REVIEWS OF MODERN PHYSICS, VOLUME 88, JULY–SEPTEMBER 2016

# Nobel Lecture: The Sudbury Neutrino Observatory: Observation of flavor change for solar neutrinos*

Arthur B. McDonald

*Queen's University, Kingston, Canada, for the SNO Collaboration*

(published 6 July 2016)

DOI: 10.1103/RevModPhys.88.030502

CONTENTS

## I. SOLAR NEUTRINOS

The nuclear fusion processes that power the Sun take place at such high temperatures that the nuclei of atoms are able to fuse together, a process that results in the creation of very large numbers of fundamental particles called neutrinos. As you heard from my friend and scientific colleague Professor Kajita, neutrinos only interact through the weak interaction and gravity and therefore can penetrate out from the core of the Sun and through the Earth with little or no interaction.

It is these neutrinos from the Sun that are the subject of our measurements with the Sudbury Neutrino Observatory (SNO), 2 km underground in a mine near Sudbury, Canada. With the use of heavy water as a central element in the design of SNO it was possible to determine clearly that electron neutrinos change to one of the other active flavors before reaching our detector, a property that requires that they have a mass greater than zero. Both of these fundamental neutrino properties are beyond the predictions of the Standard Model for elementary particles. Extensions of the Standard Model to include these neutrino properties can give us a more complete understanding of our Universe at a very basic level.

The study of the Sun and the processes that power it has been the subject of strong interest for many years and it is clear that in our work we "see farther because we stand on the shoulders of giants" as was said by Isaac Newton. Nobel Laureates Hans Bethe (1967) and Willy Fowler (1983) were pioneers in the study of the physics of nuclear reactions in the sun: Bethe for his work on energy production in stars via nuclear reactions and Fowler for working out the details of the $pp$ reactions and others that are responsible for the creation of the majority of the elements in stars and supernovae. The general conclusion of their work was that the "$pp$ cycle" shown in Fig. 1 was the principal source of energy generation in the Sun.

I was fortunate to be a graduate student in Fowler's Kellogg Laboratory at Caltech in the 1960s, an intellectual center for the understanding of solar and stellar physics. During my time there, I met two other pioneers in the study of the Sun and neutrinos, Ray Davis (Nobel Laureate 2002) who made the first measurements of neutrinos from the Sun and John Bahcall, who pioneered complete and accurate calculations of the numbers of neutrinos emitted by the Sun. Their pioneering work established what came to be known as "The Solar Neutrino Problem" in that the measurements of Davis showed that the number of electron neutrinos reaching the Earth were about 3 times smaller than the calculations of Bahcall (Bahcall, Bahcall, and Shaviv, 1968; Davis, Harmer, and Hoffman, 1968).

Possible reasons for the discrepancy could have been that the experiment or the theory was incorrect. Another possibility was put forward at the same time that Davis began his experiment in 1968 by other pioneers in the field of neutrino physics. Gribov and Pontecorvo (1969) proposed that perhaps the electron neutrinos from the Sun were oscillating into other flavors (muon neutrinos were known at that time) and escaping detection by Davis' experiment that was only sensitive to electron flavor neutrinos. This was a variation on a theoretical prediction that Pontecorvo (1958) had made that electron neutrinos might oscillate into electron antineutrinos.

## II. THE SUDBURY NEUTRINO OBSERVATORY ORIGINS

The Sudbury Neutrino Observatory Scientific Collaboration was established in 1984 with Professor Herb Chen of the University of California, Irvine, USA and Professor George Ewan of Queen's University, Kingston, Ontario, Canada as Co-Spokesmen. In 1985 the UK joined the collaboration with Dr. David Sinclair of Oxford University as UK Spokesman. The motivation for the experiment was described in a paper by Chen (1985) wherein the deuterium nuclei in heavy water would enable two separate reactions to be observed, one sensitive only to the electron flavor neutrinos created in the Sun and the other sensitive to all three active neutrino flavors. A comparison of the rates for these detection reactions for neutrinos from $^8$B decay in the Sun would enable a clear determination of whether electron neutrinos were changing into other flavors independent of any calculations of initial solar neutrino fluxes. In addition, the second detection reaction could be used to obtain an accurate measure of the flux of

---

*The 2015 Nobel Prize for Physics was shared by Takaaki Kajita and Arthur B. McDonald. These papers are the text of the address given in conjunction with the award.

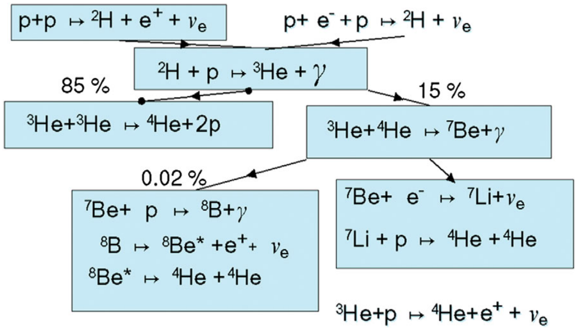

FIG. 1. The "*pp* cycle" of nuclear reactions that dominate the energy production in the Sun and produce neutrinos with varying numbers and energies as shown in Fig. 11.

electron neutrinos from $^8$B decay, independent of whether neutrino oscillation was occurring.

Sinclair *et al.* (1986) shows the list of the original 16 collaboration members and Fig. 2 shows members at a collaboration meeting at Chalk River Nuclear Laboratories in Canada in 1986. By that time, tentative approval for the loan of 1000 tonnes of heavy water from Canada's reserves had been obtained from Atomic Energy of Canada Limited (AECL) and tentative approval had been obtained from INCO Limited, the owner of the Creighton mine near Sudbury, Ontario, a location that had been previously identified by Professor Ewan as an ideal location for a deep, low radioactivity laboratory. Tragically, Professor Chen passed away from leukemia in 1987, about six months after the picture of Fig. 2 was taken.

