ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
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Solar neutrino experiments were originally conceived as a way to demonstrate that nuclear reactions are responsible for energy generation in stars. When solar neutrinos were first detected, the measured flux was much less than what solar models predicted. The Solar Neutrino Problem thus came to be and it persisted for over thirty years. It is now known that the deficit in solar neutrinos (of electron neutrino flavour) was due to neutrino oscillations and that matter effects are important. Solar neutrino experiments played a key part in these discoveries and in recent developments in neutrino physics. This report summarizes Pontecorvo Neutrino Physics School lectures that explored the physics of solar neutrinos and the experiments that detected them. The lectures also included a look forward to future solar neutrino experiments and their physics goals and these are also discussed here.

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1. NEUTRINOS FROM THE SUN

Fusion of hydrogen into helium takes place in the Sun and proceeds via two processes. The *pp* chain of reactions is the dominant process in stars like our Sun, whereas the CNO cycle becomes more significant for stars that are heavier. Several reactions within these two processes are weak reactions that produce neutrinos (electron neutrino flavour). Important solar neutrinos include those from $p+p \to d+e^+ +\nu_e$, $p+e^- +p \to d+\nu_e$, $^7\mathrm{Be}+e^- \to {}^7\mathrm{Li}+\nu_e$ and from $^8\mathrm{B} \to 2\alpha + e^+ + \nu_e$.

From 1965–1967, Raymond Davis Jr. built what is now called the Chlorine experiment. Davis, along with John Bahcall, had the notion that detecting solar neutrinos would enable one «...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars». Bahcall had created solar models that predicted the flux of solar neutrinos, and those fluxes (the ^{8}B solar neutrinos in particular) were at a level that the Davis Chlorine experiment could detect.

2. CHLORINE EXPERIMENT AND THE SOLAR NEUTRINO PROBLEM

The Chlorine experiment is a radiochemical neutrino detector. The experiment consisted of a tank of 615 t of perchloroethylene C_2Cl_4 located in the

Homestake mine in South Dakota, USA. This tank of chlorinated liquid would be «exposed» to the solar neutrino flux. The charged-current neutrino capture reaction: $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$ has an energy threshold of 0.814 MeV. Solar neutrinos including the abundant ^{7}Be solar neutrinos and the much less abundant, but more energetic, ^{8}B solar neutrinos would contribute to this charged-current neutrino capture process.

^{37}Ar has a half-life of 35 days. After an exposure of roughly two half-lives, the aim of the Davis Chlorine experiment was to sweep these argon atoms from the entire tank volume of perchloroethylene in order to collect the ~ 10 atoms of argon that would have been produced by neutrino reactions. Radiochemistry was used to collect, concentrate and purify the argon atoms. The ^{37}Ar atoms were collected and their electron capture decays were counted in low-background proportional counters.

The Davis Chlorine experiment took exposures and processed runs from 1970–1994. Each run would determine the average solar neutrino flux during that exposure in Solar Neutrino Units (SNU) — one SNU corresponding to one neutrino capture per second per 10^{36} target atoms. A weighted average of all runs gives a final result for the Chlorine experiment of: (2.56 ± 0.23) SNU [1].

Solar models predicted the rate in the Chlorine experiment should be $\sim 7{-}8$ SNU (arising mostly from ^{8}B and ^{7}Be solar neutrinos). The discrepancy between measured and predicted rates gave birth to the «Solar Neutrino Problem». How could this discrepancy be explained? Was there some inefficiency in the Davis experiment that was not understood? Were solar models missing some physics that could lower the predicted fluxes? Were nuclear reaction cross sections understood and measured well enough so as not to introduce errors in the solar model predictions? Or, were new neutrino properties responsible for explaining this apparent deficit? The significance of the Solar Neutrino Problem cannot be overstated. New solar neutrino detectors were built in order to understand and resolve this deficit. Solar neutrinos became the breeding ground of the field of experimental neutrino physics and these experiments ultimately played an important role in uncovering what we now know to be physics beyond the Standard Model.

Experiments that followed the Chlorine experiment can be categorized as: radiochemical, water Čerenkov detectors and liquid scintillator. Each of the experiments that detected solar neutrinos will be discussed briefly.

