LBNL-39099
UC-414

CONF-9508219--2

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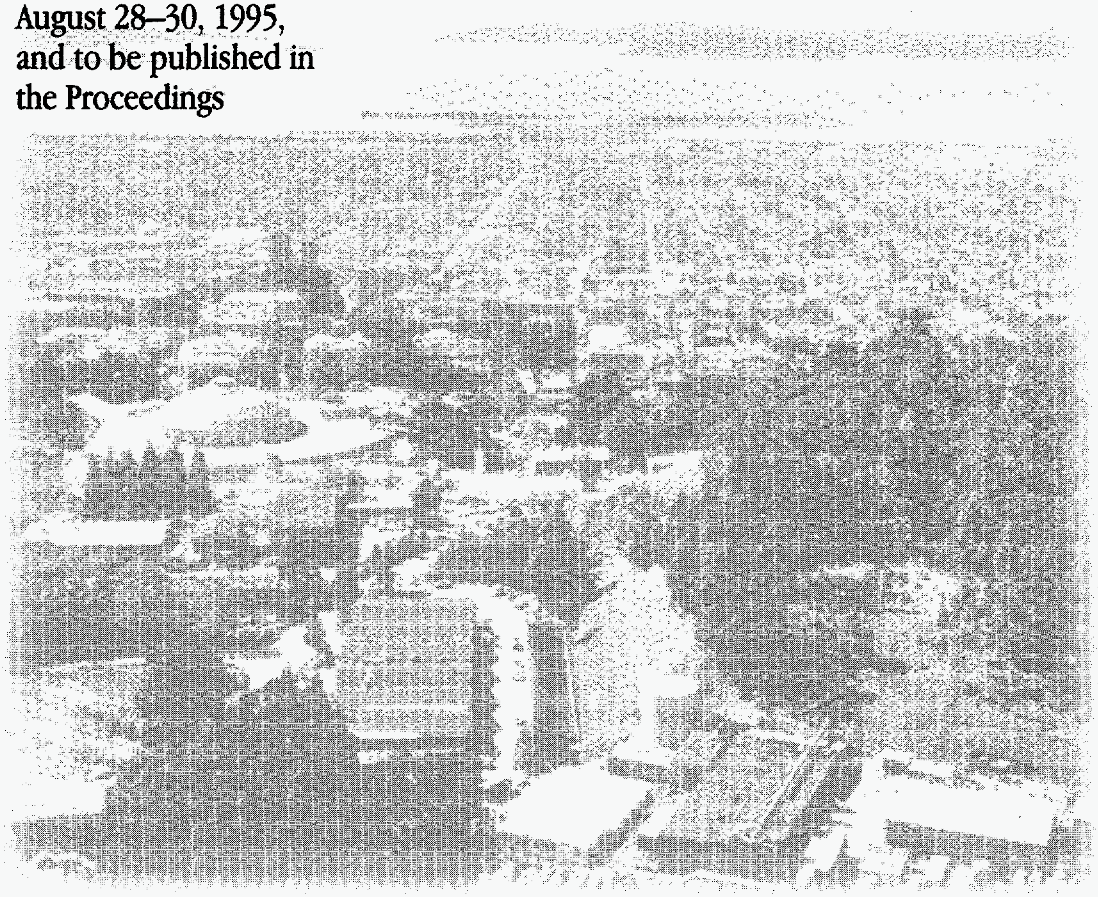
August 1995
Presented at the
Fourth International Workshop on Relativistic Aspects of Nuclear Physics,
Rio de Janeiro, Brazil,
August 28–30, 1995,
and to be published in
the Proceedings



LBNL-39099

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August 15, 1995

This work was supported by the Director, Office of Energy Research Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098

ON THE ROAD TO THE SOLUTION OF THE SOLAR NEUTRINO PROBLEM

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ABSTRACT

The present status of solar neutrino experiments is reviewed. The discrepancy between the experimental results and the theoretical expectations has come to be known as the Solar Neutrino Problem. Possible solutions to this problem are discussed. The next generation of solar neutrino experiments are described.

