collaboration was taken between November 1, 1999 and January 15, 2001 and corresponds to a live time of 241 days. Events are defined by a multiplicity trigger counting the number of hit PMTs above channel threshold. For every event trigger, the time and charge response of each participating PMT are recorded. Electronic pulsers and pulsed light sources are used for the calibration of the PMT timing and charge response. Optical calibration of the detector response is obtained using a diffuse source of pulsed laser light. The absolute energy scale and uncertainties are established with a triggered ^{16}N source (predominantly 6.13-MeV γ) deployed in the D_2O and H_2O. The detector response is tested using neutrons from ^{252}Cf, the electron spectrum from ^8Li, and a 19.8 MeV γ calibration source.

Instrumental backgrounds are eliminated from the raw data based on the timing and charge of hit PMTs in comparison with Cherenkov light. In addition, a set of high level cuts is applied to test the hypothesis that each neutrino event has the characteristics of single electron Cherenkov light.

For each neutrino event, an effective kinetic energy is calculated using prompt, unscattered Cherenkov photons, and the position and direction of the event. As an independent verification of the energy scale, the total number of triggered PMTs (which corresponds to the total light generated by the Cherenkov electron) is used to calculate the energy of every event.

Possible backgrounds from radioactivity in the D_2O and H_2O are measured by regular low level radio-assays of uranium and thorium decay chain products in these regions. Low-energy radioactivity backgrounds are removed by the high 6.75 MeV threshold, as are most neutron capture events. High energy gamma rays from the cavity are also attenuated by the H_2O shield. A fiducial volume cut is applied at R=550 cm (from the center of the detector) to reduce backgrounds from regions exterior to the heavy water volume and to minimize systematic uncertainties associated with optics and reconstruction of events near the acrylic vessel.

Results from SNO

The final data set contains 1169 neutrino events after the fiducial volume and energy threshold cuts. Figure 3a displays the solar angle distribution in $\cos\theta_\odot$, that is the angle between the reconstructed direction of the event and instantaneous direction from the Sun to the Earth. The forward peak in this distribution arises from the kinematics of the elastic scattering reaction and points away from the Sun.

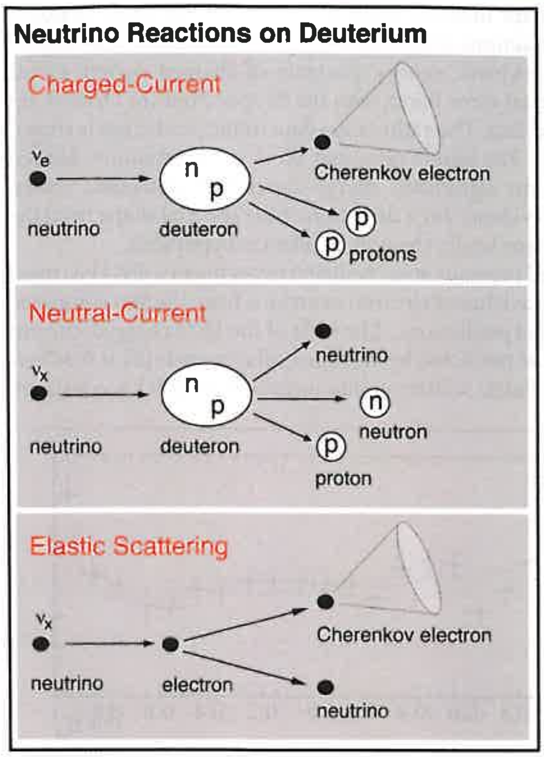


Fig. 2: Neutrino interactions with deuterium in the SNO detector: Both the elastic scattering and neutral-current reaction are sensitive to all neutrino flavors while the charged-current reaction is sensitive exclusively to ν_e. Solar neutrinos interacting via the the charged-current or elastic scattering reaction are detected by the light emitted from Cherenkov electrons.

Picture 1 and 2

Construction of the Sudbury Neutrino Observatory in 1997: The photomultiplier support structure and installation of the photomultiplier tubes is half complete.

The data are then resolved into contributions from charged-current interactions, elastic scattering, and neutron events. Figure 3b shows the kinetic energy spectrum of charged-current events (with statistical error bars), with the ^{8}B spectrum (of Ortiz *et al.*) scaled to the data. The ratio of the data to the prediction is shown in Figure 3c. The bands represent the 1 σ uncertainties derived from the most significant energy-dependent systematic errors. There is no evidence for a deviation of the spectral shape from the predicted shape under the non-oscillation hypothesis.