This was a great loss for the collaboration, but they respected Herb's memory and scientific objectives and carried on with their work on experimental design and requests for funding. At the time I was at Princeton University and took over as the US Co-Spokesman, joined shortly thereafter by Professor Eugene Beier of the University of Pennsylvania, Philadelphia. The collaboration grew significantly over the next few years and by 1989 comprised 14 institutions in Canada, the US and the UK. Considerable work was carried out to complete the design for the experiment and the underground location and in late 1989, funding was obtained from government agencies in the three countries. I had moved that year from Princeton to Queen's University and became Director of the SNO Institute with responsibility for the international project, and also Director of the SNO Scientific Collaboration.

The original collaboration included Atomic Energy of Canada Ltd. (Chalk River Laboratories), Carleton University, Laurentian University, the National Research Council of Canada, Oxford University, Princeton University, Queen's University, University of California at Irvine, and the University of Guelph. By 1989, those institutions had been joined by the University of Pennsylvania. Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, the University of British Columbia, and Brookhaven National Laboratory and the collaboration had grown to about 70 scientists. The eventual number of authors on SNO scientific papers numbered 274. Since the majority of the additional authors were graduate students and postdoctoral fellows, this shows clearly the major educational aspect of this scientific work.

FIG. 2. The picture shows some of the collaboration members at a Collaboration meeting in Chalk River, 1986. From the left: Davis Earle, Mort Bercovitch, David Sinclair, John Simpson, Doug Hallman, Hay Boon Mak, Peter Doe, Henry Lee, Cliff Hargrove, Hugh Evans, Peter Skensved, Herb Chen, Dan Kessler, George Ewan, Richard Allan, Art McDonald. Original collaboration members missing from this picture include Walter Davidson, Barry Robertson, and Robert Storey.

## III. NEUTRINO DETECTION IN SNO

With deuterium contained in the heavy water molecules (>99.92% $D_2O$) in the SNO detector, it was possible to observe three separate interactions of neutrinos in the detector, the first two mentioned before and the third, elastic scattering from electrons that takes place in any medium:

$$\nu_e + d \to e^- + p + p - 1.44\ \text{MeV} \quad (\text{Charged Current (CC) Reaction}),$$
$$\nu_x + d \to \nu_x + n + p - 2.2\ \text{MeV} \quad (\text{Neutral Current (NC) reaction}),$$
$$\nu_x + e^- \to \nu_x + e^- \quad (\text{Elastic Scattering (ES) reaction}),$$
$$\text{where } x = \text{electron, mu or tau.}$$

The first (CC) reaction is sensitive only to electron flavor neutrinos and produces an energetic electron that creates a cone of light in the detector via the Cerenkov process, observable with an array of photosensors. The second (NC) reaction is equally sensitive to all flavors of neutrino and produces a free neutron that was observed in different ways in the three phases of the SNO detector operation. By comparing appropriately calibrated rates for these two reactions it was possible to determine whether solar electron neutrinos had changed into other flavors before reaching the detector.

The third reaction (ES) is much weaker than the other two and is mostly sensitive to electron neutrinos (6 times more sensitivity than to the other two flavors for solar neutrino energies). It produces an energetic electron that is strongly peaked in the forward direction relative to the incident neutrino and therefore can be distinguished from the other two reactions by reference to the direction from the Sun.

The SNO experiment was carried out in three distinct phases. In Phase 1, pure heavy water was used and the free neutron from the NC reaction was observed as it was captured by a deuterium nucleus, producing a 6.25 MeV gamma ray that in turn generated Compton-scattered electrons producing Cerenkov light. In Phase 2, about 2 tonnes of ultrapure NaCl salt was added to the heavy water, so that the free neutron would predominantly capture in the Cl, producing a cascade of gamma rays with energies summing to about 8.6 MeV. This increased the neutron capture efficiency from 14% to 40% and provided such an isotropic distribution of light that the events from the NC reaction could be separated statistically from the cone-shaped light emission events from the CC reaction. In Phase 3, an independent array of $^3$He-filled neutron detectors (Amsbaugh *et al.*, 2007) was inserted into the heavy water providing a clear measurement of free neutrons from the NC reaction.

## IV. THE SNO DETECTOR

Figure 3 shows an artist's conception of the SNO detector (Boger *et al.*, 2000) situated in a barrel-shaped cavity 34 m high by 22 m diameter, 2 km underground in INCO/Vale's Creighton mine near Sudbury, Ontario, Canada. 1000 tonnes of heavy water enriched to 99.92% deuterium (worth $300 million Canadian) are held in a transparent acrylic vessel 12 m in diameter and 5.6 cm thick, viewed by 9438 light sensors (photomultipliers, or PMTs) mounted on a geodesic frame made from stainless steel. The cavity is lined with water- and radon-impermeable Urylon plastic. The entire cavity outside the acrylic vessel is filled with ordinary water purified to be more than a billion times purer than tap water for the content of uranium and thorium decay chain elements.

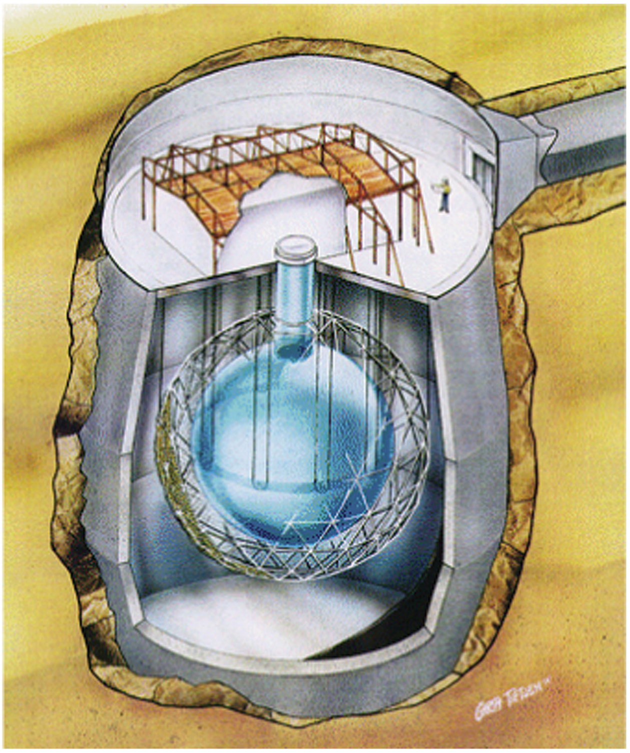

FIG. 3. Schematic view of the Sudbury Neutrino Observatory.