3. GALLIUM RADIOCHEMICAL EXPERIMENTS

Gallium is an interesting target for solar neutrinos. The neutrino capture reaction: $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$ has a threshold of 0.233 MeV. This is low enough in energy that the abundant, fundamental pp solar neutrinos can contribute to neutrino capture reactions on a target of gallium. The advantage of this (in addition to the very large flux of *pp* solar neutrinos) is that the *pp* reaction in solar models is well constrained by solar observables (i.e., uncertainties in most nuclear astrophysics cross sections do not affect the fundamental flux calculation).

Radiochemistry techniques were developed and utilized to separate ^{71}Ge atoms from gallium; the process efficiency was tuned and measured to be able to extract one germanium atom from $\sim 5 \cdot 10^{29}$ atoms of gallium with 90% efficiency. ^{71}Ge could be collected, transformed into GeH_4 gas, and its electron capture decays (half-life of 11.4 days) counted in low-background proportional counters. Two radiochemical gallium experiments were built, SAGE and Gallex.

SAGE is located in the Baksan Underground Laboratory in the North Caucasus. It consists of 50 t of metallic gallium. SAGE commenced runs (extraction of germanium from the metallic gallium) in 1990 and continues to the present day. The most recent published result from the SAGE experiment finds an average rate of solar neutrino captures of $(65.4^{+3.1}_{-3.0}(\mathrm{stat.})^{+2.6}_{-2.8}(\mathrm{syst.}))$ SNU [2] which can be compared to solar model predicted rates around 120–130 SNU.

Gallex was located in the Gran Sasso Underground Laboratory in Abruzzo, Italy. It consisted of 100 t of gallium chloride solution (30 t of ^{71}Ga). Runs were taken from 1991–1997. The Gallex experiment then continued as the Gallium Neutrino Observatory (GNO) and took runs from 1998–2003. Recently, a reanalysis of Gallex data [3] was completed that utilized pulse shape analysis methods that were used in GNO to reduce background during counting of ^{71}Ge. Cut efficiencies for the procedure had to be calibrated with high statistics (which precluded using this analysis in Gallex originally during the actual running period because of contamination to the low background counters that would only be acceptable after the experiment had concluded). Table 1 contains a summary of Gallex/GNO results, taken from [3].

It can be seen that Gallex/GNO results are in agreement with SAGE results, within experimental error. Both gallium experiments show a clear deficit in their observed neutrino rates compared to solar model predictions. When oscillations are included in the solar model predictions, the predicted gallium rates suppressed by neutrino oscillations agree with the measurements.

Though most aspects of the gallium solar neutrino experiments are understood, a few minor questions are lingering. Both SAGE and Gallex/GNO per-

Table 1. **Summary of solar neutrino results from Gallex/GNO in which the Gallex analysis was recently revised**

Updated Gallex combined, SNU	$73.4^{+6.1}_{-6.0}\,^{+3.7}_{-4.1}$
GNO combined, SNU	$62.9^{+5.5}_{-5.3}\,^{+2.5}_{-2.5}$
New Gallex+GNO combined, SNU	$67.6 \pm 4.0 \pm 3.2$

formed calibrations of their experimental procedures using artificially-created MCi neutrino sources. When all the SAGE and Gallex/GNO calibration runs are taken together, the average rate measured in those experiments is a little lower than the rate predicted from knowing the calibration neutrino source intensities and experimental extraction efficiencies. This discrepancy is almost at the 3 sigma level [4]. A second issue is that Gallex solar neutrino runs (which took place in earlier years) observed a higher flux than in GNO runs. The SAGE experiment observes the same trend — earlier runs have, on average, higher rates than recent runs. Does this suggest any time dependence in the solar neutrino flux on this timescale? Or, is all of this consistent (marginally) within experimental error?

4. SUPER-KAMIOKANDE

Large imaging water Čerenkov detectors were an important development in neutrino physics. Originally built in the 1980s as proton decay experiments, Kamiokande was upgraded (beginning in 1985) to be able to detect ^{8}B solar neutrinos. The first solar neutrino results from Kamiokande came in 1988 and these results confirmed the Chlorine experiment's deficit of solar neutrinos (of electron neutrino flavour). In order to further develop this detection approach a massive detector called Super-Kamiokande was built and became operation in 1996.

Super-Kamiokande (and Kamiokande was also) is located in the Kamioka mine near Mozumi, Japan. Super-Kamiokande contains 50 kt of water and over 11,000 50-cm diameter PMTs. Imaging water Čerenkov detectors have photomultiplier tubes (PMTs) surrounding the water volume to detect the Čerenkov light produced by energetic charged particles arising from neutrino interactions. The Čerenkov light cone produces ring-like patterns of PMTs that fire, where the cone intersects the surface formed by the PMT array. In this manner, water Čerenkov detectors can reconstruct the direction of the recoiling charged particle, along with the position (usually based upon photon time-of-arrival at the PMTs) and event energy (total charge or number of hit PMTs).

