Toward Future Solar Neutrino Experiments

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Abstract

A new generation of solar neutrino experiments has recently begun with the initial operation of the SuperKamiokande detector and will soon be joined with the expected completion of SNO and Borexino. These detectors will provide the first direct tests of spectral deformation and possible flavor non-conservation for neutrinos from the Sun. The discoveries by these three experiments will no doubt define what direction the field will take; however, the outlines of several desirable capabilities for future detectors are clear and they present significant technical challenges. This paper[1] presents a review of the several efforts known to the author which aim to offer answers to these challenges.

Introduction

The basic guidelines for this talk assume that the "future" refers to a period beyond that of SuperKamiokande, SNO and Borexino and further, since I know of no projects presently fully funded beyond those, that the "toward" in the title is to emphasize there are a large number of activities in progress aiming to provide capability for solar neutrino experiments beyond the present ones. I will mention at the conclusion the reason for my belief that there will likely be a need for a next generation. In that connection I would like to emphasize that all solar neutrino experiments are hard and that the future ones may be more difficult than the present and require new techniques, new ideas and optimism. The projects which represent these activities constitute a continuous spectrum ranging from ideas on which work is just beginning, on through active R & D projects, and on to large prototypes — some of which will be large enough to actually see solar neutrinos. Among the later are ICARUS, Iodine and GNO (Gallium Neutrino Observatory). Among the former there are six other projects. All nine projects are summarized in the Figure as to their locations in the energy spectrum and general reaction type. While I will briefly discuss all of them, in the interest of time and because the three large prototypes may be more familiar to you, I will give a bit more detail on the less familiar R & D projects. Also, most represent an important new thrust into lower energies and, largely, in real-time. For all I will try to give some flavor of the goals, techniques and status.

The Specific Projects

HERON & HELLAZ: These projects are both based upon the use of helium as the target medium but they have radically different approaches and somewhat complementary goals. Both will utilize the elastic reaction, $\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$, for real-time detection in the energy region dominated by the p-p and Be^7 neutrinos. They will both measure the energy of the recoil electron and the overall rate. Turning now to the contrasting specifics.

HERON: This project uses He^4 in its superfluid state[1]. For purity from radioactivity, liquid helium is an ideal

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target. It has no long-lived isotopes and is self-cleaning in that all other atomic species freeze out. It has a relatively high density (0.14 g/cc), is inexpensive and standard commercial procedures exist for handling it in bulk. Recoil particle detection occurs by making use of the very high multiplicity ($\sim 10^8$ for an 80 keV e^-) of energy carriers (phonons/rotons) generated by the recoil. A full scale detector would utilize a fiducial mass of 10 tons as a single volume (~ 4 meter cube) but with segmented readout external to the liquid. The operating temperature would be 30mK. The expected event rate would be 18 p-p and 7 Be^7 events/day in the standard solar model (SSM). Approaches to background suppression include exclusion of any other material in the helium, use of event position, topology, differences in mean-free paths, energy and possibly track orientation. Neutron shielding would be water external to the detector. Among the physics and technology R&D issues to be addressed are the physics of an entirely new way of particle detection, the level of sensitivity and resolution possible, backgrounds from containment and engineering challenges. The R&D carried out so far [1] includes demonstration of the validity of the basic physics detection processes in a 3 liter prototype, a new finding of scintillation and directionality for α tracks (now being tested for with e^-'s) , Monte Carlo and material tests of backgrounds; work is also underway on improvements of sensitivity and the design of a larger prototype with multiple segmented read-out.

