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Methods for Neutral-Current Neutrino Detection in the Sudbury Neutrino Observatory

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The Sudbury Neutrino Observatory will permit a comparison of the rate of neutral-current neutrino interactions to charged-current interactions, which is a test of neutrino mixing and mass. The neutral-current process can be measured by: a) comparison of the rate for electron elastic scattering to the pure charged-current rate on deuterium, b) neutron capture on Cl ions added to the heavy water, and, c) neutron capture in an array of ^{3}He-filled proportional counters. The design and construction of suitable proportional counters are described.

1. THE SUDBURY NEUTRINO OBSERVATORY

The Sudbury Neutrino Observatory (SNO) [1] is a heavy-water Čerenkov detector to study the properties of neutrinos of astrophysical origin, particularly solar neutrinos. Jonkmans [2] describes the SNO project elsewhere in these Proceedings. The heart of the detector is 1000 tonnes of 99.92% isotopically pure heavy water (D_2O) 2070 m below ground in the INCO Creighton nickel mine near Sudbury, Ontario.

Deuterium's unique nuclear properties make it ideal for the study of neutrino interactions. There are three principal modes by which solar neutrinos can interact with the heavy water:

$$\begin{array}{rcll} \mathrm{d}+\nu_e & \rightarrow & \mathrm{p}+\mathrm{p}+e^- - 1.44\,\mathrm{MeV} & \mathrm{(CC)} \\ \mathrm{d}+\nu_x & \rightarrow & \mathrm{p}+\mathrm{n}+\nu_x - 2.22\,\mathrm{MeV} & \mathrm{(NC)} \\ e^- + \nu_x & \rightarrow & e^- + \nu_x & \mathrm{(ES)} \end{array}$$

Only electron neutrinos are produced by the Sun as it burns its nuclear fuel, but if neutrino oscillations occur, then the neutrinos may reach the Earth as other flavors. SNO therefore has the capability to reveal the presence of neutrino oscillations largely independent of solar properties via the direct comparison of the CC rate to the NC rate.

Charged-current and elastic scattering events produce Čerenkov radiation that is detected in SNO by an array of photomultipliers surrounding the acrylic sphere that holds the D_2O. The detection of a free neutron is the signal that a NC event has occurred (detection of one or two neutrons in coincidence with a positron would identify a $\overline{\nu}_e$ interaction). One approach is to dissolve in the heavy water several tonnes of a chloride salt, such as NaCl or $MgCl_2$. When a neutron captures on 75% abundant ^{35}Cl, it emits 8.6 MeV in gammas, which shower. The resulting Čerenkov radiation can be detected by the PMT array in the same way CC events are detected.

The method described in this paper is to detect the neutron by the reaction

$$^3\mathrm{He}+\mathrm{n}\rightarrow \mathrm{p}+\ ^3\mathrm{H}+764\ \mathrm{keV}$$

with ^{3}He proportional counters placed in the heavy water. The NC and CC signals are completely separate in this approach [3,4].

2. NEUTRAL-CURRENT DETECTOR ARRAY

2.1. The Signal

The fluxes of active neutrinos from ^{8}B are constrained by current observations of the elastic scattering rate R_{ES} with the SuperKamiokande detector [5] because $R_{ES} \sim \phi_e + 0.142\phi_{\mu\tau}$, where the fluxes of electron flavor and mu or tau flavor neutrinos are ϕ_e and $\phi_{\mu\tau}$, respectively. The results are reported as $2.44\pm0.06\ ^{+0.25}_{-0.09}$ x 10^6 ν_e

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cm^{-2} s^{-1}. If conversion to $\nu_\mu + \nu_\tau$ is complete, the corresponding flux is 17 x 10^6 $\nu_\mu + \nu_\tau$ cm^{-2} s^{-1}, which provides an upper bound to the NC rate in SNO. The solar model of Bahcall and Pinsonneault [6] predicts a total ^{8}B flux of 6.6 x 10^6 ν_x cm^{-2} s^{-1}, yielding an intermediate scenario. The expected rates in SNO for CC and NC neutrino interactions in those scenarios are summarized in Table 1. Bahcall and Lisi [7] integrate the Kubodera-Nozawa cross sections [8] over the ^{8}B spectrum to find the CC cross section above 5 MeV and the total NC cross section used here. For simplicity, the shape of the ^{8}B spectrum is taken to be undistorted.

2.2. Neutron-Capture Efficiency

Because of the effectiveness of heavy water as a neutron moderator and the 5330-b cross section for neutron capture on ^{3}He an array of 5-cm diameter proportional counters with a total length of $\sim$ 800 m arranged on a square lattice with 1 m spacing gives a neutron capture efficiency [?] of 45 $\pm$ 5% (25% after cuts) with tolerable absorption of Čerenkov light produced by charged current interactions.

