Earth, Moon, and Planets (2006) 99:221–228
DOI 10.1007/s11038-006-9116-4

Geo-neutrinos in SNO+

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(Received 16 April 2006; Accepted 25 July 2006)

Abstract. There are plans to fill the Sudbury Neutrino Observatory with liquid scintillator after measurements with heavy water are completed. The new experiment, known as SNO+, would make an excellent detector for geo-neutrinos. SNO+ would be located amidst a thick and uniform region of continental crust, away from nuclear power reactors. As a result, the geo-neutrino signal to reactor background ratio in SNO+ will exceed that from previous measurements. Geo-neutrino measurements by SNO+ will shed light on the amount of uranium and thorium radioactivity in the crust, as well as deeper inside the Earth. Spectral information from SNO+ geo-neutrino detection will provide the first direct measurement of the U/Th ratio.

Keywords: Continental crust, geo-neutrinos, geochemistry, neutrino geophysics, radioactivity

1. Introduction

A follow-up experiment to the Sudbury Neutrino Observatory is being developed. The experiment is called SNO+ and it consists of filling SNO with liquid scintillator after the physics program with heavy water is completed and the heavy water is removed in 2007. SNO+ would be a large, low background, liquid scintillator detector in the deepest underground site for neutrino physics. The physics capabilities of this detector include the precision study of the pep solar neutrinos, confirmation of reactor neutrino oscillations at a longer baseline, and, of particular interest in this article, the study of geo-neutrinos.

Transforming SNO into a liquid scintillator detector would boost the light yield in the detector by a factor of ~100 or greater, compared to Čerenkov light. The new detector would have a large number of protons in the CH_2-based liquid scintillator instead of the deuterons currently in SNO's heavy water. A liquid scintillator is thus an ideal detector for electron antineutrinos.

Using the inverse beta decay reaction, electron antineutrinos ($\bar{\nu}_e$) interacting with protons in a liquid scintillator produce positrons and neutrons

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$

Scintillation light is emitted when the positron is produced in this reaction. The neutron in the event can be detected in delayed coincidence, when it captures about 200 μs later on hydrogen in the scintillator producing a 2.2 MeV gamma. This coincidence signal is distinctive and correlated backgrounds are few and limited, especially for a detector that is deep underground. The depth of the SNO (or SNO +) detector is 6 km water equivalent of overburden and this basically eliminates correlated backgrounds from muon-induced fast neutrons, or from cosmogenically produced β-n decaying isotopes.

The visible energy produced by the positron in these events is equal to the kinetic energy of the positron plus 1.022 MeV, coming from the annihilation of the positron. Thus, $\bar{\nu}_e$ signals produce at least 1 MeV of visible energy (even for positrons with zero kinetic energy), easily observable in a large scintillator detector. A liquid scintillator with suitably low background can thus detect $\bar{\nu}_e$ interactions all the way down to the reaction threshold of $E_\nu = 1.804$ MeV. These are the reasons why a large, low background liquid scintillator detector is well suited for detecting geo-neutrinos from uranium and thorium, for which the signal is $\bar{\nu}_e$ with energy up to 3.3 MeV and an event rate of the order of tens of events per kiloton of scintillator per year.

KamLAND is a neutrino detector with 1 kiloton of liquid scintillator. KamLAND reported the first detection of geo-neutrinos in 2005 (Araki et al., 2005). Ways in which to improve upon KamLAND's first observation include:

– increased statistics, which KamLAND is acquiring
– reducing the correlated background from $^{13}C(\alpha, n)$, which KamLAND is also working on by purifying their liquid scintillator
– ultimately, KamLAND's geo-neutrino measurements will be limited by their large reactor neutrino event rate, so another geo-neutrino experiment with a smaller reactor background is required.

