Antineutrino Search at the Sudbury Neutrino Observatory

Thomas Kutter,[1] for the SNO Collaboration
(1) Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada

Abstract

The Sudbury Neutrino Observatory (SNO) is an imaging water Cherenkov detector. Its one kiloton heavy water core provides a unique means for an electron antineutrino search via the charged current reaction $\overline{\nu}_e + d \rightarrow e^+ + n + n$. The reaction signature are two- and three-fold coincidence events which allow for rigorous background rejection. Hence, SNO is able to reach high electron antineutrino sensitivity. The appearance of electron antineutrinos is a smoking gun for spin flavour precession models which require neutrinos to have a magnetic moment. Furthermore, observation of a significant solar antineutrino flux could be indicative of CPT violation in the neutrino sector. A limit on the antineutrino flux sets an upper limit on the thermal power of a hypothesized geo-fission reactor at the center of the Earth.

1. Introduction

Over the past few years convincing evidence has been found for a non-vanishing neutrino rest mass [1],[2],[3],[5]. All evidence stems from neutrino oscillation searches in the atmospheric and solar sector as well as from reactor experiments. A crucial piece of evidence came from the Sudbury Neutrino Observatory (SNO), which demonstrated the dominant part of solar neutrinos to reach the Earth as an active flavour other than ν_e [2],[3]. The flavour of the active neutrinos is not known and it cannot be excluded that they are antineutrinos. Global analyses of solar neutrino data favor the large mixing angle (LMA) solution [4],[19]. However, more general analyses which allow for spin flavour precession (SFP) and CPT violation in the neutrino sector indicate that SFP models are an equally good description of the data as are oscillation scenarios [12]. If a magnetic moment is associated with massive neutrinos, antineutrinos could originate from SFP in the solar magnetic field. Some models predict this precession to be resonantly enhanced by matter (RSFP) [6],[7]. To produce any significant conversion via this mechanism, the neutrino magnetic moment has to be of the order of $\mu_\nu \approx 10^{-11} - 10^{-10} \mu_B$. This is several orders of magnitude larger

pp. 1233–1237

than expected from Standard Model predictions [8]. However, some theoretical scenarios allow larger magnetic moments [9], [10].

If SFP were the solution to the solar neutrino problem the recently measured ratio of charged to neutral current of CC/NC $\approx 1/3$ [3] would reveal the nature of neutrinos to be of Majorana type. Because of their CPT properties Majorana neutrinos cannot have a static magnetic moment, but off-diagonal terms (transition moments) would allow $\nu_e - \bar{\nu}_{\mu_R}$ transitions. A subsequent vacuum oscillation $\bar{\nu}_{\mu_R} - \bar{\nu}_{e_R}$ or an overlap of RSFP and MSW resonances could therefore result in a significant flux of $\bar{\nu}_e$ [11] and a CC to NC ratio smaller than 1. For Dirac neutrinos, the magnetic field precession would result in ν_{e_R} which do not take part in weak interactions and can be considered as sterile. Although results from the KamLAND experiment [5] supports the LMA solution to the solar neutrino problem, SFP could still contribute to the observed neutrino flavour conversion mechanism at a sub-dominant level. KamLAND's support of the LMA solution is based on the assumption of CPT conservation in the neutrino sector. If however CPT is violated in the neutrino sector, as suggested by some theoretical models [15] and allowed by all experimental data [16], SFP could still turn out to be the mechanism which explains the solar neutrino problem.

An additional motivation to look for electron antineutrinos is to test the hypothesis of a geo-fission reactor at the center of the Earth via detection or by placing a limit on the associated antineutrino flux. It has been speculated that a reactor with a power output of 3 to 10 Tera Watts might be the energy source of the Earth's magnetic field [20]. Bounds on the solar antineutrino flux imply constraints on $\mu_\nu B$, the product of the neutrino magnetic moment and the solar magnetic field.