HELLAZ: This project [2] will utilize helium in gaseous form under high pressure (8 atmos. and 100 K) yielding a 0.003 g/cc density. Detection would be via a large time projection chamber (TPC) immersed in the helium thus the detected carriers are the charges resulting from ionization ($\sim 10^3$ for 90 keV). The TPC would use a gas mix of helium and methane. With the TPC, full track reconstruction is aimed for to provide a very powerful signature when referred to simultaneous solar position. The 7 ton fiducial volume (25 m long x 10 m diam.) would produce 11 p-p and 3 Be^7 per day (SSM). Approaches to background suppression would include use of ultrapure materials in the TPC and specially purified methane, use of full track reconstruction (position, direction and energy); neutron shielding to be provided by a 77K CO_2 shield. Among the physics and technology R&D issues to be addressed are TPC operation in an unconventional pressure, temperature & mixture, drift dispersion over 10 m., backgrounds from components and engineering challenges. After some initial R&D at CERN a few years ago work is now resuming at FSU and WSU [2] on the construction of a 5 liter, high pressure, cold TPC where some of the issues related to TPC operation and drift dispersion will be addressed.

YBEX: This new effort [3] is intended to produce a real-time detector which would be flavor specific to ν_e's from the same portion of the spectrum sampled by Borexino — the line at $E_\nu = 862$keV; Borexino's events do not distinguishing among ν_e,ν_μ and ν_τ. (This function might conceivably be provided also to HERON or HELLAZ.) To achieve this, the scintillator would be loaded with Yb^{176} which is stable and has a 12% natural abundance. With a total Yb loading of $\sim$ 12% wt., a 100 ton detector is estimated to detect yearly rates (SSM) for p-p : Be^7 : p-e-p : N,O of 20: 183: 26: 106 with backgrounds (after cuts) of 0.7: 4: 8: 50. The initiating reaction is by inverse beta decay from the 0^+ to 1^+ excited states of Lu: $\nu_e + Yb^{176} \rightarrow e^- + (Lu^{176})^*$. The produced e^- has $E_e = E_\nu - 301$ keV. In addition to the produced e^-, there are γ's resulting from two decay channels: in one, a γ of 71.5 keV in 50 nsec while in the second a prompt 144.4 keV γ is produced also tagging the energy level. In order to defeat the enormous background without having to purify the scintillator to 10^{-16} g/g and make use of these nearly unique event signatures it is proposed to segment the detector into 132 physical modules and those further into smaller segments by relative timing and to require e^- and γ's to be in the same logical cell. A particularly important question as to the feasibility of the experiment concerns the determination of the presently unmeasured cross sections although estimates have been made [3]. R&D has only just begun with some successful tests of scintillator loading with Yb (Se^{82} and Gd^{160} will also be tried) [3]; an experiment to do a low energy, 0^o (p,n) cross section measurement has also been proposed.

Gallium Arsenide: This is perhaps the most ambitious project [4] and while it does not aim to be the "complete" solar neutrino detector it does give a measure of the task to realize a single detector more inclusive of reaction types and range of energies. Its principal aims are to make a model independent test of flavor non-conservation (including sterile ν's), to determine the precise energies and widths of the lines of Be^7(862keV), p-e-p(1.4MeV) and the end point of the p-p continuum using the three channels of elastic, charged current and neutral current scattering of ν's. Further, in the case of any observed flavor non-conservation, they wish to determine the MSW parameters precisely if that is the mechanism involved. To carry out such a program, a massive detector with ≤ 2 keV energy resolution is required. Their idea is to create a GaAs based, electronic, real-time detector. Gallium and arsenic are chosen because they have no long-lived isotopes or (n,γ) daughters and for the prospect of good resolution due to the high multiplicity of e-hole pairs and low noise when cooled. However, they estimate this would require a 125 tonne (60 t of Ga) in 40,000 hyperpure 3.2 kg segments. Among the primary reactions to be exploited are $\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$, $\nu_e + Ga^{71} \rightarrow e^- + Ge^{71}$ and $\nu_{e,\mu,\tau} + Ga^{71} \rightarrow \nu_{e,\mu,\tau} + (Ga^{71})^*$. Good resolution of the p-e-p and upper Be^7 line would be an important advance; however, a successful data analysis to achieve fully the above goals will be a very challenging one in that it relies upon use of the shape of the elastic differential cross-section to separate ν_e and $\nu_{\mu,\tau}$ as well as requiring a separation of the charged current p-p events. R&D on this project is just beginning. Extreme purity (from U,Th,K & C) of the GaAs as well as electronic performance for 3.2kg devices must be tested and assured. To this end, a 1kg boule of GaAs has been produced and preliminary tests of electrical properties appear promising.

