

Solar neutrinos: present and future

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Abstract. There has been considerable progress in understanding the sun and properties of neutrinos through measurements of solar neutrinos. This paper will discuss the present status of such measurements, the physics information obtainable from them and from the wide variety of measurements planned for the future.

1. Introduction

Measurements of solar neutrinos have been reported for radiochemical measurements with Cl and Ga detectors and real-time measurements observing Cerenkov light from neutrino-electron elastic scattering in light water and reactions on deuterium in heavy water. The measurements on Chlorine [1] have now been completed as have the Gallex and GNO experiments on Ga [2]. The SAGE experiment (Ga) [3] as well as the SuperKamiokande (light water) [4] and SNO (heavy water) [5] are ongoing.

Measurements by SNO of Charged Current (CC) and Neutral Current (NC) reactions on deuterium (sensitive to electron neutrinos and all neutrino types, respectively) provide results that are inconsistent with the hypothesis of no flavor change by more than 7 standard deviations [5]. The results from these experiments, combined with solar model calculations, are best fit by the oscillation of massive neutrinos, using the Maki, Nakagawa, Sakata, Pontecorvo (MNSP) formalism [6] with matter interactions included via the MSW (Mikheyev-Smirnov-Wolfenstein) [7] mechanism. Measurements of reactor anti-neutrino disappearance by the KamLAND experiment [8] show effects that are best fit with MSW parameters that overlap the best fit region for solar neutrinos.

The MNSP matrix U_{ii} can be written for three active neutrino types as:

$$U_{ii} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

where $c_{ij} = \cos \theta_{ij}$, and $s_{ij} = \sin \theta_{ij}$ and l, i represent neutrino flavors.

For non-degenerate mass eigenstates, and for small θ_{13} , oscillations of solar neutrinos are dominated by the first sub-matrix involving θ_{12} . The second sub-matrix dominates the oscillation of atmospheric neutrinos, the third sub-matrix involves the CP violating angle δ and the fourth sub-matrix is tested by reactor and accelerator neutrino measurements. For oscillations in vacuum in the two neutrino mixing approximation, the survival probability for solar neutrinos with energy E , that have travelled a distance L is:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{12} \sin^2 \left(1.27 \frac{\Delta m_{12}^2 L}{E} \right)$$

If the neutrinos travel in a region of high electron density, such as in regions within the Sun or Earth, the interaction of neutrinos with electrons can produce matter enhancement of the oscillation process, the MSW effect [7]. The MSW process could result in an energy dependence of the oscillation probability beyond the vacuum dependence and could produce a difference in the neutrino fluxes for neutrinos that have travelled through the Earth. This could produce differences in the measured fluxes at detectors for day and night time periods.

In order to seek clear evidence for effects that were independent of solar model calculations and could only arise from changes in neutrino properties, time dependence and energy distortion was also studied in the solar neutrino measurements. Studies by SuperKamiokande (SK) and SNO of the variation in flux as a function of time showed no statistically significant effects at the few percent level [4, 5]. The neutrino energy spectrum observed in these experiments was found to be very similar to that expected from ${}^8\text{B}$ decay and no significant distortion due to the MSW effect [4, 5] has been observed.

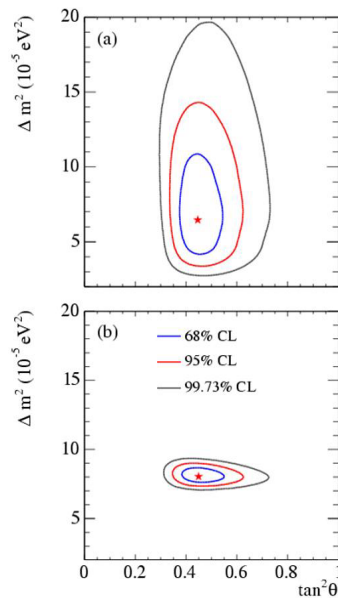


Figure 1. (a) Global neutrino oscillation analysis using only solar neutrino data, and (b) including KamLAND 766 ton-year data.

