REVIEWS OF MODERN PHYSICS

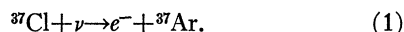# The Solar Neutrino Problem—
A Progress(?) Report

VIRGINIA TRIMBLE* AND FREDERICK REINES

Department of Physics, University of California, Irvine 92664

The conflict between observation and theoretical prediction of the flux of electron neutrinos from the sun has advanced in the past year from being merely difficult to understand to being impossible to live with. We review here attempts to explore the nature of the conflict, to seek possible ways out of it, and to inquire into additional experiments that have the capability either of resolving the conflict or at least of deciding which branch of physics or astrophysics is responsible for it.

I. INTRODUCTION—THE PRESENT PICKLE

Bahcall and Sears (1972) have reviewed the physics and astrophysics of neutrino production by the sun. Table I indicates the relevant nuclear reactions and their contributions to the neutrino flux at the earth's surface, according to a standard solar model. The last Column gives the predicted rates of capture of neutrinos from each reaction by chlorine-37 due to the reaction

$$^{37}Cl + \nu \rightarrow e^- + {}^{37}Ar. \qquad (1)$$

One SNU (solar neutrino unit) is 10^{-36} capture per second per ^{37}Cl nucleus. The dominant contributions are from the beta decays of ^7Be and ^8B, which are extremely sensitive to the central temperature of the solar model adopted. Since the preparation of that review, corrected solar opacity calculations by the Los Alamos group have reduced the total rate expected from 9.1 SNU to about 5.5 SNU (Bahcall, private communication).

The 0.5 SNU contribution from the $H + H + e^- \rightarrow D + \nu$ (*pep*) reaction and the CNO cycle is nearly independent of model temperature, and the 0.3 SNU from *pep* is also composition independent. For instance, if the interior of the sun contained no elements heavier than hydrogen and helium (thus reducing the opacity) or if the ^8B neutrinos just are not produced for some reason, then we would predict a capture rate of about 2 SNU. But if the sun produces its present luminosity at a constant rate through nuclear fusion processes, then at least the 0.3 SNU due to the *pep* neutrinos must be present.

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* Alfred P. Sloan Foundation Research Fellow.

We will see in Sec. II that a generous upper limit to the observed capture rate is 1 SNU. This is strictly inconsistent with the predictions of any solar model whose central heavy element content is the same as that at the solar surface and which is producing energy at a constant rate, provided that we have understood all the relevant nuclear and weak interaction physics. The critical problem is to determine whether the discrepancy is due to faulty astronomy, faulty physics, or faulty chemistry.

The situation has also been reviewed by Zatsepin (1972).

II. THE DAVIS EXPERIMENT—NO SNUS IS NOT GOOD SNUS

Davis and his colleagues have described their search for solar neutrinos, their results, and the prospects for further improving and checking the experiment (Davis, 1964; Davis, *et al.*, 1968, 1971; and Reines and Trimble, 1972, hereafter called RT72). The experiment is conceptually straightforward, but technologically very difficult. A 100 000 gallon tank of C_2Cl_4 is placed in a deep mine (to reduce cosmic ray backgrounds). Incident electron neutrinos with energies above 0.814 MeV can trigger (albeit with extremely low cross section) Reaction (1). About once every 100 days (^{37}Ar has a half-life of 35 days), 0.05 cm^3 of ^{36}Ar is introduced as a carrier and the tank swept with helium to remove the argon. The argon is adsorbed on charcoal and placed in a small proportional counter which distinguishes the Auger electrons produced by ^{37}Ar beta decay from background events in terms of both pulse height and pulse rise time.

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TABLE I. Solar nuclear reactions and their contributions to the neutrino capture rate.