SNO + would also be a 1 kiloton liquid scintillator detector. The province of Ontario has three nuclear power generating stations with a total of 14 operating reactor cores. The total power output of these reactors is smaller than what's in Japan and distances from Sudbury to the nuclear generating stations are longer. SNO + thus offers the possibility to improve upon KamLAND's geo-neutrino studies by having a larger signal to reactor background. Since the SNO + experiment is a retrofit of an existing detector, it is an imminently realizable experiment for relatively little cost. SNO + and KamLAND geo-neutrino signal rates and reactor background rates will be compared below.

2. The SNO+ detector

The SNO+ detector will be located where SNO is currently, at 46.475° N, 81.201° W in INCO's Creighton Mine, near Sudbury, Ontario, Canada. The center of the detector is 2039 m below the surface. The surface is 309 m above sea level. Figure 1 is an illustration of the detector configuration for SNO. The only change for SNO+ is that rather than heavy water (D_2O) inside the acrylic vessel, there would be liquid scintillator. PSUP in the figure refers to the photomultiplier tube (PMT) support structure, which holds 9438 PMTs viewing the inner volume. The 20-cm diameter Hamamatsu R1408 PMTs are mounted on the PSUP with light collecting reflectors and provide 54% effective photocathode cover. Further technical details on the existing SNO detector can be found in (Boger et al., 2000).

The liquid scintillator to be used in SNO+ needs to be compatible with acrylic. The SNO+ project initiated the development of liquid scintillator using linear alkylbenzene (LAB) as a solvent. Undiluted LAB appears to be

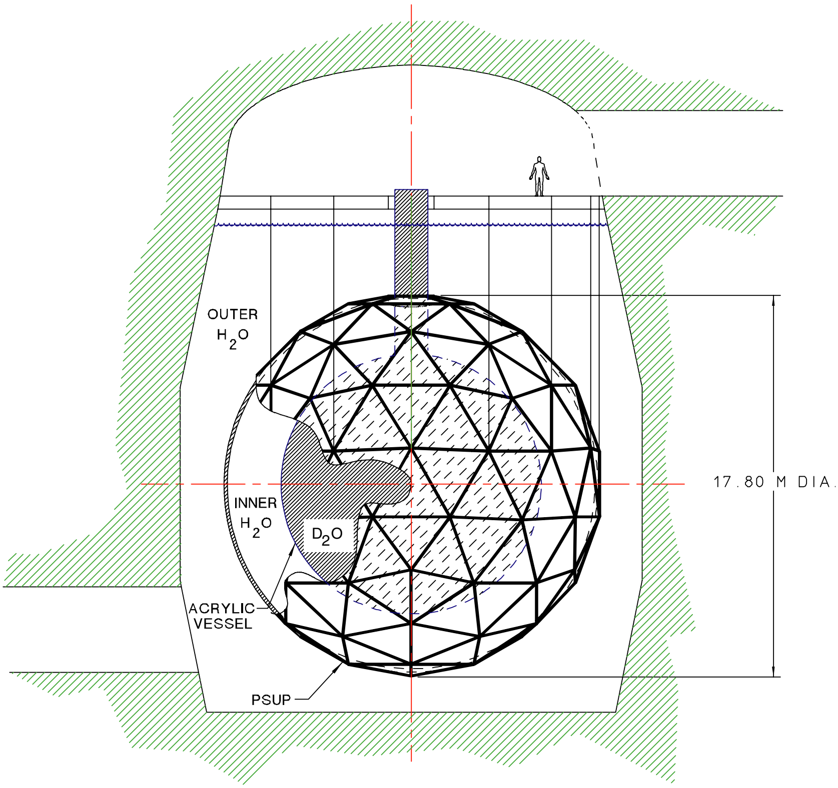

Figure 1. A drawing of the SNO detector showing the geodesic PMT support structure and acrylic vessel. SNO+ will maintain the same general configuration.

compatible with acrylic. LAB is very transparent; we have measured attenuation lengths greater than 20 m at 420 nm. LAB has high light yield. In comparison with KamLAND scintillator which is 20% pseudocumene diluted in dodecane, we have measured the light yield of undiluted LAB as being 50–75% greater than the KamLAND scintillator, depending on the concentration of fluor used. LAB is also a relatively inexpensive substance (it is much cheaper than most high quality mineral oils). Our study of the long-term properties of this scintillator are ongoing. Details of our development of what appears to be a very suitable scintillator for SNO+ and for other neutrino experiments will appear in a technical publication, in preparation.

