The Sudbury Neutrino Observatory: observation of flavor change for solar neutrinos

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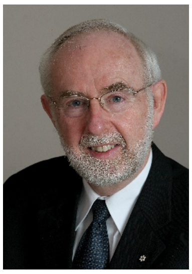

In 1984, the original 16 members of the Sudbury Neutrino Observatory (SNO) came together to discuss the proposal put forward by Herb Chen to resolve the discrepancy between Ray Davis measurements and solar neutrino calculations by John Bahcall. The proposal was to use heavy water to measure the charged current reaction on deuterium sensitive only to electron neutrinos and simultaneously the neutral current reaction sensitive equally to all active neutrino types. The comparison of these reactions could provide an indication of neutrino flavor change without reference to solar model calculations and also test those models directly through the second reaction. In this paper the development of the SNO project is described, culminating in results presented in 2001/02 that showed clearly that ^8B solar neutrinos have changed flavor before reaching the Earth. For the initial SNO results a comparison was made between the charged current reaction in SNO and the data for elastic scattering from electrons obtained by Super-Kamiokande and for the second results, a more accurate (5.3 sigma) determination of flavour change was made using the neutral current reaction in SNO itself.
The beautiful measurements made by the KamLAND experiment will also be described, where clear indications of electron anti-neutrino oscillations were obtained using the flux from many reactors in Japan. These results showed oscillations for electron neutrinos with the same mass 1 and 2 parameter set appropriate for solar neutrinos, where the Mikheyev-Smirnov-Wolfenstein (MSW) effect in the Sun influences the oscillations for ^8B neutrinos.
Subsequent measurements of solar neutrinos by the Borexino experiment will also be described where fluxes of ^7Be, *pep* and *pp* neutrinos have been reported using techniques that created extremely low radioactive backgrounds. These results have been valuable as verification of the energy dependence of the MSW effect for solar neutrinos.

1 Introduction

In 1984, measurements begun by Ray Davis in 1968 [1] continued to show a flux of electron neutrinos from the Sun that was a factor of 3 smaller than the calculations of John Bahcall and co-workers [2]. There were several possibilities to explain this observation, including incomplete or incorrect solar calculations, experimental problems or perhaps change of flavor for electron neutrinos in transit from the solar core to the Earth, as suggested by Pontecorvo and Gribov [3,4].

Herb Chen, a professor at the University of California at Irvine, contacted his friend Cliff Hargrove at the National Research Council in Ottawa in 1984 and inquired if it might be possible to borrow 4000 tonnes of heavy water from Canada's reserves to make a measurement of solar neutrinos that would show unambiguously whether solar electron neutrinos were changing their flavor. With deuterium, it was known that one could make a measurement of two types, one specific to electron neutrinos and another sensitive equally to all three active neutrino flavors. Comparing these two reactions would provide an unambiguous measure of neutrino flavor composition and the second reaction would enable a measure of the total flux of active neutrinos from the Sun regardless of whether flavor change was occurring [5]. Cliff's enquiries with senior executives at Atomic Energy of Canada Limited (AECL) elicited a response that the loan of 1000 tonnes might be considered (value $300 million Canadian dollars). In the preceding year, enquiries had been undertaken by George Ewan, a Professor at Queen's University and others to see if there might be an underground location in Canada suitable for low-background physics measurements. A potentially positive response was obtained from International Nickel Company (INCO) for a location in one of their very deep nickel mines near Sudbury, Ontario.

In 1984, 16 original collaboration members came together and formed the Sudbury Neutrino Observatory Collaboration [6] with Herb Chen and George Ewan as US and Canadian co-spokesmen. The collaboration then set about the design and sensitivity calculations for a detector, as well as investigating a specific underground location more extensively. In 1985, David Sinclair brought a UK group into the collaboration and became UK co-spokesman. Figure 1 shows a picture taken at a collaboration meeting at Chalk River Nuclear Laboratories in the fall of 1986 with nearly all of the original collaborators [6] included.

Figure 1 – The picture shows some of the SNO 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, Robert Storey.