Solar neutrinos are detected in water Čerenkov detectors by observing neutrino–electron elastic scattering. The cross section for: $\nu_e + e^- \rightarrow \nu_e + e^-$ is known from electroweak theory. The cross section for: $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ exists, too, but is approximately 6 times lower than for ν_e (at ^{8}B solar neutrino energies). Hence, water Čerenkov detectors will be predominantly sensitive to electron neutrino flavour but have some sensitivity to detect ν_μ or ν_τ.

Water Čerenkov detectors have an analysis threshold determined by the minimum number of PMTs that need to fire for an event to be easily recognized and reconstructed. This threshold is around 5 MeV. Thus, Super-Kamiokande only detects the ^{8}B solar neutrinos (and could also detect the *hep* solar neutrinos if the flux were not so low). The flux of ^{8}B solar neutrinos measured by Super-Kamiokande in their 1496-day dataset was: $(2.35 \pm 0.02(\mathrm{stat.}) \pm 0.08(\mathrm{syst.})) \times 10^6\ \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ [5]. In comparison, the solar model predicted flux of ^{8}B solar neutrinos is around $(5-6) \cdot 10^6\ \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$. Super-Kamiokande (and Kamiokande in a preliminary manner) solidly confirmed the solar neutrino deficit observed by Davis and did so using a detection technique that was not radiochemical.

5. SUDBURY NEUTRINO OBSERVATORY

The Sudbury Neutrino Observatory (SNO) was a water Čerenkov detector that was filled with heavy water. Located in the Vale Creighton mine near Sudbury, Canada, the SNO detector contained 1000 t of ultra-pure heavy water D_2O in an acrylic vessel. The entire vessel is surrounded by ordinary light water and roughly 9,500 20-cm diameter PMTs.

Heavy water provides deuterons to serve as targets for neutrino interactions and this was proposed to provide a way to resolve the Solar Neutrino Problem [6]. Deuterons have both charged-current and neutral-current neutrino interactions that are detectable (and with appreciable cross section at solar neutrino energies). Charged-current (CC) interactions: $\nu_e + d \rightarrow p + p + e^-$ result in a recoiling electron that produces Čerenkov light. These interactions only detect electron neutrino flavour. Neutral-current (NC) interactions: $\nu_x + d \rightarrow p + n + \nu_x$ cause the dissociation of the deuteron and have an equal cross section for all neutrino flavours. The appearance of a free neutron in the detector heavy water volume would be a signature of a neutral-current neutrino-deuteron event.

The SNO experiment ran in three phases that are distinguished by the manner in which the neutrons from NC events were detected. The pure D_2O phase collected data from November 1999 to May 2001. In this phase some fraction of neutrons produced by NC events would capture on deuterons: $n + d \rightarrow t + \gamma$ with a single monoenergetic gamma ray of 6.25 MeV emitted. From July 2001 to September 2003, the SNO heavy water had 0.2% sodium chloride salt added to it. With Cl in the heavy water volume, neutrons from NC events would capture on chlorine with its higher capture cross section. The multiple gamma-ray signal, from the de-excitation of chlorine nuclei after neutron capture, has total energy of 8.6 MeV and produces a pattern of hit PMTs that is more isotropic (and hence different from the single Čerenkov ring made by CC events with single recoiling electrons). Finally, SNO took data from November 2004 to November 2006 in a third phase in which dedicated neutron counters (^{3}He proportional counters) were deployed throughout the heavy water volume, after the salt was removed. Neutrons from NC events in the heavy water would be detected in the ^{3}He counters, allowing CC and NC events to be detected in separate detector subsystems and thus breaking correlations present when extracting those

Table 2. **Results from SNO salt phase and third phase. Fluxes of ^{8}B solar neutrinos are given. The electron neutrino flavour ν_e flux is less than the total flux of all active neutrino flavours ν_x**

Salt CC flux ν_e, 10^6 cm$^{-2}\cdot$s^{-1}	$1.68^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$
Salt NC flux ν_x, 10^6 cm$^{-2}\cdot$s^{-1}	$4.94^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$
^{3}He counter CC flux ν_e, 10^6 cm$^{-2}\cdot$s^{-1}	$1.67^{+0.05}_{-0.04}(\text{stat.})^{+0.07}_{-0.08}(\text{syst.})$
^{3}He counter NC flux ν_x, 10^6 cm$^{-2}\cdot$s^{-1}	$5.54^{+0.33}_{-0.31}(\text{stat.})^{+0.36}_{-0.34}(\text{syst.})$

two signals from PMT data alone. Results from the 2nd and 3rd phase are presented in Table 2 [7, 8].