The design and construction of this massive, complicated detector 2 km underground in ultraclean conditions was a major engineering accomplishment. We were very fortunate to have a skilled team of engineers, technicians and construction workers to carry out this one-of-a-kind project. Scientific teams distributed across the collaboration accepted responsibilities for major parts of the experiment, led by Group Leaders for elements such as the Acrylic Vessel, PMT's, PMT Support Structure, Water Systems, Electronics, Data Acquisition, Calibration, Simulation and Analysis. These groups took responsibility for their detector elements from design through construction and operation to meet the scientific and engineering requirements, with coordination among groups through regular meetings and discussions.

All parts of the detector were carefully chosen and sampled to be as low as possible in radioactivity and the whole laboratory area was maintained at better than Class 2000 air quality (fewer than 2000 dust particles of diameter greater than 0.5 μm per cubic foot of air). It was determined that less than 1 g of mine dust was present on the entire detector after construction. It was extremely important to maintain ultralow radioactivity levels in the detector and in the heavy water because any gamma ray with energy greater than 2.2 MeV (such as from the uranium or thorium decay chains) could possibly cause the disintegration of the deuterium nucleus, producing a free neutron and mimicking the NC reaction from neutrinos. By keeping the radioactivity very low (less than $3\times10^{-15}$ g of Th per gram of heavy water) and measuring accurately the content it was possible to keep the numbers of neutrons from this gamma disintegration process on deuterium well below those from neutrino reactions. This background contribution was measured accurately by sampling the water for Th decay chain content and by analyzing the low energy data that were dominated by radioactivity. Similar care

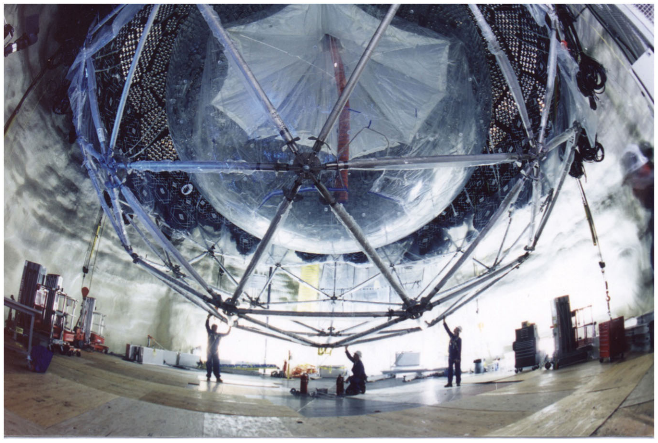

FIG. 4. SNO detector during construction.

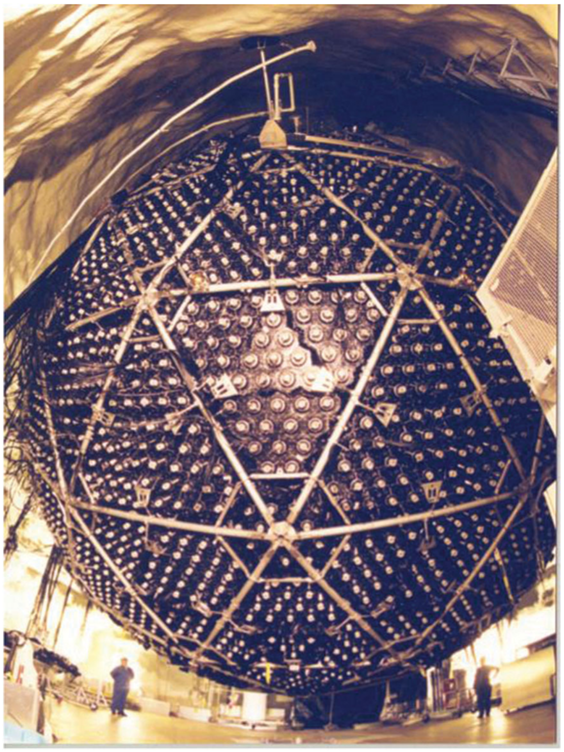

FIG. 5. Wide angle picture looking up from the bottom of the sphere of photomultipliers.

was taken to restrict U and measure contamination in the heavy water and the ordinary water.

Figure 4 shows the detector during construction, after the acrylic sphere had been bonded together in place from 122 pieces small enough to fit within the underground hoist used for access.

Figure 5 shows the completed detector prior to water fill and Fig. 6 shows a wide angle camera shot looking up from the bottom of the sphere of photomultipliers (PMT's).

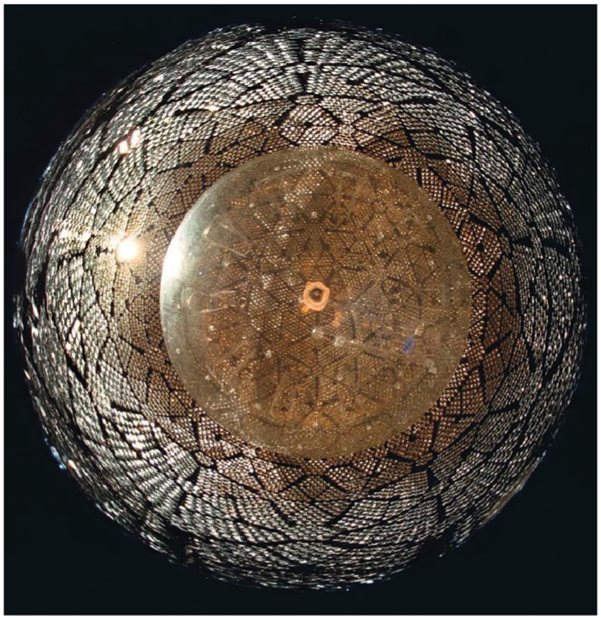

FIG. 6. Completed SNO detector prior to water fill.

FIG. 7. Part of the water purification systems.

