The Search for Solar Neutrinos

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HONORABLE MENTION
HUGHES **GRIFFITH OBSERVER** CONTEST

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Neutrinos

Radioactivity was discovered in the 1890s. When the mysterious new radiation was placed in a magnetic field, it was found to be of three different types. One was bent to the left by the field, one to the right, and the third was unaffected. They were named alpha, beta, and gamma, respectively.

In the next 3 decades physicists discovered that atoms consist of tiny, dense nuclei surrounded by clouds of negatively charged electrons. The number of units of positive charge in a nucleus was found to equal the number of electrons in the atom and also the number of the atom in the periodic table of the elements.

Alpha particles were found to be the nuclei of helium atoms and beta particles to be electrons of high energy. It was also found that the emission of either of these signaled the transmutation of an atom of one element into an atom of another, the ancient alchemist's dream.

Quantitative work in the atomic domain required the development of a new physical theory, quantum mechanics. The theories of Newton and Maxwell had to be drastically modified. One feature of these theories was unchanged however: the conservation laws. Energy, momentum, and angular momentum are conserved quantities in quantum physics as well as in classical physics. This means that the total amount of each is unchanged by any physical process.

However, a problem soon appeared with beta decay. When precise measurements were made, it was found that neither energy nor angular momentum was conserved in reactions in which one nucleus emitted an electron and was changed into another, with its atomic number increased by one. In fact, later work showed that linear momentum was not conserved either!

This can be seen in Figure 1, a cloud chamber photograph of the beta decay of He^6, initially at rest, into Li^6 and an electron. To a physicist, this looks as strange as Figure 2. If the rope in the latter figure is taut, you know that there must be an invisible third force pulling on it.

Similarly, Wolfgang Pauli, in a letter written to Geiger and Meitner in 1930, suggested that there must be a third, invisible particle emitted in beta decay and that it must carry away precisely the missing energy, momentum, and angular momentum. The new particle had to have no charge, negligible rest mass, and spin equal to that of the electron. He admitted that it was a radical idea to propose a new particle which was not detected, but he wrote:

> Nothing venture, nothing win. And the gravity of the situation with regard to the continuous beta spectrum is illuminated by a pronouncement of my respected predecessor in office, Herr Debye, who recently said to me in Brussels, "Oh it is best not to think about it at all . . . like the new taxes." One ought therefore to discuss seriously every avenue of rescue. So, dear radioactive folks, put it to the test and judge.

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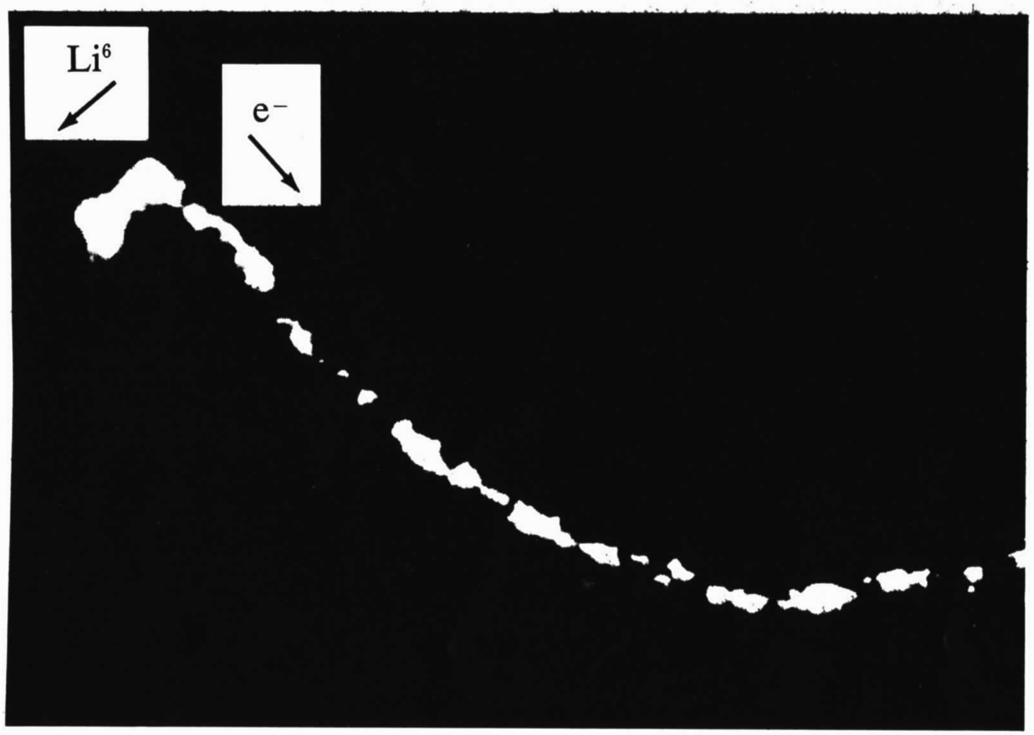