Unfortunately, this was the last collaboration meeting that Herb Chen could attend, as he passed away from leukemia about a year after this photo was taken. The collaboration reveres his memory and carried on the development of the detector to build on his pioneering initiative. Art McDonald of Princeton University became the US spokesman, followed in the next several years by Gene Beier of the University of Pennsylvania and Hamish Robertson of Los Alamos (and later the University of Washington) as US co-spokesmen as Art moved to Queen's University, Kingston, Canada in 1989 to become the SNO Project Director in anticipation of George Ewan's impending retirement. In 1990, project funding was obtained from sources in Canada (70 %) the US (25%) and the UK (5%) and excavation began shortly thereafter.

2 Detection Processes

With 1000 tonnes of heavy water (>99.92 % D_2O) in the SNO detector, it was possible to observe three separate interactions of neutrinos:

$\nu_e + d \rightarrow e^- + p + p - 1.44\,MeV$ (Charged Current (CC) reaction)

$\nu_x + d \rightarrow \nu_x + n + p - 2.2\,MeV$ (Neutral Current (NC) reaction)

$\nu_x + e^- \rightarrow \nu_x + e^-$ (Elastic Scattering (ES) reaction),

where x = electron, mu or tau.

The first (CC) reaction is sensitive only to electron flavor neutrinos. Detection is via light from the energetic electron that creates a cone of light in the detector via the Cerenkov process. The second (NC) reaction is equally sensitive to all flavors of neutrino. The free neutron was the signature of this reaction and was observed differently 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. It was important to maintain a very low level of radioactivity in the detector as any gamma with energy greater than 2.2 MeV can photo-disintegrate deuterium, producing a free neutron. Radioactivity was carefully controlled and measured so that this background was much smaller than the signal from solar neutrinos via the NC reaction and contributed a small systematic error.

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

There were three phases for the SNO experiment, particularly distinguished by the technique to measure the NC reaction. The first phase (Nov. 1999 to May 2001) used pure heavy water 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. The gamma ray produced Compton-scattered electrons that were observed via Cerenkov light. For the second phase (July 2001 to Sep. 2003), about 2 tonnes of ultra-pure $NaCl$ salt was added to the heavy water. The free neutron from the NC reaction predominantly captured in the Cl, producing a cascade of gamma rays with energies summing to about 8.6 MeV. The neutron capture efficiency was increased from 14% to 40% and the gamma cascade created an isotropic distribution of light so that the events from the NC reaction could be separated statistically from the cone-shaped Cerenkov light emission events from the CC reaction. For the third phase (Nov. 2004 to Nov. 2006), an independent array of ^3He-filled neutron detectors [7] was inserted into the heavy water, thereby enabling an independent measurement of free neutrons from the NC reaction.

3 The SNO detector

The SNO detector is illustrated in Figure 2.

The detector [8] is situated in a barrel-shaped cavity, 34 m high and 22 m diameter at the equator, situated 2 km underground in Vale's (formerly INCO's) Creighton mine, an active

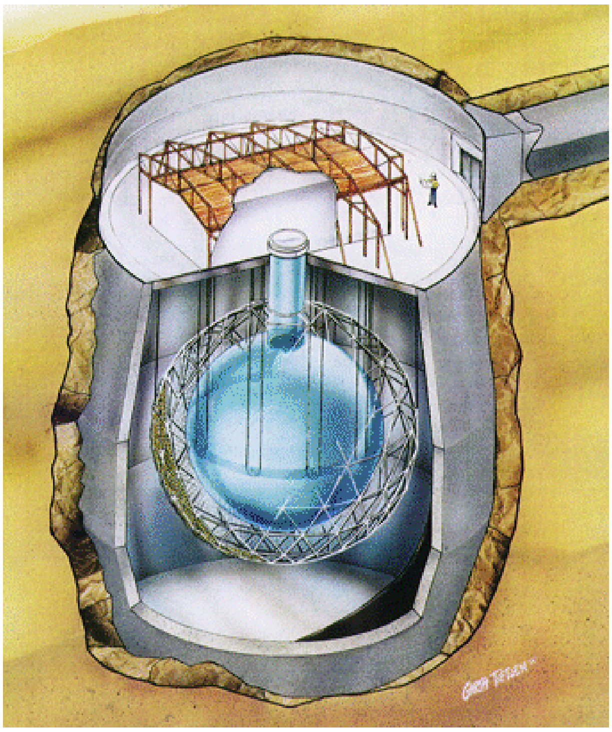

Figure 2 – Artist's conception of the SNO detector.

