Direct Approach to Resolve the Solar-Neutrino Problem

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A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

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The solar-neutrino problem, i.e., fewer neutrinos are assigned to the sun in the chlorine-argon radiochemical experiment of Davis and co-workers[1] than predicted by the standard solar model,[2] has prompted a variety of possible solutions ranging from neutrino oscillations[3] to a very large number of nonstandard solar models.[4] The neutrino-oscillation hypothesis postulates interesting new properties of the neutrino in order to decrease the electron-neutrino flux, but this hypothesis cannot be fully tested in experiments using terrestial neutrino sources. The nonstandard solar models were developed primarily to decrease the central temperature of the sun in order to suppress ^{8}B production. Then, the smaller number of ^{8}B-decay neutrinos would reduce the anticipated signal in the chlorine-argon radiochemical experiment. These possibilities have been discussed widely over the past decade, and the discussions continue. In the absence of further experimental information, there will not be a resolution to this problem.

The new radiochemical experiments—^{71}Ga,[5-7] sensitive to neutrinos from the *pp* reaction; ^{81}Br,[8] sensitive to the ^{7}Be-decay neutrino—and the geochemical experiment—^{98}Mo,[9] sensitive to the ^{8}B-decay neutrino flux averaged over the past several million years—have been widely discussed, and they will add to our knowledge when completed. However, these experiments address the problem indirectly because they detect neutrinos via the charged-current (CC) reaction, and thus have a sensitivity only to electron neutrinos.

An experiment which directly addresses the solar-neutrino problem should be sensitive to all neutrino species equally. Such a measurement could determine the total solar-neutrino flux *even if neutrinos oscillate.* At the low energies relevant for solar neutrinos, however, the only possible reactions are neutral-current (NC) reactions with nuclei since these NC cross sections are independent of the neutrino type. Note that the (ν,e^-) scattering reactions are not appropriate because the (ν_e,e^-) reaction, in the standard electroweak theory, has both CC and NC contributions that make its cross section about 6 times larger[10] than the other (ν,e^-) reactions.[11,12] Thus, a measurement of the CC and NC rates on a nucleus fixes the ν_e flux and the total neutrino flux, respectively. Measurement of the total neutrino flux tests the standard solar model independent of the neutrino-oscillation hypothesis and measurement of the ratio of the electron-neutrino flux to the total neutrino flux tests the neutrino-oscillation hypothesis[13] independent of the standard solar model.

The NC reaction on a nucleus is difficult to detect since the outgoing neutrino carries most of the available energy, especially at the energies relevant here. But one NC reaction, the neutrino disintegration of the deuteron, was observed some time ago with use of reactor $\bar{\nu}_e$'s by detecting the product neutron.[14] The neutron was seen by ^{3}He-gas proportional counters immersed in a tank of heavy water which provided the target deuterons.

Recently, the possibility of observing ^{8}B-decay solar neutrinos in a large heavy-water Cherenkov detector (1000 to 1500 metric tons) by use of (ν,e^-) scattering and the CC ν_e-d reaction was raised.[15] That this experiment can be seriously considered is a result of the successful operation of large light-water Cherenkov detectors built deep underground to search for proton decay.[16,17] The existence of many reactors with heavy water as a moderator, e.g., the Canadian deuterium uranium power reactors, provides encouragement that a large volume of heavy water could be made available for this purpose.

The CC reaction on the deuteron is relevant in the present discussion. The event rate can be calculated by use of the upper limit for the ^{8}B ν_e flux allowed by Davis and co-workers[1] and the theoretical cross section.[18] This reaction has been observed,[19] albeit with large errors. The expected rate is

$$R(\mathrm{CC}) = F(\nu_e)\sigma_{\mathrm{CC}}N_d = (2\times10^6\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1})\times(1.2\times10^{-42}\ \mathrm{cm}^2)\times(6\times10^{31}) = 12/\mathrm{kt\text{-}d}\ (\text{kiloton-day}),$$

where $F(\nu_e)$ is the ^{8}B electron-neutrino flux allowed by Davis, $\sigma_{\rm CC}$ is the average CC ν_e-d cross section, and N_d is the number of target deuterons per kiloton of heavy water. These CC events produce an electron which carries essentially all of the energy of the incident neutrino (minus the threshold energy). Thus about 70% of these events would be above 7 MeV.

