In Search of Solar Neutrinos

New experiments are being designed to solve the solar neutrino problem and determine the power source of the sun.

Neutrinos—energetic, massless particles produced in certain nuclear processes—are possibly the only probe of the nuclear furnace alleged to power the sun and other stars. After gathering data for a decade, an experiment designed to measure the flux of neutrinos from the sun finds only one-third the amount predicted by theorists. Possible explanations of the discrepancy call into question the current understanding of such fundamental subjects as what powers the sun, the underlying nuclear physics, or the properties of neutrinos themselves. However, evidence from only one experiment bears on the problem. That experiment primarily collects the highest energy neutrinos thought to be emitted by the sun, and those neutrinos are supposed to comprise only a minor part—less than 0.01 percent—of the total solar neutrino flux.

To get at the root of the discrepancy between measurement and theory and prove that the neutrinos captured do, in fact, come from the sun, researchers are developing several new neutrino detectors. Some of these instruments are expected to be capable of measuring the flux of low energy neutrinos that are characteristic of hydrogen fusion—the nuclear process thought to be dominant in the sun. Other experiments are being designed to prove that the neutrino flux originates in the sun. Scientists are optimistic that some of the new detectors will be operational within a few years, and that the experiments will obtain the key data for solving the solar neutrino problem.

According to current astrophysical models, most solar neutrinos should be very low energy particles (less than 0.42 million electron volts) emitted when two protons combine to form a deuterium ion. These proton-proton, or p-p, neutrinos are thought to be diagnostic of hydrogen fusion reactions. In fact, exactly two p-p neutrinos are emitted whenever four hydrogen nuclei (protons) combine to form one helium nucleus. This composite reaction always releases 4.2×10^{-5} erg of energy. Physicists estimate the expected flux of p-p neutrinos by assuming that all the solar energy incident on the earth (1.36×10^{6} ergs per square centimeter per second—the solar constant) comes from hydrogen fusion. Thus, 6.5×10^{10} p-p neutrinos per square centimeter per second should hit the earth.

Measuring the flux of p-p neutrinos would test directly the assumption that the sun is powered by hydrogen fusion. If these neutrinos can be detected coming from the sun at the predicted rate, astrophysicists will be encouraged that their understanding of the solar energy source is substantially correct. However, if the flux of p-p neutrinos (like that of the high energy neutrinos) is only one-third the amount predicted by theory, the scientists will question their understanding of neutrino behavior—possibly the particles decay en route or oscillate, or both.

Capturing neutrinos or getting evidence of their passage is not easy, because neutrinos rarely interact with anything. This property makes it possible for them to travel, nearly unimpeded, through any substance, including the sun, earth, and man-made detectors. Most of the proposed experiments take advantage of the fact that neutrinos can be trapped by certain nuclei, in the reverse of the nuclear reactions that produce them. But the yield is extremely low.

From the standpoint of capturing neutrinos, the nuclei behave like targets less than 10^{-42} square centimeters in area. The neutrino has to score a direct hit in order to transform one nucleus into a nucleus of the next heavier element. In the existing solar neutrino experiment, conducted by Raymond Davis, Jr., of Brookhaven, chlorine-37 (^{37}Cl) nuclei trap neutrinos and are transformed into radioactive argon-37 (^{37}Ar) nuclei. However, only neutrinos more energetic than 0.814 million electron volts can trigger the nuclear conversion. The more energetic the neutrino, the more easily it is captured. Of the neutrinos thought to be emitted by nuclear reactions in the sun, only those produced when boron-8 (^{8}B) is converted to beryllium-8 (^{8}Be) have enough energy (up to 14.02 million electron volts) to be captured by ^{37}Cl in significant numbers. However, it is the nature of neutrinos that even an extraordinarily efficient detector can trap only a tiny fraction of the total flux. In Davis' experiment, three ^{37}Cl nuclei are converted to ^{37}Ar nuclei each week in 615 tons of perchloroethylene. If the agents causing the nuclear transformations are neutrinos—something impossible to prove—then the capture rate indicates to the researchers that the ^{8}B neutrino flux is 10^{6} particles per square centimeter per second.