Fig. 1 Here is a dramatic display of apparent nonconservation of momentum in the beta decay of helium-6 (at rest!) into lithium-6 and an electron (from J. Csikay and A. Szalay, Proceedings of the International Congress on Nuclear Physics in Paris, 1958, Publications Dunod, Paris, 1959).

He made the suggestion publicly at the June, 1931, meeting of the American Physical Society in Pasadena.

1932 was a vintage year for physicists. The neutron was discovered and also the positron, the latter being the positively charged "anti-electron" predicted by Dirac's relativistic quantum theory. The neutron made a picture of the atomic nucleus possible at last. Each nucleus contained Z protons and (A - Z) neutrons, where Z was the atomic number and A the atomic mass number.

Now beta decay could be seen as the splitting of a neutron into a proton and an electron inside a nucleus. Pauli strongly advocated the view that a new, unseen particle must also be produced and that it must carry away the missing energy, momentum, and angular momentum. He discussed this with the Italian physicist Enrico Fermi, who named the "little neutral one" the **neutrino** to distinguish it from the neutron.

In 1934 Fermi succeeded in calculating the observed energy distribution of the electrons emitted in beta decay. His calculation did not require any knowldege of the type of force involved but was based on the existence and postulated properties of the neutrino.

After this triumph, physicists, or at least theoretical physicists, accepted the idea of the neutrino. In accordance with Dirac's theory, an antineutrino was postulated too, and the beta decay reaction could now be written

$$n \longrightarrow p + e^- + \bar{\nu}$$

A neutron was now believed to split into a proton, an electron, **and** an antineutrino. When this occurred inside a nucleus, the proton remained, while the electron and antineutrino were ejected.

But Do They Really Exist?

Reviewing the situation in 1948, H. R. Crane wrote,

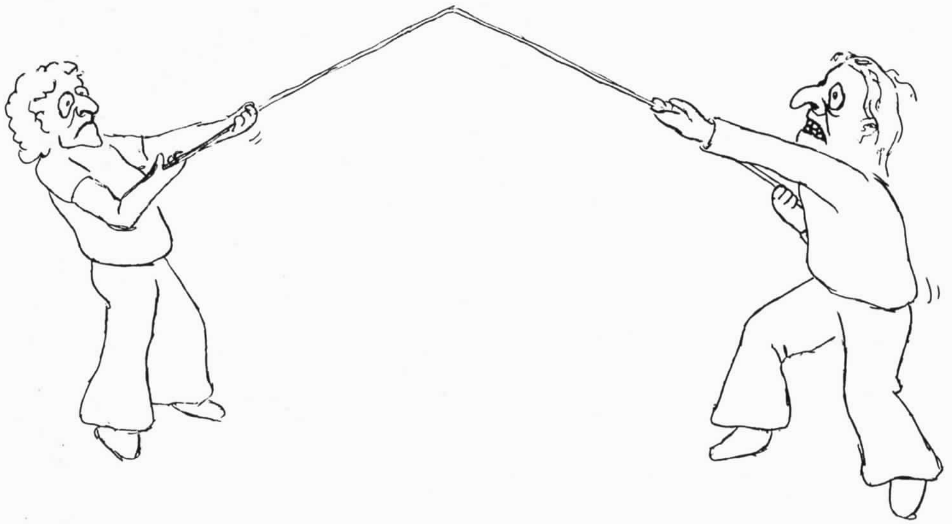


Fig. 2 There must be an invisible person pulling on the rope!

