SNO and the new SNOLAB

To cite this article: A B McDonald 2009 J. Phys.: Conf. Ser. 173 012002

View the article online for updates and enhancements.

Related content

- The SNOLAB Science Program
  Chris Jillings
- Solar neutrino experiments
  M C Chen
- Solar neutrinos, SNO and SNOLAB
  A B McDonald

Recent citations

- Measurement of very low (\gamma,n) cross sections of astrophysical interest
  J L Tain et al
SNO and the new SNOLAB

A B McDonald
Queen’s University, Kingston, Ontario, Canada K7L 3N6
art@snolab.ca

Abstract. The SNO experiment has completed data taking for the last of three phases in which an array of ultra-low radioactivity \(^3\)He-filled proportional counters were deployed in the heavy water medium to observe neutrons from the neutral current reaction on deuterium. Data analysis is nearly completed and will provide a new independent measure of the neutral current reaction for \(^8\)B solar neutrinos with completely different systematic uncertainties from previous measurements. The new SNOLAB international underground science facility, expanding the experimental area 2 km underground, is nearly complete and will be ready for experiments this year. Brief descriptions of several experiments planned for this facility will be provided, including dark matter measurements by PICASSO, DEAP-1, Mini-CLEAN, DEAP/CLEAN and Super-CDMS; double beta decay measurements by SNO+ and EXO-gas and solar, geological, reactor and supernova neutrinos by SNO+ and HALO.

1. Introduction
Thank you for the opportunity to speak at this conference honoring Frank Avignone and Ettore Fiorini, who have made and continue to make major contributions to our field and Peter Rosen who was a pioneer of the field and is missed by all of us. These are long-time friends of mine and it is a pleasure to speak in their honor today.

2. The Sudbury Neutrino Observatory (SNO)
The Sudbury Neutrino Observatory [1] is a water Cerenkov detector 2 km underground that used 1000 tonnes of heavy water on loan from Canada’s reserves together with an array of about 9500 photomultipliers (PMT’s) (see figure 1) to observe solar \(^8\)B neutrinos through several reactions with different sensitivities.

\[ \nu_e + d \rightarrow p + p + e^- \quad (CC) \]
\[ \nu_x + d \rightarrow p + n + \nu_x \quad (NC) \]
\[ \nu + e^- \rightarrow e^- + \nu \quad (ES) \]

where the charged current (CC) reaction is sensitive specifically to electron neutrinos and provides an energetic neutrino that produces Cerenkov light in the heavy water, the neutral current (NC) reaction is sensitive equally to all active neutrino types above a threshold of 2.2 MeV and the elastic scattering (ES) reaction is sensitive to all active neutrino types with about 6 times larger sensitivity for electron neutrinos. The CC reaction produces electrons with an energy nearly equal to the incoming neutrino less the 1.4
MeV Q value and has a small directional sensitivity. The ES reaction is strongly directional, producing electrons travelling in nearly the same direction as the incident neutrino. The NC reaction is detected by the observation of the free neutron that is quickly thermalized in the heavy water.

In the first phase of SNO with pure heavy water, these neutrons were observed through the light from Compton scattering of the 6.25 MeV gamma ray produced when the neutron is captured by deuterium. In the second phase, about 2 tonnes of NaCl was added to the heavy water so that the neutrons from the NC reaction were mainly captured on Cl, producing several gammas with total energy of about 8.6 MeV. The total capture probability was enhanced and the pattern of light produced by these gammas was much more isotropic than the Cerenkov light cone produced by the electrons from the CC reaction, enabling the two reactions to be distinguished on a statistical basis in this phase. In the third phase, an array of about 400 meters of $^3$He-filled proportional counters was placed in pure heavy water in the central acrylic vessel of the SNO detector [NCD paper]. These so-called Neutral Current Detectors (NCD’s) provided a measure of the neutrons from the NC reaction that was independent from the light observed by the PMT’s, providing a very separate but simultaneous measurement of the CC and NC reactions.