nickel mine near Sudbury, Ontario, Canada. The cavity is lined with Urylon plastic, applied in many layers alternating between gray and white to identify and cover pin-holes, giving a total thickness of about 75 mm, making it water-tight and reducing radon permeation by a factor of about 10^5. The central volume of 1000 tonnes of heavy water is contained within a transparent acrylic sphere, 12 m in diameter and 5.6 cm thick, fabricated from 120 pieces sized to be transported in the mine elevator and bonded together in situ. Figure 3 shows the bonding of the final row of the sphere. Also evident in the figure are some of the 9438 20-cm diameter photomultipliers (PMTs) used for light detection. Each PMT was equipped with a conical reflector that enhanced the light collection.

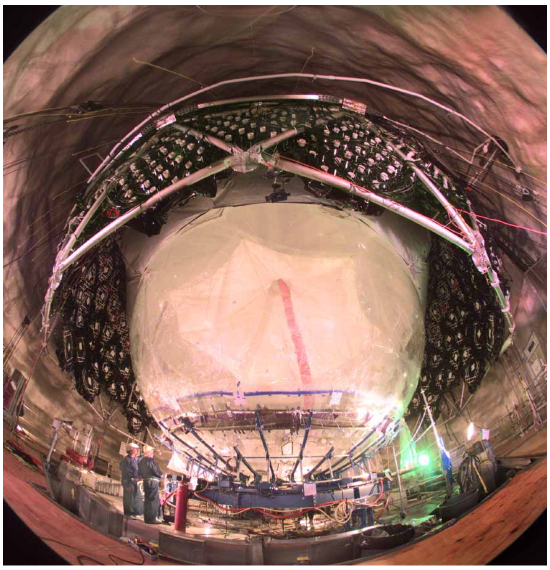

Figure 3 – Picture of the SNO detector as construction of the acrylic vessel was nearing completion.

The entire cavity volume outside the acrylic vessel was filled with about 7000 tonnes of ultra-pure light water, providing thermalization and shielding from neutrons generated by (α, n) reactions from radioactivity in the surrounding rock and in the PMTs and supporting structure. All materials used in the detector were subjected to stringent screening for inherent radioactivity and detailed simulations were made of the expected signals and backgrounds to influence the design of the detector. After the Urylon coating of the cavity walls had been completed, the entire detector region was turned into a Class 2000 clean room and all personnel took showers and changed into lint-free clothing for the construction process. The mine air in the cavity was highly filtered by HEPA filters and thereby it was possible to restrict the mine dust on detector components to less that 1 $\mu g/cm^2$, as required by the background modelling.

Two extensive water purification and monitoring systems were constructed for the heavy and light water volumes [8]. The principal concern was the removal of elements in the ^{232}Th and ^{238}U decay chains, including particularly ^{222}Rn. To strongly reduce the radon, the light water was de-gassed and re-gassed with low-radon nitrogen obtained from boil-off of liquid nitrogen. To maintain the low radon levels in the water volumes, another stream of boil-off nitrogen was flowed continually over the surface of the water through piping systems that contained large buffer tanks to enable the flow of low radioactivity nitrogen to be maintained during fluctuations in the mine pressure created occasionally by the ventilation systems. Systems were developed to assay the residual radioactivity in the heavy and light water with good accuracy. Filters loaded with manganese dioxide or hydrous titanium oxide were used to extract radium and thorium from the ^{238}U and ^{232}Th decay chains and measure the extracted isotopes [8]. Systems for quantitative removal of ^{222}Rn by degassing were also applied to the water to obtain independent measures of this isotope. By analysis of the isotropy of the low energy events it was possible to obtain further identification of background from the U and Th chains. In the center of the detector there was less than 1 radioactive decay per day per tonne of heavy water from radioactivity from the ^{238}U and ^{232}Th chains. Overall, it was possible to restrict the systematic uncertainty on the contribution to the NC signal from radioactive background to less than 4%.