In order to trap lower energy neutrinos, Davis' Brookhaven group is collaborating with scientists at the University of Pennsylvania, the Institute for Advanced Study, the Max Planck Institute in Heidelberg, and the Weizmann Institute in Rehovot to develop a detector with gallium-71 (^{71}Ga) as the target nucleus. Neutrinos with only 0.236 million electron volts can convert ^{71}Ga into radioactive germanium-71 (^{71}Ge), thus the important p-p neutrinos can be captured with a gallium-based detector. Although the chemistry is different, the experiment is a radiochemical one, like Davis' ^{37}Cl experiment. Neutrino capture by ^{71}Ga is thought to be particularly well understood; therefore a measured capture rate can be converted accurately into a solar neutrino flux.

Davis reports that most of the technological and chemical problems of the gallium experiment have been solved. A method has been developed for separating accurately and completely a few atoms of ^{71}Ge from the large volume of ^{71}Ga. By monitoring the radioactive decay rate of the separated ^{71}Ge, the researchers can determine how many ^{71}Ga nuclei were transformed. Funding has been provided by the Department of Energy and the Federal Republic of Germany to build a prototype detector containing 1.5 tons of ^{71}Ga.

John N. Bahcall, at the Institute for Advanced Study, has calculated that 50 tons of ^{71}Ga are required for the full-scale experiment, if it is designed to capture about one solar neutrino a day. The

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cost of this much material—in the form of metal or gallium trichloride—is about $25 million. But, as only a few ^{71}Ge are formed, and these are purged periodically from the ^{71}Ga, the gallium will be as good as new after the experiment is over. The investigators have considered renting the expensive substance for the 5-year duration of the experiment, but the cost would be nearly as high as buying it outright. Thus, the researchers hope to convince the Department of Energy to fund the purchase of the ^{71}Ga. When the experiment is over, the material could be sold, and the experiment conceivably could turn a profit!

Another experiment capable of detecting p-p neutrinos is expected to count the neutrinos directly, and even measure the energy of each captured particle. This detector design, based on the conversion of indium-115 (^{115}In) to tin-115 (^{115}Sn), was conceived only $2^1/_2$ years ago by Ramaswamy S. Raghavan at Bell Laboratories. When ^{115}In captures a neutrino, it emits an electron, which carries away all the neutrino's energy in excess of 0.128 million electron volts. The ^{115}Sn is produced in an excited state, and decays to the ground state within a few microseconds by emitting, in sequence, two distinctive γ-rays (the first at 0.116 and the second at 0.498 million electron volts). According to Raghavan, the triplet event—electron plus two delayed γ-rays—is the nearly unambiguous signature of a neutrino capture, especially if all three events occur at the same place in the detector.

By measuring the energy of the emitted electron, the investigators can determine directly the energy of the captured neutrino. In essence, they hope to record a neutrino spectrum, showing the number of neutrinos detected as a function of their energy. This spectrum would provide direct information about many of the neutrino-producing processes in the sun. The neutrino spectrum could be compared with that predicted for the sun. If there is reasonable agreement, some scientists would consider it highly likely that the neutrinos are produced in the sun.

Raghavan's experiment may be able to determine the source of high energy neutrinos directly. When such a neutrino strikes an ^{115}In nucleus, the electron is ejected preferentially in the direction of neutrino travel. By recording the direction of electron travel and comparing it with the position of the sun, the researchers think they might be able to determine whether the neutrinos come from the sun. Since high energy neutrinos are rare, it will take several years to decades to monitor enough electron paths and prove the neutrinos originate in the sun.

Counting neutrinos directly by detecting, identifying, and locating three nearly synchronous events is technologically complicated. However, Raghavan and Martin Deutsch, a collaborator from the Massachusetts Institute of Technology, think the instrumentation problems can be solved. They expect to start constructing a prototype module soon. According to independent calculations by Raghavan and Bahcall, the full-scale detector, capable of collecting one neutrino per day, should contain 4 tons of ^{115}In. The researchers estimate that the overall cost of the experiment might be around $10 million.