Monte Carlo simulations (using essentially the same code that is being used in SNO simulations and data analysis) of the amount of light collected in SNO+ estimate 1200 photoelectrons per MeV of energy deposited, which is exceedingly good for a large liquid scintillator detector. This high light yield should not be surprising. KamLAND detects 300 photoelectrons/MeV for 22% photocathode coverage. SNO has 54% coverage and undiluted LAB has 50–75% greater light output.

The density of LAB is 0.86 g/cm^3. Filling the SNO+ acrylic vessel with LAB, and keeping water (H_2O) on the outside would place the acrylic vessel in a buoyant configuration. In SNO, with heavy water on the inside, the acrylic vessel is supported by ropes holding it up, due to the 10% higher density of heavy water. Preliminary engineering studies have concluded that supporting a 14% buoyant load is feasible. Two designs are being explored. One would involve machining reverse "rope grooves" in the existing acrylic plates around the equator of the vessel (see Figure 2). In the other option for the hold down system, a net or collar would be placed over the top of the upper hemisphere of the acrylic vessel. In both designs, ropes would hang down from the acrylic vessel, penetrate the bottom of the PSUP and be anchored to the bottom of the cavity.

3. Signal and background

Estimating the geo-neutrino event rate and the nuclear reactor background in SNO+ is straightforward. These estimates are based upon the work of Rothschild, Chen and Calaprice (Rothschild et al., 1998) with slightly updated values. In particular, suppression of the event rate due to neutrino oscillations must be included given the observation of reactor neutrino disappearance (Eguchi et al., 2003). When an average suppression factor of 0.59 is included, the event rate predicted for SNO+ is 51 events per 10^{32} proton-years exposure. Note that a kiloton of liquid scintillator (CH_2) has about 8.6×10^{31} target protons. This rate in SNO+ is for a Bulk Silicate Earth-based "reference" model, a concept first introduced in the Rothschild, Chen and Calaprice paper.

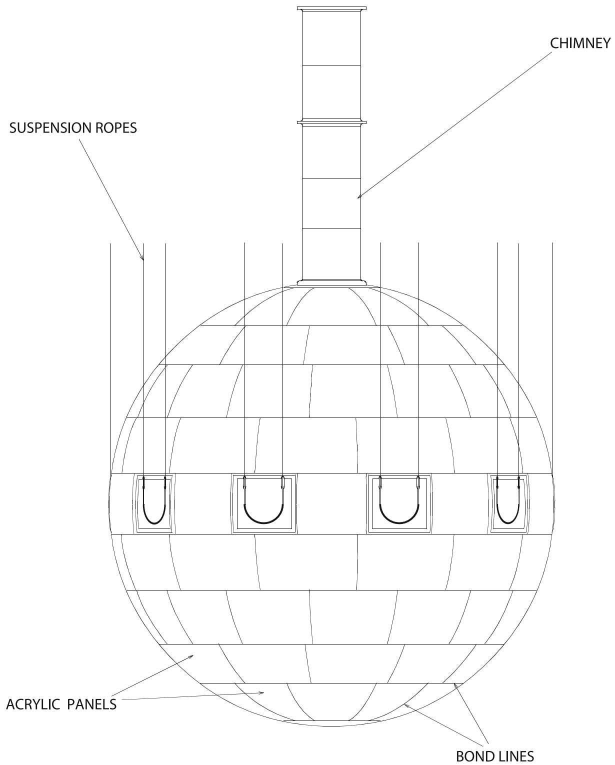

Figure 2. The existing SNO acrylic vessel, showing the ropes that hold up the acrylic vessel. SNO+ requires engineering a system to hold down a buoyant acrylic vessel filled with $\rho = 0.86$ g/cm^3 liquid scintillator.