The second phase of the project involved the addition to the heavy water of about 2 tonnes of $NaCl$ that was subsequently removed by a reverse osmosis system. The final phase involved the installation of about 400 meters of ^3He-filled proportional counters for the independent detection of neutrons. These detectors were fabricated from nickel bodies that had been created from nickel carbide that does not form compounds with U or Th, thereby maintaining the radiopurity [7]. Figure 4 shows an artist's conception of the neutron detector array.

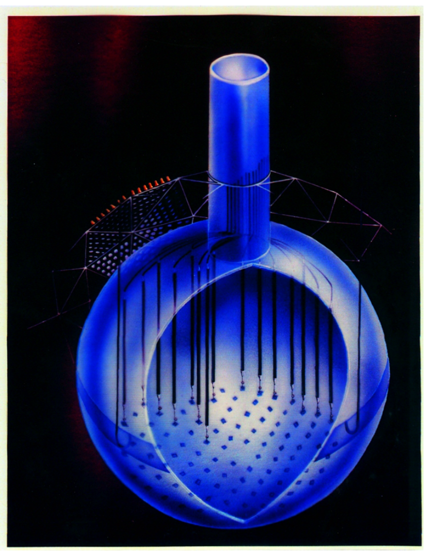

Figure 4 – Artist's conception of the neutron detector array partially installed in the SNO detector.

The neutron detectors were proportional counters using ^3He to detect neutrons by observing the resultant triton and proton signals. They were produced in sections up to 3 m long and 5 cm in diameter that were welded together at the top of the neck of the detector forming lengths up to about 12 meters. These lengths of detector were then "flown" into place in the heavy water using a remotely controlled submarine that attached them to points on the bottom of the acrylic sphere that had been installed during its fabrication. It was found that the video game generation made the best operators and so most if not all of them were less than 25 years old.

4 SNO results

Figure 5 shows data from the first phase of the SNO project with pure heavy water in the acrylic vessel [9,10].

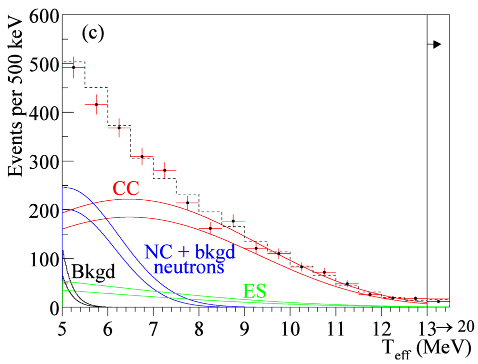

Figure 5 – Data from the first phase of the SNO experiment [10].

The data in Figure 5 comes from the innermost 11 meter diameter of the pure heavy water during 306 days of data accumulation. A very detailed Monte Carlo simulation of the expected pulses from the detector was performed. The detector was accurately calibrated using calibration sources with known energies and distributions of gamma rays, neutrons and electrons. These sources could be moved through about 70% of the volume of the heavy water in two perpendicular planes, providing a detailed mapping of the detector sensitivity. The expected shapes of simulated event data from the CC, NC and ES reactions are shown, assuming no distortion of the spectrum of events from the decay of ^8B in the Sun. The radioactive background shape is extrapolated from the lower energy region.

In the first SNO paper in 2001 [9], data for ^8B neutrinos detected via the CC reaction was compared with results from Super-Kamiokande for ^8B solar neutrinos detected by the ES reaction in light water [11]. This comparison provided evidence for violation of the no flavor change hypothesis with 3.3 standard deviation significance.

For the full data for the first phase, the data of figure 5 was used for a hypothesis test [10] for the assumption that electron neutrinos were not changing their flavor before reaching the SNO detector. 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 million chance that there is no flavor change. This was a clear discovery of neutrino flavor change, independent of questions of spectral distortion or absolute flux.

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 ^8B electron neutrinos as illustrated in figure 5, were (in units of 10^6 neutrinos per square cm per second):

$$\Phi_e = 1.76^{+0.05}_{-0.05}(stat.)^{+0.09}_{-0.09}(syst.)$$
$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(stat.)^{+0.48}_{-0.45}(syst.)$$

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.

