WHY DO SOLAR NEUTRINO EXPERIMENTS BELOW 1 MEV?[a]

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I discuss why we need solar neutrino experiments below 1 MeV. I also express my prejudices about the desired number and types of such experiments, emphasizing the importance of *p-p* solar neutrino experiments.

The great challenge of solar neutrino research is to make accurate measurements of neutrinos with energies less than 1 MeV. We need to develop experiments that will measure the the total flux, the flavor content, and the time dependence of the ^{7}Be neutrinos (energy of 0.86 MeV), and the total flux, flavor content, energy spectrum, and time dependence of the fundamental *p-p* neutrinos (< 0.43 MeV).

More than 98% of the calculated standard model solar neutrino flux lies below 1 MeV. The rare ^{8}B neutrino flux is the only solar neutrino source for which measurements of the energy have been made, but ^{8}B neutrinos constitute a fraction of less than 10^{-4} of the total solar neutrino flux.

The *p-p* neutrinos are overwhelmingly the most abundant source of solar neutrinos, carrying about 91% of the total flux according to the standard solar model. The ^{7}Be neutrinos constitute about 7% of the total standard model flux.

I want to express first my own views about what we should and should not emphasize in developing new experiments and then say a little bit about specific experiments.

Each of the measurable quantities for low energy solar neutrinos is important and can be used to constrain models of the neutrino and of the sun. In my view, too much emphasis has been placed in the past on trying to devise experiments that can do everything. I think we should be happy if a low energy solar neutrino experiment can measure any of the desired physical quantities accurately. For example, an experiment that is sensitive to time dependences need not necessarily measure a flux accurately. If an experiment measures a charged current rate, it does not need to provide detailed spectral information. We have to learn how to crawl before we try to run.

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We should aim at ultimately developing experiments with high statistical significance in order to refine the tests of solar models and neutrino oscillations. But, the first experiments do not have to have high counting rates, especially if they are modular and can demonstrate proof-of-principle.

The interaction cross sections must be known accurately, to a 1σ accuracy of $\sim \pm 5\%$ or better, if we are to have a measurement that is good to $\pm 10\%$. I think a 1σ measurement of the total rate, for ^{7}Be and for *p*-*p* neutrinos, that is at least as accurate as $\pm 10\%$ is necessary in order to make real progress. There is no reason to believe that we can rely on (p,n) measurements or nuclear model calculations to provide a determination of the absolute cross section to this accuracy. Instead, we must either make use of the related beta-decay process when available or carry out precise measurements with intense radioactive sources.

Solar neutrino experiments are all difficult and all take a very long time to carry out. It is tempting to say that a given part of parameter space is covered by a particular experiment and so we must design an experiment that tests an entirely different part of parameter space. I think this type of reasoning is dangerous, because the history of science shows that experimental results are misinterpreted or are misleading much more often than one would expect from the quoted errors. Moreover, the claim that two different experimental techniques measure the same quantity often rests upon a theoretical assumption, a theoretical model that itself requires testing.

We must have redundancy. We must have different ways of measuring the same quantities. The implications of the experimental results, for physics and for astronomy, are too important to depend upon single experiments.

A number of promising possibilities were discussed at the LowNu2 workshop. These include the BOREXINO observatory, which can detect $\nu - e$ scattering and is so far the only approved solar neutrino experiment that is both being built at full scale and that can measure neutrino energies less than 1 MeV. Other very promising experiments that were described at this workshop include CLEAN, GENIUS, HERON, KamLAND, LENS, MOON, and XMASS. After the workshop, Raju Raghavan[1] succeeded in demonstrating that one can build a stable In liquid scintillator that could potentially be used for a very low threshold $p - p$ solar neutrino detector (if one can overcome by coincidence and modular techniques the unfavorable raw signal to noise ratio of 10^{-11}).

We want to test and to understand neutrino oscillations with high precision using solar neutrino sources.

Magic things can be done with neutrino lines [2], like the 0.86 MeV ^{7}Be line. To make the magic work, one has to measure the neutrino-electron scattering rate (as will be done for the ^{7}Be line with the BOREXINO experiment), and also the CC (neutrino-absorption) rate with the same line (no approved experiment). Assuming there are no sterile neutrinos, one can then use the two measurements to determine uniquely the survival probability at a particular energy and the total neutrino flux. One can test for the existence of sterile neutrinos by measuring[2] the neutrino-electron scattering rate and the CC rate for both the 0.86 MeV and the 0.34 MeV ^{7}Be neutrino lines, but this is a tough job.

The time dependences, seasonal and day-night, of the observed event rates of the ^{7}Be neutrino lines will be valuable diagnostic tests of neutrino oscillation scenarios.

I believe that we have calculated the flux of *p-p* neutrinos produced in the sun to an accuracy of ±1%. This belief should be tested experimentally. Unfortunately, we do not yet have a direct measurement of this flux. The gallium experiments, which have played an enormously important role in understanding what is happening to solar neutrinos, nevertheless only tell us the rate of capture of all neutrinos with energies above 0.23 MeV.

The most urgent need for solar neutrino research is to develop practical experiments to measure directly the *p-p* neutrino flux, hopefully both charged current and neutrino-electron scattering, the energy spectrum, and the time dependences. An experiment, or a combination of different experiments, that measures the total flux of *p-p* neutrinos can be used to test the precise and fundamental standard solar model prediction of the *p-p* neutrino flux.