Reaction and neutrino energy (MeV)	Flux on earth (ϕ in cm^{-2} sec^{-1})	Cross section (σ in cm^2)	Capture rate in ^{37}Cl ($\phi\sigma\times10^{36}$ sec^{-1})
H+H→D+e^++ν(0–0.42)	6.0×10^{10}	0.0 (below threshold)	0.0
H+H+e^-→D+ν(1.44) (*pep*)	1.5×10^8	1.72×10^{-45}	0.26
D+H→^{3}He+γ	...	...	...
^{3}He+^{3}He→^{4}He+2H (about 85% of the time)	...	...	...
^{3}He+^{4}He→^{7}Be+γ (about 15% of the time)	...	...	...
^{7}Be+e^-→^{7}Li+ν(0.86)	4.5×10^9	2.9×10^{-46}	1.31
^{7}Be+p→^{8}B+γ (about .05% of the time)	...	...	...
^{8}B→^{8}Be+e^++ν(0–14)	5.4×10^6	1.35×10^{-42}	7.28
^{7}Li+p→2 ^{4}He	...	...	...
^{12}C+H→^{13}N+γ	...	...	...
^{13}N→^{13}C+e^++ν(0–1.19)	3.3×10^8	2.1×10^{-46}	0.07
^{13}C+H→^{14}N+γ	...	...	...
^{14}N+H→^{15}O+γ	...	...	...
^{15}O→^{15}N+e^++ν(0–1.74)	2.7×10^8	7.8×10^{-46}	0.21
^{15}N+H→^{12}C+^{4}He	...	...	...

The chemical problem is to get a very small amount of ^{37}Ar (less than 100 atoms even if the capture rate is as large as predicted and the sample is allowed to build up to saturation) out of a very large tank of perchlorethylene. The efficiency of the recovery has been tested both by introducing a known amount of ^{36}Ar and sweeping it out again and by producing ^{37}Ar in the tank using a fast neutron source. The efficiency in these cases appears to be at least 95%. An additional test, in which a measured amount of C_2Cl_4 tagged with ^{36}Cl (which beta decays to ^{36}Ar with a half-life of 350 000 years) is introduced into the tank and the argon collected, is also planned. One should perhaps be concerned about the possibility of ^{37}Ar, which would be produced at lower kinetic energy by solar neutrinos than by the fast neutron source, being trapped chemically in the tank. Rowland has pointed out that, indeed, if you consider beta decays in methyl iodide, that the methyl xenon bond after the decay is stable only for those recoils with low energy, but that there are, of course, no argon compounds of any kind known. Additional tests of recovery efficiency have been suggested (RT72).

The proportional counters have been tested by counting a premeasured amount of ^{37}Ar. They record both pulse height and pulse rise time, and thus discriminate against background events with high efficiency.

The last five runs prior to the end of 1971 produced, respectively, about 8, 9, 3, 0, and 2 counts that could be attributed to ^{37}Ar, above the background left after several half-lives. A water shield was introduced around the tank between the third and fourth of these runs to reduce the background due to neutrons produced by radioactivity in the rock walls. The average of the last three runs amounts to a production rate of about 0.18 atoms per day in the tank. The production of ^{37}Ar by cosmic ray muon secondaries at the depth of the experiment in the Homestake Mine should amount to about 0.12 atoms per day. Ignoring the fast neutrons from the rock walls (which may contribute 0.04 atoms per day), we are left with 0.06 atoms per day above the background. If this is due to solar neutrinos, it is equivalent to 0.3±0.6 SNU.

The present experiment is not capable of measuring capture rates below 1 SNU because of uncertainties in the cosmic ray background, although improvement in statistics will occur with additional runs. It may be possible to scale up the present experiment by a factor of about ten, so that it would be capable of detecting one

pep neutrino per day. Such an experiment would have to be located at a depth of about 9000 m of water equivalent, more than twice the depth of the Homestake experiment, to control the cosmic ray background, and new records will have to be set in controlling neutron-producing contaminants. Unfortunately, such a scaled up detector would suffer from backgrounds arising from neutrinos of atmospheric origin.

III. THEORETICAL LOOPHOLES—
DESPERATE MEASURES

If the ^{37}Ar produced in the perchlorethylene tank is, in fact, being recovered with reasonable efficiency, then there must be a flaw somewhere in the calculation of the expected capture rate. The seriousness of the situation can be judged from the implausibility of the desperate measures discussed below. Three areas, nuclear physics, astrophysics, and neutrino physics, have been suggested as possible sites of the flaw. The most obvious explanation, that the cross section for Reaction (1) has been greatly overestimated can be excluded (Lanford and Wildenthal, 1972). Nor is there any way to destroy ^{7}Be or ^{8}B before they can beta decay, once they are formed (Parker, 1972).

Fowler and Tombrello have reviewed the calculation of the rates of the reactions in Table I (Fowler, 1972; RT72). There seem to be only two viable possibilities for significantly reducing the production of high-energy neutrinos. The rates of the reactions producing ^{7}Be and ^{8}B vary with temperature, T, roughly as T^7 and T^{20} respectively. If the real rate of $H+H\rightarrow D+e^++\nu_e$ (which appears impossible to measure in the laboratory) is much higher than has been calculated, the observed solar luminosity could all be produced at a low enough temperature that no ^{7}Be or ^{8}B is ever formed. There is no evidence that this is the case, although until quite recently the best calculated rate for $n+p\rightarrow d+\gamma$ was about 10% smaller than the measured value, and there is probably a small correction to the predicted neutrino capture rate from a similar effect in $p+p$ (Gari and Huffman, 1972).