This contribution describes a direct search for solar antineutrinos with SNO via the charged current reaction

$$\bar{\nu}_e + D \rightarrow e^+ + n + n - 4.03 \text{ MeV}.$$

The total cross-section for $\bar{\nu}_e D$ scattering is taken from [14]. It shows a 1 % increase with respect to earlier calculations giving an estimate for the systematic uncertainty of the calculations. SNO is an imaging water Cherenkov detector located at a depth of 6010 m of water equivalent in the Inco, Ltd. Creighton mine near Sudbury, Ontario, Canada. SNO detects neutrinos by means of ultra-pure heavy water contained in a transparent acrylic spherical shell 12 m in diameter. Cherenkov photons generated in the heavy water are detected by 9456 photomultiplier tubes (PMTs) mounted on a stainless steel geodesic sphere 17.8 m in diameter. The geodesic sphere is immersed in ultra-pure light water to provide shielding from radioactivity in both the PMT array and the cavity rock. The SNO detector itself has been described in detail in ref. [13].

2. Data

The first stage of the antineutrino analysis focuses on a data set which was recorded between Nov. 2, 1999 and May 28, 2001 and represents a total of 307.5 live days. These data span the entire first phase of the experiment, in which only D_2O was present in the sensitive volume. Data reduction consists of the elimination of instrumental backgrounds. These backgrounds have characteristics very different from Cherenkov light and are eliminated using cuts based only on PMT positions, PMT time and charge data, and veto PMTs. Cuts based on event-to-event time correlations were not applied with the exception of a muon follower cut which removes spallation events.

3. Analysis

The analysis procedure consists of two steps, the first is similar to the neutral current analysis and is described in [3]. In this step PMT times and hit patterns are used to reconstruct event vertices and assign to each event a most probable kinetic energy, T_{eff}. The analysis threshold was $T_{\text{eff}} \geq 5$ MeV, providing sensitivity to neutrons from the antineutrino CC and the NC reactions. In order to reduce external backgrounds and systematic uncertainties associated with optics and event reconstruction near the acrylic vessel the fiducial volume was limited to within 550 cm of the detector center. The second step of the analysis focuses on the relative time separation between accepted events. The size of the coincidence window, chosen to be 150 ms, was optimized to give maximal sensitivity to twofold positron-neutron coincidences under the measured background conditions. Two-fold coincidences have about 10 times higher detection efficiency than three-fold ones.

The background can be divided into two categories, coincidences caused by antineutrinos from known sources and coincidences from other processes. The former category contains atmospheric, relic supernovae, terrestrial and reactor antineutrinos. The second class of background consists of spallation neutrons, accidental coincidences and intrinsic backgrounds from radioactivity. The number of estimated background events is expected to be available by the time of the conference.

Amongst coincidences originating from antineutrinos positron-neutron coincidences have the highest detection probability. The detection efficiencies for two and three-fold coincidence events were found to be $\epsilon_{(e^+,n,n)} \approx 1.8\%$, $\epsilon_{(e^+,n)} \approx 22\%$, and $\epsilon_{(n,n)} \approx 2.4\%$ These efficiencies take into account the small loss of signal caused by the data reduction cuts. Within 550 cm from the detector center and above a kinetic energy threshold of 5 MeV a search for coincidence events is performed. Due to the 95% positron detection efficiency the first event in each coincidence is to a very good approximation a positron and as a consequence correlated to the antineutrino energy. Based on Monte Carlo expectations and the number of observed candidate events energy dependent limits on the electron antineutrino flux can be derived. The most conservative limit can be derived under the assumption of zero background signal. However, since the contribution from various background sources can be estimated with good confidence a background subtracted analysis can provide reliable and more stringent limits.