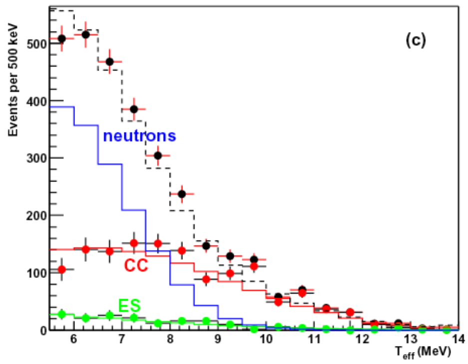

Figure 6 – Data from the second phase of the SNO experiment [12].

Figure 6 shows results from 254.2 days of data collection following the addition of 2 tonnes of $NaCl$ to the heavy water [12]. As can be seen, the addition of salt increased the efficiency for the detection of the neutrons from the NC reaction from 14 to 40% and increased the average energy of emission of gamma rays following the neutron capture. In the salt phase, the NC events were significantly more isotropic than the CC, enabling them to be separated on a statistical basis, thereby defining the magnitude and shape of the CC spectrum which showed no significant spectral distortion from that expected for ^8B neutrinos. The results agreed with those from the first phase and ruled out the null hypothesis for flavor change by more than 7 sigma. They also provided a measure of the total flux of all active neutrinos reaching the Earth from ^8B decay in the Sun with an uncertainty of less than 9%, in good agreement with solar models [15,16].

The results from the third phase were also in excellent agreement with previous phases and added to the accuracy of the results [13]. Pulse shape analysis of the signals from the neutron detector array was used to discriminate between neutron signals and internal alpha particle background in the detectors. An overall joint analysis [14] of all three phases was carried out and provided the following result for the ratio of the fluxes of electron neutrinos to all neutrino flavors: 0.317±0.016 (statistical)±0.009 (systematic). The total observed flux of neutrinos from ^8B decay in the Sun was determined to be: 5.25 ± 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 ^8B electron neutrino flux produced in the Sun [16]. The accuracy of this measurement is being used to refine models of the Sun [see, for example ref. [17]], in combination with many other observations, including helioseismology.

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.

5 Combining SNO with other solar neutrino measurements

Figure 7 shows calculations by Bahcall and Pinsonneault [15] of the fluxes of solar neutrinos, together with thresholds for measurements with chlorine (Homestake) [18], gallium (SAGE, GALLEX, GNO) [19], and water (Super-Kamiokande) [20]. The effective neutrino energy threshold for SNO for the CC reaction was about 7 MeV and for the NC reaction was 2.2 MeV.

Figure 8 shows the ratios of measurements to solar model calculations for SNO and the experiments listed above. It is clear from the figure that neutrino flavor change is the favored solution to what is happening to neutrinos from the Sun. This data, along with other solar and reactor data has been analyzed in many global analyses as discussed by Concha Gonzalez-Garcia in this conference [21]. The formalism used is the PMNS formalism involving massive neutrinos as developed by Pontecorvo [3,4] and Maki, Nakagawa and Sakata [22]. The preferred solution is the so-called Large Mixing Angle (LMA) solution. For solar neutrinos and including interactions in

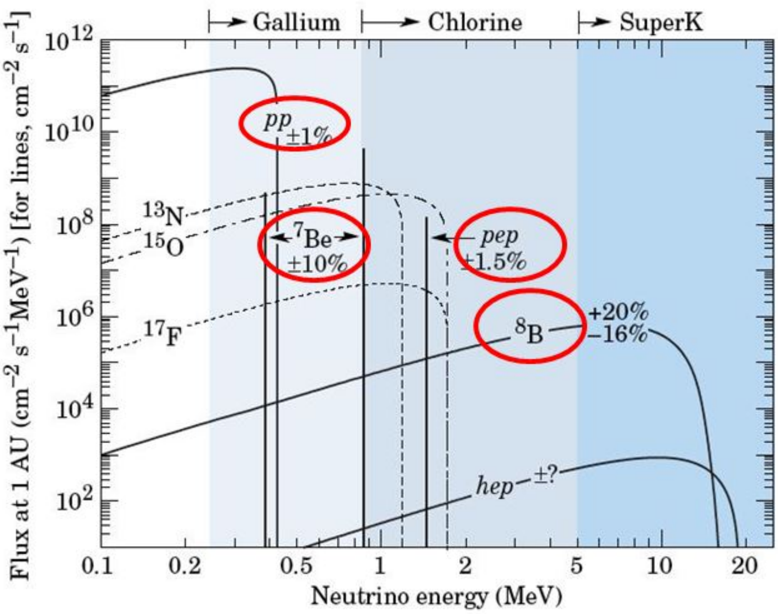

Figure 7 – Calculated electron neutrino fluxes from nuclear reactions in the Sun, using a standard solar model [15].

