SOLAR NEUTRINOS*

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INTRODUCTION

The topics to be covered are, in order: an overview of the subject of solar neutrinos, a brief summary of the theory of stellar evolution, a description of the main sources of solar neutrinos, a brief summary of the results of the Brookhaven ^{37}Cl experiment, an analysis of the principal new solar neutrino experiments that have been proposed, a discussion of how solar neutrino experiments can be used to detect the collapse of stars in the Galaxy, and finally, a description of how the proposed ^{71}Ga experiment can be used to decide whether the origin of the present discrepancy between theory and observation lies in our conventional solar models or our conventional physics.

The most important fact is that there is a serious discrepancy between the standard theory and observation.

Neutrinos can be used directly and quantitatively to test the theory of nuclear energy generation in stars like the sun. Of the particles released by the assumed thermonuclear reactions in the solar interior, only neutrinos have the ability to penetrate from the center of the sun to the surface and escape into space. Thus neutrinos offer us a unique possibility of "looking" into the solar interior.

The theory of stellar aging by thermonuclear burning is widely used in interpreting many kinds of astronomical information and is a necessary link in establishing such basic data as the ages of the stars and the abundances of the elements. The parameters of the sun (its age, mass, luminosity, and chemical composition) are better known than those of any other star, and it is in the simplest and best understood stage of stellar evolution, the quiescent main sequence stage. Thus an experiment designed to capture neutrinos produced by solar thermonuclear reactions is a crucial one for the theory of stellar evolution.

A number of exotic solutions to the solar neutrino problem, modifying either the physics or the astronomy (and in some cases both), have been proposed. Even if one grants that the source of the discrepancy is astronomical, there is no general agreement as to what aspect of the theory is most likely to be incorrect. As indicated above, many of the proposed solutions of the solar neutrino problem have broad implications for conventional astronomy and cosmology. Some of them would change the theoretical ages of old stars or the inferred primordial element abundances. On the other hand, modified theories of the weak interactions have been proposed in which neutrinos may disappear

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by mixing or decay in transit from the sun to the earth, but for which there are no terrestrially measurable consequences. It is conceivable that one of these modified theories of the weak interactions is correct and the standard solar model is not in conflict with observations.

STELLAR EVOLUTION

Table 1 summarizes the principles that are required for constructing solar models that are tested by solar neutrino experiments. There are many more things in stellar evolution theory, but they are not essential for understanding solar neutrino experiments, certainly not for the purposes of this talk.

The first principle is hydrostatic equilibrium, which in practice is used together with the special assumption of spherical symmetry. The second principle is that the energy source is postulated to be nuclear; the rates of the nuclear reactions depend on the density (ρ) and the temperature (T), and the composition (X_i). The practical part of this principle is that the rate at which the nuclear reactions produce energy when integrated over the whole sun is equal to the observed solar luminosity today. The "today" is an essential part of this principle.

The third principle is that the energy is transported from the deep interior to the surface via radiation and convection. In practice, for most (but not quite all) of the models, the great bulk of the energy is transported by radiation. The key quantities are the gradient of the temperature (dT/dr) and the opacity of the solar matter.

The assumption that the initial composition was uniform and is equal to the presently observed surface composition is closely related to the question of which opacity should be used. It is plausible that the surface composition has not changed much because of nuclear reactions since the sun was formed. It is not quite so obvious that nothing has been added to the solar surface since the sun was born. However, that is the assumption which is widely used throughout astronomy and is the basis for making the standard calculations.

The final principle is that the sun evolves because it burns its nuclear fuel. It has burned for something like 5 billion years so far. One mocks up this evolution by computing several quasistatic models which march along in time.

The bottom line of this brief course in stellar evolution is: within our store of observational information about stars, only the Brookhaven Chlorine 37 experiment of Ray Davis and his colleagues is inconsistent with the stand[illegible]ry of stellar evolution. It is the only place where we do not see a [illegible] out of observational difficulties unless we modify something among the basic assumptions.

