Solar neutrino oscillation phenomenology

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Abstract. This article summarises the status of the solar neutrino oscillation phenomenology at the end of 2002 in the light of the SNO and KamLAND results. We first present the allowed areas obtained from global solar analysis and demonstrate the preference of the solar data towards the large-mixing-angle (LMA) MSW solution. A clear confirmation in favour of the LMA solution comes from the KamLAND reactor neutrino data. The KamLAND spectral data in conjunction with the global solar data further narrows down the allowed LMA region and splits it into two allowed zones – a low $\Delta m^2$ region (low-LMA) and high $\Delta m^2$ region (high-LMA). We demonstrate through a projected analysis that with an exposure of 3 kton-year (kTy) KamLAND can remove this ambiguity.

Keywords. Solar neutrino; reactor neutrino.

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1. The neutrinos from the Sun

Solar neutrinos are produced via the reaction

$$4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e + 28 \text{ MeV}.$$  

(1)

The above process occurs through two main cycles of nuclear reactions – the pp chain (CNO cycle) which is responsible for 98.5% (1.5%) of the energy. There are eight different types of neutrino fluxes, named according to the parent nuclei of the decay chain which generates it. The pp chain gives rise to the neutrinos pp, pep, hep, $^7\text{Be}$, $^8\text{B}$ while the neutrinos $^{13}\text{N}$, $^{15}\text{O}$, $^{17}\text{F}$ are generated through nuclear reactions forming the CNO cycle. The solar neutrino fluxes are calculated by the so-called ‘standard solar models’ (SSM) among which the most extensively used are the ones due to Bahcall and his collaborators [1]. The flux predictions from the SSM are robust. Different solar models agree to a very high degree of accuracy (to within 10%) when the same input values of the parameters are used and also demonstrate striking consistency with helioseismological measurements. The pp neutrinos are mainly responsible for solar luminosity and the SSM prediction for the pp flux is least uncertain. The prediction for the $^8\text{B}$ neutrino flux is most uncertain stemming from the uncertainties associated with the cross-section of the reaction $^7\text{Be}(\gamma)^8\text{B}$ producing these neutrinos.
2. Solar neutrino experiments

The pioneering experiment for the detection of solar neutrinos is the $^{37}$Cl experiment in Homestake which started operation in 1968 [1a]. It utilises the reaction [4]

$$\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^{-}.\quad (2)$$

The threshold for this is 0.814 MeV and hence it is sensitive to the $^8\text{B}$ and $^7\text{Be}$ neutrinos.

Three experiments, SAGE in Russia and GALLEX and its updated version GNO in Gran-Sasso underground laboratory in Italy uses the reaction [5]

$$\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^{-}\quad (3)$$

for detecting the solar neutrinos. This reaction has a low threshold of 0.233 MeV and the detectors are sensitive to the basic $pp$ neutrinos.

The radio chemical $^{37}$Cl and $^{71}$Ga experiments are sensitive only to $\nu_e$ and can provide the total solar $\nu_e$ flux.

The first real time measurement of the solar neutrino flux was done by the Kamiokande imaging water Čerenkov detector, located in the Kamioka mine in Japan [6]. It was subsequently upgraded to SuperKamiokande – a same type of detector but with much larger volume increasing the statistics [7]. The neutrinos interact with the electrons in the water via

$$e^- + \nu_e \rightarrow e^- + \nu_e.\quad (4)$$

This reaction is sensitive to all the three neutrino flavours. However, the $\nu_\mu$ and $\nu_\tau$ react via the neutral current which is suppressed by a factor of 1/6 compared to the $\nu_e$ interaction which can be mediated by both charged and neutral currents. The recoil electron energy threshold in Kamiokande was 7.5 MeV which could be reduced to 5 MeV in SuperKamiokande. Thus both the detectors are sensitive mainly to the $^8\text{B}$ neutrinos.

The Sudbury Neutrino Observatory (SNO) experiment also uses a Čerenkov detector but containing heavy water ($D_2O$). The deuterium in heavy water makes it possible to observe solar neutrinos in three different reaction channels [8,9]

$$\nu_e + d \rightarrow p + p + e^- \quad (CC),$$
$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (ES),$$
$$\nu_x + d \rightarrow n + p + \nu_x \quad (NC).$$

The charged current (CC) reaction is exclusive for $\nu_e$. The electron scattering (ES) reaction is same as in SK. The unique feature of SNO is the neutral current (NC) reaction which is sensitive to all the three flavours with equal strength. For both CC and ES reactions, the final state electrons are directly detected through the Čerenkov light emitted by them which hits the PMTs and an event is recorded. For the NC reactions, the final state neutron can be captured (i) by another deuteron, (ii) by capture on Cl in an NaCl-enriched heavy water and (iii) by $^3\text{He}$ proportional counters. For both (i) and (ii) the nuclei after capturing the neutrons emit