A detector based on the conversion of lithium-7 (^7Li) to radioactive ^7Be is appealing, because its price tag is estimated at only $1 million. Like the ^{37}Cl and ^{71}Ga experiments, the number of captures is measured periodically by extracting the product element and counting its decay rate. The threshold of the ^7Li reaction is 0.862 million electron volts. Thus, ^7Li is not an ideal target; it cannot trap the important, low energy p-p neutrinos to monitor the presumably dominant hydrogen fusion reaction directly.

However, ^7Li has an extraordinarily large target area. It can catch, in addition to high energy neutrinos, significant numbers of the neutrinos emitted when two protons and an electron combine to produce deuterium—a minor reaction involved in hydrogen fusion. These 1.442-million-electron-volt neutrinos are thought to be 400 times rarer than solar p-p neutrinos. Because ^7Li catches neutrinos comparatively easily, only 15 tons of ^7Li should be able to capture an estimated particle per day.

According to Davis, the major hurdle for the designers at Brookhaven has been devising a way to count the product ^7Be. A collaborator at Oak Ridge, Samuel Hurst, thinks the problem can be solved by using "laser ionization"—a method for counting single atoms.

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There are ways to observe neutrinos without capturing them. According to William R. Kropp at the University of California, Irvine, these methods might be well-suited for determining where the neutrinos are coming from. In one technique, used currently to monitor neutrinos in accelerator experiments, the researchers detect collisions between neutrinos and electrons—so-called neutrino-electron scattering. Such collisions are even rarer than neutrino captures; but after the collision, the electron travels in a straight line and its path can be recorded in a bubble chamber or on a track detector. The higher the energy of the neutrino, the more likely the electron will proceed in the direction the neutrino was headed. Boron-8 neutrinos have enough energy to scatter electrons preferentially in this way.

All the neutrino experiments face some serious problems. One of these is that the proposed detectors are very expensive. Another difficulty is that other agents, such as cosmic rays and natural radioactivity, are capable of transforming nuclei or scattering electrons. Under normal circumstances the unwanted background exceeds the solar neutrino signal by a few orders of magnitude. To minimize the cosmic ray background Davis is conducting his ^{37}Cl experiment in a mine shaft more than a kilometer underground. But that exposes the detector to radioactivity in the nearby rock. Davis reduced that contribution to the nuclear transformation of ^{37}Cl by shielding the experiment with water—an excellent absorber of the decay products of uranium and thorium. However, if the radioactive elements contaminate the detector chemical in even trace amounts (a problem plaguing the ^7Li experiment), the problem cannot be solved as easily.

There are two major parts to the solar neutrino puzzle: determining the power source of the sun, and understanding why the ^8B neutrino flux appears to be only a third as large as theory predicts. Several of the proposed experiments directly tackle the first part. Now nuclear physicists are focusing on the ^8B neutrino problem, in an attempt to improve the experimental basis of the theory.

Boron-8 is thought to play only a minor, peripheral role in solar nuclear processes. Since ^8B is the product of a series of nuclear reactions, its abundance in the sun is calculated by considering the rates of all the involved reactions. These rates have been extrapolated from rates measured in the laboratory under conditions quite different from those thought to exist in the sun. Considerable uncertainty in the ^8B abundance is introduced by the extrapolation. Furthermore, the reaction rates are very sensitive to the conditions in the sun—conditions which have not been measured directly. For example, Bahcall suspects that the flux of ^8B neutrinos depends roughly on the 13th power of the sun's internal temperature.

Now nuclear physicists are remeasuring the rates of many of the nuclear reactions in the ^8B series. With more accurate reaction rates, measured under closer-to-solar conditions, theorists hope to be able to reduce the uncertainty in the ^8B abundance within the sun, and thereby improve the predicted ^8B neutrino flux.

Whether or not the discrepancy between the observed and predicted flux of ^8B neutrinos is resolved, physicists think it is vital to establish the main line of energy generation in the sun. To this end, the favored solar neutrino detectors are the gallium experiment—because it will measure directly the flux of p-p neutrinos, and the technology is straightforward—and the indium experiment—because it will record the entire solar neutrino spectrum. However, each of the proposed new detectors could provide information vital to understanding the power source of the sun and settling the solar neutrino problem.