NUCLEAR FUSION IN THE SUN

I shall now outline briefly the conventional wisdom regarding nuclear fusion as the energy source for main sequence stars like the sun. It is assumed that the sun shines because of fusion reactions similar to those envisioned for terrestrial fusion reactors. The basic solar process is the fusion of four protons to form an alpha particle, two positions (e^+), and two neutrinos (ν), that is, $4p \rightarrow \alpha + 2e^+ + 2\nu_e$. The principal reactions are shown in Table 2 with a column indicating in what percentage of the solar terminations of the proton-proton chain each reaction occurs. The rate for the initiating proton-proton (p-p) reaction, number 1 in Table 2, is largely determined by the total luminosity of the sun. Unfortunately, these neutrinos are below the threshold, which is 0.81 MeV , for the ^{37}Cl experiment. Several of the proposed new experiments, especially the ^{71}Ga experiment, will be primarily sensitive to neutrinos for the p-p reaction. The p-e-p reaction (number 2), which is the same as the familiar p-p reaction except for having the electron in the initial state, is detectable in the ^{37}Cl experiment. The ratio of p-e-p to p-p neutrinos is approximately independent of which model (see below) one uses for the solar properties. Two other reactions in Table 2 are of special interest. The capture of electrons by ^{7}Be (reaction 6) produces detectable neutrinos in the ^{37}Cl experiment. The ^{8}B beta decay, reaction 9, was expected to be the main source of neutrinos for the ^{37}Cl experiment because of their relatively high energy (14 MeV), although it is a rare reaction in the sun (see Table 2). There are also some less important neutrino-producing reactions from the carbon-nitrogen-oxygen (CNO) cycle, but we shall not discuss them in detail since the CNO cycle is believed to play a rather small role in the energy-production budget of the sun.

THE BROOKHAVEN SOLAR NEUTRINO EXPERIMENT

The Brookhaven solar neutrino detector is based on the neutrino capture reaction (refs. 1,2)

$$\nu + {}^{37}\text{Cl} \underset{\text{decay}}{\overset{\text{capture}}{\rightleftarrows}} {}^{37}\text{Ar} + e^- \qquad (1)$$

which is the inverse of the electron capture decay of ^{37}Ar . The radioactive decay occurs with a half-life of 35 days. This reaction was chosen for the Brookhaven solar neutrino experiment because of its unique combination of physical and chemical characteristics, which were favorable for building a large-scale solar neutrino detector. Neutrino capture to form ^{37}Ar in the ground state has relatively low energy threshold (0.81 MeV) and a favorable cross section, nuclear properties that are important for observing neutrinos from ^{7}Be , ^{13}N , and ^{15}O decay and the p-e-p reaction.

The ^{37}Cl reaction is very favorable from a chemical point of view. Chlorine is abundant and inexpensive enough that one can afford the many hundreds of tons needed to observe solar neutrinos. The most suitable chemical compound is perchloroethylene, C_2Cl_4 , a pure liquid, which is manufactured on a large scale for cleaning clothes. The product, ^{37}Ar , is a noble gas, which should ultimately exist in the liquid as dissolved atoms. The neutrino capture process produces an ^{37}Ar atom with sufficient recoil energy to break free of the parent perchlorethylene molecule and penetrate the surrounding liquid, where it reaches thermal equilibrium.

The Brookhaven ^{37}Cl detector was built by Davis deep underground to avoid the production of ^{37}Ar in the detector by cosmic rays. This was done with the cooperation of the Homestake Gold Mining Company (Lead, South Dakota), who excavated a large cavity in their mine (~1500 m below the surface) to house the experiment. The final detector system consists of an ~400,000 liter tank of perchloroethylene, a pair of pumps to circulate helium through the liquid, and a small building to house the extraction equipment.

A set of 39 experimental runs carried out in the Brookhaven ^{37}Cl experiment over the last 10 years show that the ^{37}Ar production rate in the tank is 0.50 ± 0.06 ^{37}Ar atoms per day (refs. 1,2,3). Even though the tank is nearly a mile underground, a small amount of ^{37}Ar is produced by cosmic rays. An evaluation of data obtained by exposing 7500 liters of C_2Cl_4 at various depths underground suggests that the cosmic-ray production rate in the detector may be 0.08 ± 0.03 ^{37}Ar atoms per day (refs. 2,3), Fireman's (ref. 4) measurements of the muon background using a ^{37}K detector suggest a background rate of (0.18 ± 0.09) ^{37}Ar atoms per day. If this background rate is correct, then there is no evidence for any solar neutrino detection beyond the 3-σ level of significance.

If the background rate determined from the C_2Cl_4 measurements is assumed, then a positive signal of (2.2 ± 0.4) SNU is inferred (refs. 1,2,3) ($1 SNU = 10^{-36}$ captures per target particle per second).

The predicted capture rates for one recently constructed solar model are shown in Table 3 (ref. 5). The results are expressed in terms of SNU's $= 10^{-36}$ captures per target atom per second, the characteristic counting rate for solar neutrino experiments. The neutrino absorption cross sections used to compute the rates given in Table 3 are from reference 6. The best values to use for various nuclear parameters is currently under investigation and the total predicted rate may well differ by as much as 1 to 1.5 SNU from the value of 7.8 SNU shown in Table 3 (and be as low as 5 SNU if the preliminary cross-section measurement of $^3He(\alpha,\gamma)^7Be$ by C. Rolf *et al.* is verified).