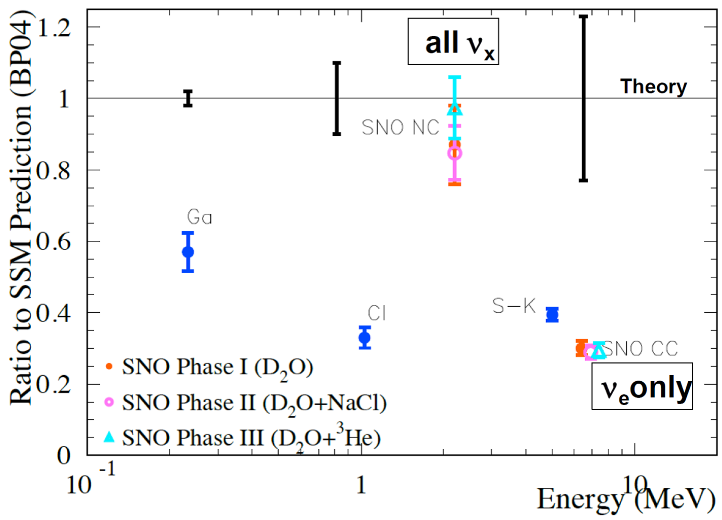

Figure 8 – Ratios of measurements of solar neutrinos [9,10,12,13,14,18,19,20] to solar model calculations [15].

the Earth, the MSW formalism developed by Smirnov, Mikheyev and Wolfenstein (MSW) [23] is important, as described by Alexei Smirnov at this conference [24]. The MSW effect for ^8B electron neutrinos, through interactions with the dense material in the Sun, results in transformation almost completely into a mass 2 state, with no further oscillation before reaching the Earth. The matter interactions in the Sun also define the hierarchy between mass 1 and 2, with mass 2 larger.

6 Further solar neutrino and related measurements

Shortly after the initial SNO results, the KamLAND collaboration, using liquid scintillator in the former Kamiokande detector, clearly measured oscillations of electron anti-neutrinos from an array of reactors in Japan [25]. When analyzed using the PMNS formalism, the results were in agreement with the solar results (including the MSW effect) for similar values of the mass 1-2 mixing parameters for the LMA solution. KamLAND provides excellent accuracy for the difference between mass 1 and mass 2 and the ratio of NC to CC in SNO provides the best accuracy for the 1-2 mixing angle. Much more accurate data obtained from further operation has been reported by the KamLAND collaboration. A clear oscillation pattern has also been established for these measurements [26], as can be seen in Figure 9. They have also reported measurements for ^7Be and ^8B solar neutrinos [27].

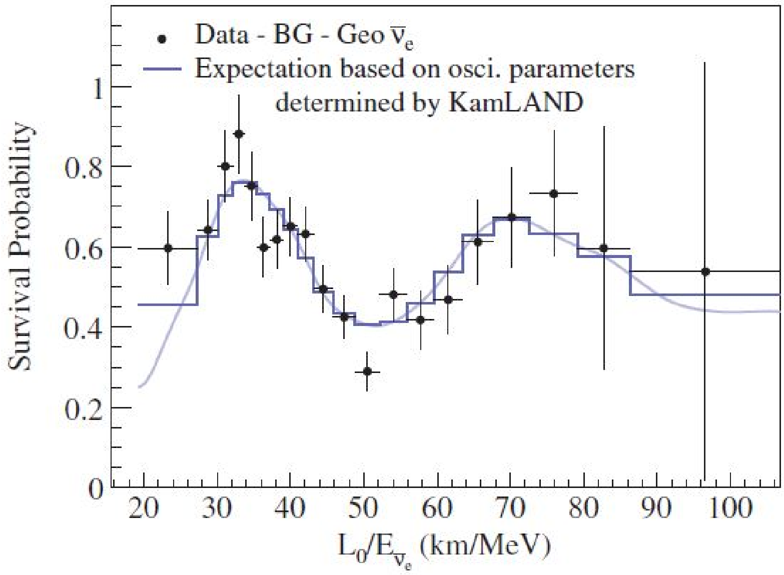

Figure 9 – KamLAND data [26] for the ratio of the background and geo-neutrino-subtracted ν_e spectrum to the expectation for no-oscillation as a function of L_0/E.