Figure 1 (a) shows the acceptable region of parameter space for fits to the latest data for solar neutrinos [5] indicating that only the Large Mixing Angle region, including matter effects through the MSW formalism, gives acceptable fits. With such matter interactions it is possible to define the mass hierarchy for mass 1 and 2, with mass 2 larger. The constraint on the mixing angle arises predominantly from the SNO solar-model independent measurements of the survival probability for electron neutrinos from the ratio of charged current to neutral current reactions on deuterium. The measurements show that the mixing is non-maximal ($\theta_{12} < 45$ degrees) by more than 5.5 standard deviations. The KamLAND experiment has observed the disappearance of reactor anti-neutrinos with vacuum mixing parameters that overlap the acceptable region defined by the solar neutrino experimental results [8]. If CPT symmetry is assumed, then these data provide further strong confirmation of the validity of the MNSP and MSW formalisms for solar neutrinos and rule out other possible mechanisms such as neutrino decay or resonant-spin-flavor oscillations. Figure 1 (b) shows the more restricted acceptance region when the KamLAND data are combined with the solar neutrino

data, assuming CPT symmetry. The combination of solar and KamLAND data can also be used to set limits on the θ_{13} mixing angle [9], particularly for the lowest range of accepted values of Δm_{23}^2 .

2. Future Solar Neutrino Experiments

2.1. Physics Objectives

The neutrino physics objectives of future measurements of solar neutrinos can be summarized as follows. Measurements of neutrino properties will focus on:

- Improvement of the accuracy of oscillation parameters (θ_{12} , Δm_{12}^2 , θ_{13})
- Confirmation of matter effects (MSW)
- Searches for effects arising from new physics such as sterile neutrinos, non-standard flavor-changing interactions or mass-varying neutrinos.

Studies of lower energy solar neutrinos are planned in a number of new experiments capable of observing pp, pep, ^7Be and CNO neutrinos, as well as ongoing measurements of ^8B neutrinos. Figure 2 shows these predicted fluxes and their uncertainties [10].

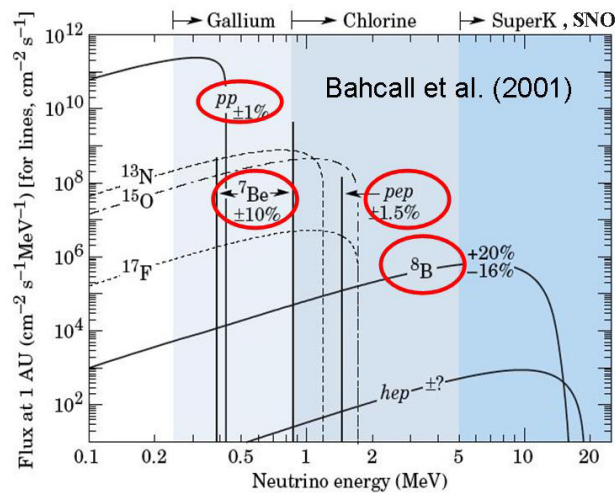


Figure 2. Calculated spectrum of neutrinos from the sun [10]

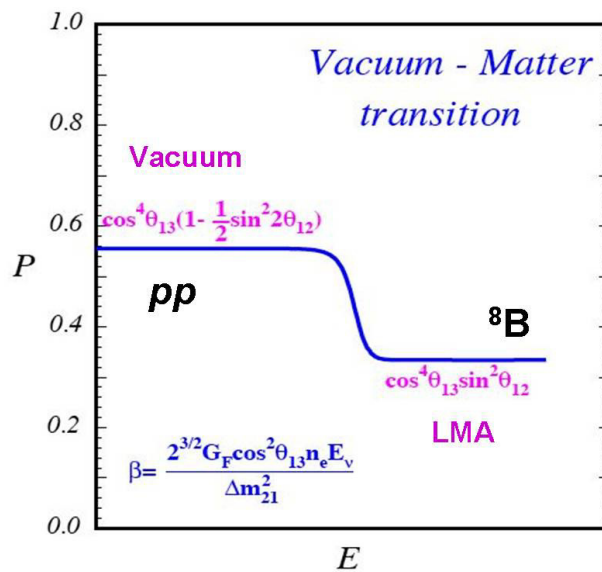


Figure 3. Survival probability for solar electron neutrinos as a function of energy [10].

The conditions in the sun for oscillations including the MSW effect can be quite different for low energy neutrinos, depending on their energy. Vacuum oscillation will dominate if the term $\Delta m_{12}^2 \cos(2\theta_{12})/4E$ is much larger than $2^{1/2} G_F N_e$ (such as for pp neutrinos at $E < 0.4$ MeV), where G_F is the Fermi constant and N_e is the electron density. Matter oscillations will dominate for larger energies (such as for ${}^8\text{B}$ neutrinos with $E > 5$ MeV). In the intervening energy regions (for ${}^7\text{Be}$ and pep neutrinos), the energy dependence is well defined for the MNSP formalism including the MSW effect for massive neutrinos. However, in this region, there is cancellation between the two terms, so it is a particularly sensitive region for the observation of possible sub-dominant effects such as from non-standard flavor-changing interactions [11] or mass-varying neutrinos [12]. The comparison of accurate vacuum (pp) and LMA (${}^8\text{B}$) measurements will enable improved accuracy for θ_{12} and θ_{13} as can be seen from the different sensitivities indicated in figure 3.