OBSERVATIONAL IMPLICATIONS

The ^{37}Cl experiment tests theoretical ideas at different levels of meaning, depending on the counting rate being discussed. The various counting rates and their significance are summarized in Table 4. It is obvious from a comparison of Table 4 with the experimental results given above that the value of 28 SNU's based on the CNO cycle is ruled out. More surprisingly, the best current models based on standard theory, which imply ~6 to 8 SNU's are also inconsistent with the observations. This disagreement between standard theory and observation has led to many speculative suggestions of what might be wrong. One such suggestion (ref. 7), that in the solar interior the heavy element abundance is at least a factor of 10 less than the observed surface abundance, leads to an expected counting rate of 1.5 SNU's (see Table 3), which is about as low a prediction as one can obtain from solar models without seriously changing current ideas about the physics of the solar interior. We note that present and future versions of the ^{37}Cl experiment are not likely to reach a sensitivity as low as 0.3 SNU, the minimum counting rate (from reaction 2 of Table 2) that can be expected if the basic idea of nuclear fusion as the energy source for main sequence stars is correct.

NEW EXPERIMENTS

Another experiment is required to settle the issue of whether our astronomy or our physics is at fault. Fortunately, one can make a testable distinction. The flux of low energy neutrinos from the p-p and p-e-p reactions (numbers 1 and 2 in Table 2) is almost entirely independent of astronomical uncertainties and can be calculated from the observed solar luminosity, provided only that the basic physical ideas of nuclear fusion as the energy source for the sun and of stable neutrinos are correct. If these low energy solar neutrinos are detected in a future experiment, we will know that the present crisis is caused by a lack of astronomical understanding. If the low energy neutrinos are absent, we will know that the present discrepancy between theory and observation is due at least in part to faulty physics, not just poorly understood astrophysics.

I have analyzed in detail the theoretical aspects of eleven experiments that have been studied by various experimental groups as possible new solar neutrino experiments (ref. 6). Those eleven proposed targets are listed in the first column of Table 5. I also list in the other columns the following information: (a) whether the total cross-section solar neutrinos can be calculated to an accuracy of at least ten percent; (b) whether something new will be learned about the solar interior, or neutrino physics, by performing the proposed experiment; and (c) whether (in my opinion) the experiment is feasible with current technology. A check mark (✓) indicates that the answer to the relevant question is affirmative; a negative answer is indicated by (X).

The detectors for solar neutrinos can be classified according to their relative sensitivity to different parts of the solar neutrino spectrum. Five of the experiments are primarily sensitive to ^{8}B neutrinos; these are ^{2}H, ^{37}Cl, ^{51}V, ^{55}Mn, and neutrino-electron scattering.

Four detectors, ^{71}Ga, ^{87}Rb, ^{115}In, and ^{205}Tl, are primarily sensitive to neutrinos from the proton-proton reactions. The expected capture rates for these detectors are practically independent of the astronomical assumptions that are made provided only that the sun produces, in a steady-state fashion and via the proton-proton chain, the energy that it radiates from its surface.

The p-e-p neutrinos (reaction 2, Table 2) are expected to make the largest single contribution to the capture rate of a ^{7}Li detector, even for the standard solar model. The observational results from the ^{37}Cl experiment show, moreover, that the higher energy ^{8}B neutrinos should contribute, for a ^{7}Li target, at most one-half the capture rate due to p-e-p neutrinos. Since the p-e-p neutrinos are as good a measure of the proton-proton reaction rate as are the p-p neutrinos, one can also classify the ^{7}Li detector as a p-p sensitive target. The ^{7}Li and ^{115}In targets share the property of being reasonably sensitive to more than one neutrino branch (the p-e-p, ^{7}Be, ^{8}B, and ^{15}O branches for the ^{7}Li detector; the p-p and ^{7}Be branches for the ^{115}In target). The p-p and ^{7}Be capture rates could be determined separately for the ^{115}In experiment since the energies of the individual electrons could be measured.

The ^{81}Br detector is primarily sensitive to ^{7}Be neutrinos.

The ^{115}In and neutrino-electron scattering experiments could in principle be used to measure the direction of the electrons that are produced and thus to establish that the incident neutrinos come from the sun.

