Solar neutrino measurements at SNO and how these solved the solar neutrino problem

Abstract

This report presents the relevance of the solar neutrino problem and how the Sudbury Neutrino Observatory (SNO) experiment worked and took measurements to provide evidence of the discrepancy in observed and expected solar neutrinos. SNO demonstrated that solar neutrinos from ^{8}B decay into other flavour neutrinos on their way to Earth solving the problem.

1. Introduction

During the mid-1960s, John Bahcall suggested that only the study of neutrinos would allow us to see into the interior of a star as a way to confirm the hypothesis suggesting that there are nuclear energy generations happening in a star. He suggested a series of calculations for the solar neutrino fluxes and Ray Davis suggested pioneer measurements for these.[1]

The persistence of a discrepancy between observed fluxes and the calculations across the years motivated the creation of new experiments focused on solving the solar neutrino problem, in this document we expose the contributions of the Sudbury Neutrino Observatory.

2. Solar Neutrino Problem

The Sun's source of energy is nuclear fusion, a process it undergoes via the proton-proton reaction chain which converts four protons (of mass 938.27 MeV each) into alpha particles (^{4}He of mass 3.7272 GeV), positrons, neutrinos and an energy remainder:

$$4p \rightarrow \ ^{4}He + 2e^{+} + 2\nu_e + energy\ reminder$$

During the 1960s, Ray Davis (experimentalist) and John Bahcall (theorist) designed the Homestake radiochemical Experiment with the purpose to collect and count these neutrinos emitted by nuclear fusion in the Sun. To do so they used the reaction:

$$^{37}Cl + \nu_e \rightarrow \ ^{37}Ar + e^{-}$$

They consistently observed 1/3 of the expected rate, presenting the first indication of a discrepancy between predicted and measured number of neutrinos. Although initially, these results were not readily accepted by the scientific community.[2]

3. SNO experiment

The SNO experiment is located 6800 feet underground in Ontario, Canada, from 1999 to 2006, featuring a heavy-water Cherenkov detector designed to detect solar neutrinos. With over 1000 tonnes of deuterium (D_2O) located inside a 12 meter in diameter acrylic vessel, when neutrinos react with D_2O these produce flashes of light called the Cherenkov radiation which can be detected by an array of 9600 photomultiplier tubes surrounding the D_2O vessel.[3] Because of its location underground, the detector was shielded from incoming cosmic rays.

The use of heavy water provides three signals with different flavour sensitivity, the SNO experiment detects solar neutrinos through the charged-current (CC) and neutral-current (NC) interactions on the deuteron, and by elastic scattering (ES) on electrons:

$$\text{CC}: \quad \nu_e + d \ \rightarrow \ \text{p} + \text{p} + \ e^- - 1.442 \text{ MeV}$$

$$\text{NV}: \quad \nu_x + d \ \rightarrow \ \text{n} + \text{p} + \ \nu_x - 2.224 \text{ MeV}$$

$$\text{ES}: \quad \nu_x + e^- \rightarrow \ \nu_x + e^-$$

The theory behind this experiment suggested that if there is a significant deficit in ^{8}B neutrino flux measured by the CC reaction over that measured by the NC reaction then this would directly demonstrate that the Sun's electron neutrinos change to one of the other two types, tau or muon neutrinos.

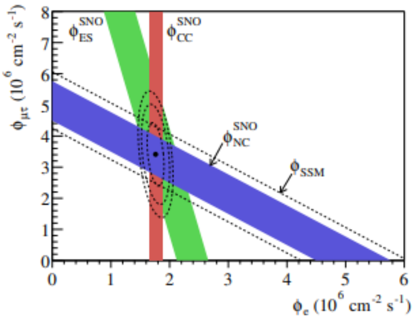
4. Solar Neutrino Measurements

The measurements done by the SNO experiment were divided in three different phases: [4]

4.1 Phase-I

Investigated measurements of the rates of CC and NC reactions on deuterium by ^{8}B solar neutrinos. Events from NC reactions was low as the energy released by gamma rays in the capture was 6.25 MeV near SNO's threshold. Here, the signals from ES, CC and NC reactions could not be differentiated on an event-by-event basis, instead they used a PDF fit.

In figure 1, we show the constrains of the flux of electron neutrinos versus tau and muon neutrinos combined. The three rates were inconsistent with the hypothesis that ^{8}B flux is made out of electron neutrinos only but, it is consistent with an admixture of around 1/3 electron and 2/3 of tau and muon.



$$\phi(\nu_e) = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.})$$
$$\phi(\nu_{\mu\tau}) = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.}).$$

Figure 1: Shows the flux of ^{8}B solar neutrinos muon or tau flavour versus the flux coming from electron one as obtained for all three neutrino reactions. Evidence of the admixture for electron vs tau and muon neutrinos is also shown.

