Engineering & Science
MAY-JUNE 1978

# The Case of the Missing Solar Neutrinos

by WILLIAM A. FOWLER

We live on planet earth, warmed by the energy of a nearby star, the sun. In its deep interior, nuclear fusion powers that star. At least, that is the conventional point of view. Fusion produces penetrating radiations but fortunately the nuclear radiations from fusion in the sun penetrate only a short distance from their place of origin before being changed into internal thermal energy. After perhaps as much as ten million years, this energy diffuses to the solar surface and is converted there into earth-warming light rays.

There is one exception. Certain types of elementary particles called neutrinos are also generated in solar fusion. They penetrate the one million kilometers of solar material and reach the earth in approximately eight minutes, traveling at the speed of light—except for one in 100 million neutrinos that is intercepted on the way to the surface of the sun. Each second, 60 billion neutrinos penetrate every square centimeter of the earth and pass on, just as they pass through the sun, without producing any damage.

That is what physicists and astronomers believe, but we have no positive proof, and, in fact, observations have not found enough of one rare type of neutrino, which we should be able to observe with sensitive detectors already in operation here on the earth. This is "The Case of the Missing Solar Neutrinos."

Briefly, the case is this. Raymond Davis Jr. of the Brookhaven National Laboratory, one of the greatest experimentalists in the world, observes at most only one-third as many neutrinos as theorists compute there should be, using the best physical model of the sun (we call it the standard model) plus numerical data from the Kellogg Radiation Laboratory at Caltech and other experimental laboratories around the world. The numerical nuclear data are almost entirely from Kellogg and are primarily the work of Professors Ralph Kavanagh and Thomas Tombrello and of Dr. Mirmira Dwarakanath, now at the Bell Telephone Laboratories.

I have to come clean with you right here: I'm not going to give you the solution because the case is still open. What fascinates us in the business is the possibility that the eventual solution may be new knowledge about the neutrinos or other elementary particles, or new ideas about the structure and evolution of the sun, or new knowledge about plasma physics in the solar interior. In any case it could be very exciting.

Why do we want to know about solar neutrinos? The sun is an enormous fusion reactor that converts light hydrogen into helium. We know that we will never be able to do that here on earth, but we may be able to convert heavy hydrogen into helium. If terrestrial fusion can be made to work, we will have an almost limitless supply of energy from the heavy water of the oceans if we wish to use it. The processes are different in detail, but the same in principle. We know that the fusion of light hydrogen in the sun produces neutrinos along with energy. Thus if we cannot find these neutrinos, it may mean that we do not understand solar fusion, and maybe not even the processes proposed for terrestrial fusion. No one really believes the puzzle is that serious, but all of us would breathe a lot easier if the neutrinos from the sun could be found.

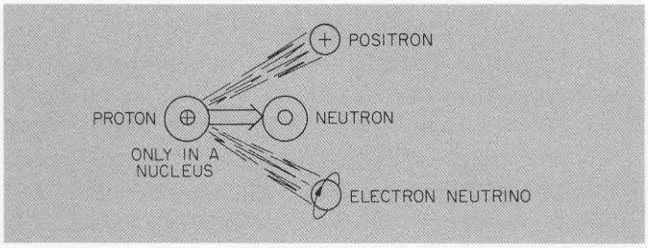
Much more important from the scientific standpoint is the fact that the neutrinos tell us what is going on in the interior of the sun essentially right now—just over eight minutes ago when they left the center of the sun. (The light from the sun tells us about its surface, not its interior, and the energy that was transformed into that light was generated many millions of years ago, even before the advent of humankind here on earth.) Moreover, the number of certain neutrinos we expect is very dependent on the central temperature of the sun. Thus neutrinos serve as a solar thermometer. Our theories, plus experiments we can make in the laboratory, tell us that the central temperature of the sun should be 15 million degrees Kelvin. Ray Davis and his neutrino observations indicate that this temperature is too high by more than a million degrees. Finally, all life here on earth depends on light and heat from the sun. Philosophically and aesthetically it would be very satisfying to understand in detail how that light and heat are being produced.