> Not everyone would be willing to say that he believes in the existence of the neutrino, but it is safe to say that there is hardly one of us who is not served by the neutrino hypothesis as an aid in thinking about the beta-decay process . . . While the hypothesis has had great usefulness, it should be kept in the back of one's mind that it has not cleared up the basic mystery and that such will continue to be the case until the neutrino is somehow caught at a distance from the emitting nucleus.

Direct proof would require observation of the inverse beta reaction, either

$$\nu + n \longrightarrow p + e^-$$

or

$$\bar{\nu} + p \longrightarrow n + e^+$$

ν = neutrino

$\bar{\nu}$ = antineutrino

p = proton

e^+ = positron

e^- = electron

Finally, in 1953, F. Reines and C. Cowan detected antineutrinos by the latter reaction. They used protons in water as their target and performed the experiment at a nuclear reactor which was calculated to emit 10^{13} (ten trillion) antineutrinos per square centimeter per second.

Despite this enormous flux on a target of about 150 kilograms of water, they obtained only about one event per hour. The probability for a nucleus to interact with a neutrino is some 10^{28} times less than that for an atom to interact with a photon of light. This is why physicists refer to processes involving neutrinos as **weak** interactions.

It was not yet clear whether the neutrino and antineutrino were different or the same particle. (The photon, which also has zero mass and charge, is its own antiparticle.) To detect a neutrino, one must observe the former of the two inverse beta decays listed above, that is, the change of a neutron into a proton, with the emission of an electron.

One of the best places for this to occur is inside a nucleus of chlorine-37. Then the chlorine nucleus is changed into a nucleus of argon-37, which can be separated out of the chlorine. The radioactive argon can be identified when it decays back into chlorine a few weeks later. Raymond Davis, Jr., a nuclear chemist at the Brookhaven National Laboratory, attempted to observe this reaction by placing a target containing chlorine next to the Savannah River reactor in the 1950s. This was the same reactor which had been shown to emit a detectable number of antineutrinos. The failure to detect the neutrino-induced reaction was taken as the first proof that neutrinos and antineutrinos are truly different.

You may be wondering how these 2 particles can differ. Experiments have shown that antineutrinos have their spin axes pointing in the direction they are traveling, while neutrinos have their spins pointing in the opposite direction. It is said that neutrinos are left-handed and antineutrinos are right-handed.

Other experiments dealing with these fascinating particles have shown that there are actually two different kinds of neutrinos, each with an associated antineutrino, and that experiments involving neutrinos make a distinction between our world and a world seen in a mirror, or, alternatively, between our world of matter and a world of antimatter (but a world of antimatter, seen a mirror, would be just like our world). It is time for us to move on, however, to see what all this has to do with astronomy.

The Sun and Stars

How well do we know the sun and stars? For most stars we can measure only a few properties: the luminosity (if the distance can be measured or if the star can be shown to be identical to one whose luminosity is known), the mass (only if it is in a binary system with convenient properties), the **surface** temperature (from the color), and the spectrum, or distribution of light emission over different wavelengths.

Applying the laws of quantum and statistical mechanics to the stellar atmosphere, we can use the spectrum to determine the density, pressure, temperature, and composition of the star's atmosphere. The sun turns out to be typical of the largest category of stars, those called main sequence stars. Its atmosphere is a gas at a temperature of nearly 6000 degrees Kelvin with a composition of about ¾ hydrogen and ¼ helium by mass. Approximately 2 percent of the mass is in the form of heavier elements, the relative abundances of which are in general agreement with other solar system objects.