Alternatively, if the real rate of ^{3}He$+^3$He$\rightarrow^4$He$+2$H is much larger than has been calculated (as an extrapolation of higher energy laboratory data), the competing reaction ^{3}He$+^4$He$\rightarrow^7$Be$+\gamma$ would never get a chance to take place, and only the *pep* and CNO neutrinos would be produced above 0.81 MeV. This requires that there be a strong, narrow resonance in the reaction cross section below the lowest energy (90 keV) at which measurements have been made. The optimum resonance would correspond to a 0^+ excited state of ^{6}Be with a width of about 10 keV and ~11.5 MeV excitation energy (i.e., about 20 keV above threshold for ^{3}He$+^3$He). States this narrow are not common, but do occur for ^{5}He and ^{5}Li. The 50-keV resolution at which the relevant range of excitation of ^{6}Be has been studied

(Mangelson, *et al.*, 1966) is not sufficient to exclude the existence of such a state.

In the realm of astrophysics, Iben (in RT72) has said that no solar model, with or without rotation, convection, or mixing could bring the predicted capture rate below 3 SNU. If, however, the solar system formed in such a way that all the heavy elements were confined to the planets and the outer layers of the sun, the resulting reduction in the solar opacity would lower our estimate of the central temperature sufficiently to yield a predicted capture rate of about 2 SNU.

Fowler (1972) and Cameron (RT72) have considered the possibility that the present solar central temperature is below its average value. Because photons take about 10^7 years to diffuse out through the sun, changes in the nuclear energy generation rate on time scales shorter than that would not be observable, except through the variable neutrino flux! Radial pulsations appear to be rapidly damped, and no suitable driving mechanism has been found. A sudden recent change in the solar structure is not so easily excluded. The center of the sun is thought to be only marginally stable against convection at the present time. The onset of convection after the sun had been burning hydrogen in its interior for most of its lifetime would greatly reduce the central mean molecular weight, and thus the central temperature and neutrino production rate. In addition, the mixing makes available additional ^{3}He at the solar center, which raises the burning rate and so expands the center, cooling it, and reducing the neutrino production rate.

Fowler (RT72) has quoted a suggestion by Clayton that the high-energy tail of the Maxwell–Boltzmann distribution of particle velocities might be less well populated than is usually supposed, thus inhibiting the reactions producing ^{7}Be and ^{8}B, for which the Coulomb barriers are higher than those for the other reactions of the pp chain.

Finally, we might suppose that, although the neutrinos are produced at more or less the predicted rate, they do not reach, or do not all reach, the terrestrial detector. The oscillatory process $(\nu_e\leftrightarrow\nu_\mu)$ suggested by Pontecorvo (1968) would reduce the capture rate by only about a factor of 2. If the neutrino, on the other hand, has a nonzero rest mass and decays (Bahcall, *et al.*, 1972), the flux at the earth's surface could be vanishingly small. Unpublished results of Gurr, Reines, and Sobel obtained at a fission reactor place the lifetime for decay into a lighter ν and a gamma ray, $\bar{\nu}_e\rightarrow\bar{\nu}'+\gamma$, at more than 10^5 times the eight minutes it takes light to travel from the sun to the earth, for the case in which $m_{\bar{\nu}'}/m_{\bar{\nu}_e}\ll1$.

Significant reductions could also be accomplished if the neutrino has a finite magnetic moment and rotates to an antineutrino in a strong solar interior magnetic field (Cisneros, 1971), or if [as Bahcall pointed out (RT72), quoting a suggestion by Regge] there is a

massive, uncharged boson that interacts only with neutrinos (with about 10^8 times the strength of the weak interaction). These bosons would be kept distributed throughout the sun by neutrino pressure, but the terrestrial supply, if any, would, of course, fall to the center of the earth. Any neutrinos reaching the earth's surface would, then, as a result of multiple scatterings, have energies well below the threshold for Reaction (1).