Figure 1: Schematic picture of the SNO detector, showing about 9500 PMT’s looking inward towards a transparent acrylic vessel holding 1000 tonnes of heavy water. The space outside the acrylic vessel is filled with about 8000 tonnes of ultra-pure light water.

The CC and NC reactions provide a determination of the solar electron neutrino flux and the total flux of active neutrinos, respectively. Therefore their ratio can determine the fraction of solar electron neutrinos reaching the earth. The results from the first phase of SNO gave a clear indication of solar neutrino flavor change for $^8$B neutrinos as a hypothesis test of non-oscillation at the 5.5 sigma level. [2]. The second phase with salt provided an independent measure of the CC and NC reactions, [3] reinforcing
the evidence for flavor change and providing a measure of the original $^8$B electron neutrino flux in agreement with solar model calculations [4,5].

In order to accomplish the measurements, extreme care was taken with the selection of detector materials and in the cleanliness of the laboratory during construction. Gamma rays greater than 2.2 MeV are capable of photo-disintegrating deuterium, creating a free neutron that mimics the NC reaction. By maintaining the laboratory as a Class 2000 clean room throughout construction, it was possible to restrict mine dust to a total of less than about a gram distributed on the detector parts. Water purification and monitoring systems were developed to measure the residual U and Th radioactivity in the light and heavy water with sensitivities of better than $10^{-14}$ gm U (or Th) per gm of water.

The fluxes determined from the salt phase data (in units of $10^6$ cm$^{-2}$ sec$^{-1}$) are:

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

A comparison of the CC and NC fluxes shows that about two-thirds of the electron neutrinos have changed their flavor to other active neutrino types, violating a hypothesis test for no flavor change at greater than $7\sigma$. The observed total flux of active neutrinos (NC) is in excellent agreement with the flux of $^8$B neutrinos obtained from solar models [4,5]:

$$\Phi_e = 5.82 \pm 1.3[4]; 5.31 \pm 0.6[5]$$

Oscillation purely to sterile neutrinos is strongly disfavored. By comparison of the active total flux of $^8$B solar neutrinos observed by the NC reaction with the $^8$B flux calculated with solar models, restrictions are placed on sub-dominant oscillations to sterile neutrinos.

A two neutrino oscillation analysis [6] including the MSW effect in the Sun [7] for this data plus previous solar data, including Phase 1 of SNO and terrestrial reactor neutrino data from KamLAND [8] provides the following best-fit parameters:

$$\Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5} \text{ eV}^2$$
$$\theta = 33.9^{+2.4}_{-2.2} \text{ deg.}$$

This data shows agreement only for the Large Mixing Angle solution for solar neutrinos and confirms the 1-2 mass hierarchy with mass 2 larger than mass 1. The result for the mixing angle is primarily defined by the CC/NC ratio from SNO and shows that the mixing angle is non-maximal by more than 5 standard deviations. A further measurement has recently been reported [9] by KamLAND that provides a significant improvement in the mass uncertainty.

The third and final phase of SNO included data obtained from November 2004 to November 2006. The NCD’s provided a signal for the NC reaction on deuterium from neutron capture on $^3$He producing a triton and a proton with a combined energy of 764 keV. A blind analysis of the data is being carried out by adding a number of extra pulses from neutrons produced by atmospheric muons and removing a fraction of events. Figure 2 shows a spectrum of neutrons from the NCD’s showing the neutron peak and the underlying alpha particle background corresponding to only about 0.5 counts per hour in the region of interest. This illustrates the ultra-low radioactivity of the NCD detector array [10]. A few weeks after the
presentation of the present paper, the results of this analysis were submitted for publication [11] showing independent results in good agreement with previous phases of SNO and providing improved best-fit parameters for neutrino oscillation.

Figure 2: Blinded neutrino data from the $^3$He-filled proportional counters in Phase 3 of SNO. The neutron calibration spectrum shows the response from a neutron source producing protons and tritons by capture on $^3$He. The alpha background is from residual activity in the detectors.