In order for a solar neutrino experiment to be most useful, the absorption cross sections must be accurately known. Of the new targets discussed in this paper, only ^{2}H , ^{7}Li , ^{71}Ga , ^{87}Rb , ^{115}In , and neutrino-electron scattering satisfy this requirement. A new detector should also help discriminate between the possible explanations of the discrepancy between theory and observation in the ^{37}Cl experiment. Experiments with ^{2}H or neutrino-electron scattering are sensitive primarily to ^{8}B neutrinos, as is the ^{37}Cl experiment. In order to provide new information of astrophysical importance, these experiments must be sensitive to a ^{8}B flux that is significantly below that already reached by the Brookhaven ^{37}Cl experiment. There has not been a recent and detailed experimental feasibility study for the proposed ^{87}Rb experiment, perhaps because of the uncomfortably short lifetime (2.8^{hrs}) of the daughter nucleus, ^{87}Sr . If we set aside ^{87}Rb because of the absence of a feasibility study, then the preferred targets are: ^{7}Li , ^{71}Ga , ^{115}In , and either ^{2}H or electron scattering (if sufficiently sensitive).

There are four major neutrino branches that must be measured in order to carry out a program of neutrino spectroscopy of the solar interior. These branches are the p-p, ^{7}Be , ^{8}B , and ^{13}N + ^{15}O neutrinos. The future experimental solar neutrino program should include all of the preferred new detectors. The ^{71}Ga experiment is primarily sensitive to p-p neutrinos and the ^{37}Cl experiment to ^{8}B neutrinos. The ^{7}Li and ^{115}In experiments provide additional information about the ^{7}Be and ^{13}N + ^{15}O fluxes. Taken together, the results of the four experiments (^{7}Li , ^{37}Cl , ^{71}Ga , and ^{115}In) should allow us to solve for the parameters of the solar interior (temperature range density and composition). An ^{2}H or an electron-neutrino experiment should also be performed at some future date in order to check on the upper limit to the ^{8}B flux determined by the ^{37}Cl experiment. If a feasible experiment is proposed in which a ^{8}B flux as low as twenty percent of the prediction from the standard model could be measured then this would also be a preferred experiment since it would provide qualitatively new astrophysical information.

Either a ^{71}Ga or an ^{115}In experiment can distinguish between explanations that are based on presumed inadequacies in, respectively, the astronomical theory or the weak interaction theory provided only that the sun produces in a steady-state fashion the energy it radiates from its surface. A low counting rate in either of these experiments could also arise, in principle, if the sun is now in an abnormal phase in which its nuclear energy generation is much less than its surface luminosity. However, for most of the models of this kind that have appeared in the literature, the reduction in the counting rate of a ^{71}Ga or an ^{115}In experiment would not be nearly as great as is expected on either the oscillation or the decay hypothesis. Moreover, these latter two processes lead to specific predictions for the ^{71}Ga and ^{115}In experiments when combined with the results of the ^{37}Cl experiment.

THE ^{71}Ga EXPERIMENT

A preliminary background experiment has been completed with 1.3 tons of gallium and plans are underway for an approximately 10-ton calibration experiment to be performed in a mine in Tennessee using a strong (megacurie) radioactive source made in the reactor at Oak Ridge. This program involves an international collaboration (ref. 8) between Brookhaven National Laboratory, the Max-Planck Institute for Nuclear Physics at Heidelberg, the Institute for Advanced Study, and the Weizmann Institute.

STELLAR COLLAPSES

It is now generally believed by workers in the field that much of the potential energy which is released when stars collapse is emitted in the form of neutrinos (see, *e.g.*, refs. 9 and 10). The rate at which optically undetected stellar collapses occur in the galaxy is not known, but plausible estimates might vary from once a year to once in a hundred years. The solar neutrino experiments that have been discussed in this talk can all be used to detect occasional stellar collapses in the galaxy. In fact, I have even suggested that the exceptionally high result observed in Run 27 of the ^{37}Cl experiment might be interpreted in terms of a stellar collapse.

Using plausible parameters for the energy liberated in the form of neutrinos, I estimate (ref. 6) that stellar collapses can be detected to a typical distance of a few kpc with the proposed solar neutrino detectors. The specific values are: ^{7}Li (3 kpc), ^{37}Cl (4.5 kpc), ^{71}Ga ($\geq$ 0.3 kpc), ^{115}In ($\gtrsim$ 10 kpc), ^{2}H ($\sim$ 10 kpc), and neutrino-electron scattering experiments ($\lesssim$ 2 kpc).

