Title
SNO: solving the mystery of the missing neutrinos

Authors
Jelley, Nick
Poon, Alan

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SNO Completes Neutrino Data-Taking

Nick Jelley (*University of Oxford*), Alan Poon (*Lawerence Berkeley National Lab*)

The end of an era came on 28 November 2006 when the Sudbury Neutrino Observatory (SNO) finally stopped data-taking after eight exciting years of discoveries. During this time the Observatory saw evidence that neutrinos, produced in the fusion of hydrogen in the solar core, change flavour while passing through the Sun on their way to the Earth. This observation explained the longstanding puzzle as to why previous experiments had seen fewer solar neutrinos than predicted and confirmed that these elusive particles have mass.

Solar neutrinos were first detected in Ray Davis's radiochemical experiment in 1967, for which discovery he shared the 2002 Nobel Prize in Physics. Surprisingly he found only about a third of the number predicted from models of the Sun's output. This deficit, the so-called Solar Neutrino Problem, was confirmed by Kamiokande-II while other experiments saw related deficits of solar neutrinos. A possible explanation for this deficit, suggested by Gribov and Pontecorvo in 1969, was that some of the electron-type neutrinos, which are produced in the Sun, had 'oscillated' into neutrinos that could not be detected in the Davis detector. The oscillation mechanism requires that neutrinos have non-zero mass.

The unique advantage, which was pointed out by the late Herb Chen in 1985, of using heavy water (D_2O) to detect the neutrinos from ^8B decays in the solar fusion process is that it enables both the number of electron-type and of all types of neutrinos to be measured. A comparison of the flux of electron-type neutrinos to that of all flavours could then reveal whether flavour transformation is the cause of the solar neutrino deficit. In heavy water neutrinos of all types can break a deuteron apart into its constituent proton and neutron (*neutral-current reaction*), while only electron-type neutrinos can change the deuteron into two protons and release an electron (*charged-current reaction*).

SNO was designed by scientists from Canada, the USA and the UK to attain a detection rate of about 10 solar neutrinos per day using 1000 tonnes of heavy water. Neutrino interactions were detected by 9,456 photomultiplier tubes surrounding the heavy water, which was contained in a 12-m diameter acrylic sphere. This sphere was surrounded by 7000 tonnes of ultra-pure water to shield against radioactivity. Figure 1 shows the layout of the SNO detector, which is located about 2 km underground in Inco's Creighton nickel mine near Sudbury in Canada, to all but eliminate cosmic rays from reaching the detector. The pattern of hit photomultiplier tubes following the creation of an electron by an electron-type neutrino is shown in Figure 2.

Crucial to the success of this experiment was making the components of SNO very clean and, in particular, reducing the radioactivity within the heavy water to exceedingly low levels. To achieve this aim the detector was constructed in a Class-2000 clean room and entry to SNO was via a shower and changing rooms to reduce the chance of any contamination from mine dust. The fraction of natural thorium in the D_2O had to be less than a few parts in 10^{15}, roughly equivalent to one small teaspoonful of rock dust added to the 1000 tonnes of heavy water. Such purity was required to reduce the break up of deuterons by gamma rays from natural uranium and thorium radioactivity to a small fraction of the rate from the solar neutrinos. This required complex water purification and assay systems to reduce and measure the radioactivity. Great care in handling the heavy water was also required as it is on loan from Atomic Energy of Canada Ltd. (AECL) and is worth about $300M.

SNO's results from the first phase of data-taking with unadulterated D_2O were published in 2001 and 2002, and provided strong evidence that electron-type neutrinos do indeed transform into different types of neutrinos. The second phase of SNO involved the addition to the D_2O of 2 tonnes of table salt (NaCl) to enhance the detection efficiency for neutrons. This large 'pinch of salt' enabled SNO to make the most direct and precise measurement of the total number of solar neutrinos, which is in excellent agreement with solar model calculations. The results to date reject the null hypothesis of no neutrino flavour change by more than 7 standard deviations.

Together with other solar neutrino measurements, the SNO results are best described by neutrino oscillation enhanced by neutrinos interacting with matter as they pass through the Sun — a resonant effect predicted by Mikheyev, Smirnov and Wolfenstein in 1985. To a good approximation, the electron-type neutrino flavour eigenstate is a linear combination of two mass eigenstates with masses m_1 and m_2. The mixing angle between these two mass eignenstates, which is constrained by the ratio of the electron-type neutrino flux to the total neutrino flux measured by SNO, is found to be large (~34 degrees) but is excluded from maximal mixing (45 degrees) by more than 5 standard deviations. The matter enhancement enables the ordering (hierarchy) of the two mass eigenstates to be defined, with $m_2 > m_1$ and a difference of ~0.01 eV/c^2. That neutrino mixing occurs and is large as seen for solar neutrinos was confirmed in 2003 by the KamLAND experiment, which used 1000 tonnes of liquid scintillator to detect anti-neutrinos from Japan's nuclear reactors.