3. The new SNOLAB International Underground Science Facility

The new SNOLAB facility has been created by excavating three new experimental areas near the original SNO cavity 2 km underground at Vale-INCO’s Creighton mine near Sudbury Ontario, Canada. The excavation is very nearly complete and the new areas will be ready for experimental occupancy towards the end of 2008. The newly excavated volume is almost two times the original volume for the SNO experiment and provides space for an additional 5 or more experiments. The entire laboratory will be maintained as a Class 2000 or better clean room, as has been done for the SNO area.

Many letters of interest or intent have been received from experiments wishing to be sited in SNOLAB. These requests have been studied by an International Experiment Advisory committee and recommendations have been made to the Director for siting of an initial set of experiments. The following describes a number of experiments that are already in operation in the underground location or are planned for the future, covering measurements that will benefit significantly from the 2 km depth (about 6000 meters of water equivalent, presently the deepest operational international laboratory) and the cleanliness of the laboratory. These experiments involve direct searches for dark matter with spin-dependent and spin-independent interactions (PICASSO, DEAP-1, Mini-Clean, DEAP/CLEAN, SuperCDMS), searches for neutrino-less double beta decay (SNO+, EXO-gas), searches for Supernovae (HALO, SNO+), solar, geo and reactor neutrinos (SNO+).
Figure 3: The new SNOLAB facility provides three new experimental areas 2 km underground near the existing SNO cavity (bottom left). These areas in the center of the figure can house 5 or more new experiments in a total newly excavated volume about twice the original volume in the SNO cavity. The entire underground laboratory will be maintained as a Class 2000 clean room facility.

3.1. Dark Matter Experiments

The PICASSO experiment [12] uses super-heated droplets containing fluorine compounds in a gel to search for dark matter via the spin-dependent interaction. They are presently operating about 2 kg of active material in an array of detectors in an auxiliary area near the SNO detector. This array is providing results at sensitivity levels at or better than current limits for spin-dependent detection. Future plans involve scaling up by factors of 100 or more and siting in one of the new underground experimental areas.

The DEAP-1, Mini-CLEAN-360 and DEAP/CLEAN-3600 detectors are being designed by the DEAP/CLEAN international collaboration to use pulse shape discrimination in liquid noble gases (Ar, Ne) to search for dark matter via the spin-independent interaction. The DEAP-1 detector is currently in operation underground in the former SNO control room with 7 kg of liquid argon viewed by 2 photomultiplier tubes (PMT’s) in a shielded enclosure. The large difference between the timing for light output by nuclear recoils and ionizing events is being used to discriminate between these types of events. This discrimination will be used to deal with the beta decays from $^{39}$Ar that provide a background of about 1 Bq/kg in atmospheric argon [13]. The DEAP-1 detector has been operated on surface to demonstrate discrimination of gammas at the level of $6 \times 10^{-9}$. The lower background levels underground will enable this sensitivity measurement to be extended beyond $10^{-9}$ with a triggered gamma source. It also provides an excellent opportunity to study processes for lowering radioactivity on inner surfaces. The
Mini-CLEAN 360 kg detector is being prepared for siting in 2009 with the ability to define a 100 kg fiducial volume as well as pulse-shape discrimination. It will have a potential sensitivity with liquid argon about 10 times beyond current limits [14] for spin-independent dark matter detection and the capability to be operated with liquid Ne as an alternate detection medium. The DEAP/CLEAN 3600 kg detector is being designed for siting in 2010, also with the ability to perform pulse-shape discrimination and define a 1000 kg fiducial volume to remove effects of residual radioactive contamination on inner surfaces. The projected sensitivity is 100 times better than current limits obtained with the spin-independent interaction. Figure 5 shows the preliminary layout for these two detectors in the new Cube Hall in SNOLAB. It is intended to construct the external water shielding for the two experiments at the same time to minimize interference.