Besides the Sun, a hypothetical geo-fission reactor at the center of the Earth has been suggested to represent an intense antineutrino source [20]. If a geo-fission reactor at the center of the Earth exists the associated antineutrino flux is expected to be spectrally indistinguishable from a generic power reactor. An antineutrino spectrum was composed from literature values [17],[18] and the total flux was normalized according to $\phi_{\bar{\nu}}^{\text{reactor}} = 1.5 \times 10^{12} \, \frac{P/\text{MeV}}{L^2/\text{m}^2} \, \text{cm}^{-2}\text{s}^{-1}$ [21], where P and L are the average thermal power of the reactor and the distance, respectively. The number of expected events for a geo-fission reactor at the center of the Earth and a constant thermal power output was evaluated by means of MC simulation. An upper limit on the reactor antineutrino flux can be placed. Under the assumption of neutrino oscillations with the currently favored mixing parameters of Δm^2=5.5 $\times 10^{-5}$ eV^2 and $\sin^2 2\theta$=0.833 the observable antineutrino flux would be reduced to 60% of its intensity at the source. For the period of data taking the above flux limit can be converted into a limit on the thermal power of a hypothetical geo-fission reactor at the center of the Earth.

4. Summary

In summary, the analysis presented here is the first search for a solar antineutrino flux based on measurements via the antineutrino CC reaction on deuterium. The analysis is also the first experimental search for an antineutrino flux from a hypothetical geo-fission reactor at the center of the Earth. At the time of the deadline for these proceedings, analysis results are being reviewed by the SNO collaboration. Results are expected to be available by the time of the conference.

Acknowledgements

This research was supported by: Canada: NSERC, Industry Canada, NRC, Northern Ontario Heritage Fund Corporation, Inco, AECL, Ontario Power Generation; US: Dept. of Energy; UK: PPARC. We thank the SNO technical staff for their strong contributions.

References

[1] Y. Fukuda et al., *Phys. Rev. Lett.* **81**, 1562 (1998)

[2] Q.R. Ahmad et al., *Phys. Rev. Lett.* **87**, 071301 (2001)

[3] Q.R. Ahmad et al., *Phys. Rev. Lett.* **89**, 011301 (2002)

[4] Q.R. Ahmad et al., *Phys. Rev. Lett.* **89**, 011302 (2002)

[5] K. Eguchi et al., *Phys. Rev. Lett.* **90**, 021802 (2003)

[6] C.S. Lim, W.J. Marciano *Phys. Rev.* **D 37**, 1368 (1988)

[7] E.K. Akhmedov, *Phys. Lett.* **B 213**, 64 (1988)

[8] B.W. Lee, R.E. Shrock, *Phys. Rev.* **D 16**, 1444 (1977)

[9] K.S. Babu, R.N. Mohapatra, *Phys. Rev. Lett.* **63**, 228 (1989)

[10] S.M. Barr, E.M. Freire, A. Zee *Phys. Rev. Lett.* **65**, 2626 (1990)

[11] E.K. Akhmedov, *JETP Lett.* **68**, 690 (1989)

[12] O.G. Miranda et al., *Nucl. Phys.* **B 595**, 360 (2001); B.C. Chauhan, J. Pulido, *Phys. Rev.* **D 66**, 053006 (2002); E.K. Akhmedov, J. Pulido, *Phys. Lett.* **B 553**, 7 (2003)

[13] The SNO collaboration, *Nucl. Instrum. Methods* A **449**, 172 (2000)

[14] S. Nakamura et al. *Nucl. Phys.* **707**, 561 (2002)

[15] G. Barenboim, J. Lykken, *hep-ph/0210411*(2002)

[16] G. Barenboim et al. *hep-ph/0212116*(2002)

[17] P. Vogel et al. *Phys. Rev.* C **24**, 1543 (1981)

[18] K. Schreckenbach et al. PL **160B**, 325 (1985); K. Schreckenbach et al. PLB **218**, 365 (1989);

[19] J.N. Bahcall et al. JHEP **0207**, 054 (2002); G.L. Fogli et al. *Phys. Rev.* **D 066**, 093008 (2002); V. Barger et al. *Phys. Lett.* **B 537**, 179 - 186 (2002)

[20] J.M. Herndon, Proc. Nat. Acad. Sci. **646**, 1996 (;) R.S. Raghavan,*report*(2002)

[21] P.H. Frampton, P. Vogel *Phys. Rep.* **82**, 339 (1982)