The detection of such low-energy electrons using Cherenkov light in water is made feasible[20,21] by the development of large (20-in.-diam) photomultiplier tubes (PMT's)[22] for the Kamioka proton-decay experiment. These allow coverage of a large fraction of the surfaces surrounding the detector volume by photocathodes in order to maximally collect the small amount of Cherenkov light.

Considerations of backgrounds for this experiment led to a problem which is unique to heavy water, i.e., photodisintegration of the deuteron followed by neutron capture on a deuteron to produce a 6.25-MeV γ ray. These γ's would undergo either Compton scattering to produce an electron of up to 6 MeV or pair production to generate a background event. This mechanism for the production of a relatively high-energy γ from low-energy γ's (and from thermal neutrons) places a most severe constraint on the allowable radioactivity in detector materials.

On the assumption that such backgrounds can be reduced to the required level, then neutrino disintegration of the deuteron may be detected either via the same 6.25-MeV γ from neutron capture on the deuteron or by loading the heavy water. In order to detect these γ's, the heavy-water Cherenkov detector being considered will have to be more highly instrumented since several Compton electrons and/or an electron-positron pair would be produced and each electron (positron and γ) with less than 0.26 MeV kinetic energy would be below the Cherenkov threshold in water. It is also possible, if necessary, to enhance Cherenkov light detection by loading the heavy water with an appropriate wavelength shifter.[19] Besides increasing the number of photoelectrons produced in the PMT's of the detector, the isotropic light distribution from this wave-shifted light improves event reconstruction which, at these low energies, depends only on PMT position and event timing.

The neutrino disintegration rate of deuterons by ^{8}B-decay neutrinos in the standard solar model is

$$R(\mathrm{NC}) = F(^8\mathrm{B}) \times \sigma_{\rm NC} \times N_d = (4.6\times10^6\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}) \times (0.6\times10^{-42}\ \mathrm{cm}^2) \times (6\times10^{31}) = 14/\mathrm{kt\text{-}d},$$

where $F(^8\mathrm{B})$ is the expected ^{8}B neutrino flux from the standard solar model,[2] and $\sigma_{\rm NC}$ is the average NC deuteron disintegration cross section.[23] The fourteen neutrons will produce about eleven γ's of energy 6.25 MeV from deuteron capture with the remainder mostly captured[24] by ^{16}O or ^{17}O to produce a low-energy γ or an α, respectively. A small residual fraction of light water will further decrease conversion of the neutron to this high-energy (6.25 MeV) γ ray. However, appropriate loading of the heavy water could improve this detection efficiency back towards 14/kt-d. Alternatively, it is also possible to decrease the neutron detection efficiency in order to have less backgrounds for the CC ν_e-d reaction by appropriate loading of the heavy water, e.g., by ^{10}B.

Atmospheric-neutrino–generated backgrounds cannot be avoided. This flux has been measured by the proton-decay experiments with use of CC reactions[16,17] and these results agree well with calculations.[25] Thus, the atmospheric-neutrino flux is known and it is substantially lower than the solar-neutrino flux though much higher in energy. We note that the total atmospheric-neutrino CC rate is about 100/kt-d, i.e., much lower than the ^{8}B rates quoted above which are about 4000/kt-d.

Cosmic-ray- and radioactivity-induced backgrounds and many other questions relevant to a large heavy-water detector in an experiment to detect ^{8}B solar neutrinos via the (ν,e^-) and CC ν_e-d reactions are being fully addressed in a collaborative effort which has been underway since early this year.[26] If the NC ν-d reaction suggested here is to be used to detect ^{8}B solar neutrinos, a further increase in light detection sensitivity and in background reduction beyond that considered so far would be required.

However, detailed considerations suggest that there are no insurmountable problems, in principle, that would prevent such an experiment using this direct approach from resolving the solar-neutrino problem. In practice, the radioactivity-background problem is the most severe, though the use of water which can be continuously purified[27] and of acrylic which is made from highly processed polymers provides encouragement that the extremely low levels of radioactivity, which are required within the detector, can be achieved and maintained.

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