Neutrino Astronomy: Probing the Sun's Interior

Until very recently everything known about what goes on inside of the sun was based on observations of its surface. Astrophysicists speculated that the sun's energy was derived from nuclear transmutations deep within the solar interior. But under most circumstances the sun's interior cannot be observed because of its high density. It is opaque to most particles, including photons. By the time particles created near the sun's center do work their way to the surface, they no longer carry firsthand information about their formation. There is one exception—the elusive neutrino.

Neutrinos, which are massless and chargeless and travel with the speed of light, are created during weak decays of nuclei (beta decay) and of some elementary particles. They interact so rarely with matter that a beam of neutrinos can pass virtually unattenuated through the entire earth. Copious supplies of neutrinos, which are supposedly generated during nuclear transmutation in the sun, can easily escape through the solar surface and impinge on the earth in measurable quantities. They comprise about 3 percent of the energy released by the sun. Detecting neutrinos is not a simple matter. Yet after 4 years of effort, Raymond Davis, Jr., and his colleagues at Brookhaven National Laboratory believe that they have succeeded in recording signals that arise from solar neutrinos. Although their count rate is a trifle low compared with that expected from the best models of the sun, it should cause no serious theoretical problems. If substantiated by further work, the Brookhaven solar neutrino experiment will be the first direct evidence that nuclear transmutations are the internal source of energy in the sun.

Davis detected the solar neutrinos in a bath of 378,000 liters of tetrachloroethylene, C_2Cl_4, a fluid commonly used in dry cleaning. The apparatus was placed 1.48 kilometers down the Homestake gold mine located at Lead, South Dakota. The mile of rock above the detector absorbs cosmic rays which can produce false signals.

Neutrinos can easily penetrate the mine and, in most instances, pass straight through the tank of cleaning fluid. On rare occasions a neutrino will interact with the isotope chlorine-37 and transmute it to argon-37 and an electron. Depending on the neutrino's energy, the cross sections or reaction probabilities are in the range 10^{-46} to 10^{-42} square centimeter. Initial estimates of the neutrino flux indicated that about five argon-37 nuclei would be created daily. This argon isotope is radioactive with a half-life of about 35 days. Auger electrons, emitted after the decay of argon-37, can be detected when the radioactive gas is swept from the tetrachloroethylene; stable argon-36 is used as a carrier and large amounts of helium are used to purge both argon species from the fluid. Trial runs have convinced Davis that this technique recovers at least 95 percent of the argon. In practice he isolates about 25 atoms of argon-37 from a bath of 10^{30} atoms.

In his first results, which he published in 1968, Davis did not see a positive signal because of background events in the proportional counter used to detect the radioactive argon. Nonetheless, his upper limit for the neutrino flux was lower than that predicted by the theorists. Improved electronics eliminated some of the background problem, but the new rate of one solar neutrino count every 2 days is still low.

There are two plausible nuclear reaction chains which could be responsible for the production of energy in stars that are generally similar to the sun. Both of them consume hydrogen and produce helium; and both of them release neutrinos (Tables 1 and 2). The most likely sequence of reactions, according to current theoretical predictions, is the so-called "proton-proton chain." This mechanism is supported by the Brookhaven results in preference to the alternative series of reactions, the "carbon-nitrogen chain."

As is shown in Tables 1 and 2, neutrinos are emitted during four different reactions in the proton-proton chain. In the initial proton-proton interaction, a relatively low energy neutrino is released (0.42 megaelectron volt maximum energy). In the less common three-body reaction, or "pep" reaction, which occurs once for every 400 proton-proton reactions, the emitted neutrino carries more energy (1.44 Mev). This is important, as Davis' apparatus is most sensitive to those neutrinos with the highest energy. Furthermore, neutrinos with an energy of at least 0.814 Mev are needed in order to initiate a reaction with chlorine and thus to have a finite chance of creating argon. Consequently neutrinos from the proton-proton reaction go completely undetected. The most energetic neutrinos are emitted from boron-8, which is produced in a minor branch of the reaction chain. The detection of solar neutrinos only seemed possible after William A. Fowler of the California Institute of Technology, suggested in 1958 that boron-8 should be produced in significant amounts in the sun. The decay of boron-8 generates high-energy neutrinos which should have a relatively high probability of being captured by chlorine-37.