Figure 7 shows part of the water purification systems, including systems for the measurements of ultralow levels of radioactivity by recirculation of the water through filters specially designed to measure the important daughter products of U, Th decay. Radon gas was another important radioactive component that had to be restricted strongly and measured carefully. The restriction was accomplished by covering the heavy water with nitrogen gas that was obtained from the boil-off of large liquid nitrogen dewars. This gas was very low in radon content and the system was designed to avoid contamination by mine air by requiring positive flow of pure nitrogen over the heavy water even during mine pressure excursions. The ordinary water was degassed and then regassed with similar "boil-off" nitrogen with ultralow radon content. All of these precautions resulted in less than one radioactive decay from the Th or U chains per day per tonne of heavy water, as required to avoid interference with the neutrino event rates.

## V. SNO EXPERIMENTAL MEASUREMENTS

Photons of light generated by neutrino interactions in the heavy water were converted to electronic pulses by the photomultipliers, shaped via specially designed circuits and collected on computer systems, along with the pulses generated by radioactive background. These data were carefully analyzed to extract the pulses from a neutrino interaction, using information on the magnitude of pulses and time of arrival at all of the photomultipliers triggered simultaneously by the neutrino interaction. This set of information was collectively referred to as an event. This information was carefully analyzed to differentiate neutrino events from those generated by radioactivity or other instrumental artifacts.

Figure 8 shows a collection of events obtained from Phase 1 of the experiment with pure heavy water in the detector. The data shown here come from the innermost 11 m diameter of the heavy water during 306 days of data accumulation. The expected shapes of event data from the CC, NC and ES reactions and from the radioactive background pulses extrapolated from lower energies are also shown on the figure. These shapes were calculated from a very detailed Monte Carlo simulation of the expected pulses from the detector, calibrated accurately by a series of subsidiary measurements using calibration sources emitting known energies and quantities

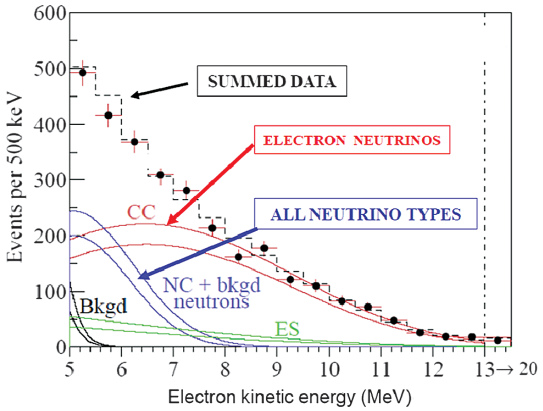

FIG. 8. Data from Phase 1 of the SNO experiment showing the number of events vs the effective kinetic energy for an electron. The double lines on the CC, NC and background components indicate uncertainties.

of gamma rays, neutrons and electrons. These sources could be moved throughout over 70% of the volume of the detector in two perpendicular planes with a calibration source manipulator, providing a detailed mapping of the detector sensitivity.

The shape of events from the NC reaction as a function of energy was very well defined by the emission of 6.25 MeV gamma rays from the capture of free neutrons in deuterium and could be calibrated accurately by the use of a source of 6.13 MeV gamma rays from the decay of $^{16}$N. The $^{16}$N was generated in a shielded nearby location in the underground laboratory and transported via capillary tubes to the heavy water volume (Dragowsky *et al.*, 2002). The contributions of background events from radioactivity producing Cerenkov light in the detector, as shown by the black lines in the figure were calculated from measurements made with encapsulated U and Th sources moved within the detector with the calibration source manipulator. The number of free neutrons created by gamma rays from U and Th breaking apart deuterium nuclei was calculated from measurements of U, Th decay chain elements in the heavy water and ordinary water volumes of the detector as well as smaller contributions from the known radioactivity of other detector materials. The amount of U and Th decay chain elements in the water volumes was determined by direct sampling of the recirculated water with manganese-dioxide or hydrous-titanium-oxide loaded filters and also by analysis of the U and Th events observed in lower energy regions, including differentiation between these elements using the isotropy of the light patterns on the detector. The contributions for Cerenkov light events and neutrons from gammas breaking up deuterium were respectively 8% and 12% of the total number of neutrinos observed by the NC reaction and the total combined systematic uncertainty in that quantity was only 4%.

A hypothesis test was made for the assumption that electron neutrinos were not changing their flavor before reaching the SNO detector. The test used the data shown in Fig. 8, together with the additional information obtainable for each neutrino interaction, particularly the inferred direction and the location within the heavy water volume. The hypothesis of no neutrino flavor change was ruled out with a combined statistical and systematic accuracy of 5.3 standard deviations, corresponding to less than one in $10 \times 10^6$ chance that there is no flavor change. The best fit fluxes of electron neutrinos and the combined muon and tau neutrino flavors inferred from the data, assuming no distortion of the energy distribution of $^8$B electron neutrinos, were (in units of $10^6$ neutrinos per square cm per second)

$$\phi_e = 1.76^{+0.05}_{-0.05}(\mathrm{stat})^{+0.09}_{-0.09}(\mathrm{syst}),$$
$$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}\,(\mathrm{stat})^{+0.48}_{-0.45}\,(\mathrm{syst}).$$

This “best fit” implied that about two-thirds of the electron neutrinos produced in the core of the Sun had changed into other active flavors before reaching the SNO detector.

More detailed scientific discussion of these results is contained in the two SNO papers published in 2002 (Ahmad *et al.*, 2002a, 2002b). These results were consistent with a previous SNO paper in 2001 (Ahmad *et al.*, 2001) where data for $^8$B neutrinos detected via the CC reaction in SNO were compared with results from SuperKamiokande for $^8$B solar neutrinos detected by the ES reaction in light water. This comparison provided evidence for violation of the no flavor change hypothesis with 3.3 standard deviation significance.

The results for Phase 2 of the experiment, with 2 tons of NaCl dissolved in the heavy water are shown in Fig. 9. Comparison with Fig. 8 shows that the contribution of events from the NC reaction has increased due to the increase in detection efficiency for free neutrons from 14% to 40%. In addition, the difference in the isotopy of the light emission between NC and CC events was used as an additional means to separate the events from the two reactions, providing additional improvement in accuracy.

