Future 'Realtime' Solar Neutrino Experiments

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Abstract. I summarize here the goals of the future solar neutrino program, and the proposed experiments.

1. Introduction

The story of solar neutrinos follows an archetypal scientific tale: an unexpected discovery criticized by the establishment, a theorist over-reaching with claims of new fundamental physics based on the results, then slow acceptance by the community that perhaps neither the measurements nor the theory are so outlandish, ultimately culminating in an unequivocal and universally accepted demonstration that they were right all along. What isn't part of the trope is what happens after the success—that, suddenly, the motivations that drove decades of experiments and theoretical creativity have arguably disappeared. On the day after, we are left wondering where to go from here.

The motivations to pursue measurements of solar neutrinos have not disappeared, but they have changed. No longer are we after a clear demonstration of flavor transformation, but rather *newer* physics of neutrinos and new astrophysics using neutrinos. The future program is therefore potentially very rich, affecting a broad range of topics from non-standard interactions to the formation of the solar system.

2. Current Status

The fusion reactions which power the Sun lead to several different neutrino energy spectra, born of two distinct processes, the *pp* chain and the CNO cycle. For a medium-temperature star like the Sun, the CNO cycle is expected to contribute only 1% or so to the total neutrino flux. At high energies (above ~2 MeV or so), neutrinos from the β^+ decay of ^{8}B in the *pp* chain dominate, though there is a small contribution from neutrinos produced through the 'hep' reaction ($^3He + p \rightarrow^4 \mathrm{He} + e^+ + \nu_e$) that extend out to energies of 17 MeV or so. Below 2 MeV are neutrinos from two line sources from ^{7}Be electron capture, and from the two reactions at the 'head' of the chain: $p + p \rightarrow^2 H + e^+ + \nu_e$ (*pp*) and $p + e^- + p \rightarrow^2 H + \nu_e$ (*pep*).

Figure 1 summarizes the solar neutrino measurements to date [1, 2, 3, 4, 5, 6, 7, 8, 9, 10], as a function of the effective energy threshold of each experiment. The figure shows the ratio of the measurement made by each experiment to the relevant Standard Solar Model prediction, illustrating not only the effects of mixing but the energy-dependent effects predicted by the Mikheyev-Smirnov-Wolfenstein (MSW) or matter effect [11, 12]. The SNO neutral current measurement is sensitive to all flavors, and shows agreement with the predictions of the Standard Solar Model.

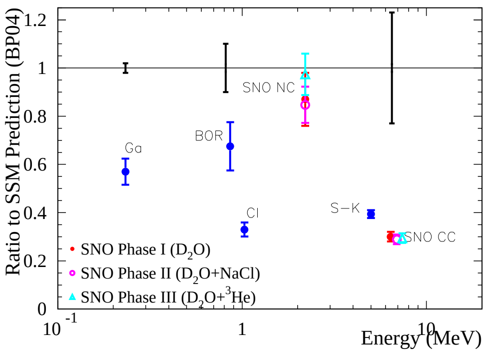

Figure 1. Summary of solar neutrino measurements relative to Standard Solar Model prediction.

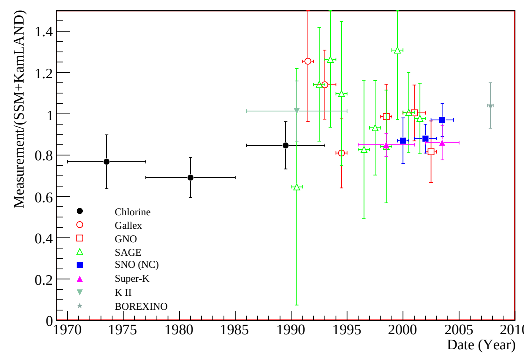

Figure 2. Summary of solar neutrino measurements as a function of time, with the effects of mixing removed using the KamLAND mixing removed.

Aside from the energy-dependent oscillation differences, the experiments also differ because some are 'inclusive', measuring neutrinos from all sources above their detection energy theshold, while others are 'exclusive', separating each neutrino source. Exclusive experiments are also typically called 'realtime' experiments, because they allow event-by-event identification, providing information about the interaction energy, direction, and time. Until the recent BOREXINO results [13], all the measurements below 2 MeV had been done by inclusive radiochemical experiments.

Although it does not look (yet) at solar neutrinos themselves, the KamLAND reactor antineutrino experiment does explore the same (1,2) parameter region of neutrino oscillations. But the solar experiments differ from KamLAND in many significant ways: they observe neutrinos rather than antineutrinos, they have an enormous 150×10^6km baseline compared to KamLAND's $\sim$150 km baseline, and the matter effect is critical to the solar observations but almost negligible for KamLAND. The comparison of the KamLAND [14] and solar neutrino results thus provide the first precision test of the standard neutrino oscillation scenario: as far as we know *only* MSW-enhanced neutrino oscillations can lead to the same values of the measured Δm^2_{12} and θ_{12} seen by the two experiments.