INTRODUCTION

The energy generated by the fusion of hydrogen into helium provides main sequence stars, like our Sun, their support against gravitational collapse. While this does not actually occur in one step, the net effects of these fusion reaction are to combine four protons with two electrons to produce one ^{4}He nucleus, approximately 26 MeV of energy, and two electron-type neutrinos. One can easily estimate Φ_ν , the flux of solar neutrinos at the Earth's surface. Assuming that the present observed luminosity of the Sun is produced by the fusion of hydrogen into helium, then

$$\Phi_\nu = 2L_\odot/Q \qquad (1)$$

where $L_\odot$ = 1.2 kilowatt/m^2 (the power of sunlight at the Earth's surface) and Q = 26 MeV (the energy released in the fusion of four hydrogen atoms into one helium atom). One thus obtains

$$\Phi_\nu = 6 \times 10^{10}/\mathrm{cm}^2\text{-sec} \qquad (2).$$

The central temperature of the Sun is approximately 1.5×10^7 K and the density is 150 g/cm^3. It is believed that under such conditions, hydrogen is fused into helium via the reactions shown in Figure 1.

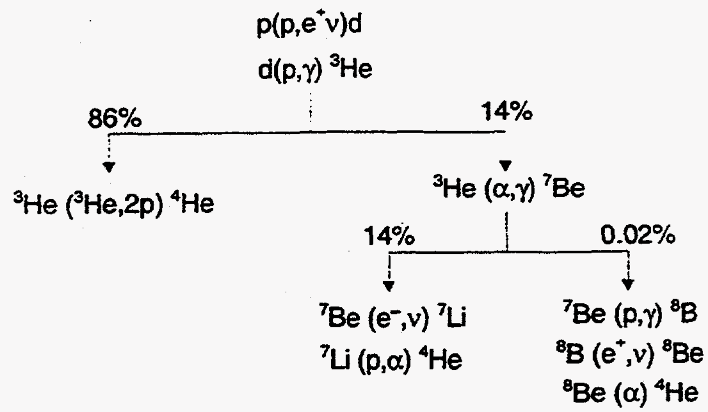

Fig 1. The sequence of nuclear reactions by which hydrogen is fused into helium in the Sun (Ref. 1).

The first reaction involves the "weak" interaction and is the rate-determining step in the sequence. The mean lifetime against this reaction for a hydrogen nucleus at the center of the Sun is about ten billion years, which ensures the long lifetime of stars such as our Sun. Unfortunately, we cannot directly see what is actually going inside the Sun. A photon produced at the center of the Sun scatters many times and loses memory of its nuclear origin as it works its way outward. In fact, it takes about 10^4 years for such a photon to travel to the surface.

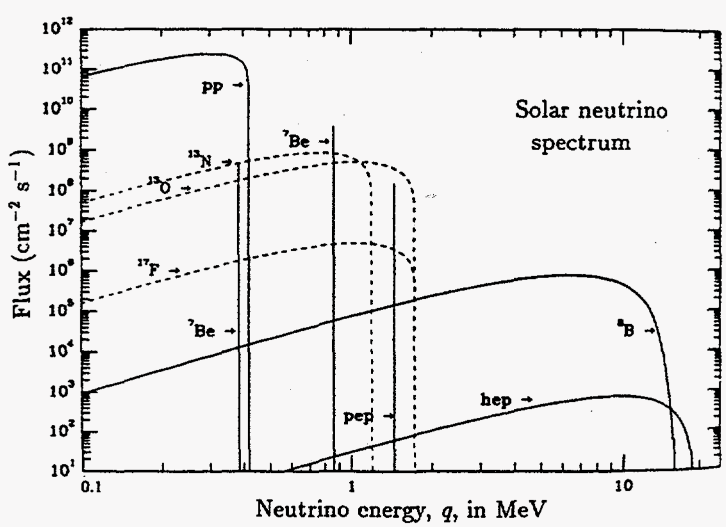

Fig. 2. Energy spectra of solar neutrinos expected at the surface of the Earth (Ref. 2).