2.3. Gas Fill

The detectors are filled with a gas mixture of 85% ^{3}He and 15% CF_4 at a total pressure of 2.5 atm [4] to provide a good compromise between gas gain and stopping power (to mitigate "wall effect" wherein either the proton or the triton strikes the wall before the end of its range). A lower pressure, and therefore operating voltage, would simplify microdischarge management and increase drift speeds, but would require thick-walled counters to resist collapse at the bottom of the vessel, where the absolute pressure is 3.2 atm. At 1800 V a gas gain of 100 is realized.

To assure long-term gas performance in a sealed counter and to remove contamination, counter surfaces are acid-etched, baked under vacuum, and purged with boiloff N_2 prior to fill.

The ^{3}He gas from the Department of Energy facility in Savannah River contains a small amount of tritium, which is reduced to 5 nCi/l or less by passage through a charcoal-loaded cold trap and by recirculation through a SAES St101 getter.

2.4. Construction

The bodies and endcaps of the proportional counters are made of ultra-pure nickel fabricated at Mirotech (Toronto) Inc., by thermolysis of $Ni(CO)_4$ vapor. A limited number of elements (Pb, Ra, Th, and U not among them) react with CO to form carbonyls, and the metals formed by chemical vapor deposition from this precursor can be expected to be free of the most troublesome radioactivities. Analysis of the nickel deposit, by radiochemical neutron activation analysis has shown [9] Th levels in the bulk material of order 10^{-12} (1 ppt) by weight or less.

Insulators are synthetic fused silica tubes internally coated with a layer of pyrolytic graphite at anode potential to eliminate electric fields inside them. They extend 2.5 cm into the gas volume to act as field tubes and prevent multiplication of electrons from regions where the electric field is distorted. Counters are filled through copper tubes, which are then pinched off. All assembly is carried out in a Class 10-1000 cleanroom. A cross section of a counter is given in Hime [4].

The detectors have a wall thickness of 0.36 - 0.48 mm and are fabricated in unit lengths of 200, 227, and 272 cm in order to fill the sphere efficiently. The active length is 13 cm less than the mechanical length. A total mechanical length of 750 m is to be deployed in the heavy water in the form of 96 "strings" up to 11 m long welded during deployment. A single 91-ohm coaxial cable, positively buoyant in heavy water, carries signals from the top of each string up the neck of the vessel to preamplifiers.

2.5. Backgrounds

Of several possible sources of background, the most serious is photodisintegration of deuterium by gammas above 2.22 MeV, as the neutrons produced cannot directly be distinguished from neutrinodisintegration neutrons.

With adequate shielding against gammas from outside the vessel, the 2.6-MeV γ from ^{208}Tl and the the 2.44-MeV γ from ^{214}Bi are the only ones capable of breaking up the deuteron once the ^{56}Co has decayed. Nevertheless, since detection of Čerenkov light is the principal means of quantifying the photodisintegration background *in situ*,

Table 1
Rates for neutral-current interactions in SNO and charged-current interactions above $T_e = 5$ MeV induced by ^{8}B neutrinos.

Flux 10^6 cm^{-2} s^{-1}	Species	Detected CC y^{-1}	Total NC y^{-1}	Detected NC y^{-1}	NC/CC
2.44	ν_e	4170	2210	550	0.132
6.6	$\nu_e + \nu_\mu + \nu_\tau$	3040	5980	1500	0.493
17.2	$\nu_\mu + \nu_\tau$	0	15600	3900	∞

the production of light by other activities is also important.

The backgrounds that will accompany the NCD array in SNO are assessed in advance by neutron activation analysis, radiochemical methods, direct gamma counting, and alpha counting, applied both to samples and to the complete inventory of smaller components. About half of all neutron capture events can be unambiguously identified via track length *vs* energy as being distinct from alpha particles (for this reason the array efficiency is taken to be 25% rather than the nominal 45% capture efficiency). Electron and Compton backgrounds, and microdischarge events, have topologies separated still further from neutron events. As a result, photodisintegration is the only background requiring a separate determination and subtraction.

3. Conclusions

In 1997, radioassay indicates that approximately 130 neutrons per year will be produced in the main volume of the vessel by the NCD array, and a further 300 near the wall by cables and termination components. Initial ^{56}Co activity produces about 200 per year. The determination of the actual photodisintegration rate once the array is deployed depends primarily on observing the Čerenkov spectrum of the gammas responsible, and is expected to be dominated by Th and U in the heavy water. If the levels are as anticipated (≤ 5 fg/g of Th, ≤ 10 fg/g U), and ^{222}Rn in the water can be adequately controlled and independently assayed, after one year's operation the uncertainty in the NC production rate will be less than 8% at 6000 neutrons per year.

The Sudbury Neutrino Observatory is uniquely suited to make a determination of the neutrino flavor content of the ^{8}B neutrino flux from the Sun, essentially independent of the actual magnitude of that flux within the range allowed by current data. By this means a model-independent determination of neutrino oscillations to active species can be made, if they are the explanation for the solar neutrino problem.

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