After the removal of salt in the heavy water, the third and final phase of SNO was with an array of proportional counters, 36 of which were filled with ^{3}He and 4 with ^{4}He gas, deployed in the heavy water to further improve the detection of neutrons. Figure 3 shows part of this array during its deployment with a remotely operated submarine. The additional information acquired during this phase will enable the oscillation parameters describing the neutrino mixing to be better determined. Data analysis is in progress for this phase.

The scientific achievements of the Sudbury Neutrino Observatory were marked at the end of data-taking by the inaugural award of the John C. Polanyi Award by the Canadian funding agency NSERC, as shown in Figure 4. The completion of SNO does not mark the end of experiments in Sudbury though as a new international underground laboratory, SNOLAB, with expanded space to accommodate 4 or more experiments, is nearing completion. SNOLAB has received a number of letters of interest from experiments on dark matter, double beta decay, supernovae and solar neutrinos. In addition, a collaboration of scientists is planning to put 1000 tonnes of scintillator in the SNO acrylic vessel once the heavy water is returned by the end of 2007. This experiment, called SNO+, aims to study lower energy solar neutrinos from the pep reaction in the pp chain, and to study the double beta decay of ^{150}Nd by the addition of a metallo-organic compound.

As a historical anecdote, SNO was not the first heavy water solar neutrino experiment. In 1965, Tom Jenkins, along with other members of Fred Reines's neutrino group at the then Case Institute of Technology, began the construction of a 2-tonne heavy water Cerenkov detector, complete with 55 photomultiplier tubes, in the Morton salt mine in Ohio, USA. Unlike Chen's proposal, Jenkins had only considered the detection of electron-type neutrinos through the charged-current reaction as other flavours were not expected, nor had the neutral-current reaction been discovered. This experiment was stopped in 1968 after Davis had obtained a much lower ^{8}B solar neutrino flux than had been predicted.

Figure 1: The Sudbury Neutrino Observatory. One thousand tonnes of heavy water were the heart of the detector, which is located 2 km underground in a cleanroom.