As have all previous solar neutrino experiments, SNO has measured a reduced flux of electron neutrinos from the Sun compared to solar model predictions. The ratio of the SNO charged-current ^{8}B flux to that predicted by standard solar models [2] is 0.347+/-0.029. The elastic scattering flux measured by SNO is consistent with the high-precision measurement performed at Super-Kamiokande [3], a light water Cherenkov detector located in Kamioka, Japan. It is particularly interesting to compare SNO's charged-current flux to the elastic-scattering measurement at Super-Kamiokande. The charged-current reaction on deuterium is sensitive exclusively to ν_e's while the elastic scattering off electrons also has a small sensitivity to ν_μ's and ν_τ's. The difference between the charged-current and elastic scattering interaction rates is more than 3 σ. This is an indication of the non-electron flavor component of the solar neutrino flux. The total flux of active ^{8}B neutrinos is the sum of the electron and non-electron flavors, and it is in good agreement with solar model predictions.

The difference between the elastic scattering and charged-current interaction rate (normalized to the standard solar model predictions) disfavors the oscillations of ν_e's to sterile neutrinos, which would lead to a reduced flux of electron neutrinos but equal charged-current and elastic scattering rates. (Sterile neutrinos might be, for example, right-handed neutrinos or left-handed antineutrinos which do not interact through Standard Model interactions.) On the other hand, the different interaction rates are consistent with oscillations of ν_e's into active ν_μ's and ν_τ's. SNO's result is consistent with both the hypothesis that electron neutrinos from the Sun oscillate into other active flavors, and with the standard solar model prediction for the total number of neutrinos released in the solar fusion reactions.

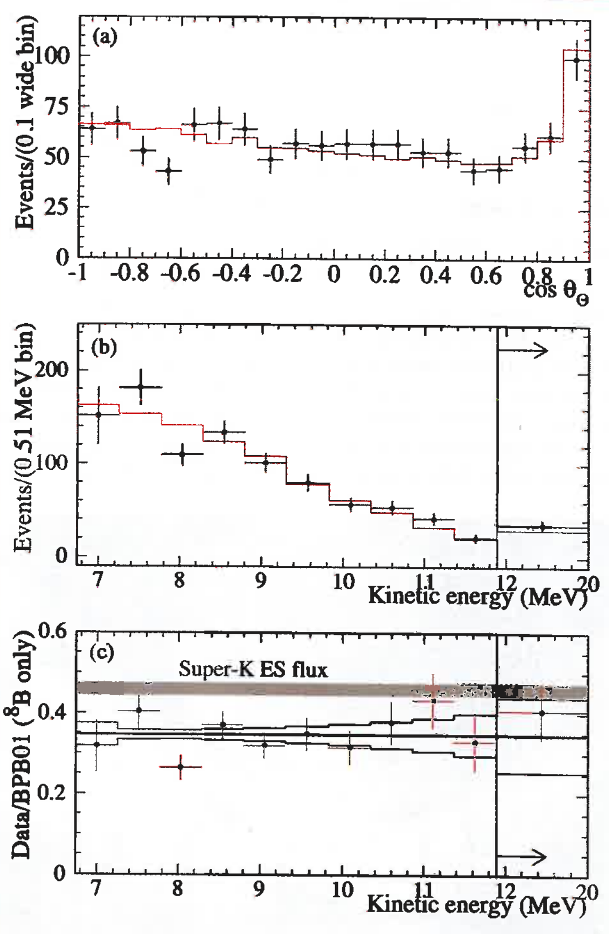


Fig. 3a: displays the solar angle distribution in cos$\theta_\odot$, that is the angle between the reconstructed direction of the event and instantaneous direction from the Sun to the Earth. The forward peak in this distribution arises from the kinematics of neutrino elastic scattering off electrons and points away from the position of the Sun. Cherenkov electrons from the charged-current reaction on deuterium have a distribution which is (1-0.340 cos$\theta_\odot$) before detector response. **Fig. 3b:** shows the kinetic energy spectrum of charged-current events (with statistical error bars), with the ^{8}B spectrum (of Ortiz *et al.*) scaled to the data. The ratio of the data to the prediction is shown in **Fig. 3c**. The bands represent the 1 σ uncertainties derived from the most significant energy-dependent systematic errors. There is no evidence for any spectral distortion.

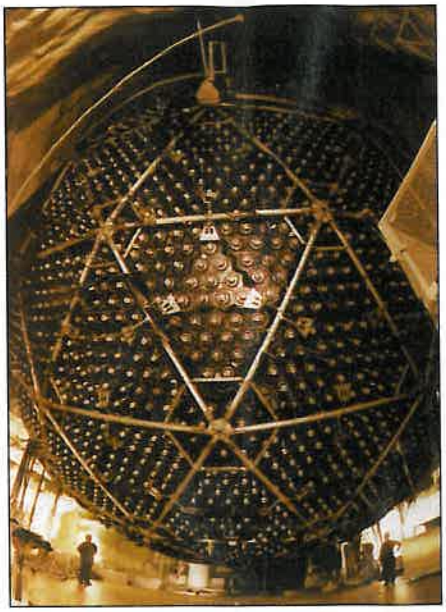
Implications of the SNO Result

Phenomenological studies have analyzed the recent SNO result in terms of 2, 3, and even 4-flavor neutrino oscillation scenarios [4] and determined the favored oscillation parameters, i.e. the most likely values for the mixing angle and the splitting of the neutrino mass eigenstates. A 2-flavor analysis finds that only the solutions with large mixing angles survive at the 3 σ level, with a slight preference for the one with the larger mass splitting. This is the so-called large mixing angle solution. Global analyses with 3 and more neutrino species find that additional active and sterile neutrino oscillations solutions are currently allowed at 3 σ. Interestingly, all favored solutions involve large, but not necessarily maximal, mixing angles. In summary, the recent SNO result disfavors complete conversion of electron neutrinos into sterile neutrinos and appears to favor large mixing angles.