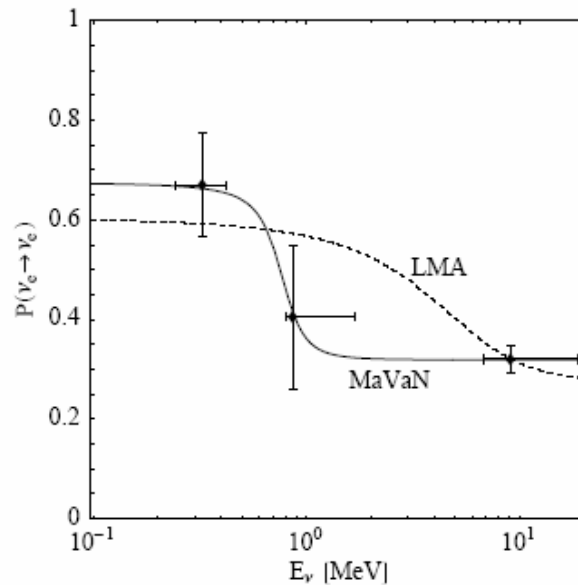


Figure 4. Solar electron neutrino survival probability vs. neutrino energy for MaVaN oscillations (solid curve). The dashed curve corresponds to conventional oscillations with the best-fit LMA solution. The data points and the procedure to extract them can be found in hep-ph/0501247.

Figure 4 shows one example of an energy dependence calculated with an assumption for mass-varying neutrinos [12], comparing it with the Large Mixing Angle (LMA) best fit for the MSW effect. The experimental results and uncertainties for Ga, Cl and light and heavy water measurements are also shown. Similar plots have been given for non-standard interactions [11] and there have been calculations [13] showing energy distortions arising from sterile neutrinos in the energy region below 5 MeV. Future experiments aimed at accurate measurements of pp, ${}^7\text{Be}$ and pep neutrinos will provide very interesting tests of the MSW matter interactions and will have sensitivity to these other sub-dominant effects.

The future experiments fall into two classes:

- Measurements of elastic scattering from electrons with some sensitivity to all neutrino types
- Measurements using the Charged Current reaction sensitive only to electron neutrinos

Accurate measurements at the same energy with both types of experiment will enable the electron neutrino survival probability to be measured directly from the neutral current sensitivity, with little or no dependence on solar models. However, given the strong solar model constraints estimated for pp (and the related pep) electron neutrino fluxes related to the total solar luminosity, accurate measurements of either class for these neutrinos will provide valuable results for neutrino properties. Comparison of pp and ${}^8\text{B}$ survival probabilities will provide improved accuracy for θ_{12} . Measurements

of pep neutrinos, at an energy where there is some cancellation of the two terms affecting the energy variation, will provide a sensitive test for sub-dominant effects (as will ${}^7\text{Be}$ with somewhat reduced sensitivity). Measurements of lower energy neutrinos will also seek to improve our knowledge of the sun such as by measurement of the fluxes of ${}^7\text{Be}$ and CNO neutrinos.

2.2. Experiments in Progress

The SAGE experiment [3] is continuing its operation and has recently performed a new calibration with a ${}^{37}\text{Ar}$ neutrino source. This experiment will provide improving accuracy for pp solar neutrinos. The Super-Kamiokande experiment [13] is in the process of restoring the full set of photomultipliers damaged several years ago and will have capabilities starting in 2006 to observe ${}^8\text{B}$ solar neutrinos with a threshold below 5.5 MeV, improved analysis tools and lower radon backgrounds. They are seeking an observation of distortion in the spectrum predicted by the LMA fits and project a 3 sigma effect after about 4 years of further running in the new configuration. The SNO experiment [14] has been taking production data since November 2004 with an array of neutron detectors that provide an independent measure of the NC reaction on deuterium. The schedule calls for operation with heavy water until the end of 2006. The principal objectives are improved sensitivity for the CC/NC ratio and therefore θ_{12} and for distortions in the CC spectrum.

2.3. Future Experiments

As shown in figure 2, the pp, pep and ${}^7\text{Be}$ fluxes are well defined by the standard solar model, with uncertainties of 1%, 1.5% and 10% respectively. Whereas it would be very valuable to observe the survival probability directly through measurements of both elastic scattering and the charged current interaction, clear measurements of these fluxes by either technique could provide valuable physics results by comparison with solar model values. There are a number of experiments planned for each of these techniques.