The results for Phase 2 (Ahmed *et al.*, 2004) are consistent with and more accurate than those from Phase 1, with a significant improvement in the accuracy of the NC measurement of the total flux of $^8$B neutrinos. In addition, the separation of NC and CC events on the basis of the isotropy of light emission allowed a separate extraction of the shape of the spectrum of electron neutrinos via the CC detection reaction. The observed shape was consistent with the expected

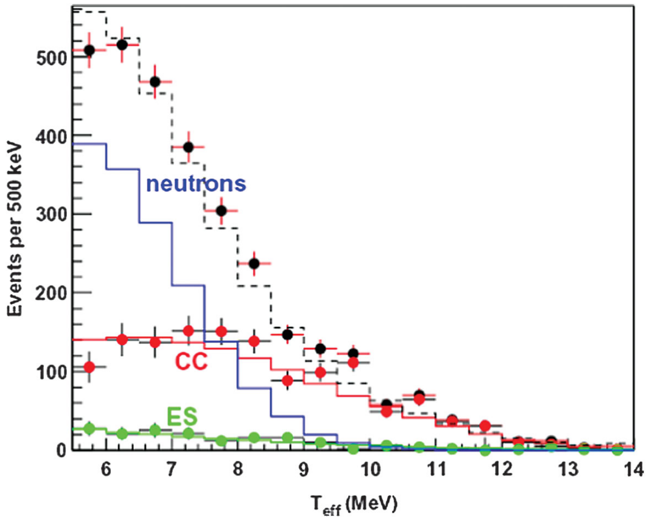

FIG. 9. Data from Phase 2 showing the number of events vs the effective kinetic energy for an electron.

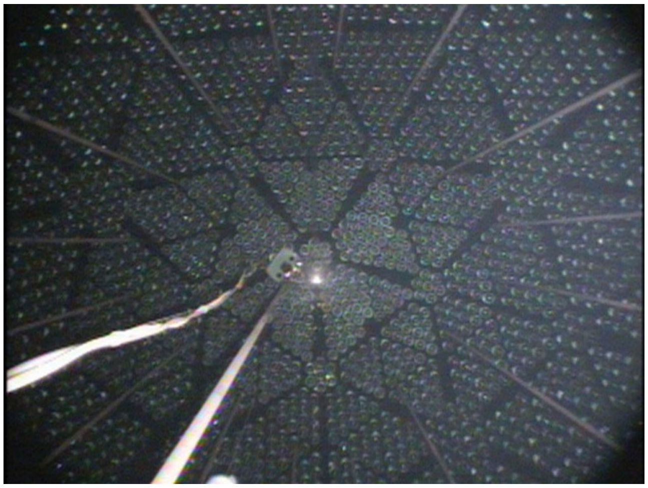

FIG. 10. A remotely controlled submarine installing one member of the array of $^3$He-filled neutron detectors for Phase 3 of the SNO experiment.

shape for neutrinos from $^8$B decay in the Sun, consistent with the assumption made to extract the "best fit" values for neutrino fluxes in the Phase 1 analysis. The hypothesis of no neutrino oscillation was now excluded with greater than 7 standard deviations or one in $400 \times 10^9$. The total flux of all neutrino flavors was defined with substantially improved accuracy and found to be in excellent agreement with the solar model calculations of Bahcall and others.

In Phase 3 of the experiment, an array of 400 m of ultralow background $^3$He-filled neutron detectors was installed in the heavy water volume using a remotely controlled submarine (Amsbaugh *et al.*, 2007). Figure 10 shows the submarine being used to install one of the final neutron detectors. You may notice that the submarine is a dull green color, not the first choice for anyone with a bit of whimsy in their soul, as most scientists do. Of course, our first choice was a yellow submarine and that was the original color. However, as luck would have it, the yellow paint was much too radioactive for us to consider using it and so we had to strip it off and be satisfied with the prosaic green color shown. This is just one example of the detailed process that we went through for many of the materials used in the detector to achieve our stringent radioactivity requirements and also of the surprises that you sometimes have to deal with in a complex project like this.

The neutron detectors were used to make further measurements of the CC and NC reactions with completely different systematic uncertainties from the first two phases. The results (Aharmim *et al.*, 2008) of Phase 3 were also in agreement within errors with the previous results from Phases 1 and 2, increasing the accuracy of the overall result and providing added confidence in the clear separation of CC and NC events. The analyses of SNO data through the three phases of the experiment were carried out with several approaches applied to "blind" the final result for those performing the analysis until all of the parameters to be used had been fully defined.

A final combined analysis of the three phases was obtained with the following result for the ratio of the fluxes of electron neutrinos to all neutrino flavors: $0.317 \pm 0.016$ (statistical) $\pm 0.009$ (systematic). This final result (Aharmim *et al.*, 2013) shows clearly that over two-thirds of the electron neutrinos have changed into other flavors before reaching the SNO detector. The total observed flux of neutrinos from $^8$B decay in the Sun was determined to be $5.25 \pm 0.16$ (statistical) $+0.11 - 0.13$ (systematic) million neutrinos per square cm per second. This is in agreement with and more accurate than calculations of the $^8$B electron neutrino flux produced in the Sun (Serenelli *et al.*, 2009). The accuracy of this measurement is being used to refine models of the Sun (Lopes and Turck-Chieze, 2013), in combination with many other observations, including helioseismology.

## VI. COMPARING SNO RESULTS WITH OTHER SOLAR NEUTRINO MEASUREMENTS

Following Davis's pioneering measurements of solar neutrinos using the interaction of electron neutrinos with chlorine (Bahcall, Bahcall, and Shaviv, 1968; Davis, Harmer, and Hoffman, 1968; Cleveland *et al.*, 1998), and prior to the SNO results, several other experiments observed solar neutrinos with exclusive sensitivity to electron neutrinos (gallium-based radiochemical detectors) [(Abdurashitov, 2009, contains combined analysis with the following references: Altmann (2005) and Kaether (2007)] or predominant sensitivity to electron neutrinos through the use of the ES reaction on electrons in light water (Kamiokande and SuperKamiokande detectors) (Abe *et al.*, 2011b). The thresholds for neutrino detection are indicated in Fig. 11 which shows the calculated fluxes from various $pp$ cycle reactions in the Sun. The results from these other measurements of solar neutrino flux are shown graphically in Fig. 12 where it is apparent that the measurements are factors of 2 or 3 lower than the expectations from the solar model calculations.