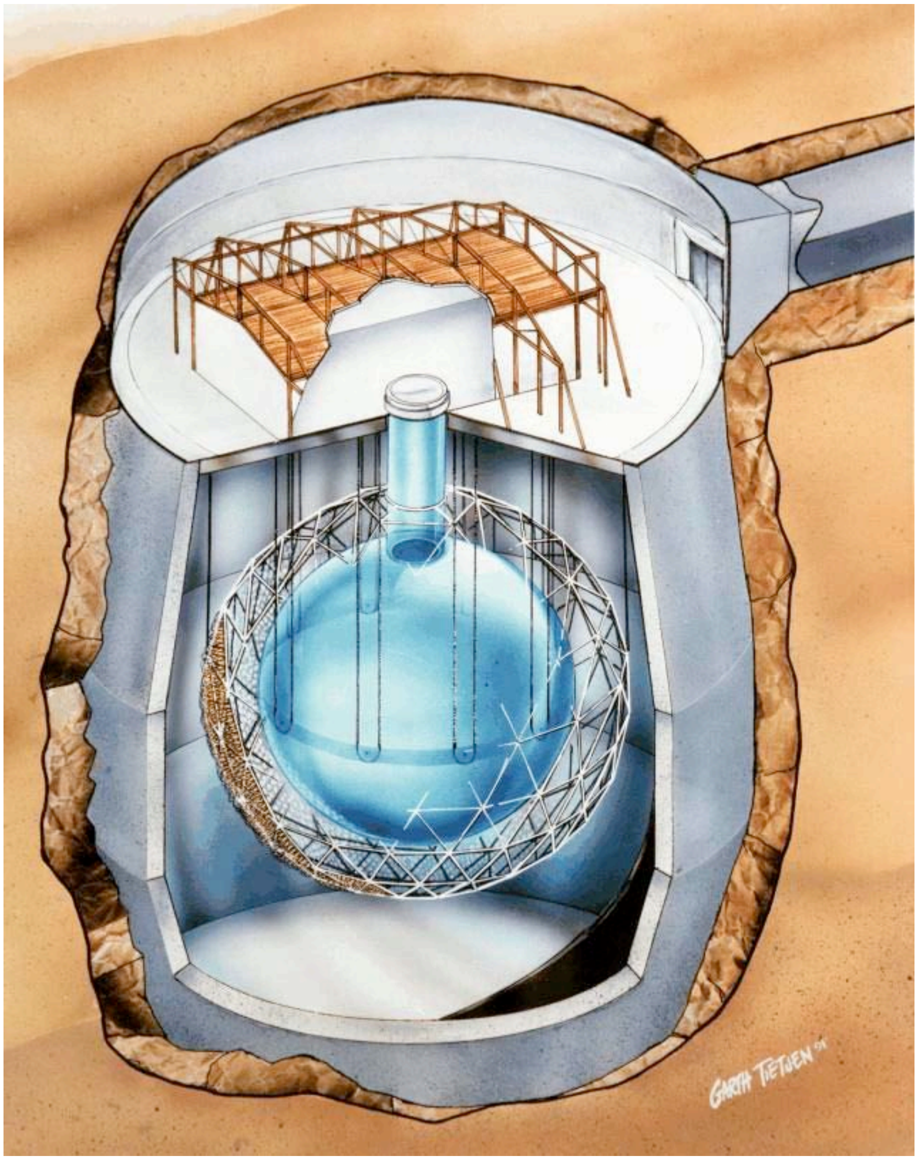

Figure 2: Event display of a neutrino candidate. Cherenkov light from relativistic electrons following a neutrino interaction is detected by photomultiplier tubes mounted on a geodesic structure.

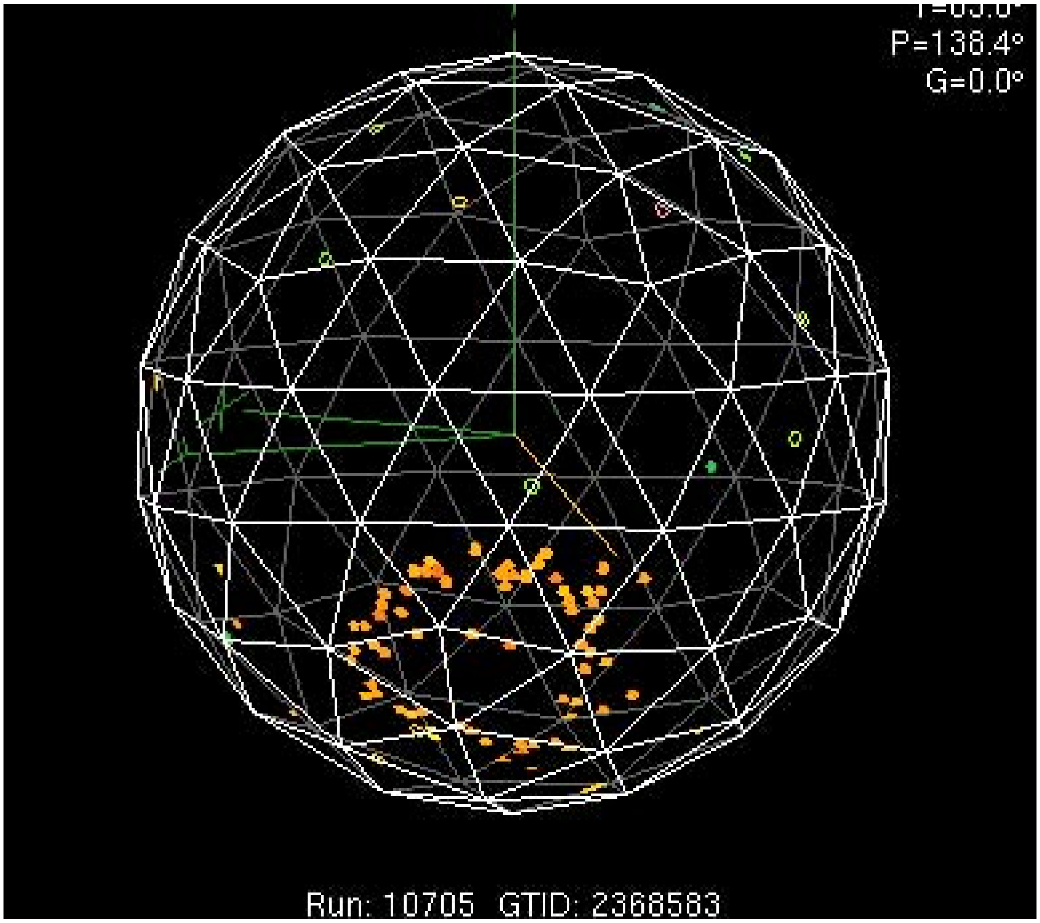

Figure 3: Deployment of the ^{3}He proportional counter array with a remotely operated submarine in 2004. Bright reflection from our of these proportional counters are seen in this picture.