The energy spectra of neutrinos expected to be produced by fusion reactions in the Sun are shown in Fig. 2. The most abundant are the so-called "pp neutrinos" produced in the first reaction of the sequence. Their maximum energy is only 420 keV, which makes them difficult to detect. The much more rare, but higher energy ^{8}B neutrinos are easier to detect and hence are of the species sought in several solar neutrino experiments. These neutrinos interact so feebly with matter that they are able to freely escape from the center of the Sun. Thus, by building detectors which can "see" neutrinos, we can learn much about what really goes on inside a star.

Since about 1970, Davis and his co-workers[3] have been using a ^{37}Cl-based detector to measure the ^{7}Be and ^{8}B solar neutrino flux. They utilize the fact that electron-type neutrinos above an energy threshold of 814 keV can capture on a ^{37}Cl nucleus and transform it into the radioactive isotope ^{37}Ar plus an electron. Being a noble gas, it is relatively easy to chemically extract the ^{37}Ar from a large sample of a chlorine-containing compound. The ^{37}Ar electron-capture decays back to ^{37}Cl with a half life of 35 days. This decay mode produces 2.8-keV Auger electrons that can be counted by putting the argon into a small proportional counter. By extracting the argon fraction from a sample of approximately 100,000 gallons of a dry-cleaning fluid (perchloroethylene, C_2Cl_4) periodically and then measuring the ^{37}Ar decays, Davis and his collaborators can determine the number of ^{37}Ar atoms produced in their target. This is an example of a "radiochemical" solar neutrino experiment. They find that the net ^{37}Ar production rate above known backgrounds to be approximately 0.5 atoms per day!

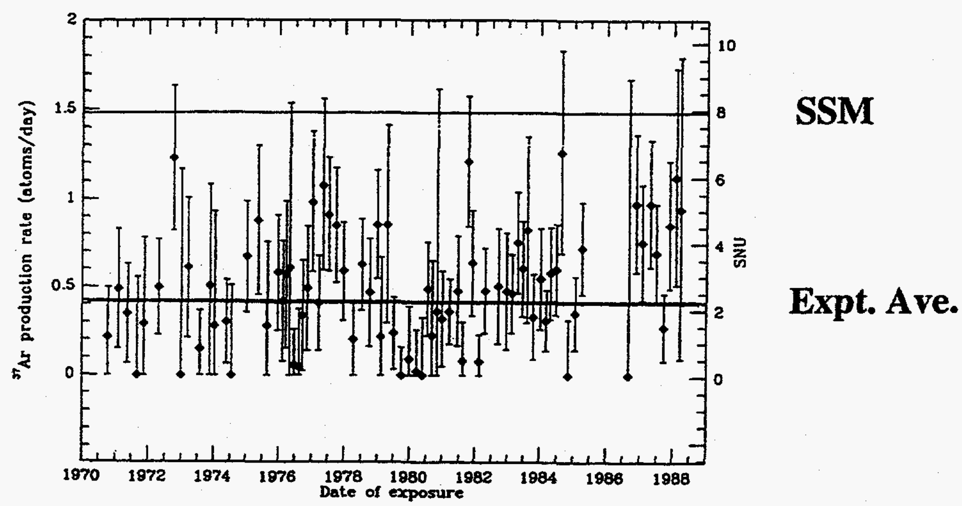

Fig. 3. Results from the ^{37}Cl solar neutrino experiment of Davis *et al.* (Ref. 3).

In solar neutrino physics, one often uses another unit to indicate the capture rate in an experiment of this kind:

$$1 \text{ solar neutrino unit (SNU)} = 10^{-36} \text{ neutrino captures/target atom-second} \quad (3).$$

Expressed in these units, the Davis experiment yields a result of 2.2$\pm$0.3 SNU. The results of approximately 20 years of studying this system are illustrated in Fig. 3. While the statistical uncertainties from a single argon extraction are large, one can clearly see that the average of all the measurements is at least a factor of three lower than the 7.9 SNU predicted by the Standard Solar Model[2] (SSM).