What else do we know about the sun? Its luminosity, or energy output, is 4×10^{26} watts, a typical value for main sequence stars. Its mass is about 2×10^{30} kg, or about 330,000 times the mass of the earth, again a typical value.

We have one more important bit of information about the sun, one which is unobtainable for other stars, its age. Radioactivity, the phenomenon with which we began this discussion, provides a means of determining the age of a rock. The slow, steady transmutation of one element into another provides a sort of hour glass, provided only that the daughter product cannot escape. As this is the case in a rock, a measure of the ratio of parent to daughter gives us the time which has elapsed since the rock formed.

The oldest rocks on earth are about 3 billion years old, so we know that the earth has been cool enough for rock to remain solid for at least that long. Older still are the meteorites. These rocks have been wandering around the solar system for 4.6 billion years since they formed. They provide evidence that the solar system is that old. Recent measurements of moon rocks and moondust have confirmed this: rocks solidified in the solar system a little less than five billion years ago. From this we conclude that the sun formed at that time.

When we multiply the sun's luminosity by its age, we obtain the amount of energy it has emitted. One of the great problems of late Nineteenth Century and early Twentieth Century science was to determine how the sun could have produced so much energy. If the entire solar mass were wood, TNT, or even coal, it could not provide this much energy by undergoing chemical reactions. The energy that might be obtained by gravitational contraction from a huge cloud to its present size is equally insufficient.

The solution to the problem is, of course, nuclear reactions. These typically produce a million times as much energy per kilogram of fuel as chemical reactions. This was seen as early as 1920 by the great pioneer of astrophysics, Sir Arthur Eddington. When his colleagues pointed out that the central temperature of the sun could not be hot enough for such reactions to proceed, he responded,

> "We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place:"

Fortunately (for scientists, not the stars) quantum mechanics explained how hydrogen could fuse into helium at the "low" temperature calculated for the center of the sun, about 15 million degrees Kelvin.

Once it was realized that nuclear reactions were possible in the interior of the sun, the sun's energy budget could be worked out. The overall result of the reactions is that 4 protons (nuclei of hydrogen atoms) fuse together to form one alpha particle (helium nucleus) with the emission of 2 positrons (which annihilate electrons to form gamma rays) and 2 neutrinos. Seven tenths of one percent of the initial mass is converted into energy according to the famous Einstein equation $E = mc^2$. This means that one kilogram of hydrogen is converted into 993 grams of helium plus 175 million kilowatt hours of energy.

A simple calculation shows that the sun's luminosity can be provided by the fusion of a little over 600 billion kilograms (600 million tons) of hydrogen per second. The hydrogen in the sun's core, about 1/10 of the sun's total mass, is sufficient for this to continue for a total of 10 billion years. Since we saw above that the sun has been shining for only about 5 billion years, we need not worry about the sun facing an energy crisis for a long time.

Several chains of nuclear reactions have been found. Their reaction rates have been measured, mostly at Caltech's Kellogg Radiation Laboratory and extrapolated to the lower energies found in stellar interiors.

These rates go into one of a group of equations which describe the structure of a star. This equation tells how energy is generated and also how new elements are formed. Other equations require that the star's atmosphere not collapse under its weight, that mass and energy be conserved, that energy be transported correctly by radiation or convection, and that the gases have the correct opacity and pressure.

When these equations are solved simultaneously on a large computer, a stellar model is made. The observable properties of the model, surface temperature, mass, luminosity, and radius, can then be compared with what is observed of real stars in the sky.

The results have been remarkably successful. All of the observable properties of stars can be computed. In addition, when the evolution with time of the models is computed, it is possible to determine how long the stars spend in each phase of their lives. Stars spend the longest period on the main sequence burning hydrogen, and main sequence stars are the most abundant in the sky. When the hydrogen in their cores is exhausted, the stars become red giants whose properties again match the observations. It is even possible to account fairly well for the observed abundances of the elements from the nuclear reactions which produce these elements in stars.

But Can We Be Certain?