The most energetic neutrinos released in the carbon-nitrogen cycle have a maximum energy of 1.74 Mev from the decay of oxygen-15. These neutrinos and those from the beta decay of nitrogen-13 have sufficient energy to register signals in the large Brookhaven detector. The relative abundance of the various neutrinos from both reaction chains depends on details of the sun's interior. Factors such as the central temperature, the central density, and the primordial abundances of hydrogen, of helium, and of the other atomic elements are crucial parameters used in the calculations. Most of the theoretical work relating to the flux of neutrinos at the earth's surface and their subsequent interaction in the tetrachloroethylene was performed by Richard Sears and John Bahcall at the California Institute of Technology and by Icko Iben, Jr., at the Massachusetts Institute of Technology who revised and updated earlier calculations by Hans Bethe, Charles Critchfield, and Edwin Salpeter at Cornell.

The latest capture rate calculated for solar neutrinos depends on details of the solar model which is adopted, but the rate seems to be about 10×10^{-36} sec^{-1} per ^{37}Cl atom. The experimental value is about a factor of 6 lower at $(1.5 \pm 1.0) \times 10^{-36}$. If all the solar neutrinos were created in the carbon-nitrogen cycle, the capture rate should be about 35×10^{-36}. Thus less than

10 percent of the sun's energy appears to be supplied by this route. When Hans Bethe and Carl von Weizsäcker independently proposed the carbon-nitrogen cycle in 1938, there was a paucity of good data on nuclear cross sections. Now much better data are available, and, with the neutrino results, the carbon-nitrogen cycle is being pushed gently into the background. Prior to the neutrino experiment there was not much doubt that the proton-proton chain was the dominant source of solar energy. Experimental results serve to confirm these speculations.

In calculations using the proton-proton chain, the intensity of neutrinos from boron-8 decay is sensitive to the central temperature raised to approximately the 28th power. In most models of the sun the central temperature is taken to be about 15 million degrees. If the temperature were only 6 percent lower, or 14 million degrees, it would be sufficient to lower the theoretical neutrino capture rate to the same value as was measured by Davis. This would be a tidy solution, except for the fact that the central temperature of the sun is fixed by the physical conditions at the surface and by the laws of physics. The temperature is constrained by the sun's age, luminosity, mass, and radius. Fowler made an intriguing suggestion that reconciles the difference. It takes about 1 to 10 million years for heat and light to diffuse from the sun's interior to its surface. Thus the figure of 15 million degrees determined from the surface properties is characteristic of the central temperature of about 1 million years ago. On the other hand, neutrinos reach the earth about 8 minutes after they are created. Thus if the present central temperature is 14 million degrees, as is consistent with the neutrino flux, a decrease in the temperature of 1 million degrees over the past million years would solve the puzzle. Unfortunately, Fowler added, all present theories of stellar evolution predict that the sun's central temperature is increasing.

An equally imaginative explanation —although considered by many less likely—was advanced by V. N. Gribov and Bruno M. Pontecorvo of the USSR Academy of Sciences. They suggested that the electron neutrinos originating in the sun may transpose into muon neutrinos, which cannot react with the chlorine in the tetrachloroethylene. Neutrinos come in two kinds, as was shown in 1962, by Leon Lederman and his co-workers at Brookhaven.

Table 1. Sequence of events in the carbon-nitrogen nuclear reaction chain. ν, Neutrino; e, electron; p, proton.