The first thing you can say about neutrinos is that they've got plenty of nothing. If we disregard the inevitable uncertainties in our experimental measurements, we can make some strong negative statements about neutrinos and their antiparticles, the antineutrinos. They have no mass, and in that they are like photons, the quanta of ordinary light. They have no electric charge, and they have no magnetic moment, so they have no electromagnetic interactions—unlike electrons, protons, and other particles. Furthermore, they do not take part in what we call the strong nuclear interaction—the interaction that holds the nuclei of atoms together, linking protons with neutrons.

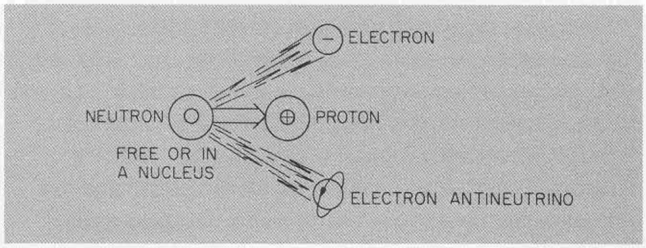
What properties do neutrinos have? Since they have no mass, they travel with the velocity of light, just like photons, and that is why it takes them only about two seconds to get to the surface of the sun and then 8 minutes and 20 seconds to get to the earth. They can carry momentum—that is, they can push other particles around. Because they don't take part in the electromagnetic and the strong nuclear interaction, they do this infrequently. They can carry energy, which means they can transform nuclei. They do take part in the weak nuclear interaction, and in that they are like electrons and muons ( the muons that Carl Anderson and Seth Neddermeyer discovered in the Bridge Laboratory at Caltech many years ago). Finally, they have rotation, or spin. Neutrinos are left-handed, which means that they spin while advancing like a left-handed screw. Antineutrinos are right-handed, and this is the way we tell the difference between neutrinos and antineutrinos. Neutrinos and antineutrinos are uncharged so it is not as easy to tell them apart as in the case of the electron, which is negative, and its antiparticle, the positron, which is positive. All we can use for the neutrino and the antineutrino, except for some other subtle effects in the weak interaction, is their direction or sense of spin.

How are neutrinos produced in the sun? The sun consists primarily of hydrogen, and the nucleus of the hydrogen atom is the proton. Due to the high temperature at the center of the sun, the protons are rushing madly about, and two protons can collide and fuse into a deuteron (the nucleus of an atom of deuterium, which is an isotope of hydrogen). In this collision, one of the protons transforms into a neutron (the neutral particle of practically the same mass as the proton), and the positive charge comes off as a positive electron, or positron. At the same time as the positron comes off, we know that a neutrino is given off and zips toward

**VARIETIES OF NEUTRINOS**

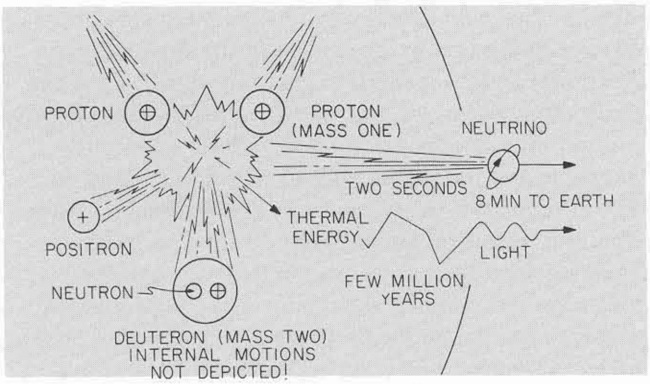



A proton in a nucleus transforms into a neutron and a positron plus an electron neutrino spinning in the left-handed sense relative to its direction of motion.




A neutron, free or in a nucleus, transforms into a proton and an electron plus an electron antineutrino spinning in the right-handed sense relative to its direction of motion.

**NEUTRINO PRODUCTION IN THE SUN
PROTON-PROTON REACTION**




This illustration (and the other similar diagrams) must not be taken too literally. The rapid internal motion of the neutron and proton in the deuteron is not depicted (even the "motion" is only a useful classical mechanics concept). The fact that the neutron and proton consist of Murray Gell-Mann's "quarks" or George Zweig's "aces" is ignored. These illustrations are only a form of "bookkeeping" for what goes into nuclear fusion and what comes out.

earth or out into space. We will dub this the proton-proton or pp neutrino.