The KamLAND results also provide us with a new way of viewing the solar neutrino program. With KamLAND's terrestrial measurement of the oscillation parameters, we can now unfold the effects of mixing on the measurements by the solar neutrino experiments, thus turning the entire forty-year history of solar neutrino experiments into a continuous observation of the Sun's neutrino output. Figure 2 shows the results of all the solar neutrino experiments as a function of time, now with the effects of mixing removed. We see that our forty years of observing the solar core show no significant variations with time—an interesting measurement all by itself.

3. Goals of the Future Solar Neutrino Program

To date, solar neutrinos have given us a clear signal of mixing and a general confirmation of the Standard Solar Model, as well as the restriction of the solar-sector mixing parameters to the LMA region. With KamLAND, they have also given us the first check for new physics beyond the standard oscillation scenario. But the next phase of the program will be even harder: making precision tests with a particle which so rarely interacts. The specific goals of the future program include both using neutrinos as astrophysical probes of the Sun, and as particle physics probes of new interactions and oscillation phenomena.

Although the original intent of solar neutrino studies was to 'see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation' [15], very little of this was possible without a basic understanding of the measured fluxes. The situation has now changed substantially. A current example of how neutrinos may resolve astrophysical problems is the 'solar metallicity problem'. Recent re-analyses [16] of data on the metal content of the solar photosphere have claimed that the Sun has a relatively lower metal content than previously thought. A lower metal content alters significantly the helioseismologic predictions of the Standard Solar Model—enough that it would now be in disagreement with measurements. The disagreement is somewhat historically ironic, as it was the excellent agreement with helioseismology that lead many to believe that the Standard Solar Model could make accurate predictions.

The re-analyses of the metallicity are still controversial, but a measurement of the CNO neutrinos could resolve the issue, telling us what the core metallicity really is—the new metallicity predicts a difference in the CNO neutrino flux by as much as a factor of two. In a very interesting paper, Haxton and Serenelli [17] suggest that perhaps both measurements are correct: the metallicity of the core is what we always thought (and hence the SSM helioseismologic predictions are still in agreement) but the photosphere is metal-poor. They suggest that the gas giants may have removed metals from the primordial solar nebula and that the last material that accreted on the new Sun was therefore deprived of metals, even though the core metallicity was still high. While the authors admit that the idea is highly speculative, it nonetheless provides us with a delightful 'neutrino application': a measurement of the CNO neurinos could provide us with information about solar system formation.

The project of understanding the Sun itself using the measured neutrino fluxes is not easy. There are many Standard Solar Model parameters and the flux measurements can at best constrain combinations of these parameters. Nevertheless, some workers [18] have begun this process. A simpler analysis is just the comparison of the total luminosity of the Sun measured via neutrinos, to that measured via photons. Any significant difference between these two would be an indication of new physics or astrophysics. Currently (before the recent BOREXINO results) the ratio of the neutrino luminosity to the photon luminosity is known only at the level of 20-40% [19, 20]. A measurement of the lowest energy neutrinos (from the *pp* or *pep* reactions) would provide the most stringent constraint.

With our understanding of neutrino oscillations and with the measurements of KamLAND, we are also in a position to begin looking for new neutrino physics. The best place to look for this new physics is in the transition region between high-energies (> 2 MeV) where the MSW effect dominates the neutrino survival probability and the low energy regime which is almost exclusively vacuum oscillations. Any new physics—such as flavor-changing neutral currents or some other non-standard interaction—will alter the transition region [21, 22, 24, 23]. In addition to searching for new physics, a direct observation of the expected Day/Night effect would be a beautiful confirmation of the predictions of the new model. There is no more direct evidence for the MSW effect than to place matter in front of the neutrino beam and see the difference in the oscillation probability. For solar neutrinos, we get to see this for free using the rotating Earth.

We can further test the neutrino model by comparing solar measurements of the mixing parameters to terrestrial measurements like those done by KamLAND (or even, potentially, by very long baseline experiments [25]). Future neutrino measurements will improve precision on the mixing parameters, perhaps even helping to constrain the as-yet-unmeasured value of θ_{13}. And lastly, as has been true for a long time: looking 'upward', at astrophysical bodies like the Sun, has often given us discoveries in the purest sense, in which we are surprised by something totally new.