Everything calculated depends on the nuclear reactions. In a main sequence star like the sun, these occur only in the core, where the temperature and density are sufficiently high for atomic nuclei to overcome their mutual repulsion. (This is the problem for those trying to achieve fusion here on earth.) The rates of the various reactions are extremely sensitive to temperature. It was first suggested by Bethe in 1939 that the sun burned hydrogen by the carbon-nitrogen-oxygen cycle in which carbon acts as a catalyst. Later work has shown that this reaction dominates above 18 million degrees, a temperature calculated for the cores of stars somewhat more massive than the sun.

The sun's central temperature has been calculated to be 14 or 15 million degrees, where the proton-proton, or p-p, chain is dominant. Knowledge of the relative rates of these two types of fusion provides a very sensitive measure of temperature. Thus an experiment which

could discriminate between these two reaction chains would at the least determine the temperature of the sun's core.

Even more important has been the need for a direct test of astrophysical theory. After all, no one has ever detected **direct** evidence of nuclear reactions in the center of the sun. The gamma ray photons produced there are absorbed and re-emitted for 10 million years before their energy appears as light emitted from the solar surface. Only the neutrinos, which are so reluctant to interact with matter, can emerge directly, bringing evidence of what is happening all the way to earth. Of course, nearly all of them pass right through the earth and continue on into space. It is estimated that more than 60 billion of them are passing through each square centimeter of our bodies each second, yet we do not feel a thing. The challenge is to detect these solar neutrinos.

The Search for Solar Neutrinos

We have seen that neutrinos interact extremely weakly with matter, and also that one of the best means of detecting them is to let them convert nuclei of chlorine-37 into radioactive argon-37 nuclei. Unfortunately, a certain threshold energy is necessary, and this means that the great majority of solar neutrinos lack sufficient energy to be detected. Those which can be detected come from some relatively obscure branches of the proton-proton chain.

The number of neutrinos emitted at each energy can be calculated from a model of the sun. When this is combined with the measured receptivity (called cross section) of the target chlorine nuclei, the expected reaction rate is determined. This turns out to be extremely small, so small that a new unit, the Solar Neutrino Unit, or SNU, was introduced by John Bahcall, the theorist who has been closely associated with this work from the beginning. One SNU equals 10^{-36} captures per target nucleus per second. The calculated capture rates are typically a few SNU.

The brave scientist willing to undertake the experiment is the above-mentioned Raymond Davis, Jr. As you might expect, he is not sitting around with one chlorine atom waiting 10^{36} seconds for an event. This would be 10^{19} times the estimted age of the universe. No, he needs a lot of chlorine atoms.

Figure 3 shows his apparatus. The cylindrical tank contains one hundred thousand gallons of perchloroethylene, C_2Cl_4, a common cleaning fluid. Since one-fourth of the chlorine atoms are the necessary chlorine-37, this works out to about 2×10^{30} atoms of chlorine-37. Thus if the counting rate is one SNU, he should get a capture every 5×10^5 seconds, or 6 days.

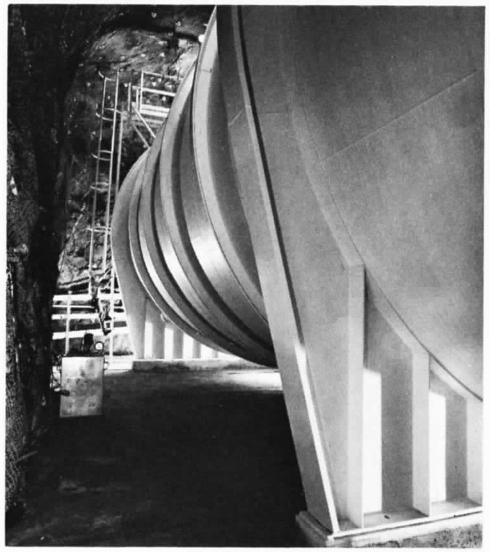


Fig. 3 Solar neutrinos are detected by this equipment in the Homestake Gold Mine, Lead, South Dakota (photograph by permission from R. Davis, Jr., Brookhaven National Laboratory).