Sodium Bromide : For completeness, mention should be made of a fully cryogenic project[5] which also aimed at exploiting the line spectra and upon which exploratory R&D has been carried out. The reaction was to have been $\nu_e + Br^{81} \rightarrow e^- + (Kr^{81})^*$ with delayed coicidence detection of the electron and de-excitation γ's. A precise determination of the event energy was to be achieved by phonon detection in a highly segmented crystal array at mK temperatures — a technique pioneered very successfully by this group for double-beta-decay experiments in other crystal types. The R&D on NaBr has not been promising; the thermal properties are much worse than expected. It is very difficult to grow large crystals and the signals are an order of magnitude too small. This work has ceased but is well summarized in [5].

Lithium: For some time, Li^7 has attracted interest as a radiochemical target with special relevance for the p-e-p and CNO neutrinos because the strength of the ground and first excited states can be accurately inferred from laboratory experiments [6]. The reaction is $\nu_e + Li^7 \rightarrow e^- + Be^7$ with a threshold of 862 keV. A particular challenge to the realization of a lithium-based detector has been the counting of the electron capture decays ($\tau_{1/2}$=53d) of the extracted Be^7 in which 90% go to the Li^7 ground state but produce an Auger electron of only 55 eV and is therefore not amenable to the usual proportional counter methods. Consequently, interest had centered on utilizing the decay to the first excited state by detecting the subsequent 474 keV gamma but, with only a 10% branching ratio, a 100 ton detector was required to achieve a rate of 0.5/day. Presently, a joint Russian-Italian project [7] is making interesting progress toward capitalizing on the use of the 90% channel thus obviating the need for so large a detector. In tests using cryogenic microcalorimeter techniques with accelerator produced samples of Be and BeO, they have detected Be^7 decays via the summed energy deposited by the Auger electron (55eV) and the recoiling nucleus (57eV) giving a well resolved peak at 112eV with a 24eV FWHM at $\sim$ 80% efficiency. The microcalorimeter consists of a 100x200x200 μm NTD thermistor at 45mK glued to the few μg sample. While further work along these lines is in progress, this result seems to establish feasibility of the method. Additionally, a prototype to hold 300 kg of liquid lithium has been constructed and they hope to fill it at Obninsk at the end of the year. Funds for this purpose have been applied for. The principal R&D work to be carried out with the prototype is study of the Be extraction process in forms most suitable for the microcalorimetry counting method.

GNO : The Gallium Neutrino Observatory [8] is designed to improve and extend the very successful gallium radiochemical technique. It is intended to do so in a phased approach during which the total mass in the target might eventually reach 100 tons. Among the principal goals are the long term ($\sim$ 11 year solar sunspot cycle) observation of the solar ν_e flux and significant improvement of the systemaic errors ($\leq 3\%$). The first phase, which could commence within the year with the original 30 tons and new counting electronics, is already fully approved. Proposals for $\sim$ 30 ton step-wise increments are expected later.

Iodine : This project [9] to build a 235 ton (100 tons of iodine from NaI in solution) prototype for a potentially much larger detector is already well underway. A radiochemical detector, it is similar to that of the pioneering experiment with chlorine but with important differences. Iodine is expected to have a significantly larger cross-section for ν_e, with different relative sensitivity to the Be^7 and B^8 fluxes and it is expected to be equipped with 12 hour cycling so that possible day-night flux variation could be tested for. The initiating reaction is $\nu_e + I^{127} \rightarrow e^- + (Xe^{127})^*$, Q = 662keV; however, transitions to the Xe ground state is forbidden but to the two, $3/2^+$ excited states at 125 and 322keV are allowed. The electron capture half-life of the extracted Xe^{127} is 36.4 days and proceeds 46% and 54% to excited levels in I^{127} yielding, respectively, γ's at 375 and 203keV. The counting signature would then be the post-electron capture Auger electron in coincidence with one or more of the γ's detected by additional NaI counters surrounding the proportional counter. This coincidence feature should provide an important control on backgrounds. Annual neutrino event rates are suggested to fall between 100 and 300 depending upon assumptions. Presently, 8 of the 10 tanks needed for the 100 ton experiment are in the mine at Homestake but are not yet fully installed nor filled. The processing and preparation of the NaI solution is projected to take six months. It is hoped that a major portion of the detector will be operating by year's end. Initially, the fast extraction system will not be implemented; however, it has been successfully tested in one module with a neutron source and found to give 99% recovery in 1 hour independent of source position. A major project to address the present lack of precise knowledge of the cross-sections to the excited states is under discussion with Russian colleagues. It is proposed to construct a 400kilo-Ci Ar^{40} calibration source to provide ν_e's of 814keV into a suitable test vessel; funds are being sought for this purpose.