The comparison of CC and NC results from SNO provided clear resolution of the Solar Neutrino Problem. The electron neutrino flavour content of the solar neutrinos (of several MeV energy) is only about 0.30–0.34 of the total flux of all active neutrino flavours. Thus, ν_μ and/or ν_τ content is identified in the solar neutrino flux arriving on the Earth despite the fact that all neutrinos produced by weak interactions in the Sun are born as electron neutrinos.

Furthermore, the comparison of the total flux of all active neutrino flavours (from the SNO NC measurements) can be compared to the solar model predicted flux of ^{8}B solar neutrinos. BS05(OP) calculates the ^{8}B flux: $(5.69 \pm 0.91) \times 10^6$ cm$^{-2}\cdot$s^{-1} [9]. The SNO NC measurements provided confirmation of the solar models — energy generation in stars is understood! The solar model predicted flux agrees with the SNO NC measurement telling us that all of the solar neutrinos produced in the Sun are present. They were rendered undetectable (or less detectable) in other solar neutrino experiments and only caused an *apparent* deficit.

6. ^{7}Be SOLAR NEUTRINOS

It is instructive to compare the solar ν_e deficit measured and understood by SNO with that in other experiments. Comparing SNO to Super-K strengthens the overall conclusion. Super-K measures a «flux» of ^{8}B solar neutrino to have a value of $2.35 \cdot 10^6$ cm$^{-2}\cdot$s^{-1} whereas SNO CC measures $1.68 \cdot 10^6$ cm$^{-2}\cdot$s^{-1}. The difference is due to the fact that Super-K is not really measuring a pure flux but infers a quantity from the rate of neutrino–electron scattering events. If the ν_e content in the solar neutrino flux is about 0.33 of the total flux of neutrinos produced in the Sun, then 0.67 of the solar neutrino flux is ν_μ and/or ν_τ (after oscillations) and they contribute to the neutrino-electron scattering rate. The inferred flux in Super-K should be higher than SNO CC if there is flavour mixing between active neutrino flavours. A more quantitative analysis of the amount by which the Super-K result exceeds the SNO CC ν_e measurement supports the conclusion that neutrino oscillations between the known, active flavours are occurring.

The SNO results can be compared to the Chlorine experiment rate and solar model predictions. One can calculate the expected rate in the Chlorine experiment using solar model calculated fluxes (without oscillations) and known cross sections for neutrino reactions on Cl. The solar neutrino reactions that contribute to the Chlorine experiment rate are: 5.76 SNU from ^{8}B; 1.15 SNU from ^{7}Be, 0.22 SNU from pep solar neutrinos, 0.42 SNU from the CNO cycle neutrinos, and 0.04 SNU contributed by the hep neutrinos. The total SNU expected is the sum: 7.82 SNU, compared to the experimental result of 2.56 SNU, or a ratio of about 0.32.

An instructive calculation would be to scale the ^{8}B contribution to Chlorine using the ν_e fraction measured by SNO (that has been suppressed because of neutrino oscillations). If the SNO CC data is used for this scaling, this reduces the ^{8}B component in the Chlorine experiment rate down to (1.92 ± 0.17) SNU, where the error quoted is due to the uncertainty in the SNO measurement of CC/NC (which is the ν_e fraction). There is room between the SNO-scaled ^{8}B contribution to Chlorine and the measured Cl rate, so we can be confident that ^{7}Be solar neutrinos ν_e can be contributing to the Chlorine rate also.

7. BOREXINO

The Borexino experiment is a liquid scintillator solar neutrino detector located in the Gran Sasso Underground Lab in Italy. The original concept for the Borexino experiment was a boron-loaded liquid scintillator that would look for CC and NC reactions on ^{11}B. However, the focus of Borexino was switched many years ago to measuring the ^{7}Be solar neutrinos. Prior to the results from SNO, one could perform an analysis similar to the one in the previous section except the scaling of the measured ^{8}B solar neutrino component in Chlorine was based upon the Super-Kamiokande measured ^{8}B solar neutrino flux (or based upon the Kamiokande value, as was the case in [10]). Analyses like this found that there was little room for ^{7}Be solar neutrinos to contribute to the Chlorine experiment rate and it was an intriguing suggestion (ultimately not the way nature selected for the neutrino oscillation parameters) that perhaps the ^{7}Be neutrinos at 0.86 MeV were completely suppressed because of oscillations. Because of the great interest in a direct measurement of the ^{7}Be solar neutrinos, Borexino made this measurement to aim for and thus it did not require loading the liquid scintillator with boron.