After the fusion of light hydrogen into deuterium, what happens? The deuterons are also in violent motion because of the high temperature at the center of the sun, and they can collide with a proton and fuse, producing a nucleus with two plus charges—two protons—and a neutron. This nucleus has a mass three times that of the proton, and it has an electrical charge of plus two, so it is an isotope or form of helium and is called helium 3. Helium 3 is a very rare constituent of terrestrial helium, most of which is helium 4. The energy that comes off in the fusion of a deuteron with a proton to form helium 3 is gamma radiation, and it soon gets thermalized. No neutrino is produced in this.

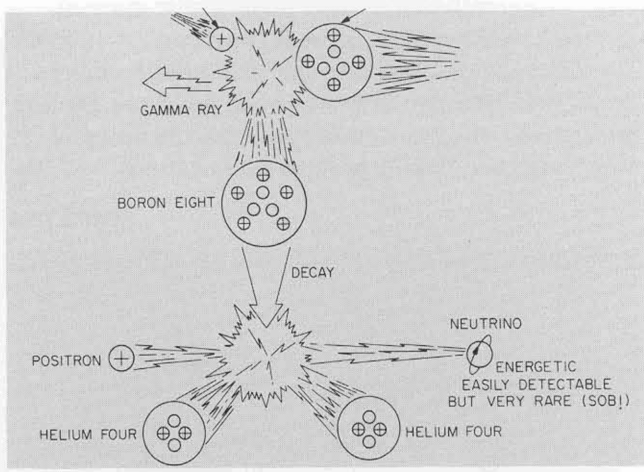
Of course, the helium 3's share in the motion, but laboratory measurements show that they cannot fuse with hydrogen. What does happen is that two helium 3's collide, with rather strange results. After the collision, there are six particles—two free protons that are very energetic, plus two other protons and two neutrons fused together to form a nucleus with charge 2 and mass 4. This is the normal, abundant isotope of the element helium. Overall, four protons have been converted into helium 4, and we get a positron and a neutrino every time a proton converts into neutrons. That happened twice in producing the two intermediate helium 3's, so we get two positrons and two neutrinos. That is, in the basic fusion process in the sun, 4 protons are converted into helium, 2 positrons, and 2 neutrinos.

That's not the whole story, because the helium 3 can also interact with the helium 4 to make a nucleus with mass 7 and 4 charges, which makes it an isotope of the element beryllium. We call it beryllium 7. In the process, a gamma ray is emitted and is transformed into thermal energy, but no neutrino is produced. However the beryllium 7 can capture electrons and give off neutrinos. Unfortunately the helium 3 interacts much more frequently with helium 3 than with helium 4 so the production and subsequent decay of the beryllium 7 happen relatively infrequently.

When an electron is captured by beryllium 7, one of the protons changes back into a neutron. The result is a nucleus of mass 7 and charge 3, which is an isotope of lithium. We call it lithium 7. Lithium 7 can capture a proton and transforms to two helium 4's. A large amount of thermal energy is produced but the main point is that in spite of all this complication the final result is the conversion of hydrogen into helium.

Thus beryllium 7 can capture an electron and give off a neutrino. It can do something else even more interesting. It can capture a proton to produce a nucleus of charge 5, which makes it an isotope of the element boron. The masses add up to 8, so we call it boron 8. Boron 8 is radioactive; it decays within a second or so, gives off a positron and a neutrino, and reverts to two of those ubiquitous helium 4's. The nice

**PROTON CAPTURE BY BERYLLIUM 7**




One way in which beryllium 7 interacts in the laboratory and in the sun. The radioactive nucleus boron 8 is produced and subsequently decays with the emission of the most easily detectable neutrinos from the sun.

things about these neutrinos is that they are very energetic, and are thus easily detected. The not-so-nice thing is that they are very rare.

The point of all this story is that there is competition in the nuclear reactions. The competition is expressed as the ratio of these processes—whether helium 3 interacts with another helium 3 or with a helium 4, or whether beryllium 7 interacts with an electron or with a proton. Those competition ratios—the relative frequencies with which each of these interactions occur—are very sensitive to temperature, and we have no way of calculating accurately what the ratios should be. Measurements must be made in the laboratory. In Kellogg, protons, deuterons, helium 3 nuclei, and helium 4 nuclei are accelerated to high energy in electrostatic accelerators and are then shunted through high vacuum systems to an observation room where they are allowed to impinge on a target. With sensitive detectors we study the reactions that take place. We are able to duplicate—one at a time, mind you—the very processes that are going on in the center of the sun. The laboratory measurements show that the rates at which the processes occur increase rapidly as the energy of the accelerated particles is increased. This translates into a rapid increase with increasing temperature in the sun.