ICARUS : As a step in the modular construction of a 6 kiloton proton decay detector, the first module (600 tons) to be installed in the Gran Sasso will, as part of its operational commissioning, be used in a solar neutrino experiment[10]. The target material is liquid argon (540 tons fiducial) in which the ionization products are drifted in a TPC and pattern recognition achieved by providing full track reconstruction of an event. Extensive R&D has been carried out with a 3 ton prototype. The primary goal is to search for direct evidence of ν oscillations in the B^8 flux by measuring the ratio of rates between the two channels: $\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$ and $\nu_e + Ar^{40} \rightarrow e^- + (K^{40})^*$, Q = 1.504 MeV. The threshold for the former is set by the minimum electron energy visible (expected to be $\simeq 4$ MeV) and for the latter by also reaching the Fermi level (F) at 4.384 MeV or by the various Gamow-Teller(G-T) levels below it. The signature for the $(K^{40})^*$ events will consist of an $E_e \geq 5$ MeV associated with one or more lower energy tracks (γ's) within a 50 cm sphere. Some discrimination can be made between the F and G-T transitions by the γ multiplicity. In a year, they expect a total of 290 elastic and 760 charge current (330 F and 430 G-T) events(SSM). Contamination from various other reactions appearing as the same event topologies are 18 "elastic" and 178 "charge current" (68 to F and 110 to G-T). Expected radioactive background is, respectively, 13 and 46 (3 and 43). A cone of 25^o is expected to contain 65% of the elastic angular distribution and will be used with the Sun's position in background reduction. The planned for location of the module, and its neutron shield, is Hall C in Gran Sasso with cool-down by the end of 1998.

Conclusions

We might reasonably ask how likely is it that one or more future experiments will be needed and to what extent can we foresee just what shape it or they might take. I believe it is highly likely there will be a long run of new experiments before the physics is fully understood. It now seems inescapable that the results we currently have on ν's from the Sun are not due to any experimental artifacts. The legacy from the elegant and careful work by Homestake, Kamiokande and GALLEX/SAGE is the possibility of entirely new physics. The present group of SuperK, SNO and Borexino will directly test this proposition but are unlikely definitively to provide all answers. Three possible outcomes seem reasonable to think about: a) "Smoking gun" = "evidence for spectrum deformation and neutral current" in which case, what are the full parameters? Are there 2 or 3 ν's involved? Is it MSW vs. vacuum oscillations? Is there a magnetic moment? Are there sterile neutrinos? or b)"Loaded but not smoking" = "e.g., clear spectral deformation but not yet neutral current evidence", in which case, what is(are) the source(s) of the solar ν problem(s)? Is it still new physics? Is it astrophysics? or c)"Entirely new surprises", in which case, what relation do they have to the new terrestrial experiments now evolving? Is it still new physics or astrophysics? The discoveries of SuperK, SNO and Borexino will indeed shape the details of what comes next. However, any detailed tests of the full spectrum, in real time and with reaction specificity await the capabilities sought by just such projects as those discussed here. They employ a rich, varied and imaginative range of new techniques and ideas to address hard problems. There is room for much optimism and for more new ideas as well.

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