We now know, in hindsight, that the Chlorine experiment ^{8}B contribution scaling analysis using the Super-K measurement does not give the correct implication because the quantity that Super-Kamiokande measures is not a pure ν_e

flux but also contains the ν_μ and/or ν_τ component. This leads to over-predicting the ν_e ^{8}B contribution in the Chlorine experiment, leaving less room for the ^{7}Be solar neutrinos, if not taken into account.

Borexino detects solar neutrinos using neutrino–electron scattering. The ^{7}Be solar neutrinos are monoenergetic. They produce a recoil electron spectrum that has a «Compton» edge shape. This becomes a signature of ^{7}Be solar neutrino interactions in the detector. A liquid scintillator gives off more light when charged particles deposit energy in it compared to the amount of light produced by Čerenkov emission. Hence, a liquid scintillator detector can observe solar neutrino interactions that deposit less than 1 MeV energy. The scintillation light emitted is isotropic; thus a liquid scintillator detector cannot reconstruct the direction of arrival of the solar neutrinos or of the recoiling electron. Furthermore, background from natural radioactivity produces the same isotropic scintillation light (and is more abundant at lower energies). Consequently, the main technical challenge of liquid scintillator solar neutrino experiments, like Borexino, is the control of ultra-low radioactivity background levels.

The Borexino detector contains 300 t of liquid scintillator made from pseudocumene. It has a fiducial volume of 100 t. The detector was filled in May 2007 and continues to operate. Borexino's most recent published result [11] has the observed rate of ^{7}Be solar neutrinos: $(49 \pm 3 \pm 4)$ counts/(day-100 t). In comparison, the solar model predicted, no-oscillation rate would be 74 counts/(day-100 t). Solar neutrino oscillations cause this suppression, as is well known now, and when the best-fit neutrino oscillation parameters are included, the model predicted rate would be (48 ± 4) counts/(day-100 t).

8. FUTURE SOLAR NEUTRINO PROSPECTS

Recently, the SNO experiment published a new lower energy threshold analysis (LETA). This lowering of the threshold points the way to the physics objectives of future solar neutrino experiments, so the new SNO LETA analysis will be summarized here. The SNO LETA analysis [12] lowered the analysis threshold from 5 MeV down to 3.5 MeV. This analysis featured a joint analysis of the data from SNO Phase I (pure D_2O) and Phase II (NaCl salt added). The combined analysis of the two data sets leads to more than just the simple statistical combination of the results since neutrino signals, backgrounds, and detector parameters in one phase help to constrain their extraction in the other phase, and vice versa. Additionally, systematic uncertainties were reduced and several improvements in simulations and analysis helped to lower uncertainties.

By looking at energies less than 5 MeV, backgrounds from internal and external radioactivity start to dominate but it is possible to extract the neutrino signal content in those lower energy bins provided there is a detailed understanding of these backgrounds and their distributions. It should be noted that more than just energy distributions were used to characterize backgrounds during signal extraction. Radial distributions (reconstructed positions in the detector) are important, especially for external backgrounds coming from radioactivity outside the SNO heavy water volume, as are event isotropy, and the angular correlation to the Sun's direction.

The addition of neutrino data at lower energies offers improved statistics for the neutral-current events and provides a look at neutrino survival probabilities at lower energies not previously explored by SNO, using the charged-current events. The improved SNO NC measurement coming from this analysis is:

$$\Phi_{^8\mathrm{B}} = 5.046^{+0.159}_{-0.152}(\mathrm{stat.})^{+0.107}_{-0.123}(\mathrm{syst.})$$

in units of $10^6\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$.

The energy spectrum of charged-current events in SNO is shown in Fig. 1. The data points at lower energies are not observed to increase as expected for the best-fit LMA oscillations; rather, they appear to be lower than even the undistorted ^{8}B neutrino spectrum (though the statistical significance is small). It should be noted that each charged-current signal energy bin was extracted independently; however, background energy spectra were used in the extraction thereby introducing correlations between bins.