To capture the elusive neutrinos, Ray Davis uses the chlorine-argon technique. The target for capturing the neutrinos is the heavy form of chlorine, which has a mass 37 times that of hydrogen—it is called chlorine 37. Since chlorine is a gas—and not a very pleasant one—perchloroethylene, ordinary cleaning fluid, is used in Davis's experiment. It is a molecule consisting of two carbon atoms and four chlorine atoms. One of the four chlorine atoms is chlorine 37. When a neutrino from the sun hits the clorine 37, it knocks out an electron and transforms the chlorine 37 into argon 37, which is a radioactive isotope of the rare gas, argon.

The argon 37 is ejected from the perchloroethylene molecule and soon forms a neutral atom surrounded by orbital electrons. It decays with a half-life of 35 days by capturing one of these orbital electrons and ejecting a neutrino and is transformed back into chlorine 37. This would seem to put us back on square one, but the important point is that the chlorine 37 atom is produced in a highly excited state. In the de-excitation process the chlorine 37 ejects one of its orbital electrons. This orbital electron has enough energy that it can produce ionization in what is called a proportional counter. This ionizing event can be recorded electronically and thus the decay of each argon 37 can be counted. Each argon 37 decay so counted is an indication that a chlorine 37 atom in the perchloroethylene has previously captured a neutrino.

Because Davis needs an enormous number of targets to capture the elusive neutrinos, he uses a tank that holds about 100,000 gallons of cleaning fluid in a chamber about a mile deep in the Homestake gold mine in South Dakota. The reason for going into the mine is because on the surface of the earth the cosmic rays that bombard us all the time can transform the chlorine into argon, just like neutrinos can. Terrestrial rocks absorb the cosmic radiation so it is necessary to go deep enough in a mine to reduce the cosmic ray effects below those expected from the solar neutrinos.

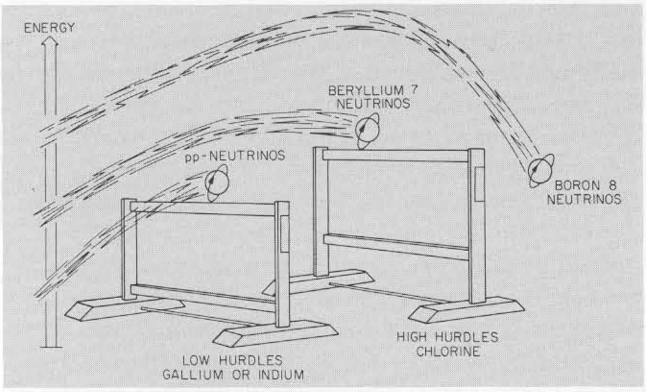
How does Davis get the argon out of the perchloroethylene and into a counter? First of all he introduces a non-radioactive form of argon, either argon 36 or argon 38, into his tank so that he has a reasonable amount of argon gas to work with. The few atoms of argon 37 produced by solar neutrinos mix with the inert argon. He flushes helium through the perchloroethylene about once a month. The helium bubbles collect the argon. He pipes the argon-laden helium over a cooling trap and, because argon freezes out at a higher temperature than helium, he can collect the argon in the trap and separate it from the helium. He heats up the argon and introduces it as a gas into a proportional counter and counts the argon 37 decay events for several months. He thus obtains a measure of how many chlorine 37 atoms in the perchloroethylene in the tank have been transformed into argon 37 by neutrinos.

By a number of clever tests using radioactive argon and chlorine, Davis has shown that he is able to recover argon 37 quantitatively from the perchloroethylene. He is then able to translate his measurements into the flux of neutrinos passing per second through each square centimeter of projected area of his tank. In doing this he uses a large body of theoretical and empirical information on the weak nuclear interaction that has been applied to the chlorine 37-argon 37 transition, largely by John Bahcall, once at Caltech but now at the Institute for Advanced Study in Princeton. It is of course an *assumption* that the neutrinos are from the sun. If the neutrino flux he does detect is from some other source, then the case of the missing solar neutrinos is even more puzzling.