IV. PROPOSED EXPERIMENTS— ROOMSFUL OF RUBIDIUM

The possible future experiments range from work in progress to mere gleams in the principal investigator's eye, and make use of both terrestrial and astronomical sources of neutrinos. The existence of and cross sections for inverse beta decay and direct electron–neutrino scattering can be tested in a variety of ways. Reines and his co-workers have thus far set an upper limit to the direct scattering of electron antineutrinos by electrons of 1.9 times the V-A theory value of the cross section (Gurr, et al., 1972).

Chen has discussed experiments that might be performed at the Los Alamos Meson Production Facility when it becomes operational (RT72). LAMPF will produce a flux of electron neutrinos about the same size as that previously expected from solar ^{8}B decays, though at rather higher energy, as well as appreciable fluxes of both muon neutrinos and muon antineutrinos. Differences between the Weinberg (1967) theory and V-A as well as the $(\nu_e \leftrightarrow \nu_\mu)$ oscillation, which can introduce factors of 2 into the predicted solar neutrino flux, can therefore be tested.

Davis (RT72) has proposed a direct measurement of the cross section for the ^{37}Cl experiment [Reaction (1)] using the LAMPF neutrino beam. This will also test the form of the lepton conservation law.

Lande has also outlined a series of reactor and LAMPF experiments with the capability of testing the existence of direct electron–neutrino scattering and the form of the lepton conservation law (RT72). He pointed out that the ideal astronomical neutrino detector will give information on fluxes, energies, time of arrival, and direction of motion of the neutrinos, all with good signal to noise ratios. Only direct scattering, observed with a scintillation or Cerenkov counter can do this, even in principle. A large water Cerenkov counter has the potential of seeing a few solar neutrino events per day, if the flux is near the Davis upper limit, and should also be able to detect the pulse of neutrinos produced by a supernova event anywhere in our galaxy. Such a detector, which because of backgrounds and other problems might best be placed under the ocean, will have some angular resolution and sufficiently good time resolution to look for correlations of neutrino events with X-ray, optical, radio, and gravitational wave pulses.

A wide variety of direct counting and radiochemical experiments have been discussed by Evans and Kropp who considered respectively methods of detecting low-energy (pep and pp) and high-energy (^{7}Be and ^{8}B) solar neutrinos (RT72). Although there are a very large number of inverse beta decay reactions with thresholds below 1 MeV, the majority of them either produce an element which seems impossible to recover (e.g., one rare earth from another) or one which has an intolerably long lifetime against the beta decay which is used to detect it. The remaining six reactions, ^{87}Rb$(\nu, e^-)^{87}$Sr, ^{55}Mn$(\nu, e^-)^{55}$Fe, ^{71}Ga$(\nu, e^-)^{71}$Ge, ^{37}Cl$(\nu, e^-)^{37}$Ar, ^{7}Li$(\nu, e^-)^7$Be, and direct scattering in, e.g., xenon suffer from varying inconveniences in: (a) cost of chemicals required to produce useful counting rates (e.g., one count per day from pep neutrinos), (b) difficulty of recovery, (c) volume of the experiment, and (d) depth at which it must be placed in order to reduce backgrounds to a tolerable level. The most serious difficulties are cost for the ^{87}Rb experiment, iron contamination for ^{55}Mn, chemical recovery for ^{71}Ga, size of the experiment for ^{37}Cl, counting the product for ^{7}Li, and backgrounds for direct scattering. Lande (RT72) has also tabulated a series of radiochemical techniques suitable for searching for antineutrinos.

Lathrop described a radiochemical technique which provides time of arrival information (RT72). The target is a nucleus such as ^{116}Cd in which the induced beta decay (threshold 0.5 MeV) produces an unstable nucleus: ^{116}Cd$(\nu, e^-)^{116}$In$(e^- \bar{\nu})^{116}$Sn. The delayed coincidence between the two emitted electrons is then the signature of the event. The amount of target material required is in the tank car realm, as for the other techniques. The radiochemical experiment employing ^{7}Li was judged to be the most hopeful.

The experiments are thus of three types. Those sensitive only to a large ($\gtrsim 10^7$ neutrinos cm^{-2} sec^{-1}) flux of high-energy solar neutrinos will test the chemistry of the ^{37}Ar recovery in the Davis experiment, and thus our understanding of the detailed structure of the sun. Those which can detect lower energy solar neutrinos will test the fundamental idea that stars produce their energy by nuclear fusion reactions, assuming that we have correctly understood the physics of the weak interaction. Finally, the terrestrial experiments are aimed specifically at testing our understanding of neutrino physics.

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