Also shown in Fig. 12 are the results from the SNO measurements for the three phases, indicating the agreement between the three sets of SNO measurements. The total neutrino flux is seen to be in good agreement with solar

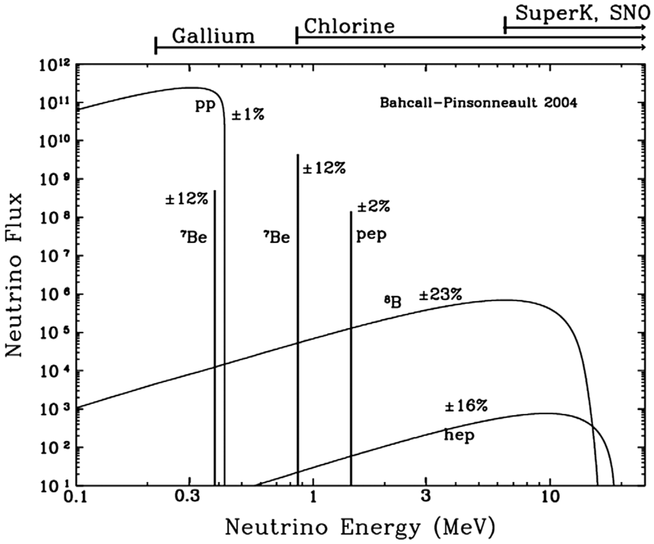

FIG. 11. Calculations (Bahcall and Pinsonneault, 2004) of fluxes of solar neutrinos arising from the set of reactions in the $pp$ cycle shown in Fig. 1. Also shown at the top are thresholds for electron neutrino detection in experiments using chlorine, gallium and light and heavy water as discussed in the text.

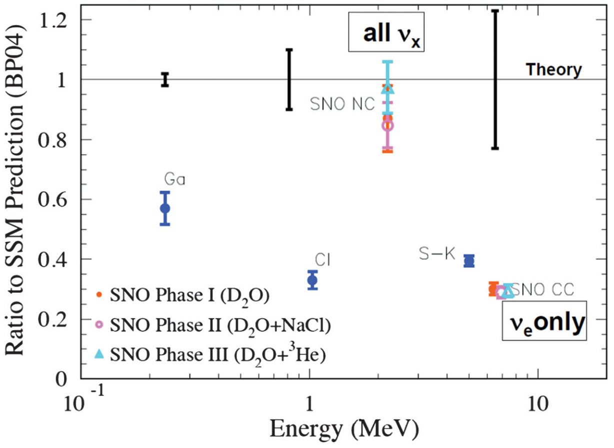

FIG. 12. Ratios of measurements of solar neutrino fluxes to calculations of electron neutrino fluxes in the core of the Sun using the Standard Solar Model (SSM) (Bahcall and Pinsonneault, 2004).

models and the observed electron neutrino flux is about a factor of 3 lower than solar model predictions due to neutrino flavor change. Note also that the difference between the ratio plotted for the SuperKamiokande (SK) experiment and the SNO CC measurements is primarily due to the fact that the ES reaction measurement in SK has some sensitivity to all neutrino flavors as used in Ahmad *et al.* (2001) to extract the total neutrino flux with more limited sensitivity.

## VII. NEUTRINO OSCILLATIONS AND FLAVOR CHANGE

The exhibition of flavor change and oscillation by neutrinos implies that they have a nonzero mass. If they had zero mass as predicted by the Standard Model of elementary particles then they would be traveling at the speed of light and would not have a measure of time in their frame of reference by which to define the process of oscillation. The presently accepted model for neutrino oscillation is based on work by Maki, Nakagawa, and Sakata (1962) and the work of Pontecorvo (1958) and Gribov and Pontecorvo (1969) wherein the quantum mechanical states of flavor generated when a neutrino is created can be expressed as superpositions of mass states as shown schematically in Fig. 13. As the originally pure flavor states travel through space there are changes in the descriptions of the flavor states in terms of the mass components. Then when a measurement is made, the neutrino state will look partly like the mass composition of an electron neutrino, partly like a muon neutrino and partly like a tau neutrino. This determines the fraction of events that are observed in measurements that are specific to these flavors.

For solar neutrinos, there is another effect adding to this process that was identified by Mikheyev and Smirnov (1978), extending ideas of Wolfenstein (1978) (referred to as the MSW effect). As the electron neutrinos pass through dense parts of the Sun containing large numbers of electrons, the MSW effect can change the oscillation process. For $^8$B electron neutrinos originating in the solar core, the MSW effect changes them to a pure mass 2 state and they then stay in that state until detected on Earth. This provides the observed fractions of flavors in the SNO results. The determination that this effect is occurring actually arises from detailed calculations of neutrino oscillation and the MSW effect in the Sun, using predicted fluxes from solar models and the results from the chlorine, gallium, ordinary water and heavy water measurements, including the SNO results and results from the oscillation of reactor antineutrinos on Earth (Abe *et al.*, 2011a). For more detail see, for example, Aharmim *et al.* (2013). The MSW effect in the Sun also determines that mass 2 is larger than mass 1.

## VIII. FUTURE MEASUREMENTS

Since the initial results from the SuperKamiokande and SNO experiments, there have been many further neutrino detection experiments that have helped to determine the properties of neutrinos and of neutrino oscillations. There are a number of questions left to be answered about neutrino properties and experiments are underway or being planned to answer these questions.