2.3.1. *Elastic scattering.* Two experiments are nearing their operational phase for the observation of lower energy solar neutrinos (principally ${}^7\text{Be}$) through elastic scattering from electrons in a liquid scintillator. The Borexino experiment, in the Gran Sasso laboratory, plans to start filling the detector with water in late 2005 and with 300 tons of scintillator in early 2006 [15]. Based on their previous success in reducing radioactivity levels for a smaller test detector, they expect to be able to observe the ${}^7\text{Be}$ flux clearly. They also plan to apply analysis techniques to reduce the ${}^{11}\text{C}$ background from cosmic ray activation of the scintillator, with the objective of observing the pep flux. The KamLAND experiment, following their very successful measurements of reactor neutrinos and geo-neutrinos, are progressing well in the reduction of radioactive backgrounds in the scintillator by the application of distillation and nitrogen purge techniques. They have achieved their goals for ${}^{238}\text{U}$ and ${}^{232}\text{Th}$ and are very close for ${}^{40}\text{K}$, ${}^{85}\text{Kr}$ and ${}^{210}\text{Pb}$ [16]. Their principal objective for operation, starting in 2007, is the measurement of ${}^7\text{Be}$ neutrinos in their 1000 ton liquid scintillator. The ${}^{11}\text{C}$ activation is expected to obscure the signal for pep neutrinos at their shallower depths.

Development work is proceeding for the replacement of the heavy water in the SNO detector with 1000 tonnes of liquid scintillator, creating the SNO+ experiment [17]. The primary physics objective is a good accuracy measurement of the pep neutrino flux to provide a sensitive test of the MSW energy dependence, or possibly observe the sub-dominant effects described above. At the 2 km depth, ${}^{11}\text{C}$ background should not be a problem and with careful control of radioactivity it should be possible to observe the CNO flux. A proposal for funding is being prepared for review, with the objective of proceeding with liquid scintillator in 2008.

Liquid scintillator is not a good medium for the detection of pp neutrinos because of the major problem of ${}^{11}\text{C}$ background. Therefore, scintillation detectors based on liquefied noble gasses are being developed. Such liquids have substantial advantages, with large light output and high radioactive purity. The CLEAN collaboration [18] is developing a liquid neon detector for pp neutrinos. A small prototype has been operated successfully above ground and a 100 kg detector is being developed for deployment underground. The large-scale objective for pp flux measurement would be 10 tons of liquid Ne. The HERON collaboration [19] has demonstrated unique techniques for neutrino detection

with liquid helium. They have observed electrons from e-bubbles drifted in an electric field, along with scintillation light. They conclude that such electron detection will be superior to the previously observed rotons for pp measurements. The XMASS collaboration [20] has made substantial progress with liquid Xenon in measurements underground at the Kamiokande laboratory. They have operated a 100 kg prototype detector, have developed an effective technique for radioactive purification of the Xe and are working on an 800 kg detector for deployment soon. This detector will be primarily for dark matter measurements, but the longer term plans include a 10 ton detector with pp neutrino detection as one of the scientific objectives.

2.3.2 Charged Current: Inverse beta decay measurements. The LENS collaboration [21] is developing a 190 ton In-loaded liquid scintillator (15 tons of In) for the observation of pp, ${}^7\text{Be}$ and CNO neutrinos via the inverse beta decay neutrino reaction on ${}^{115}\text{In}$. Coincidences between electrons and gammas will provide a unique signal to deal with detector backgrounds, including a long-lived radioactivity from ${}^{115}\text{In}$ itself. A calibration of the reaction cross section is planned with neutrinos from a ${}^{51}\text{Cr}$ mega-curie radioactive source. The MOON collaboration [22] is developing a detector based on ${}^{100}\text{Mo}$ with the dual objectives of zero-neutrino double beta decay and measurement of ${}^7\text{Be}$ solar neutrinos via the inverse beta reaction. A small prototype using multi-layers of plastic scintillator has been in operation at the Oto underground facility since 2005.

3. Conclusions

Solar neutrino experiments have provided very valuable results, showing clear evidence for neutrino flavour change and oscillation, defining oscillation parameters and confirming solar models with great accuracy. Future measurements focussing on precision measurements of lower energy neutrinos will extend these results, providing further accuracy for neutrino properties and perhaps revealing more new physics. They will also provide more complete tests of solar models by making individual, real-time measurements of lower energy fluxes from pp, pep, ${}^7\text{Be}$ and CNO reactions in the Sun. Stay tuned for results from a wide variety of sensitive future measurements!

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