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{}^{12}\mathrm{C} + \mathrm{p} \rightarrow {}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + \mathrm{e}^{+} + \bar{\nu} \quad (1.20 \text{ Mev maximum}) \\
\qquad\qquad\qquad + \\
\qquad\qquad\quad \mathrm{p} \rightarrow {}^{14}\mathrm{N} \\
\qquad\qquad\qquad\quad + \\
\qquad\qquad\qquad\quad \mathrm{p} \rightarrow {}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + \mathrm{e}^{+} + \nu \quad (1.74 \text{ Mev max}) \\
\qquad\qquad\qquad\qquad\qquad\quad + \\
\qquad\qquad\qquad\qquad\qquad\quad \mathrm{p} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He} \\
\qquad\qquad\qquad\qquad\qquad\qquad \cdots
\end{array}
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Table 2. Sequence of events in the proton-proton chain. d, Deuteron; e, electron; p, proton; $\bar{\nu}$, neutrino.

Reaction	Relative strength	Maximum $\bar{\nu}$ energy (Mev)
$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{d} + \mathrm{e}^{+} + \bar{\nu}$	400	0.42
$\mathrm{p} + \mathrm{e}^{-} + \mathrm{p} \rightarrow \mathrm{d} + \bar{\nu}$	1	1.44
$\mathrm{d} + \mathrm{p} \rightarrow {}^{3}\mathrm{He}$		
${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + \mathrm{p} + \mathrm{p}$	91	
${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be}$	9	
${}^{7}\mathrm{Be} + \mathrm{e}^{-} \rightarrow {}^{7}\mathrm{Li} + \bar{\nu}$		0.86
${}^{7}\mathrm{Li} + \mathrm{p} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$		
${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be}$	0.01	
${}^{7}\mathrm{Be} + \mathrm{p} \rightarrow {}^{8}\mathrm{B}$		
${}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + \mathrm{e}^{+} + \bar{\nu}$		14.06
${}^{8}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$		

Electron neutrinos are always associated with electrons, and muon neutrinos are associated with reactions of muons (particles that seem to be identical to the electron in every respect except that they are 207 times heavier). Gribov and Pontecorvo suggested that distances as great as that between the sun and the earth are necessary for the neutrino transformation to take place. This might explain why such an event has never been detected on earth.

The low neutrino rate may be a consequence of discrepancies in the nuclear reaction cross sections. All but one of the pertinent reactions were remeasured at the California Institute of Technology. According to Fowler, all of the measured cross sections seem to be in order. The one possible source of error in the chain is the very first reaction: proton + proton → deuteron + positron + neutrino. It has such a low cross section that it cannot be measured. Experimental determination of the less probable "pep" reaction is also ruled out. It would take 1 year of experimental effort to produce one proton-proton reaction on a conventional accelerator. Consequently physicists must rely on theory for information about this cross section. The reaction cross section depends on a parameter that is best determined from measurements of the free neutron's lifetime. A casual observer might think that the neutron's half-life of about 11 minutes is a very well-known quantity. Unfortunately this is not so. New measurements made in 1967 by C. J. Christensen and his colleagues at the Research Establishment, Risø, Denmark, gave a lifetime about 9 percent lower than the old value. This change decreased Bahcall's calculated neutrino capture rate by about 30 percent. New measurements under way in the United States and in Europe will hopefully resolve this point.

There are other uncertainties as well. New values for the relative abundance of hydrogen and other atomic elements in the sun, particularly iron, affect the calculated neutrino rate. One of the most difficult quantities to calculate is the opacity of the sun. If it is less than now thought, there would be little discrepancy between theoretical and experimental neutrino rates.

Exactly 50 years ago Sir Arthur Eddington speculated that stellar energy was released when hydrogen coalesces into helium. During the intervening half century the form of his hypothesis remained essentially unchanged, although different models were in vogue over the years. Although the details still need to be sorted out, for the first time the Brookhaven neutrino experiment allows physicists to "see" inside the sun and confirm theoretical ideas about its internal mechanisms.

—Gerald L. Wick