4.2 Phase-II

Here 2000 kg of NaCl were dissolved in the heavy-water mixture which enhanced the sensitivity from 14.4% to 40.7%. Thermal neutron capture cross-section for ^{35}Cl is 5 orders of magnitude larger than for deuterium (44 b as compared to 0.5 mb). Now when a neutron captures on ^{35}Cl the total energy released amounts to 8.6 MeV. NC produced multiple gamma rays while CC and ES produced single electrons.

In this phase, the energy-unconstrained analysis was performed where the following integral neutrino flux were determined (in units of 10^6 cm^{-2} s^{-1}):

$$\begin{aligned}
\phi_{\text{CC}}^{\text{uncon}} &= 1.68^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.}) \\
\phi_{\text{ES}}^{\text{uncon}} &= 2.35^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.}) \\
\phi_{\text{NC}}^{\text{uncon}} &= 4.94^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})\ ,
\end{aligned}$$

Where the free parameters described the total ^{8}B neutrino flux (in units of 10^6 cm^{-2} s^{-1}):

$$\Phi_{^8\text{B}} = 5.046^{+0.159}_{-0.152}(\text{stat.})^{+0.107}_{-0.123}(\text{syst.}).$$

4.3 Phase-III

An array of ^{3}H counters was deployed in the deuterium volume. The total active neutrino flux measurements were detected mostly by this new array called “Neutral-Current Detection”.

4.4 Combined all three phases

A comparison between all three phases is shown in figure 2 for the measured energy-unconstrained for the NC signal. Combining the results from all three phases produced the more relevant results for the total flux of ^{8}B which provided better separations for CC, ES and NC events. As data was recorded and identified separately for day and night, in figure 3 we can observe the presence of a day-night asymmetry in the calculations from equation (1).

$$A_{ee}(E_\nu) = a_0 + a_1(E_\nu[MeV] - 10) \quad (1)$$

Where a_0, and a_1 define the relative difference between day and night, ν_e survival probability

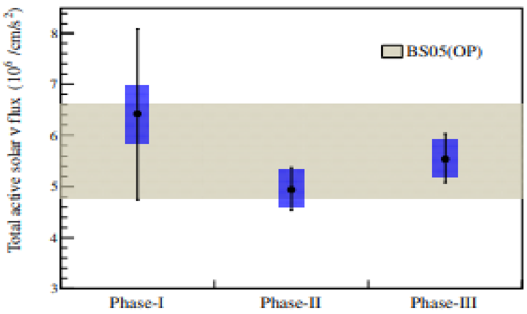


Figure 2: recorded energy-unconstrained NC flux measurements in SNO's three phases. Error bars are ±1σ

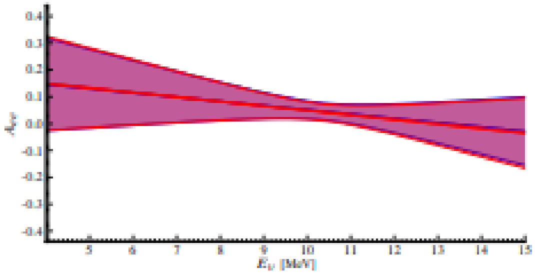


Figure 3: Root mean squared of $Aee(Ev)$.

The mass differences and mixing angles obtained from the various neutrino experiments contribute to the parametrization of neutrino survival probabilities. In the SNO experiment, the average solar neutrino survival probability was observed around 0.32 and 33.5º (neutrino oscillation parameter) which corroborates the matter-induced oscillation scenario. The following figure 4 shows the three-flavour neutrino oscillation analysis.

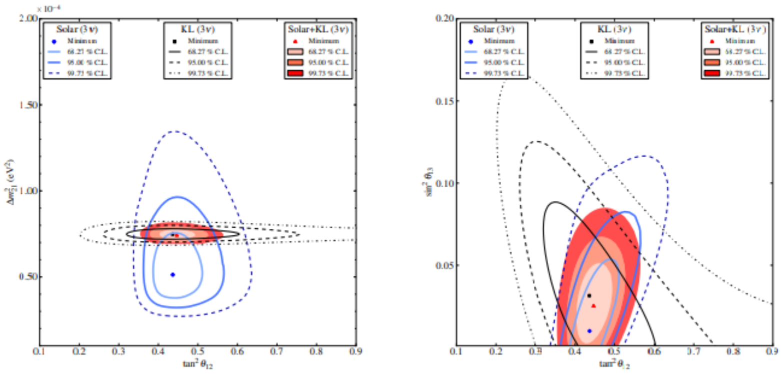


Figure 4: Using results from solar neutrinos and KamLAND (KL), here we present the three-flavour neutrino oscillation analysis.

5. Conclusion and Summary

In this report we have presented the solar neutrino problem and how the SNO experiment operates and measures solar neutrinos from ^{8}B. The combined measurements on total flux ^{8}B neutrinos lead to observe a clearly how these electron neutrinos change their flavour in transit to Earth and hence, solving the solar neutrino problem.

REFERENCES

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