At this point, it is necessary to discuss the predictions of the standard model of the sun. Of course, many sophisticated theoretical considerations enter into this model, but for our purposes the main point is that the sun is clearly in a stable situation—in spite of the fact that enormous gravitational forces are tending to collapse it. In the standard model, it is gas pressure outward that is in balance against the inward-directed gravitational forces. This is just like the gas pressure in an automobile tire that holds the tire from collapsing. The most important thing from our point of view is that the pressure in the sun is proportional to the temperature—also just like in a tire. Suppose you measure the pressure when the tire is cold and you obtain 20 pounds per square inch. You drive the car for a while and the tire gets hot. If you measure the pressure then, it is perhaps 25 pounds per square inch. It turns out that the necessary temperature for the standard model of the sun is 15 million degrees Kelvin.

What are the predictions of the standard solar model for the proton-proton neutrinos, those that are emitted in the primary fusion process that produces deuterium? We are interested in their flux; that is, the number that hit every square centimeter of the earth every second. The standard model yields a flux of 60 billion per square centimeter per second. Actually this result is practically model-independent. It is much the same for all solar models, provided the assumption is made that the sun is powered by the fusion of hydrogen into helium. One knows the energy flux in sunlight at the earth. The fusion of four protons into helium 4 yields a known amount of energy plus two neutrinos. The calculation is straightforward, and the result is

**THE NEUTRINO HURDLES**




The proton-proton, or pp, neutrinos cannot get over the high energy hurdle in chlorine 37 but can get over the low energy hurdle in gallium 71 or indium 115.

60 billion neutrinos per square centimeter per second at the earth.

How many capture events per month should Davis get in his 100,000 gallons of perchloroethylene from this enormous neutrino flux? Unfortunately, none! The reason is that the energy hurdle in the transformation of chlorine to argon is too high for the proton-proton neutrinos to get over it. They do not have enough energy. The beryllium 7 neutrinos can just barely make it, while the boron 8 neutrinos, which have greater energy, can go over the hurdle easily.

The predictions for the beryllium 7 and boron 8 neutrinos are very dependent on the temperature calculated for the center of the sun and are thus very model-dependent. The standard model yields a central temperature of 15 million degrees and corresponding to this a beryllium 7 neutrino flux of 4 billion per square centimeter per second at the earth. These neutrinos just barely surmount the chlorine-argon energy hurdle, and they result in only five capture events per month. The standard model yields a boron 8 neutrino flux of only 3 million per square centimeter per second, but with their larger energy a much greater fraction surmount the energy hurdle and produce 20 capture events per month. Thus Davis should be observing a total of 25 capture events per month with a statistical uncertainty or standard deviation of plus or minus 8. What he has observed in approximately 30 observational runs since 1970 is an average, *above known background,* of 9 capture events per month with an uncertainty of plus or minus 2. In other words Davis observes about one-third of the counting rate predicted by the standard model.

There is very small probability that this discrepancy is a statistical one. If this possibility is ignored, the results would seem to indicate the standard model is faulty. Thus other models have been developed, and everybody and his brother in the business has one. Many of the variants suggest that the central temperature of the sun is lower than 15 million degrees since that decreases the predicted flux of the temperature-sensitive beryllium 7 and boron 8 neutrinos. The necessary lowering is relatively small but is still a million degrees or more, and the variant model must compensate for this decrease in central temperature and the consequent decrease in pressure or otherwise the sun will collapse. This it is obviously not doing!