The Borexino experiment has also detected ^{8}B solar neutrinos [13]. This measurement involved subtracting backgrounds, like SNO LETA, and ends up with large uncertainties. Uncertainties are larger also because of limited statistics; Borexino is a smaller detector than SNO and neutrino–electron scattering cross

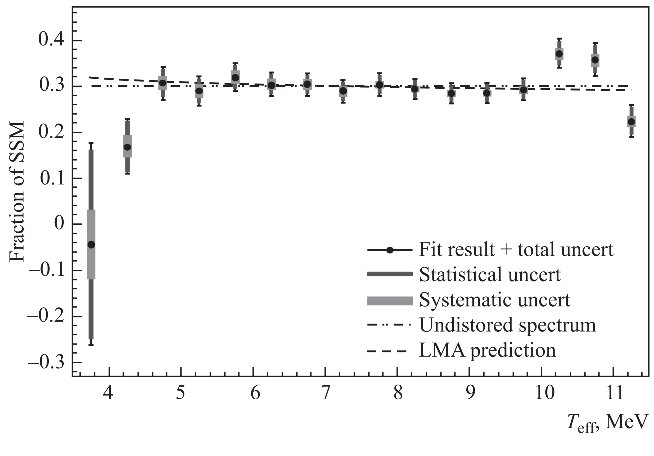

Fig. 1. Spectrum of charged-current events from the SNO low energy threshold analysis. The expectation for the best-fit LMA survival probability is shown overlaid

sections are lower than neutrino–deuteron. Borexino also sees that their lowest energy data point is lower than expectations as in the SNO LETA results.

It should be noted that Super-Kamiokande also sees a ^{8}B solar neutrino spectrum that is «flat», meaning consistent with the undistorted spectrum [5]. An objective of future measurements of lower energy solar neutrinos will be to examine whether these observations described above are possibly indicative of any new physics or whether it is just chance occurrence that all experiments have data at lower energies that suggest a flatter spectrum or even a dip before the survival probability rises at lower energies still. Several sub-dominant oscillation ideas are consistent with just such an observation, such as the possibility of nonstandard neutrino interactions [14].

9. SNO+

The SNO+ experiment is the successor to the Sudbury Neutrino Observatory. The heavy water that was in SNO has been returned (was borrowed from Atomic Energy of Canada Limited). The empty SNO acrylic vessel will be filled with 780 t of a liquid scintillator that uses linear alkylbenzene (LAB) as the solvent. This scintillator was developed by SNO+ during R&D for the experiment. It is chemically mild, compatible with acrylic, has high light yield, long attenuation length, and it is safer and cheaper than pseudocumene.

With a liquid scintillator, the light yield in SNO+ will be a factor of about 50 times higher than the light output from Čerenkov in SNO, thus allowing SNO+ to study neutrino physics at lower energies. Solar neutrinos at lower energies are interesting as precision probes of neutrino physics and recent results that push to lower energies suggest that there may still be some surprises, if neutrino survival probability as a function of energy does not behave as expected for neutrino oscillations (including propagation through matter). SNO+ will also detect antineutrinos emitted by natural radioactivity (uranium and thorium) in the Earth known as geoneutrinos. Nuclear power reactors in Ontario are farther from the SNO+ detector than the typical distance of reactors in Japan to the KamLAND experiment. The signal from reactor antineutrinos will still be easily detected by SNO+ and spectral features observed in KamLAND due to neutrino oscillations will be shifted to higher energy in SNO+ (L/E is a constant for oscillations). This observation would manifestly demonstrate the oscillation phenomenon and provide added constraints on neutrino oscillation parameters. A large liquid scintillator detector serves as an excellent supernova neutrino monitor. In a separate phase of SNO+, the double-beta decay isotope ^{150}Nd will be added and a competitive search for neutrinoless double-beta decay can be performed with a significant quantity of neodymium. All of these physics goals motivated the construction of the multipurpose SNO+ experiment.

9.1. ***pep*** **Solar Neutrinos in SNO+.** The *pep* solar neutrinos arise from the three-body, proton–electron–proton reaction in the Sun that produces monoenergetic electron neutrinos with energy 1.44 MeV. These neutrinos can be identified in a large, liquid scintillator detector via neutrino–electron scattering and looking for an edge feature (like a Compton edge) in the recoil electron energy spectrum (similar to how Borexino detects ^{7}Be solar neutrinos). The *pep* solar neutrino flux is calculated in solar models to ±1.5% uncertainty [9], whereas the ^{7}Be solar neutrino flux has ±10.5% error [9]. By using a neutrino source with known flux and using a known cross section, a precise measure of the rate of *pep* solar neutrino interactions yields a measurement of the survival probability with small uncertainty. The *pep* solar neutrinos thus enable a precise test of neutrino oscillation parameters and of subdominant oscillation effects.