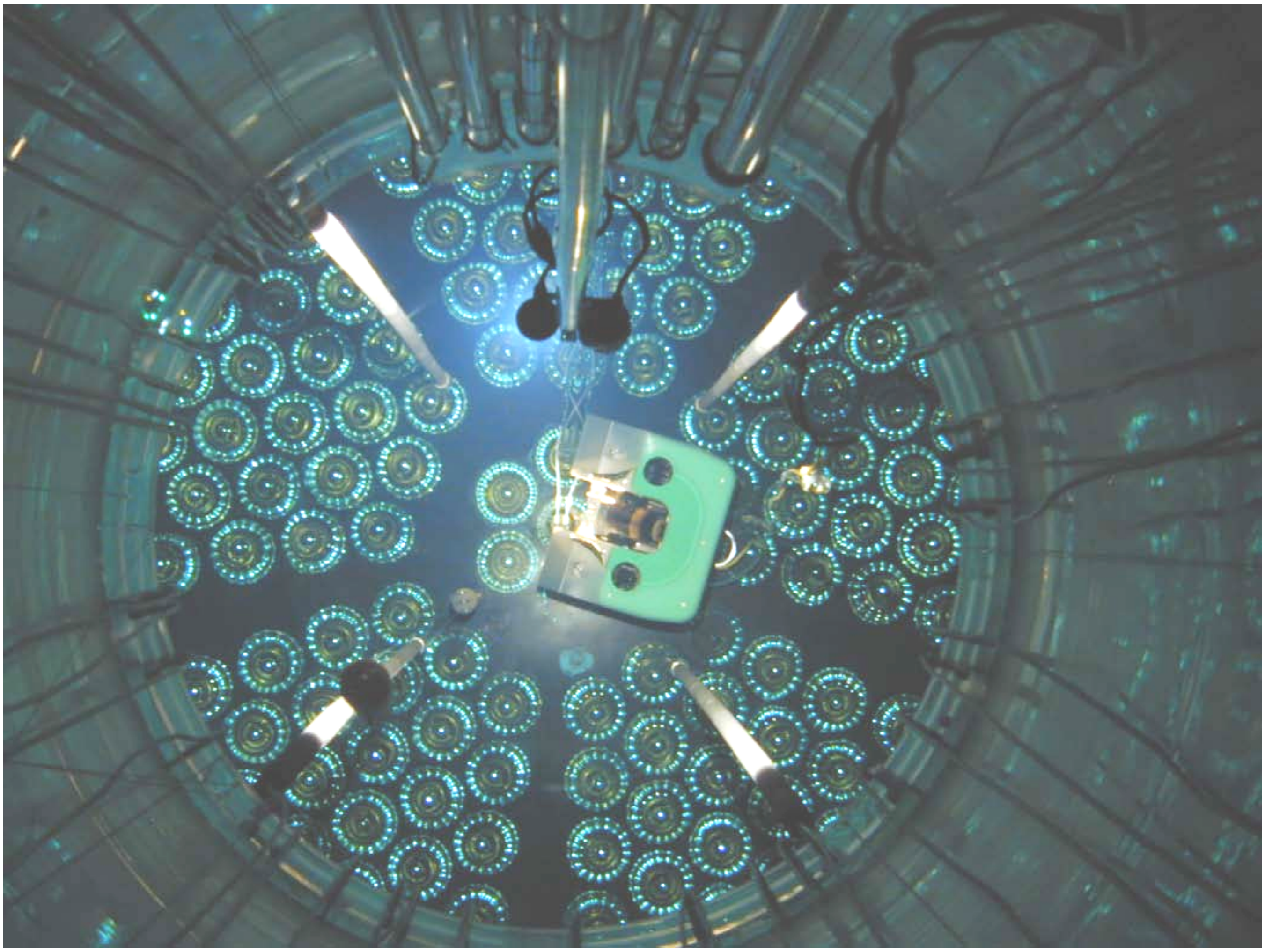

Figure 4: On behalf of the SNO Collaboration, SNO Director Art McDonald (left) accepts the inaugural John C. Polanyi Award from the President of NSERC Suzanne Fortier (middle) and Nobel Laureate John C. Polanyi (right).