In 1964, when this experiment was first seriously proposed, Bahcall used the best available solar models to calculate a capture rate of (40 ± 20) SNU. With this, Davis could expect to produce half a dozen argon atoms per day. Since the argon-37 has a half-life of 35 days before changing back to chlorine, the maximum number of argon atoms should be found after about three months.

Removing a few dozen argon atoms from one hundred thousand gallons of liquid may sound more difficult than finding a needle in a haystack, but Davis has a way to do it. He introduces a little non-radioactive argon-36, which is chemically identical to the radioactive argon-37. Then he bubbles helium gas through the huge tank. The two rare gases behave similarly. They collect into bubbles of mostly helium, which are removed, after which the argon is condensed in a cold trap. The argon is purified chemically and its radioactivity is counted in extremely sensitive, highly shielded counters.

Perhaps you doubt that he can find the argon. This has been tested by introducing 600 argon-37 atoms into the tank and recovering nearly all of them!

One further complication is that neutrinos are not only particles which can produce argon from chlorine. Protons can do it too, and protons are available from cosmic rays. For this reason, the entire experiment must be greatly shielded from cosmic rays. This is done by having the apparatus under 4850 feet of earth. It is near the bottom of the Homestake Gold Mine at Lead, South Dakota.

The experiment has been operational since 1968. From the first it has produced surprises. The neutrino capture rate was found to be less than the background expected from the few cosmic rays which get through and from "glitches" in the counters. All that could be stated with confidence in 1968 was that the capture rate was less than or equal to 3 SNU.

At the same time, Bahcall and his collaborators published a revised version of the theoretical calculations based on new, improved solar models and a more accurate rate for the proton-proton reaction. (This is the one nuclear reaction which cannot be measured directly on earth. Its rate is too low. This low rate accounts for the sun being a very slow thermonuclear reactor rather than a bomb.) The best estimates by 1968 were 7.5 ± 3 SNU.

The first experimental limit showed that the carbon-nitrogen-oxygen cycle was unimportant in the sun and thus that the sun's core temperature was probably a bit lower than calculated.

The next few years saw improvements in the experiment. Even lower background counters were developed. The area around the tank was flooded with water to further reduce cosmic rays. The upper limit on the counting rate was pushed lower and lower. While the best theoretical expectation has dropped to 5.5 SNU, it is now clear that the capture rate for solar neutrinos on chlorine-37 is less than one SNU. In fact, there is no evidence that a single neutrino has been captured! Very recent runs have brought the neutrino counting rate, averaged over 38 runs, up to 1.2 ± 0.55 SNU. This is still well below theretical predictions.

What Is Wrong?

The solution to the problem lies in nuclear physics, in neutrino physics, or in astrophysics. Workers in each field tend to believe something is wrong with one of the others.

The nuclear physics has been tested and retested. Each of the measurable reaction rates has been checked. Every conceivable problem with the experiment has been investigated.

The physics of the neutrino is harder to test. If for some reason neutrinos did not survive the 500 seconds necessary to get from the core of the sun to the Homestake mine, there would be no problem explaining their failure to be counted there. This would introduce new problems in particle physics, however. There has been some progress in recent years in understanding the weak interactions, and much would be lost if neutrinos were found to be unstable. The rest mass of the neutrino would have to be nonzero, and new particles would have to be introduced as the products of the neutrino decay. The physicists say, "Look elsewhere."

This leaves astrophysics. Can the sun, the best understood star, be not so well understood after all? Models of the sun have been recomputed, varying nearly every parameter, in efforts to compute a neutrino capture rate low enough to agree with Davis's experiment. At first it appeared that a little juggling of the rates of the branches of the proton-proton chain which produce the higher energy, more easily caught neutrinos could take care of the problem. These branches involve boron-8 and beryllium-7 and are relatively unimportant to the overall energy budget of the sun.