Figure 2 shows the *pep* neutrino signal and the CNO solar neutrinos, along with expected, target background levels. The distinctive shape of the *pep* solar neutrinos should allow it to be extracted (using a maximum-likelihood analysis). The CNO solar neutrino recoil energy distribution is not as distinct from background spectral shapes as the *pep* solar neutrinos and a measurement will rely much more on background targets being achieved.

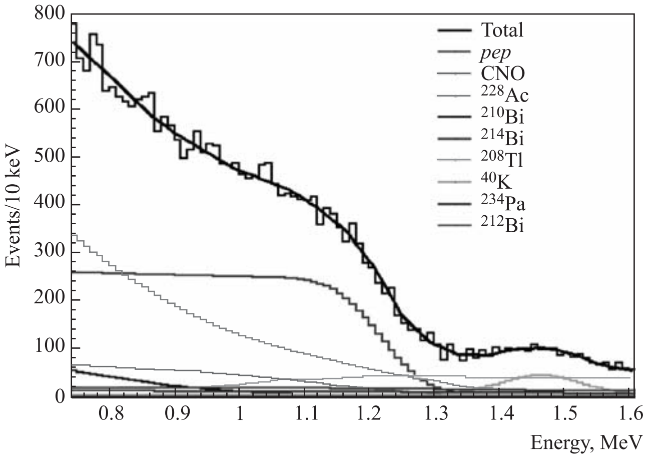

Fig. 2. Expected solar neutrino signals and backgrounds in SNO+. Backgrounds were simulated at their target levels and solar neutrino signals include oscillations

9.2. CNO Solar Neutrinos in SNO+. The flux of CNO solar neutrinos will be harder to measure precisely yet they may be unique in their ability to shed light on a new problem with solar models. Recent determinations [15] of solar surface metallicity (chemical abundances) have suggested that lower abundances (by about 30–50%) than previous best-fit values are more consistent with surface spectroscopic observations. These lower abundances cause problems in solar models. Solar models can calculate helioseismology observables and they are used to be remarkable agreement between measured helioseismology data (e.g., sound speed profile) and solar model predictions. However, with the new chemical abundances, solar models now fare worse when attempting to calculate these observables — helioseismology is «broken» in low metallicity solar models.

One possible way to account for this is to propose that solar surface chemical abundances can differ from the core abundances. Currently, this is not the way solar models treat the solar chemical composition. If solar core metallicity were more similar to values that were previously used, the helioseismology predictions from the models would be more compatible with data. This provides an opportunity to use solar neutrino experiments to probe the solar core; this is revisiting the original intent of solar neutrino experiments to serve as probes of the inner workings of our Sun.

In solar models such as [16], the solar neutrino flux predictions for the different reactions are given for both high metallicity and low metallicity calculations. For some fluxes, there is not much difference; for example, the pp solar neutrino flux only differs by about 1% (because the pp solar neutrino flux is insensitive to many factors in the model). The pep solar neutrino flux has similarly only a 2.8% difference between high metallicity and low metallicity calculations — this is a feature of the pep solar neutrinos that make it appealing to exploit by SNO+ to make neutrino physics precision measurements. On the other hand, the ^{8}B solar neutrino flux differs by 21%. Much of this difference comes from the effect the different chemical abundances have on environmental variables such as the core temperature, and the steep dependence of the ^{8}B solar neutrino flux on these variables.

The CNO solar neutrinos depend on these environmental variables, just as for the ^{8}B solar neutrinos, but in addition they depend directly on the solar core C, N, and O abundance. The difference in the fluxes between high and low metallicity calculations is between 30–40%. Additional power in this determination can come from using correlations [17]. The measured ^{8}B solar neutrino flux from SNO is used to determine the solar ^{8}B neutrino flux, thereby constraining environmental variables like the core temperature. Subsequently, taking into account the correlations, a measurement of CNO fluxes from SNO+ will have a better handle on the core C, N, and O abundance.