The SNO detector itself is undergoing a conversion to a new experiment known as SNO+ which will seek to observe a rare radioactive process known as neutrinoless double beta decay for tellurium nuclei dissolved in a liquid scintillator that will replace the heavy water that has been removed from the detector. If this rare radioactivity is

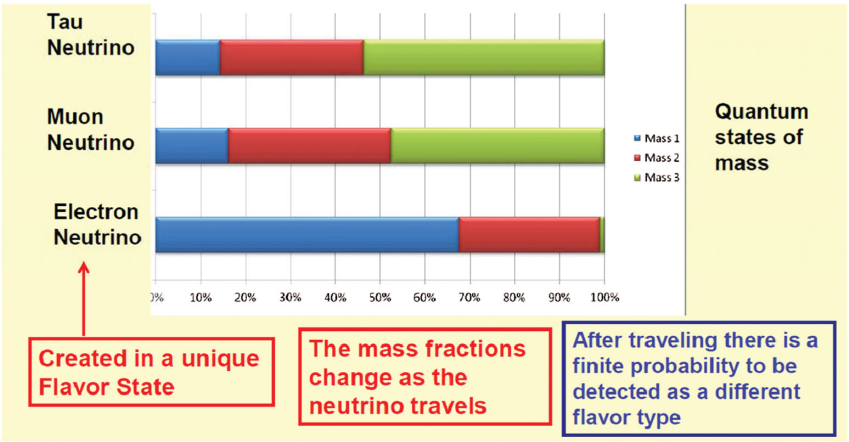

FIG. 13. Schematic description of neutrino oscillations.

observed it will confirm that neutrinos are their own antiparticles (known as Majorana particles) and the absolute mass of neutrino flavors can be observed. At present, the oscillation measurements have only determined the differences in mass of the three active mass flavors. The SNO+ detector is also planning to make measurements of lower energy solar neutrinos as well as neutrinos from the Earth and nuclear reactors and will search for neutrinos from supernovae in our Galaxy.

In addition to this future experiment the laboratory was enlarged under the Directorship of Professor David Sinclair to create SNOLAB and house a number of other experiments that presently include direct searches for dark matter particles and neutrinos from supernovae. The total excavated volume of the new laboratory is about 3 times the volume of the original SNO research area and cavity and the whole laboratory is maintained at Class 2000 air quality or better to control local radioactivity. For more details see www.snolab.ca.

## ACKNOWLEDGMENTS

In conclusion I would like to express my sincere thanks to the large number of collaborators who contributed to the success of the SNO project. The full set of authors on the SNO scientific papers are as follows: *263 SNO Physics Paper Authors*: Adam Cox, Aksel L. Hallin, Alain Bellerive, Alan Smith, Alan Poon, Alexander Wright, Allan Myers, Alysia Marino, André Krüger, André Roberge, Andre Krumins, Andrew Ferraris, Andrew Hime, Anett Schülke, Anthony Noble, Araz Hamian, Arthur McDonald, Aubra Anthony, Azriel Goldschmidt, Barry Robertson, Bassam Aharmim, Bei Cai, Benjamin Monreal, Bernard Nickel, Berta Beltran, Bhaskar Sur, Blair Jamieson, Brandon Wall, Brent VanDevender, Brian Morissette, Bruce Cleveland, Bryan Fulsom, Bryce Moffat, Carsten Krauss, Catherine Mifflin, Charles Currat, Charles Duba, Charlotte Sims, Christian Nally, Christian Ouellet, Christine Kraus, Christopher Kyba, Christopher Howard, Christopher Jillings, Christopher Tunnell, Christopher Waltham, Clarence Virtue, Colin Okada, Darren Grant, David Anglin, David Sinclair, David Waller, David Wark, Davis Earle, Diane Reitzner, Dimpal Chauhan, Doug Hallman, Douglas Cowen, Douglas McDonald, Duncan Hepburn, Ed Frank, Edward Clifford, Michael Dragowsky, Emmanuel Bonvin, Eric Norman, Erik Saettler, Etienne Rollin, Eugene Guillian, Eugene Beier, Fabrice Fleurot, Feng Zhang, Ferenc Dalnoki-Veress, Fraser Duncan, Gabriel D. Orebi Gann, Geoffrey Miller, George Doucas, George Ewan, Gerhard Bühler, Gersende Prior, Gordana Tešić, Gordon McGregor, Gregory Harper, Guy Jonkmans, Gwen Milton, Hadi Fergani, Hamish Robertson, Hans Bichsel, Hans Mes, Hardy Seifert, Hay Boon Mak, Heidi Munn, Helen M. O'Keeffe, Hendrick Labranche, Henry Lee, Hok Seum Wan Chan Tseung, Huaizhang Deng, Hugh Evans, Hui-Siong Ng, Ian Lawson, Ilan Levine, Ira Blevis, Jacques Farine, James Cameron, James Hall, James Loach, James Leslie, Jaret Heise, Jason Detwiler, Jason Hewett, Jason Pun, Jason Goon, Jeanne Wilson, Jeffrey Secrest, Jeremy Lyon, Jerry Wilhelmy, Jessica Dunmore, Jian-Xiong Wang, Jimmy Law, Jocelyn Monroe, John Amsbaugh, John Boger, John Orrell, John Simpson, John Wilkerson, Jon Hykawy, Jose Maneira, Joseph Formaggio, Joseph Banar, Joseph Germani, Joshua Klein, Juergen Wendland, Kai Zuber, Kara Keeter, Kareem Kazkaz, Karsten Heeger, Katherine Frame, Kathryn Schaffer, Keith Rielage, Kennneth McFarlane, Kevin Graham, Kevin Lesko, Kevin McBryde, Khalil Boudjemline, Klaus Kirch, Laura Kormos, Laura Stonehill, Laurel Sinclair, Louise Heelan, Malcolm Fowler, Manuel Anaya, Marc Bergevin, Marcus Thomson, Maria Isaac, Marie DiMarco, Mark Boulay, Mark Chen, Mark Howe, Mark Kos, Mark Neubauer, Martin Moorhead, Masa Omori, Melin Huang, Melissa Jerkins, Michael Bowler, Michael Browne, Michael Lay, Michael Lowry, Michael Miller, Michael Thorman, Michal Shatkay, Mike Schwendener, Miles Smith, Minfang Yeh, Miriam Diamond, Mitchell Newcomer, Monica Dunford, Morley O'Neill, Mort Bercovitch, Myung Chol Chon, Naeem Ahmed, Nathaniel Tagg, Neil McCauley, Nicholas Jelley, Nicholas West, Nikolai Starinsky, Nikolai Tolich, Noah Oblath, Noel Gagnon, Nuno Barros, Olivier Simard, Patrick Tsang, Paul Keener, Peter Wittich, Peter Doe, Peter Watson, Peter Skensved, Peter Thornewell, Philip Harvey, Pierre Luc Drouin, Pillalamarr Jagam, Ranpal Dosanjh, Reda Tafirout, Reena Meijer Drees, Reyco Henning, Richard Allen, Richard Ford, Richard Helmer, Richard Hemingway, Richard Kouzes, Richard Hahn, Richard Lange, Richard Ott, Richard Taplin, Richard Van Berg, Richard Van de Water, Rizwan Haq, Robert Black, Robert Boardman, Robert Stokstad, Robert Heaton, Robert Komar, Robin Ollerhead, Rushdy Ahmad, Ryan MacLellan, Ryan Martin, Ryuta Hazama, Salvador Gil, Sarah Rosendahl, Scott Oser, Sean McGee, Shahnoor Habib, Sherry Majerus, Simon Peeters, Stanley Seibert, Steffon Luoma, Steven Elliott, Steven Biller, Steven Brice, Teresa Spreitzer, Thomas Andersen, Thomas J. Radcliffe, Thomas J. Bowles, Thomas Kutter, Thomas Sonley, Thomas Steiger, Timothy Van Wechel, Tom Burritt, Tudor Costin, Tyron Tsui, Vadim Rusu, Vladimir Novikov, Walter Davidson, William Frati, William Handler, William Heintzelman, William Locke, William McLatchie, Xin Chen, Xin Dai, Yaroslav Tserkovnyak, Yasuo Takeuchi, Yekaterina Opachich, and Yuen-Dat Chan. *And 11 who have passed away*: Herbert Chen, John C. Barton, John Cowan, Andre Hamer, Clifford Hargrove, Barry C. Knox, Jan Wouters, Peter Trent, Robert Storey, Keith Rowley and Neil Tanner. I was truly privileged to be the Director of a project with such a talented, dedicated, cooperative and hard-working group of scientists. I also want to acknowledge the very talented and hard-working group of engineers, technical people, construction, operations and administrative personnel for SNO. Our success was truly a team effort and was strongly supported by the spouses and families of all these people. I am honored to have had the opportunity to work with these people and am very grateful for all their contributions. I would also like to thank all of the funding agencies and institutional administrations who have supported us throughout the many years it took to complete the experiment. A special word of thanks goes to Atomic Energy of Canada Limited (AECL) for the loan of the heavy water and to INCO/Vale for their continual support throughout SNO and now continuing with SNOLAB.