The rate in SNO+ can be compared with an event rate of 38 events per 10^{32} proton-years in KamLAND, as derived from values given in Araki et al. (2005) and Enomoto et al. (2005). The SNO+ detector would be located in a region surrounded by thick continental crust. This results in a greater geo-neutrino signal rate in SNO+. Oceanic crust is thin and relatively depleted in uranium and thorium, in comparison. The consequence is a somewhat lower geo-neutrino signal rate in KamLAND, which is in the vicinity of both continental crust and oceanic crust rock.

The geological region around SNO+ is known as the Canadian Shield. It is an old mass of continental crust rock that is fairly uniform and well understood. Because of the mining activity occurring around Sudbury, the local geology has been extensively studied. Because of this knowledge, one might be able to calculate the local contribution to the geo-neutrino rate reasonably accurately. Hence, a SNO+ geo-neutrino measurement could reveal the uranium and thorium content of the deep Earth – one would be subtracting from the total SNO+ signal a known, local contribution, to get at the amount of radioactivity deeper in the Earth (e.g. in the mantle).

Figure 3 shows the fractional contribution to the geo-neutrino signal in SNO+ at different distances of integration. One sees that the total signal (integrating over the whole Earth) is derived 80% from continental crust radioactivity and 20% from radioactivity in the mantle. This is a calculation that employs a crust map (Laske et al., 2001) and reference model distributions of radioactivity in the Earth.

One concludes from Figure 3 that SNO+ will test our understanding of the amount of radioactivity in the continental crust. This is the most accessible layer of the Earth, thought to be well characterized. Testing our understanding of the continental crust using geo-neutrinos serves to confirm basic and fundamental geochemical paradigms and assumptions.

One also finds from Figure 3 that 70% of the 80% continental crust contribution to the geo-neutrino rate in SNO+ comes from the closest 1200 km of continental crust rock (approximately). Since most of the signal rate comes from continental crust that is relatively near, one would aim to determine the average U and Th content of this continental crust rock by other geological methods, in order to estimate its contribution to the geo-neutrino rate. Any additional rate seen in SNO+ could then be attributed to radioactivity in the mantle.

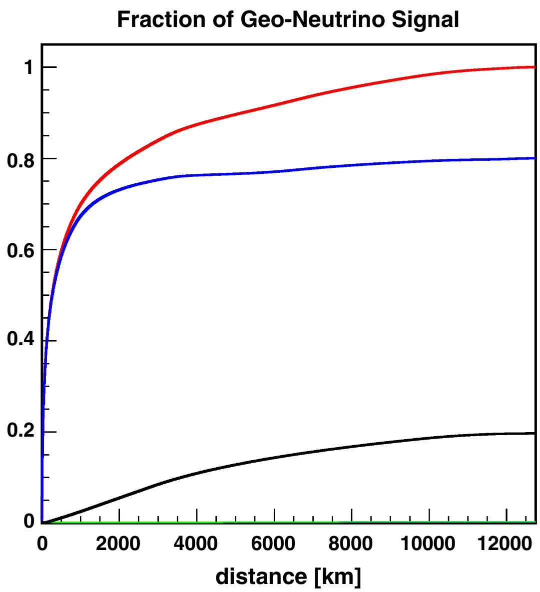

Figure 3. The fractional contribution to the geo-neutrino signal in SNO+ at different distances of integration. The upper curve is the total; below it, is the contribution from continental crust; the lower curve is the contribution from the mantle. There is also a curve for the contribution from oceanic crust which is barely visible on this plot and negligible.