Making the pep and CNO solar neutrino measurements in SNO+ will depend on achieving reductions in background counting rates in the liquid scintillator. SNO+ has an advantage over other liquid scintillator neutrino detectors. The depth of the experimental site is 6000 m water equivalent. SNO+ is located in SNOLAB with 2 km rock overburden that provides enormous reduction in cosmic ray muon backgrounds (even compared to underground labs such as Kamioka and Gran Sasso). When muons traverse a liquid scintillator they may produce ^{11}C by spallation. The ^{11}C nucleus decays by positron emission with a half-life of 20 min. The positron guarantees that the energy deposited in the scintillator is at least 1.022 MeV and places these background events right in the energy range of the *pep* and CNO neutrinos. Though muons are easy to identify in a scintillator detector, a complicated veto is required since the half-life is so long (i.e., a simple veto that kills the detector for, say, three half-lives would turn off the detector for an hour for each muon that traversed the experiment). Though experiments are underground, the muon rate in large detectors like Borexino and KamLAND exceeds 10,000 muons per day. The muon veto identification of cosmogenic ^{11}C background can be seen as a difficult challenge. In SNO+, the muon rate will be 70 muons per day (because of the great depth) and the ^{11}C background veto will be more easily designed. Furthermore, the rate of ^{11}C production in SNO+ is already low enough to be a negligible background to the *pep* and CNO solar neutrinos.

10. OTHER FUTURE SOLAR NEUTRINO EXPERIMENTS

There are several ideas for future solar neutrino experiments. These ideas aim at *pp* solar neutrino detection. The ideas being investigated and/or developed fall into two categories: charged-current experiments and neutrino–electron scattering detectors.

The LENS experiment aims to detect *pp* solar neutrinos using the low neutrino capture energy threshold in ^{115}In of 114 keV. With a detector of 8% indium-loaded liquid scintillator containing 10 t of indium (all of it ^{115}In), LENS proposes to detect 400 *pp* solar neutrino CC events per year. The main challenge in LENS is the suppression of the beta-decay background as ^{115}In is beta-unstable (but with a long half-life). Clever ideas exist to develop spatial reconstruction of neutrino events that are distinctive from random coincidences due to the beta decays.

The MOON experiment proposes to detect *pp* solar neutrinos using neutrino capture reactions on ^{100}Mo. The energy threshold for this reaction is 168 keV. A delayed coincidence is produced in the reaction: $\nu_e + {}^{100}\text{Mo} \rightarrow {}^{100}\text{Tc} + e^-$ and ${}^{100}\text{Tc} \rightarrow {}^{100}\text{Ru} + e^- + \bar{\nu}_e$, with a delayed lifetime of 15.8 s. An interesting background for the MOON experiment is that ^{100}Mo undergoes double-beta decay and the two-neutrino double-beta decay of ^{100}Mo must be distinguished from the two electrons arising from solar neutrino CC events, delayed in time.

Ideas for elastic scattering experiments that could detect the *pp* solar neutrino experiments include CLEAN and XMASS. The oscillated event rate from *pp* solar neutrinos and neutrino–electron scattering is one event per day-ton, for a 50 keV recoil electron lower threshold.

The CLEAN experiment proposes to use 100 t of liquid neon as a scintillator. The key concept for liquid neon as a cryogenic scintillator is that there should be no radioactive contamination since other radio-impurities freeze out before reaching liquid neon temperatures.

The XMASS experiment proposes to use at least 10 t of liquid xenon. Here, the key concept for a liquid xenon scintillation detector is that xenon provides very effective self-shielding (due to its density and high atomic number).

Both of these liquid noble scintillators also perform well as dark matter detectors. Hence, the development for CLEAN and XMASS is currently motivated by building detectors of several hundred to 1000 kg size, to search for dark matter signals. Achieving ultralow background counting rates in these detectors is important for both dark matter searches and pp solar neutrinos.

11. SUMMARY

Over the past decades there have been many exciting results from solar neutrino experiments. The Solar Neutrino Problem was solved and we now understand that neutrinos have finite mass and undergo oscillations in flavour detection probability due to the mixing between weak flavour eigenstates and neutrino mass states. Solar neutrino experiments played a central role in elucidating this new physics. As we continue to study solar neutrinos with future, upcoming experiments, there may be some additional surprises. The SNO+ experiment aims to be taking data after roughly two years of construction. Solar neutrino physics goals of SNO+ include neutrino oscillation studies using the pep solar neutrinos and investigations of solar chemical abundances in the core by detecting the CNO solar neutrinos. It will be very interesting to see where new experiments and their results will take the field.

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