Super-Kamiokande has continued to collect data on solar neutrinos as well as the definitive oscillation data for atmospheric neutrinos reported in this conference by Takaaki Kajita [28]. In addition to providing high accuracy for the total rate and spectrum of ^8B solar neutrinos observed via the ES process in water, they have observed a day-night difference with 2.6 sigma significance [29]. They are now shut down to install Gd for improved supernova sensitivity.

The Borexino experiment at the Gran Sasso laboratory has performed a set of measurements [30] for *pp*, *pep*, ^7Be and ^8B solar neutrinos and has provided a limit on CNO neutrinos. This has been accomplished through extensive reduction and monitoring of radioactive backgrounds in the 270 ton liquid scintillator detector and through detector design, including a low-radioactivity thin nylon containment vessel. Figure 10, from a presentation by Michael Wurm in 2018 [31] illustrates the accuracy of the results and the potential for discrimination between solar metallicity values, particularly if a measurement can be made for the CNO neutrinos. The detector has recently been operating with extensive thermal insulation that appears to be reducing the convective transport of ^{210}Po, a background presently limiting the CNO measurement, so there are prospects for a future CNO result.

The SNO+ experiment at SNOLAB [35] has been running for more than a year with pure light water in the acrylic vessel and has begun the process of installing liquid scintillator (linear alkyl benzene: LAB) in preparation for the addition of about 4 tonnes of tellurium to search for neutrino-less double beta decay. There will be some period of operation with sensitivity to solar neutrinos prior to Te addition and potentially in future after a number of years dedicated to double beta decay study. There will be lower cosmogenic background than Borexino (particularly ^{11}C) due to the greater depth. The inherent local radioactive backgrounds in pure LAB will also be observed during this interim period and will determine the potential sensitivity for observation of CNO neutrinos.

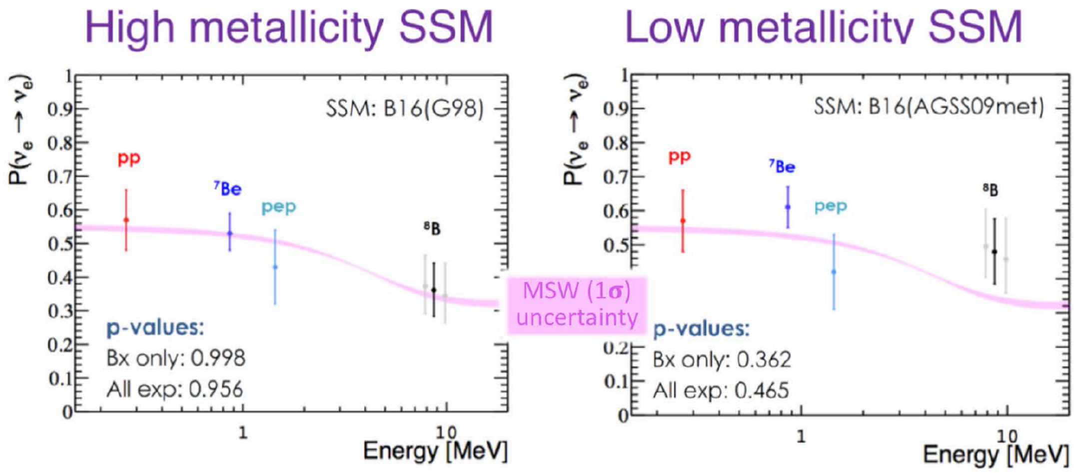

Figure 10 – Experimental results from Borexino for solar neutrinos [30,31] relative to two choices for metallicity in standard solar models [32,33,34]

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