—BEVERLY KARPLUS HARTLINE

Additional Reading

1. J. N. Bahcall, "Solar neutrino experiments," *Rev. Mod. Phys.* **50**, 881 (1978).
2. ——, "Solar neutrinos: Theory versus observation," *Space Sci. Rev.*, in press.

Gian-Carlos Rota and Combinatorial Math

One strength of combinatorics is its interaction with other areas of mathematics and science.

Gian-Carlos Rota of the Massachusetts Institute of Technology is, at age 47, one of the oldest mathematicians in the field of combinatorics. "You can count the members of my generation on your fingers," he says. Most mathematicians in this active and growing field are in their 20's and 30's and are students of a few "grand old men" like Rota. Thus Rota, although not old as a scientist, can speak of his field from the perspective of one who has been in it nearly from the beginning.

This is the first of a series of occasional articles about mathematics as seen through the eyes of its most prominent scholars.

Rota himself did not set out to be a combinatorial mathematician. Fifteen years ago, he was doing research in the field of probability, specifically ergodic theory. He kept coming across problems involving ways to count things or ways to arrange objects—problems mathematicians would call combinatorial. "I noticed that most people in the field shunned these combinatorial problems," Rota says. "But I decided to take 6 months off, learn combinatorics, and solve my problems in ergodic theory. The 6 months became 15 years and I never did return to ergodic theory."

An urbane Italian who enjoys good food and drink, Rota hardly fits the stereotype of the shy, retiring mathematician. His colleagues tell stories of his sending back $75 bottles of wine in restaurants ("If it tastes like ink, why shouldn't I send it back?" he asks).

Rota loves to talk and enjoys speculating about the origins and future of his field of mathematics. In an interview with *Science*, he discussed how combinatorics began as a field unto itself, where its most interesting and challenging problems come from, and what it is like to do research in this field.

Combinatorics, Rota explains, began as a separate discipline about 30 years ago (most other fields of mathematics are hundreds of years old), and it began partly because so many combinatorial problems had arisen in other disciplines. These problems had been ignored or converted to other forms in the past, but it was becoming increasingly obvious that techniques were needed to solve them. The time was right for the birth of combinatorics as a separate field, especially because the advent of the computer made possible experimental work, thereby opening new avenues in solving problems.

The field gained momentum in the past decade because of a movement in mathematics toward greater concreteness. Combinatorics, which deals with finite sets of objects and how to count or arrange them, is the epitome of concreteness. In contrast, in the 1950's mathematicians emphasized abstractions and great general theories. Rota calls that time "the age of nothing but," noting that mathematicians were fond of beginning sentences by saying, "Mathematics is nothing but . . . ." When he studied linear algebra as an undergraduate at Princeton in the 1950's, Rota was taught that all work was to be done in infinite dimensional spaces—the most general ones for the purpose of proving theorems. Now, according to Rota, mathematicians are reviving the spirit of the 19th century when concreteness was emphasized. They are reprinting old books and papers from that time, looking for interesting mathematical examples. It is in this context that combinatorics has come into its own.

As combinatorics gained followers it also gained methodology. Now the field is at a point where there are some standard techniques for solving problems and there are a great many important problems to be solved. When the field was born, these techniques were not available and the only combinatorial mathematicians were a few very talented people such as the Hungarian Paul Erdös (*Science*, 8 April 1977, p. 144) and William Tutte of the University of Waterloo. "Early combinatorial mathematicians used very crude methods," Rota says, "and so they had to be very bright people. Now even people who are not too bright can do research."

One of the great strengths of his field, Rota says, is its interaction with other areas of mathematics and science. He firmly believes that mathematics must interact with other sciences, that mathematics, if left to itself, will eventually dry up.

Rota foresees biology, linguistics, statistical mechanics, and elementary particle theory as contributing vast numbers of important problems to combinatorics.