There are two other radiochemical solar neutrino experiments based on the ^{71}Ga-^{71}Ge system. In this case, electron neutrinos above a threshold energy of 236 keV can capture on a ^{71}Ga nucleus and transform it into a ^{71}Ge nucleus plus an electron. Because of its lower threshold, a ^{71}Ga-based detector is sensitive to the low energy pp neutrinos. The SAGE[4] and GALLEX[5] collaborations have reported results of 73$\pm$18 and 79$\pm$12 SNU, respectively. Furthermore, the GALLEX collaboration recently reported the results of a calibration of their detector with an intense ^{51}Cr neutrino source.[6] This test showed, among other things, that the ^{71}Ge chemical separation and recovery efficiency for the GALLEX experiment is essentially 100%. The SAGE and GALLEX results are both substantially smaller than the 132 SNU expected from the standard solar model.[2]

Despite their different threshold energies, and hence different sensitivities to the mixture of pp, ^{7}Be, and ^{8}B solar neutrinos, both the ^{37}Cl and ^{71}Ga radiochemical experiments observe fewer events than are expected from the SSM. To be fair, it should be pointed out that in these radiochemical experiments, one cannot prove that the observed ^{37}Ar or ^{71}Ge atoms were really produced by solar neutrino interactions. All that one can really say is that these radioactive atoms were produced in the target and are not the results of known background effects such as cosmic ray interactions.

The first experiment to provide conclusive direct evidence of solar neutrinos was the Kamiokande II water Cerenkov counter.[7] This experiment used a large tank of water located deep underground in a lead mine in Japan to detect the interactions of solar neutrinos with electrons. The incoming solar neutrinos occasionally scatter elastically off of atomic electrons. The electrons tend to recoil in the direction in which the incoming neutrino was traveling. By surrounding the water tank with a large number of photomultiplier tubes, one can measure the amount and pattern of Cerenkov light produced in these interactions. From this information, the incoming neutrino's energy and direction can be reconstructed. In order to separate solar neutrino events from background processes in an experiment such as this, one must set a relatively high energy threshold. Thus, the Kamiokande experiment is sensitive only to the high energy ^8B solar neutrinos.

Figure 4 illustrates the results of nearly three years of operation of this experiment. What is shown is the number of events observed in this counter versus the cosine of the angle between the neutrino's incoming direction and the position of the Sun. The strong forward peaking of this distribution conclusively proves that the Sun was the origin of these neutrinos. Thus for the first time we were able to "look" inside the Sun and see direct proof that the origin of the Sun's luminosity is nuclear fusion. However, the number of ^8B neutrino events observed in this experiment is approximately one half of the number expected from the standard solar model.

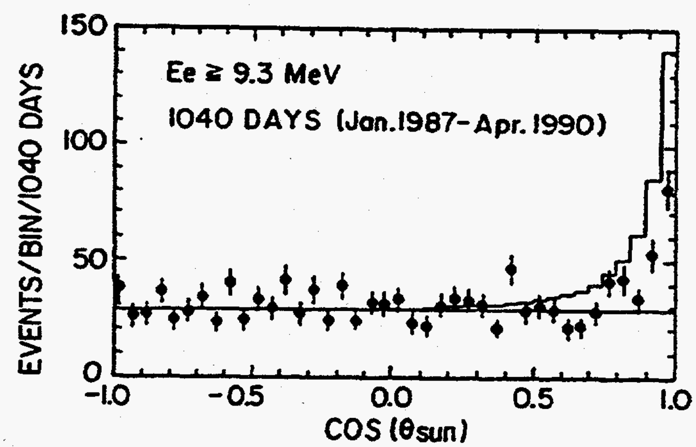

Fig. 4. Kamiokande II observation of solar neutrinos (Ref. 7).

These discrepancies between experiment and theory could arise because of inadequacies in the theoretical models of solar energy generation, errors in the nuclear cross sections, or because of previously unobserved properties of neutrinos. In particular, if at least one of the neutrino species has a finite rest mass then it is possible that ν_e's produced at the center of the Sun could be transformed into ν_μ's or ν_τ's on their journey to Earth. Matter-enhanced neutrino oscillations (MSW effect) can explain all of the solar neutrino results if neutrino mass differences are of the order of 10^{-5} eV^2. Such mass differences are far below the sensitivities achievable in terrestrial neutrino mass experiments. The Sudbury Neutrino Observatory (SNO) will provide the information necessary to decide which of these solutions to the "solar neutrino problem" is correct.