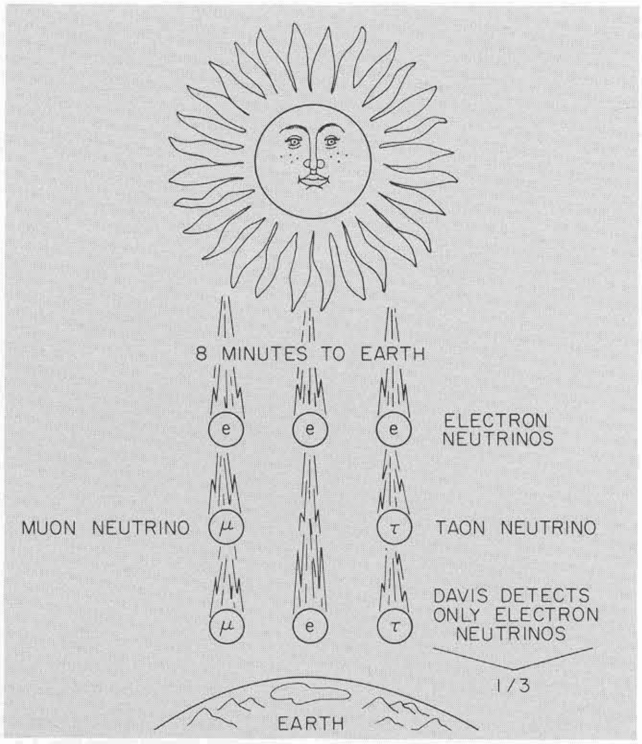
All of these variant models basically attempt to maintain the sun's stability against gravitational collapse in spite of a lower central temperature and pressure. One model assumes rapid internal rotation, so that centrifugal force due to rotation keeps the sun from collapsing against gravity. If this is indeed the solution, the sun should have an oblate shape; it should be bigger at the equator than it is at the poles. And although some observations by Robert Dicke of Princeton University indicate that there may be a very small solar oblateness, other measurements show there is none.

Another model postulates a high internal magnetic field. Magnetic fields can withstand compression and can withstand the forces of gravity. But again oblateness should result. It is true that one can conjecture a very exotic internal magnetic field, especially combined with rotation, to remove oblateness. However, large magnetic fields in the center of the sun would reside in a bubble where the density is lower than that of the surrounding material. Eugene Parker of the University of Chicago and an alumnus of Caltech, has shown that such a magnetic bubble will rise within a few million years. Thus it is impossible to maintain the large magnetic field necessary to cure the solar neutrino problem.

There are many other models, but all of them raise more questions than they solve. So we have begun to think that perhaps there is another avenue for understanding the case of the solar neutrinos. And that is through a question concerning the properties of the neutrinos themselves.

We know there are other kinds of neutrinos than the electron neutrinos that are produced in the sun. For example, there are neutrinos that are associated with the muons. Just recently at Stanford another new elementary particle has been discovered—the taon—and there should be a neutrino associated with it. So we know that there are at least two kinds of neutrinos, those associated with electrons and the muons, and perhaps a third kind, the taon neutrino. Many years ago Pontecorvo, the once Italian, now Russian, physicist suggested that, in the eight minutes it takes to get from the sun to the earth, electron neutrinos might transform into muon neutrinos, and this transformation can be extended to taon neutrinos. Work by John Bahcall and Steven Frautschi, professor of theoretical physics at Caltech, and by Mann and Primacoff of the University of Pennsylvania and many others has shown that when this transformation occurs it is possible, starting with one kind of neutrinos, to wind up with an equal number of all three. This is an extreme but possible result. In

**TRANSFORMATION OF NEUTRINOS**



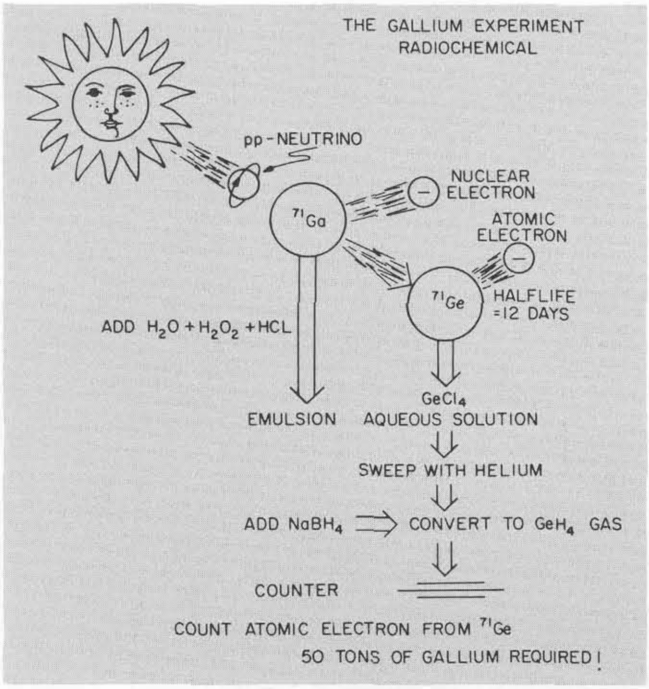

If three electron neutrinos transform on the way from the sun to the earth into one muon neutrino and one taon neutrino, leaving one electron neutrino, then the results of the Davis chlorine-argon observations are explained. This is an intriguing possibility, but is viewed with great skepticism by many elementary particle theorists.