Nuclear reactor backgrounds is present at a lower level in SNO+ compared to KamLAND. For six operating cores at the Bruce generating station (the closest reactors to Sudbury), the reactor neutrino rate in SNO+ is 179 events per 10^{32} proton-years (oscillations included). Only 49 of those events are in the same spectral region as the geo-neutrinos. The signal-to-background in SNO+ is 51/49 or about 1:1. In contrast, KamLAND has 572 events of reactor background per 10^{32} proton-years (oscillations included and corrected for detection efficiency). In the spectral region of interest for geo-neutrinos are 165 reactor background events per 10^{32} proton-years, a signal-to-reactor background ratio of about 1:4 in KamLAND.

Figure 4 shows the expected spectrum of geo-neutrino events compared with the reactor neutrino background in SNO+. As expected, the signal-to-background is favorable and the geo-neutrino events can be easily identified. An important feature for SNO+ should be the ability to separately determine the uranium and thorium contribution to the geo-neutrino signal. The higher energy spectral feature or lobe in the geo-neutrino signal spectrum is due purely to uranium. The lower energy lobe includes geo-neutrinos produced by thorium in addition to uranium. Clearly measuring the relative rates in those two lobes enables the average U/Th ratio in the Earth to be determined. Spectral features in the reactor background arise from neutrino oscillations.

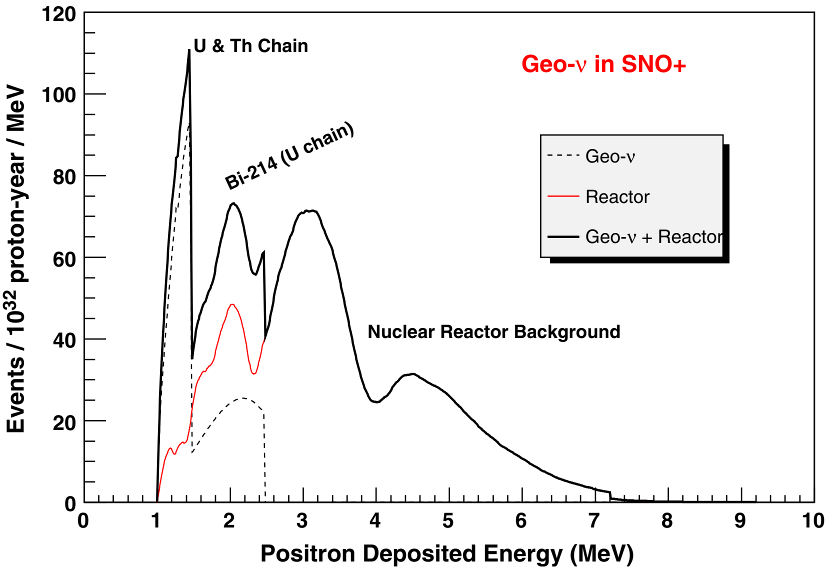

Figure 4. The energy spectrum of the geo-neutrino flux at SNO+. The background from reactor neutrinos is shown. The vertical axis is in events per MeV for an exposure of 10^{32} proton-years. Energy resolution was not included in this plot. Oscillations were included in calculating the geo-neutrino signal and the reactor background rates and spectra.

The significant reactor neutrino background in KamLAND prevents a clear separation of the two spectral lobes in the geo-neutrino signal. Projections by KamLAND suggest that this may still be difficult even with improved statistics (Enomoto et al., 2005). SNO+ could thus provide the first experimental determination, using geo-neutrinos, of the average U/Th ratio in the Earth (SNO+ measurement dominated by the U and Th composition of the surrounding continental crust).

4. Summary

With diverse physics goals and an operational start date within the next 2–3 years, SNO+ represents an opportunity to extend the science output from SNO for relatively little cost, by continuing to use much of the existing detector and investment in infrastructure and capability. One of the key science objectives for SNO+ will be the study of geo-neutrinos. Improved signal-to-background, confirmation of our understanding of the geochemistry and composition of the continental crust, probing the uranium and thorium radioactivity in the deep Earth by subtracting a knowable local contribution, and the ability to separately determine the amounts of uranium and thorium in the Earth are the main features of SNO+ geo-neutrinos. This experiment should be a very good follow-up to the first studies of geo-neutrinos by Kam-LAND.

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