SUDBURY NEUTRINO OBSERVATORY

The Sudbury Neutrino Observatory will consist of a 1000 tonne heavy water (D_2O) Cerenkov detector that is designed to measure the flux, energy spectrum, and direction of neutrinos from the Sun and from such other sources as supernovae. It is presently under construction in a very low background environment 2000 meters underground in the Creighton mine near Sudbury, Ontario, Canada. This is an operating nickel mine owned by INCO, Ltd. The D_2O used in the detector will be on loan from Atomic Energy of Canada Limited.

The basic measurements that will be made with the SNO detector are:

1) the flux and energy spectrum of electron-type neutrinos reaching the Earth, and

2) the total flux of all neutrino types above an energy of 2.2 MeV.

With these two measurements, it will be possible to :

1) determine if neutrino oscillations occur, and

2) independently test solar models by determining the production rate of high energy electron-type neutrinos in the solar core.

The SNO detector utilizes three complementary neutrino interactions with the heavy water.

1) The neutrino-electron elastic scattering (ES) reaction: $\nu_x + e^- \rightarrow \nu_x + e^-$.

The observed signal in the detector is the Cerenkov light produced by the recoiling electron. This is the primary detection mechanism for light water detectors such as the Kamioka detector. It is sensitive to all neutrino types, but is dominated by the electron neutrino. The recoiling electrons from the ES reaction are strongly forward peaked and give excellent directional information. However, information about the energy spectrum of the neutrinos is more difficult to extract because of averaging over the outgoing neutrinos.

2) The charged current (CC) reaction: $\nu_e + d \rightarrow p + p + e^-$ (Q = -1.44 MeV).

This reaction of the electron-type neutrino on the deuteron is unique to the SNO detector. It has a relatively large cross section for ^8B neutrinos and would produce about 10 events per day for one third of the SSM flux. This is greater than fifty times more sensitive than existing solar neutrino experiments. The electron energy is $E_e = E_\nu - 1.44$ MeV and the energy resolution is approximately 20%. This reaction gives good spectral information on the ^8B neutrinos and thus provides good sensitivity to the MSW effect. This reaction will also identify ν_e 's from the initial burst of a supernova.

3) The neutral current (NC) reaction: $\nu_x + d \rightarrow \nu_x' + p + n$ (Q = -2.2 MeV).

This reaction can be observed by the detection of the gamma rays resulting from the subsequent neutron capture or by a neutron detector array in the heavy water. This reaction is sensitive to all types of neutrinos equally and would be used to measure the total flux of neutrinos above the threshold energy of 2.2 MeV. The expected counting rate for the full SSM is approximately 10 per day. This will give a direct measure of the total solar ^8B neutrino production independent of neutrino oscillation effects. It will also detect all types of neutrinos from supernovae explosions.

A schematic view of the SNO detector is shown in Fig. 5. The D_2O target of the SNO detector will be contained in a transparent spherical acrylic vessel with a diameter of 12 m and a wall thickness of 5 cm. Approximately 2.5 m outside the acrylic vessel, there will be about 9500 photomultipliers (PMTs) with 20-cm diameters uniformly arranged and held in place by a geodesic support structure. A reflector is mounted in front of each PMT to increase the light collection to yield a total effective photocathode coverage of approximately 70%. The PMT array is sensitive to Cerenkov radiation produced by relativistic electrons and other particles in the central regions of the detector. The acrylic vessel, PMTs, and the support structure are immersed in 7300 tonnes of ultrapure H_2O. This reduces the background in the heavy water from radioactive impurities in the rock walls and in the detector components. The cavity which will house the detector is barrel shaped with a diameter of 22 m and a height of 30 m. The excavation of the cavity was completed in 1994. The PMT support structure and acrylic vessel are currently being constructed underground.