4. The Future Program

Several types of measurements are now needed. Exclusive measurements of the low energy neutrino fluxes (*pp*, *pep*, ^{7}Be, CNO) will provide us with our best understanding of the Sun—from the resolution of the metallicity problem to the 'unitarity' test of the solar neutrino and photon luminosities. With these measurements, and knowledge of the mixing angles, we will also continue the program of monitoring the solar core begun over forty years ago. If the future measurements have charged-current sensitivity, then in combination with elastic-scattering measurements significant improvements in our knowledge of the mixing angles can be made. By looking at the energy spectra of the neutrinos—from above the vacuum/matter transition to below—we will be able to test for new physics that could affect neutrino propagation through matter. Non-solar measurements of the mixing parameters will allow us to test the neutrino oscillation model in detail as well as reducing the uncertainties on our knowledge of the total solar neutrino flux. Precision measurements of the nuclear reaction cross sections will constrain the Standard Solar Model so that the neutrino measurements can provide a meaningful test.

There are several measurements already underway with existing detectors. At this conference, the BOREXINO experiment reported the first exclusive measurements of the ^{7}Be flux [26], and the SNO Collaboration showed their independent measurements of the ^{8}B flux from using ^{3}He proportional counters immersed in the D_2O volume [27]. The Super-Kamiokande experiment began in May 2007 taking data with a new, much lower energy threshold, with large reductions made in the backgrounds from radon. The Sudbury Neutrino Observatory is also working on a low-energy analysis, using data from the first two phases of running. For both Super-Kamiokande and SNO, the goal of the low-threshold analyses is to look into the transition region between vacuum and matter-dominated oscillations. For SNO, there is the additional advantage that the lower threshold increases significantly ($\sim 70\%$) the statistics on the neutral current reaction, and thus should provide noticeably higher precision on the measurement of the total (flavor-independent) ^{8}B neutrino flux.

With the new results of the BOREXINO experiment, and the turning off of SNO, we are beginning a new era in solar neutrino detectors. Just as the Cherenkov experiments dominated the scene after the radiochemical experiments had done the early solar neutrino work, now scintillator-based experiments are likely to be the most productive of the solar neutrino detectors. And we are perhaps even beginning to see the era that will eventually replace the scintillator era, in some of the cryogenic or TPC-based experiments. Although in the current climate the funding for solar neutrino experiments will be difficult to find, nearly all future experiments have additional physics goals: dark matter searches, neutrinoless double-beta decay, long-baseline neutrino experiments, proton decay, etc.

The KamLAND experiment is beginning a new phase, in which they will be lowering backgrounds substantially through scintillator purification. With a reduction of as much as 10^6 in ^{210}Pb and ^{85}Kr, the ^{7}Be neutrinos should become visible using the neutrino-electron elastic scattering reaction, with much higher statistics than that seen in the smaller BOREXINO detector. To date, they have been able to reduce some of the backgrounds by a factor of 100, and are working on a second stage of purification. KamLAND may also be able to see both the *pep* and CNO neutrinos by vetoing ^{11}C background events through a triple coincidence: a throughgoing prompt muon, followed by a γ-ray from neutron capture after roughly 210μs, and then finally a nearby ^{11}C event after 30 minutes or so. To do this, they are also building new deadtimeless electronics. If the triple coincidence veto is successful, KamLAND expects to have a 6% statistical uncertainty on both the CNO and *pep* neutrinos.

The SNO+ experiment is also a scintillator experiment that can make exclusive measurements of some of the lower energy neutrinos, in particular the *pep* and CNO neutrinos. SNO+'s advantage is that the SNO detector and the depth of SNOLAB mean that ^{11}C is a negligible problem—no coincidence veto is needed to see these neutrino signals.

Both KamLAND and SNO+ will be experiments looking at neutrinos through the reaction $\nu + e^- \rightarrow \nu + e^-$ on their respective scintillator targets. The proposed LENS experiment is also a scintillator experiment but will have charged-current sensitivity. LENS uses indium-doped scintillator, and neutrinos all the way down to *pp* energies can be observed through the reaction $\nu_e + ^{115}\mathrm{In} \rightarrow e^- + 2\gamma + ^{115}\mathrm{Sn}$. The γ emission is delayed by a remarkable 4.76μs, thus giving LENS a delayed coincidence that can be used to reject the enormous (1:10^{11}) background from natural ^{115}In decays. To eliminate external events, the detector is planned to be finely segmented into three dimensional lucite cubes, and light from the scintillator is piped out through total internal internal reflections off of the scintillator-plastic interface. A 128 liter MiniLENS prototype is being constructed, with the eventual hope of going up to 125 tons. The full LENS should be able to see the energy spectrum of the *pp* electron-flavor neutrinos with a statistical integral precision of 2.5%, as well as measuring the ^{7}Be, CNO, and *pep* neutrino signals, separating them via their distinctive energy spectra.