Even without knowing the exact oscillation parameters this result already has theoretical implications for neutrino masses and high energy theories. Theoretical frameworks which invoke large extra dimensions with right-handed neutrinos in the bulk to explain the small neutrino masses tend to resemble neutrino oscillations into sterile neutrinos and also involve small-mixing angles. In contrast, some *see-saw* type mechanisms readily yield solutions with large mixing angles. A *see-saw* solution would imply a large mass scale in physics associated with right-handed neutrinos. This large mass scale may be the scale at which the forces (except gravity) are unified, and hence may affect our predictions for supersymmetry (SUSY).

Summary and Outlook

The data from SNO, taken together with that from Super-Kamiokande, have provided clear evidence for neutrino flavor conversion. It is very likely that the conversion mechanism is neutrino oscillations, although other non-Standard-Model processes have also been suggested. Recent analyses have shown that small mixing angles are disfavored in solar neutrino oscillations but not ruled out. Even if the small mixing angle solution is discarded there are several allowed regions of oscillation parameter space



Picture 3
View of the SNO detector after installation of the bottom PMT panels, but before cabling. Photo courtesy of Ernest Orlando Lawrence Berkeley National Laboratory.

which fit all the data. At present, it is not clear whether the oscillation occurs only between active neutrino species or with an admixture of a sterile component. Pure $\nu_e \rightarrow \nu_s$ oscillations, however, are ruled out by the current data.

At the beginning of June, SNO started the second phase of its scientific operation. Using NaCl as an additive to the heavy water enhances the capture efficiency of neutrons produced in the neutral-current dissociation of deuterium. This enables SNO to make a precision measurement of the neutral-current interaction rate of ^{8}B neutrinos with deuterium. The comparison of the neutral-current and charged-current rates gives a very precise measure of the extent of flavor conversion. In combination with analyses of the day-night asymmetry in the neutrino rate and the shape of the charged-current spectrum, SNO may also be able to distinguish the various oscillation scenarios and determine the generic oscillation parameters for solar neutrinos.

Picture 4
View from the bottom of the SNO acrylic vessel and PMT array with a fish-eye lens. This photo was taken immediately before the final, bottom-most panel of PMTs was installed. Photo courtesy of Ernest Orlando Lawrence Berkeley National Laboratory.

The Sudbury Neutrino Observatory is a collaboration of about 100 scientists from 11 universities and laboratories in Canada, the US, and the UK. More information on the SNO project can be found on the SNO web site at http://www.sno.phy.queensu.ca.

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CERN signs draft Memorandum of Understanding with Iran

Iranian Minister for Science, Research and Technology, Dr Mostafa Moin, and CERN Director-General, Professor Luciano Maiani, today signed a draft Memorandum of Understanding concerning the participation of Iranian universities in the Laboratory's scientific programme. Under this agreement, one Iranian researcher and three students will come to CERN to participate in the CMS experiment, with Iranian industry contributing to the experiment's construction. The Memorandum also paves the way for possible further Iranian involvement with experiments at CERN.

The Iranian researchers, from the Sharif University of Technology in Teheran, the Beheshti University in Teheran, the University of Mashad, and the Institute for Physics and Mathematics in Teheran will be joining the 1800-strong CMS collaboration, which already numbers 145 collaborating institutes. CMS is currently preparing a particle detector to study high energy collisions between protons in CERN's new research machine, the Large Hadron Collider (LHC). Among the experiment's research goals are understanding why fundamental particles have mass, developing a unified picture of these particles and the forces that act between them, and investigating why nature has provided two copies of the family of particles that make up matter as we know it. The answers to these questions will have a profound impact on our understanding of the universe, its origins, and its future.

In signing this draft Memorandum of Understanding, CERN recognises the excellence of scientific talent in Iran. "We warmly welcome the researchers from Iranian universities," said Professor Maiani, "and look forward to a fruitful collaboration developing over the coming years." With many of the foundations of mathematics being laid in Persia, it is no less than appropriate that scientists from modern-day Iran should participate in the programme of one of the world's leading fundamental research organizations.

Pure science has always brought together scientists united by a common desire to learn more about their universe, and nowhere is this more apparent than at CERN. Since the Laboratory's inception in the 1950s, scientists from around the world have come to CERN to perform their research. Today, the Laboratory's experimental programme embraces some 7000 researchers from over 500 institutes in 80 countries. In keeping with CERN's convention, all results are openly published.