this case, what happens to three electron neutrinos starting off from the sun? One turns into a muon neutrino, one turns into a taon neutrino, and one survives as an electron neutrino. But Davis's techniques can only detect electron neutrinos. It's almost too good to be true—one out of three survives, and we get just one-third the number of capture events we expect, which is what Davis observes.

There's a great deal of skepticism about this idea, but many accelerator and reactor laboratories are planning experiments to test it. Felix Boehm, professor at Caltech, is now engaged in an experiment in Grenoble, France, in which he is actually looking for the transformation of electron antineutrinos coming out of a reactor into muon antineutrinos and perhaps taon antineutrinos.

A promising lead in the case of the missing solar neutrinos is to make a search for the proton-proton neutrinos. In the transformation of gallium 71 into

**THE GALLIUM EXPERIMENT**




The gallium 71-germanium 71 transformation can be used to detect the model-independent flux of pp neutrinos from the sun. It is a costly experiment that has been shown to be technically feasible in small-scale tests by Ray Davis and his collaborators at Brookhaven.

germanium 71, the energy hurdle is low enough for the proton-proton neutrinos to be effective. When gallium 71 captures a neutrino, it gives off an electron. This transforms it into germanium 71, which is radioactive just like argon 37 (except that its half-life is 12 days), and its decay produces an atomic orbital electron, which can be detected in a counter.

Gallium is a metal, and at room temperature it is a solid, but at just slightly above room temperature it is a liquid. The germanium 71 can be transformed by chemical treatment into germanium tetrachloride, a gas, which can be swept up by helium out of liquid gallium. After separation from the helium it can be converted into a combination of germanium and hydrogen, called germane, which is like methane with carbon replaced by germanium. Germane can be introduced into a proportional counter, and one has a measure of the proton-proton neutrinos from the sun. The only catch is that some 50 tons of gallium are required, and the present world production of gallium is only about 7 tons a year. (The yearly production in the Soviet Union is unknown.) Gallium is a fairly rare element that occurs in bauxite (from which we get aluminum). In the form of gallium arsenide it is used in the light-emitting diodes in pocket calculators. It is also beginning to be used in the magnetic memories of big computers, so the production is increasing. Fifty tons of gallium is not available now, but there is the possibility that this experiment can eventually be carried out by Davis and his colleagues at Brookhaven.

It is a crucial experiment because it can detect the basic proton-proton neutrinos if the sun produces them. A group at the Bell Telephone Laboratories is planning an indium-tin experiment that can also detect the proton-proton neutrinos. If the sun is powered by hydrogen-into-helium fusion, then we know the flux of these neutrinos at the earth—quite independently of our models of the solar structure. If the gallium (or indium) experiment finds nothing, then we will know the sun is not powered by fusion—and that would really throw us for a loop. If the gallium experiment yields one-third of what we expect, it will be strong evidence—not conclusive, but strong—that electron neutrinos transform in part to other types of neutrinos on their way from the sun to the earth. If the gallium experiment yields close to the full value of what we expect, then we will know from the chlorine experiment that our standard model of the sun is wrong, and we must go to some other model regardless of the consequences to our ideas. That is a strong statement. It may be that we just do not understand all the physics of the solar plasma (plasma is an almost completely ionized but neutral form of matter).

This is the end of the line. This scientific detective has reported on the still-unsolved case of the missing solar neutrinos. The only solution seems to be new experiments and observations, which will be long and difficult and costly. It must be clear that I think it would be a good investment. The new experiments promise to tell us whether we really understand the structure and the internal operation of our star, the sun. If it turns out that our understanding is correct, then the sun will have been telling us all these years that those elementary particles, the neutrinos, have fascinating transformation properties that we can look for in terrestrial experiments at the big accelerators and reactors. In any case, it's a sure way to new knowledge about the universe in which we live—new knowledge that spans the vast area between tiny particles and our massive sun. □