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REFERENCES

1. Davis, R.: Proceedings of the Brookhaven Solar Neutrino Conference, vol. 1, 1978, p. 1.

2. Bahcall, J.N. and Davis, R., Jr.: Science, vol. 191, 1976, p. 246.

3. Rowley, J.K., Cleveland, B.T., Davis, R., Jr., Hampel, W., Kirsten, T.: The Present and Past Neutrino Luminosity of the Sun. BNL preprint, no. 27190, 1980.

4. Fireman, E.L.: 16th International Cosmic Ray Conference, vol. 12, 1979, Kyoto, Japan.

5. Bahcall, J.N., Lubow, S.H., Heubner, W.F., Magee, N.H., Merts, A.L., Argo, M.F., Parker, P.D., Rozsnyai, B., and Ulrick, R.K.: Phys. Rev. Lett., vol. 45, Sept. 15, 1980, pp. 945-948.

6. Bahcall, J.N.: Rev. Mod. Phys., vol. 50, 1978, p. 881.

7. Bahcall, J.N. and Ulrich, R.K.: Ap. J., vol 170, 1971, p. 593.

8. Bahcall, J.N., Cleveland, B., Davis, R., Jr., Dostrovsky, I., Evans, J.C., Jr., Fratti, W., Friedlander, G., Lande, K., Rowley, K., Stoner, D., and Weneser, J.: Phys. Rev. Lett., vol. 40, 1978, p. 1351.

9. Colgate, S. and White, R: Ap. J., vol. 143, 1966, p. 626.

10. Brown, G.E.: Comments on Astrophysics, vol 7, 1977, p. 67.

Table 1. Three-minute Course in Stellar Evolution Principle

Hydrostatic Equilibrium

Spherical Sun

Nuclear Energy Source

Energy Transport by Radiation & Convection

Uniform Primordial Composition = Surface Composition

Evolution (age = 5×10^9 yrs.)

BOTTOM LINE: Only ^{37}Cl Experiment Inconsistent with Standard Theory

Table 2. The Proton-Proton Chain in the Sun

Number	Reaction	Solar terminations (%)	Maximum Neutrino Energy (Mev)
1	$p+p \rightarrow {}^{2}H+e^{+}+\nu$	(99.75)	0.420
	or		
2	$p+e^{-}+p \rightarrow {}^{2}H+\nu$	(0.25)	1.44 (monoenergetic)
3	${}^{2}H+p \rightarrow {}^{3}He+\nu$	(100)	
4	${}^{3}He+{}^{3}He \rightarrow {}^{4}He+2p$	(86)	
	or		
5	${}^{3}He+{}^{4}He \rightarrow {}^{7}Be+\nu$	(14)	
6	${}^{7}Be+e^{-} \rightarrow {}^{7}Li+\nu$		0.862 (90%), 0.383 (10%) (Both monoenergetic)
7	${}^{7}Li+p \rightarrow 2\,{}^{4}He$		
	or		
8	${}^{7}Be+p \rightarrow {}^{8}B+\nu$	(0.02)	
9	${}^{8}B \rightarrow {}^{8}Be^{*}+e^{+}+\nu$		14.06
10	${}^{8}Be^{*} \rightarrow 2\,{}^{4}He$		

Table 3. Predicted Capture Rates for a Recently Computed Solar Model[5]

Neutrino Source	Capture Rate (SNU's)
p-p	0
^{8}B	6.3
PEP	0.2
^{7}Be	1
^{13}N	0.06
^{15}O	0.2
Total = 7.8 SNU	

Table 4. Significance of Counting Rates in the ^{37}Cl Experiment. One Solar Neutrino Unit (SNU) = 10^{-36} Captures per Target per Second.

Counting Rate (SNU)	Significance of counting rate
28	Expected if the CNO cycle produces the solar luminosity
7±1	Predictions of current models
1.5	Expected as a lower limit consistent with standard ideas of stellar evolution
0.3	Expected from the PEP reaction, hence a test of the basic idea of nuclear fusion as the energy source for main sequence stars

Table 5. Proposed Experiments

Target	Cross-Section	New	Feasible
^{2}H	✓	?*	✓
^{7}Li	✓	✓	✓(?)
^{37}Cl	✓	✓	✓
^{51}V	X	X	✓
^{55}Mn	X	X	✓
^{71}Ga	✓	✓	✓
^{81}Br	X	✓	✓
^{87}Rb	✓	✓	X(?)
^{115}In	✓(?)	✓	✓(?)
^{205}Tℓ	X	✓	✓(?)
ν_e-$\bar{e}$	✓(W-S)	?*	?

*New if ϕ (^{8}B) ~ 6 × 10^5 cm^{-2} sec^{-1} measurable