The CDMS experiment [14] currently has the lowest limits for dark matter detection via the spin-independent interaction through measurements at the Soudan mine. The experiment uses simultaneous measurement of charge and heat (through bolometry at very low temperature) in Ge to discriminate between nuclear recoils from dark matter particles and ionizing background events. The Super-CDMS collaboration has sought and received approval from the SNOLAB Experiment Advisory Committee for siting of up to 25 kg of Ge at SNOLAB in order to take advantage of the lower background available at the greater depth. This will enable significant improvements in the present experimental sensitivity.

Figure 4 Preliminary layout of the Mini-CLEAN-360 and DEAP/CLEAN-3600 detectors in the new SNOLAB Cube Hall (about 20m by 20 m by 22 m high).

3.2. Neutrino-less Double Beta Decay Experiments
The principal initial objective of the SNO+ experiment [15] will be a study of the neutrino-less double beta decay of $^{150}\text{Nd}$. The SNO+ experiment is being designed to use the existing SNO experiment equipment with the heavy water replaced with 1000 tonnes of an organic liquid scintillator, Linear Alkyl Benzene (LAB), with a metallo-organic compound containing 1 tonne of Nd dissolved in the LAB. The LAB is lighter than the water surrounding the central acrylic vessel holding it and so the existing ropes holding up the vessel must be augmented with additional low-radioactivity ropes to hold it down when filled. A purification system for LAB is being designed to meet the stringent background requirements for the experiment. However, the neutrino-less double beta decay summed energy for the emitted electrons is 3.3 MeV and so the region of interest is above the background radioactivity from the Uranium chain, including $^{222}\text{Rn}$, so the main concern is radioactivity from the $^{232}\text{Th}$ decay chain. Levels of radioactivity already demonstrated by the KamLAND and BOREXINO collaborations for liquid scintillator would be acceptable for the proposed measurement.

The high value of decay energy provides an additional advantage compared to other proposed experiments because the decay rate for a given effective neutrino mass has a strong dependence on this energy. With one tonne of natural Nd dissolved in the LAB, there would be 56 Kg of $^{150}\text{Nd}$ isotope present and this is the initial configuration planned for SNO+. However, an international collaboration has been formed to pursue the potential production of $^{150}\text{Nd}$ at a former U laser isotope enrichment facility in France. It could be possible to produce hundreds of kg of isotope from the converted facility. Figure 5 shows a simulation of the spectrum for neutrino-less double beta decay for an effective mass of 0.15 eV for one year of counting for 500 kg of $^{150}\text{Nd}$. For 1 tonne of natural Nd it would be possible to set a 5 sigma upper limit of 0.1 eV for the effective neutrino mass after 3 years of counting and for 500 kg of $^{150}\text{Nd}$ it would be possible to set a 5 sigma upper limit of 0.04 eV after 3 years.

In addition to the development of a 200 kg liquid $^{136}\text{Xe}$ detector at WIPP, the EXO collaboration is investigating the neutrino-less double beta decay of $^{136}\text{Xe}$ in a gaseous xenon ionization chamber. Work at SNOLAB is currently exploring gaseous xenon detectors which offer tracking information as well as the prospect of a very high degree of background rejection through the identification of the daughter Ba ion. A concept is being investigated wherein the Ba ions are drifted out of the decay region to a location where single atoms can be identified by laser fluorescence. This approach will provide a specific identification of the Xe decay process.

3.3. Neutrinos from the Sun, the Earth, Nuclear Reactors or Supernovae

If very high radiopurity can be obtained for a fill of pure LAB, the SNO+ experiment will have the capability of observing low energy solar neutrinos, particularly pep and CNO neutrinos because the background from muon-induced $^{11}\text{C}$ beta decay will not be a significant background because of the depth of SNOLAB [15]. This measurement is not compatible with the presence of $^{150}\text{Nd}$ as the two-neutrino double beta decay would interfere, so it would be pursued after the measurements with Nd. The pep neutrinos are of particular interest because their energy of 1.4 MeV is in a transition region between vacuum oscillation for pp neutrinos and significant matter-enhanced oscillations for $^8\text{B}$ neutrinos. The initial pep flux is also defined by solar models [4,5] to better than 2% so they can provide a valuable test of the MSW effect or other sub-dominant physics possibilities [16] such as non-standard interactions, sterile neutrinos or mass-varying neutrinos.