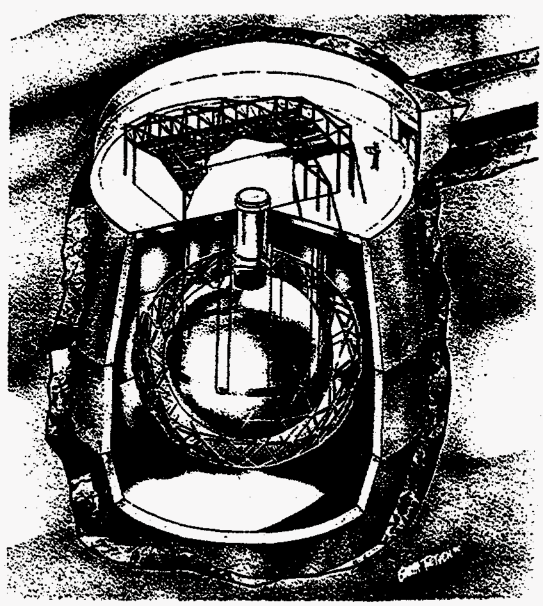

Fig. 5. Artist's conception of the Sudbury Neutrino Observatory.

The initial water fill is scheduled to begin near the beginning of 1997, with a view toward completing commissioning tests and starting to acquire solar neutrino data by the middle of that year. The data taking sequence that will be used in the experiment is still under discussion. It will begin with a D_2O fill of the acrylic vessel. The NC measurement will then be made either by adding 2 tonnes of $MgCl_2$ to the D_2O (in order to raise the neutron capture probability and to raise energy of the capture gamma rays) or through the use of discrete ^{3}He neutron detectors deployed in the D_2O. It is anticipated that SNO will operate for at least five years, and hopefully longer.

With its relatively high statistics, SNO will be able to search for evidence of neutrino oscillations in two different ways. The first method is to compare the rate of the charged-current reaction (induced only by ν_e) to that for the neutral-current reaction (induced with equal cross sections by all three types of neutrinos). If this ratio of rates is different from that expected assuming only ν_e's are present, then one would have good evidence that neutrino oscillations have occurred. The second method is to use the charged-current data to look for deviations of the shape of the ^{8}B neutrino spectrum from that deduced in laboratory studies of ^{8}B decay. The only plausible way for this neutrino spectrum to be modified is from neutrino oscillations. On the other hand, if neither of these effects are observed, SNO will be able to exclude MSW-type neutrino oscillations as the answer to the solar neutrino problem. This would point us back to errors in the nuclear physics inputs or to deficiencies in the solar physics models (or both) as the origin of this long-standing puzzle.

As was demonstrated from SN1987a, water Cerenkov counters are also powerful detectors of supernova explosions. Through both charged- and neutral-current reactions on the central D_2O and the nearby region of H_2O, SNO is very sensitive to neutrinos produced by supernova explosions. In particular, a supernova that occurred at a distance of 10 kiloparsecs, would produce on the order of 1000 events in the SNO detector over a time period of approximately 10 seconds. While the rate of supernova explosions in our galaxy is thought to be somewhere in the range of one every 30-100 years, there has not been one observed for over 300 years. Thus, we are overdue and can hope that one occurs while SNO is operational.

ACKNOWLEDGMENTS

This work is supported in part by the U. S. Department of Energy under Contract Number DE-AC03-76SF00098.

REFERENCES

1. C. E. Rolfs and W. S. Rodney, *Cauldrons in the Cosmos* (Univ. of Chicago Press, Chicago, 1988) p. 354.
2. J. N. Bahcall, *Neutrino Astrophysics* (Cambridge Univ. Press, Cambridge, 1989).
3. R. Davis, Jr., *Frontiers of Neutrino Astrophysics*, (Y. Suzuki and K. Nakamura, eds., Universal Academy, Tokyo, 1993) p. 47.
4. J. N. Abdurashitov *et al.*, Phys. Lett. B **328**, 234 (1994).
5. P. Anselmann *et al.*, Phys. Lett. B **327**, 377 (1994).
6. P. Anselmann *et al.*, Phys. Lett. B **342**, 440 (1995).
7. K. S. Hirata *et al.*, Phys. Rev. D **44**, 2241 (1991).