Figure 1 shows the calculated neutrino survival probability as a function of energy for three global best-fit MSW oscillation solutions. You can see directly from this figure why we need accurate measurements for the *p-p* and ^{7}Be neutrinos. The currently favored solutions exhibit their most characteristic and strongly energy dependent features below 1 MeV. Naturally, all of the solutions give similar predictions in the energy region, $\sim$ 7 MeV, where the Kamiokande, Super-Kamiokande, and SNO data are best. The survival probability shows a strong change with energy below 1 MeV for all the solutions, whereas in the region above 5 MeV (accessible to Super-Kamiokande and to SNO) the energy dependence of the survival probability is at best modest.

Measurements of both the CC and the neutrino-electron scattering rate of either the ^{7}Be or the *p-p* neutrinos will be extremely important. When combined, they can determine the total neutrino flux and therefore allow a direct comparison with solar model predictions. The same thing could be achieved by a neutral current measurement, although that may be more difficult to obtain in practice.

In the more distant future, we will want to measure the average energy and

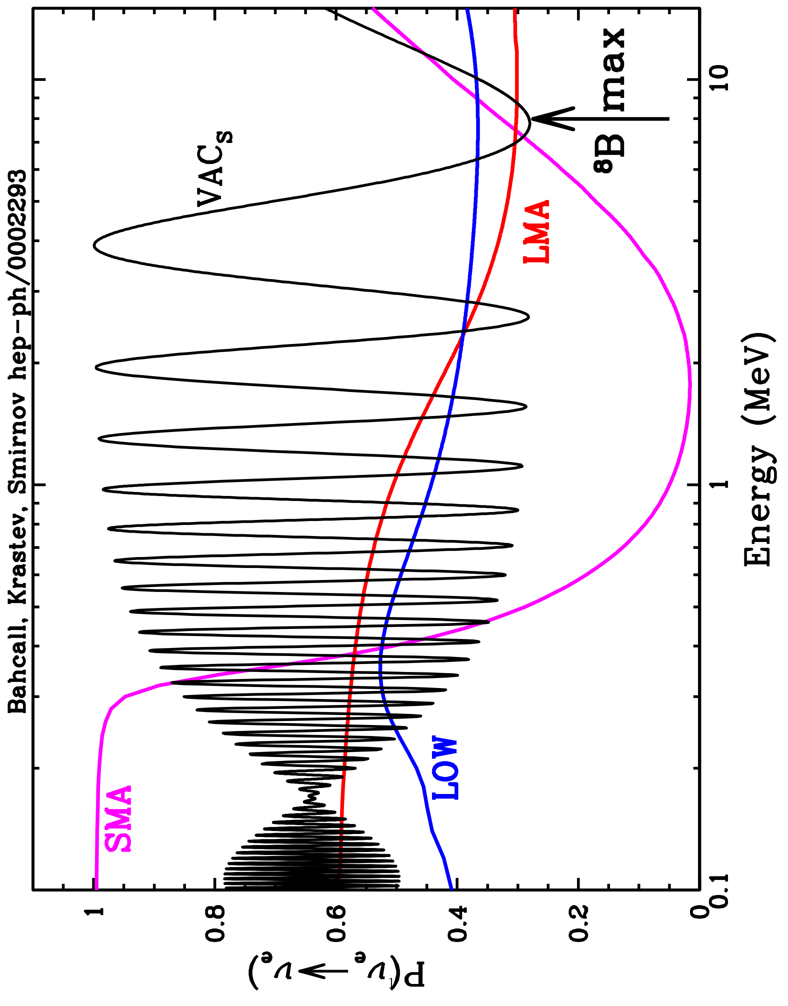

Figure 1: Survival probabilities for MSW solutions. The figure presents the yearly-averaged survival probabilities for an electron neutrino that is created in the sun to remain an electron neutrino upon arrival at the Super-Kamiokande detector.

shape of the ^{7}Be neutrino line with a precision better than 0.3 keV in order to obtain a direct determination of the central temperature of the sun. The standard solar model predicts that the average energy of the ^{7}Be neutrinos emitted from the sun exceeds by 1.3 keV the laboratory energy of the (higher energy) ^{7}Be line. This energy shift is due to the high temperature of the plasma in the region in which the ^{7}Be line is produced.

The *p-p* neutrinos are the gold ring of solar neutrino physics and astronomy. Their measurement will constitute a simultaneous and critical test of stellar evolution theory and of neutrino oscillation solutions.

No matter what we learn from experiments at higher neutrino energies, from the wonderful experiments of SNO and SuperKamiokande, we will still desperately want to measure the *p-p* neutrinos. The *p-p* neutrinos are a fundamental product of the solar energy generation process who flux is precisely predicted but not yet measured separately. The *p-p* neutrinos represent the dominant mode of neutrino emission from the sun, with a flux that is 10^4 times larger than the flux of the rare ^{8}B neutrinos measured by SNO and SuperKamiokande. Therefore, measurements of the *p-p* neutrinos will severely test theoretical ideas regarding both the interior of the sun and the nature of neturinos that are inferred from measurements of the less abundant, higher energy neutrinos.

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