With the lowering of the upper limit on the capture rate to below 1.5 SNU, however, the situation has become more critical. Our ideas of the solar interior must be drastically modified. Several suggestions have been made. If the solar interior has a substantially different composition than that observed of the solar atmosphere, it is possible to lower the predictions to about 1.4 SNU. It is difficult to explain, however, how this could occur.

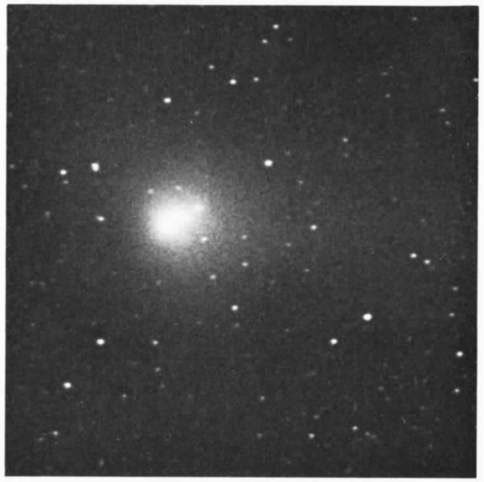
A popular suggestion is that the sun is actually a variable star, at least in its core. According to this idea, Davis is performing his experiment during a quiet time, when the nuclear reaction rate in the sun's core is low. The sun's surface, which is emitting energy produced some 10 million years ago, fits the models, but the core doesn't. This could be "explained" by periodic mixing of the core with hydrogen-rich material just outside the core. There is no known reason for the mixing to occur, however. There have also been attempts to compute a slight variation in the sun's luminosity and to link this to such phenomena as ice ages on earth and a possibly warmer past (with liquid water) on Mars. Variations in the brightnesses of Uranus and Neptune are being studied in efforts to determine whether the sun might actually be varying its light output over fairly short time periods.

Another recent suggestion is that only part of the sun's energy is transported from the core to the atmosphere by radiation, with the remainder being carried by acoustical waves. This requires less helium in the sun than has been assumed. It has also been suggested that the sun's energy comes from matter in its interior falling into a big black hole at the center or that the outer layers of the sun are of a different age than the interior.

It may sound as though astrophysicists are desperate for a solution. They are. When this occurs in any science, it is customary to call for another, more sensitive experiment. One that is being proposed by Bahcall and Davis would substitute a liquid containing lithium for the chlorine compound in the existing tank in the gold mine. It would then be necessary to find a way to separate about 30 atoms of beryllium-7, formed by the capture of a neutrino by lithium-7, from the thousands of gallons of liquid. This would be difficult, but there would be a gain in sensitivity, as the lithium has a higher cross section for capturing neutrinos than chlorine. It would be especially sensitive to the so-called pep reaction, which **must** occur if the sun is shining by nuclear reactions.

Even more sensitive would be an experiment with gallium as the target. This nucleus has a threshold sufficiently low that it could capture even the numerous neutrinos from the initial p-p reaction. Gallium is extremely expensive, however, and it is not clear how tons of it can be obtained for such an experiment.

Neutrino astronomy is a new branch of astronomy. It is more difficult than many of the other new astronomies, those involving x-rays or gamma rays, for example. As an audacious undertaking it can only be compared with the efforts to detect gravitational radiation from astronomical objects. As yet, nothing has been detected. Yet it has challenged astrophysicists and has re-opened the supposedly solved problem, "How does the sun shine?"



The head of Comet West is resolved here into 3 of the 4 nuclei into which it fragmented. R.E. Royer of Azusa obtained this photograph on 27 April 1976, 5:00 a.m., P.D.T., with the Ford Observatory's 18 inch, f/7 Newtonian, in the Angeles National Forest. By this date, one of the nuclei had already left the head.

CENTER PHOTOGRAPH

Last month 2 photographs of Comet West by R.E. Royer and Steve Padilla of Azusa were published in the GRIFFITH OBSERVER. The layout required considerable cropping, but here, in full splendour, is Comet West in yet another fine photograph by Royer and Padilla (March 9, 1976, 4:56 a.m., P.S.T., II aO, 4-inch, 5/5, from Mojave).