The CLEAN experiment also hopes to observe the *pp* neutrinos, using a cryogenic approach. CLEAN will use liquid neon to see scintillation light from neutrino-electron elastic scattering events. Neon can be made hyper-pure, virtually eliminating internal radioactive backgrounds. External backgrounds from neutrons, alphas, and γs, can be rejected through both reconstruction and pulse shape discrimination. The ultimate CLEAN detector capable of making a *pp* measurement will have a 50 ton fiducial volume. Currently, the DEAP/CLEAN collaboration is pursuing similar ideas using liquid argon and neon as to search for nuclear recoils due to WIMP interactions from the galactic dark matter halo. Two prototypes, microCLEAN (4 kg argon/neon) and DEAP-1 (7 kg of argon), are in operation, and a 100 kg fiducial volume miniCLEAN is being developed.

The XMASS experiment is similar to CLEAN, but uses xenon in place of neon as the cryogenic liquid. Xenon has a high light yield, allowing for a low threshold that will allow a measurement of the *pp* neutrinos. Also like CLEAN, the short-term goals of XMASS are directed toward a dark matter experiment, with a 100 kg prototype already built.

Both xenon and argon are being considered for a much larger detector, XAX, which would be installed in the Deep Underground Science and Engineering Laboratory in Homestake, South Dakota. By using two modules filled with 20 tons of xenon and one of 70 tons of argon, they hope to be able to simultaneously look for dark matter, perform a double beta decay experiment, and provide a very high statistics *pp* solar neutrino measurement.

Although most of the new solar experiments are aimed at looking at the low energy end of the solar neutrino spectrum, the hyper-sized experiments planned for long-baseline neutrino oscillation measurements may also be able to see the high energy solar neutrinos, ^{8}B and even perhaps the *hep* neutrinos. The ^{8}B observations would be interesting because they could provide a $\sim 3\sigma$ mesurement of the Day/Night effect, given the current best-fit value of the mixing parameters.

Table 1 summarizes the planned future solar neutrino experiments. In addition to future experiments making solar neutrino observations, there are also plans for more measurements of the solar nuclear reaction cross sections, by experiments such as LUNA and CLAIRE. These will help reduce uncertainties on the Standard Solar Model, turning the expected precision of the future solar neutrino experiments into real constraints on both solar energy generation and neutrino mixing.

5. Conclusions

While the goals of the solar neutrino program have changed due the great successes of the past decade, they have been replaced by many more compelling reasons to continue. Hopefully the next forty years of using neutrinos to study the Sun, and using the Sun to study neutrinos, will

Table 1. Summary of future solar neutrino experiments.

Experiment	Detection Detection Reaction	Targeted Solar νs	Technology	Other Physics	Status
KamLAND	$\nu + e \rightarrow \nu + e$	^{7}Be,CNO, *pep*	Liquid scintillator	Reactor $\bar{\nu}$s, geo-νs	Purification underway
SNO+	$\nu + e \rightarrow \nu + e$	CNO, *pep*	Liquid scintillator	$0\nu\beta\beta$, geo-νs	Engineering, purification
LENS	$\nu_e +^{115}$ In $\rightarrow$ $e^- + 2\gamma +^{115}$ Sn	*pp*,^{7}Be, *pep*	In-doped liq. scintillator	—	Prototype bkd studies
XMASS	$\nu + e \rightarrow \nu + e$	*pp*	Liquid Xe scintillation	$0\nu\beta\beta$, dark matter	800 kg stage in design
CLEAN	$\nu + e \rightarrow \nu + e$	*pp*	Liquid Ne scintillation	dark matter	0.1 and 1 ton engineering
MOON	$\nu_e +^{100}$ Mo $\rightarrow$ $e^- +^{100}$ Tc	*pp*,^{7}Be, *pep*	Scintillator/ fiber sandwich	$0\nu\beta\beta$	Prototype for $0\nu\beta\beta$
MUNU/TPC	$\nu + e \rightarrow \nu + e$	*pp*,^{7}Be *pep*,CNO	CF4 TPC	μ_ν (reactor)	μ_ν results, recon. studies
HERON	$\nu + e \rightarrow \nu + e$	*pp*	Cryogenic He scintillation	—	R&D complete, proposal ended
XAX	$\nu + e \rightarrow \nu + e$	*pp*	Liquid Xe, Ar scintillation	$0\nu\beta\beta$, dark matter	Design and simulation
Mega-H_2O	$\nu + e \rightarrow \nu + e$	^{8}B,*hep*	H_2O Cherenkov	p decay, long baseline	Design and simulation

be as productive as the first.

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