The SNO+ detector will also provide an interesting measurement of electron anti-neutrinos from the U and Th chain decays in the Earth. The mid-continental location provides a measurement with well defined and different characteristics than other reactor measurements such as Kamland. Measurements of
neutrinos from the major reactors in Ontario will provide a test of the KamLAND reactor anti-neutrino oscillation measurements with an effective baseline about 50% longer.

Figure 5 Simulation of the SNO+ detector response for 500 kg of $^{150}$Nd, assuming an effective neutrino mass of 0.15 eV, matrix elements from ref [17] and backgrounds as achieved at the Kamland experiment [8].

The SNO+ detector will be sensitive to neutrino bursts from Supernovae at distances out to the Large Magellanic Cloud. The SNO experiment was a participant the Supernova Early Warning System (SNEWS) and it is planned for SNO+ to re-establish that participation.

The Helium and Lead Neutrino Observatory (HALO) is a supernova detector to be created from 80 tons of lead, together with the 400 m of $^3$He proportional counters and associated electronics used in the final phase of the SNO experiment. It is estimated that this detector could observe about 50 events from a supernova at the center of our galaxy with the sensitivity dominated by electron neutrinos, unlike other supernova detectors. Implementation of the detector is planned within the next year.

References
[1] SNO Collaboration, Boger J et al. 2000 Nucl. Instrum. Meth. A449, 172
[2] SNO Collaboration, 2001 Phys. Rev. Lett. 87, 071301
SNO Collaboration, 2002 Phys. Rev. Lett. 89, 011301
SNO Collaboration, 2002 Phys. Rev. Lett. 89, 011302
[3] SNO Collaboration, Aharmim B et al 2005 Phys. Rev. C72, 055502
[4] Bahcall J N and Pinsonneault M H 2004 Phys. Rev. Lett. 93 121301
Bahcall J N and Pena-Garay 2003 hep-ph/0305159
[5] Turck-Chieze S et al 2004 Phys. Rev. Lett. 93, 211102
[6] Maki Z, Nakagawa N and Sakata S 1962 Prog. Theor. Phys 28, 870
Pontecorvo B 1957 J. Expt Theoret. Phys. 33, 549; 1958, J. Expt. Theoret. Phys. 34, 247
Gribov V and Pontecorvo B 1969 Phys. Lett. B28, 493
[7] Mikheyev S P and Smirnov A Y 1986 in Massive Neutrinos in Astrophysics and in Particle
Physics, Proceedings of the Moriond Workshop, edited by O. Fackler and J. Tran Thanh Van, Editions
Frontieres, Gif-sur-Yvette, 335
Mikheyev S P and Smirnov A Y 1985 Sov. J. Nucl. Phys. 42, 1441
Wolfenstein L 1978 Phys. Rev. D 17, 2369
[8] KamLAND Collaboration Araki T et al 2004 hep-ex/0406035
[9] KamLAND Collaboration Abe S et al 2008 hep-ex 0801.4589v2
[10] Amsbaugh J F et al 2007 Nucl. Instr. andMeth. A579, 1054
[11] SNO Collaboration, Ahammad B et al 2008 nucl-ex/0806.0989
[12] Barnabé Heider M et al 2005 hep-ex/0508098; hep/ex/0502028
[13] Boulay M and Hime A 2004 astro-ph/0411358
[14] CDMS Collaboration Ahmed Z hep-ex/080222
[15] Chen M C 2005 Nuclear Physics B (Proc. Suppl.) 145 65–68
[16] Friedland A et al 2004 hep-ph/0402266
Miranda O et al 2004 hep-ph/0406280
Barger V et al 2004 hep-ph/0502196
De Holanda P and Smirnov A 2003 hep-ph/0307266
[17] Eliott S R and Vogel P, 2002 Ann.Rev.Nucl.Part.Sci. 52 115-151