## REFERENCES

Abdurashitov, J. N., *et al.* (SAGE Collaboration), 2009, Phys. Rev. C **80**, 015807 contains combined analysis with the following references: M. Altmann, *et al.* (GNO Collaboration), 2005, Phys. Lett. B **616**, 174; F. Kaether, 2007, Datenanalyse der Sonnenneutrinoexperiments Gallex, Ph.D. thesis, Heidelberg.

Abe, K., *et al.* (Kamland Collaboration), 2011a, Phys. Rev. C **84**, 035804.

Abe, K., *et al.* (Super-Kamiokande Collaboration), 2011b, Phys. Rev. D **83**, 052010.

Aharmim, B., *et al.* (SNO Collaboration), 2008, Phys. Rev. Lett. **101**, 111301.

Aharmim, B., *et al.* (SNO Collaboration), 2013, Phys. Rev. C **88**, 025501.

Ahmad, Q. R., *et al.* (SNO Collaboration), 2002a, Phys. Rev. Lett. **89**, 011301.

Ahmad, Q. R., *et al.* (SNO Collaboration), 2002b, Phys. Rev. Lett. **89**, 011302.

Ahmad, Q. R., *et al.* (SNO Collaboration), 2001, Phys. Rev. Lett. **87**, 071301.

Ahmed, S. N., *et al.* (SNO Collaboration), 2004, Phys. Rev. Lett. **92**, 181301.

Amsbaugh, J., *et al.*, 2007, Nucl. Instrum. Methods Phys. Res., Sect. A **579**, 1054.

Bahcall, J. N., N. A. Bahcall, and G. Shaviv, 1968, Phys. Rev. Lett. **20**, 1209.

Bahcall, J. N., and M. H. Pinsonneault, 2004, Phys. Rev. Lett. **92**, 121301.

Boger, J., *et al.* (SNO Collaboration), 2000, Nucl. Instrum. Methods Phys. Res., Sect. A **449**, 172.

Chen, H. H., 1985, Phys. Rev. Lett. **55**, 1534.

Cleveland, B. T., *et al.*, 1998, Astrophys. J. **496**, 505.

Davis, Jr., R., D. S. Harmer, and K. C. Hoffman, 1968, Phys. Rev. Lett. **20**, 1205.

Dragowsky, M. R., *et al.*, 2002, Nucl. Instrum. Methods Phys. Res., Sect. A **481**, 284.

Gribov, V., and B. Pontecorvo, 1969, Phys. Lett. B **28**, 493.

Lopes, I., and S. Turck-Chieze, 2013, Astrophys. J. **765**, 14.

Maki, Z., M. Nakagawa, and S. Sakata, 1962, Prog. Theor. Phys. **28**, 870.

Mikheyev, S., and A. Smirnov, 1985, Sov. J. Nucl. Phys. **42**, 913.

Pontecorvo, B., 1958, Sov. Phys. JETP **7**, 172.

Serenelli, A. M., S. Basu, J. W. Ferguson, and M. Asplund, 2009, Astrophys. J. Lett. **705**, L123.

Sinclair, D., A. L. Carter, D. Kessler, E. D. Earle, P. Jagam, J. J. Simpson, R. C. Allen, H. H. Chen, P. J. Doe, E. D. Hallman, W. F. Davidson, A. B. McDonald, R. S. Storey, G. T. Ewan, H. B. Mak, and B. C. Robertson, 1986, Nuovo Cimento Soc. Ital. Fis., C **9**, 308.

Wolfenstein, L., 1978, Phys. Rev. D **17**, 2369.