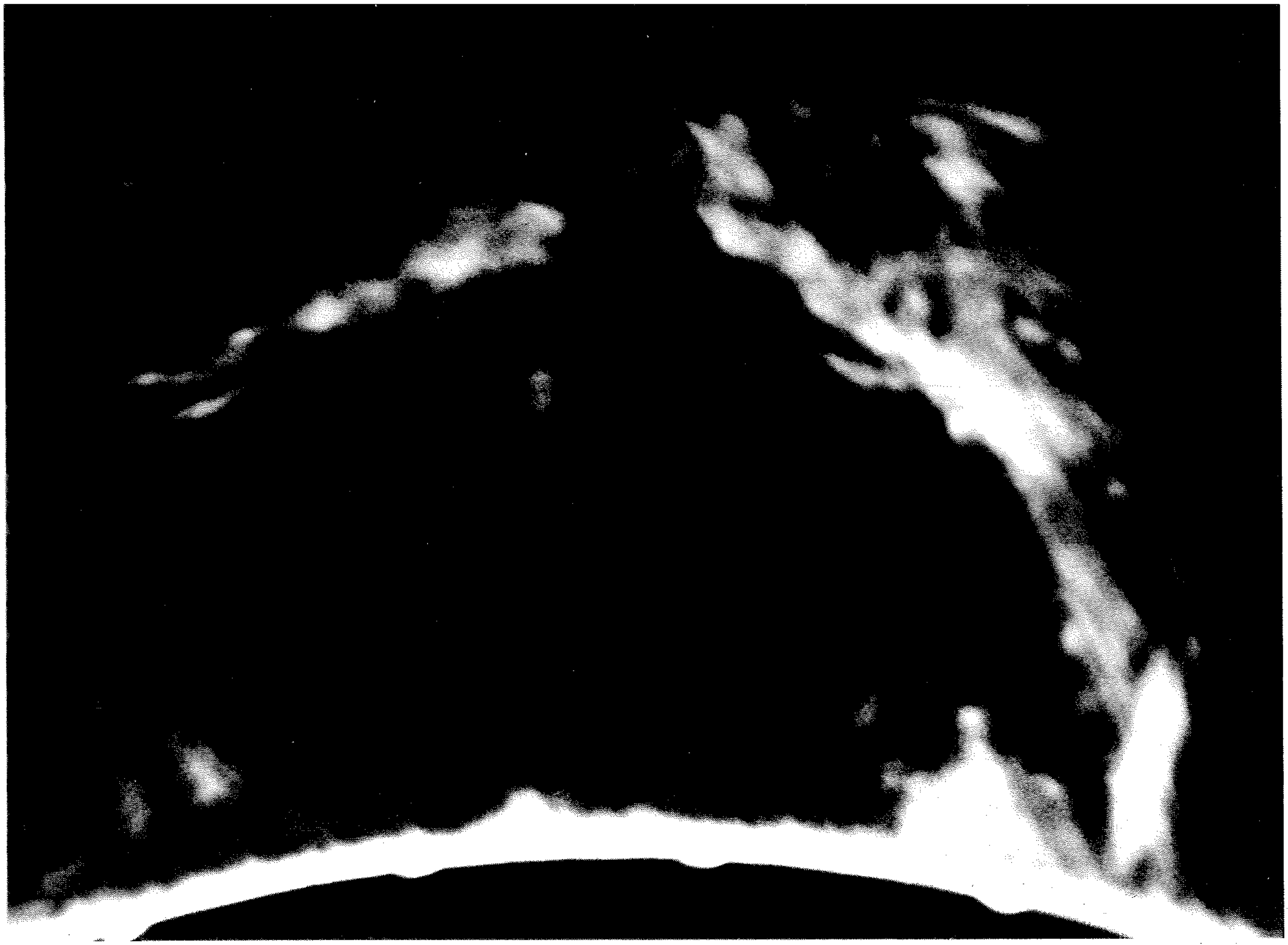

Where Does the Sun Get Its Energy?

by Ralph W. Kavanagh

A series of experiments over a period of 20 years has led to a remarkably accurate picture of energy production in the sun.

In the years since Throop College became Caltech, nuclear physics and astrophysics, in our laboratories and in many others around the world, have overlapped to produce a remarkably detailed and successful picture of the mechanisms responsible for the sustained generation of energy in stars and for the creation of the elements, in the observed abundance ratios, out of an original cosmos of hydrogen. Furthermore, the advent of large-memory, high-speed computers has made it feasible to construct precise models of evolving stars that start from a given initial mass and composition and change with time to match the present radius, mass, age, and luminosity. Besides being constrained by physical laws governing radiation transport and hydrostatic equilibrium, these models require as input a knowledge of numerous nuclear-reaction rates, or "cross sections." Because in most instances nuclear theory is, as yet, able to deduce these cross sections only crudely, experimental measurements are preferred wherever possible.

The idea that the stellar fires were kept burning by nuclear reactions germinated about 50 years ago, and

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was more or less forced on astronomers by the geologists' uranium-lead age determinations, which indicated a time scale greater than one billion years. The earlier view, due to Kelvin and Helmholtz, that gravitational contraction was the energy source, predicted a solar age about a hundredfold too small. It was also inconsistent with the observed constancy of the periods of the Cepheid variable stars.

The fusion of four hydrogen atoms to make one helium atom was known from Aston's mass-spectrographic work (ca. 1920) to release about 0.8 percent of the mass as energy, and the significance of this for stellar energy was noted by Eddington. However, the state of theoretical and experimental knowledge in the twenties was inadequate to allow specific reactions to be figured out. There was considerable doubt that temperatures in the sun were high enough to allow the fusion reaction to go at the rate required by the luminosity. It was this doubt that prompted Eddington's famous remark: "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."

In the late twenties Atkinson and Houtermans resolved the doubt, to some extent at least. They showed that the rate at which 10-million degree protons would overcome the mutual electrostatic repulsion of their positive charges (the Coulomb barrier) and penetrate to the nuclear radius was of the right order of magnitude. They assumed that penetration assured reaction. In essence, their calculation was simply the integral of the product of the Maxwell-Boltzmann (M-B) distribution with the penetration-probability factor which Gamow had published the previous year. From that product, we find that the *effective* energy of 10 to 25 keV at which proton reactions go is many times the actual mean energy (i.e., temperature) of 1 or 2 keV.

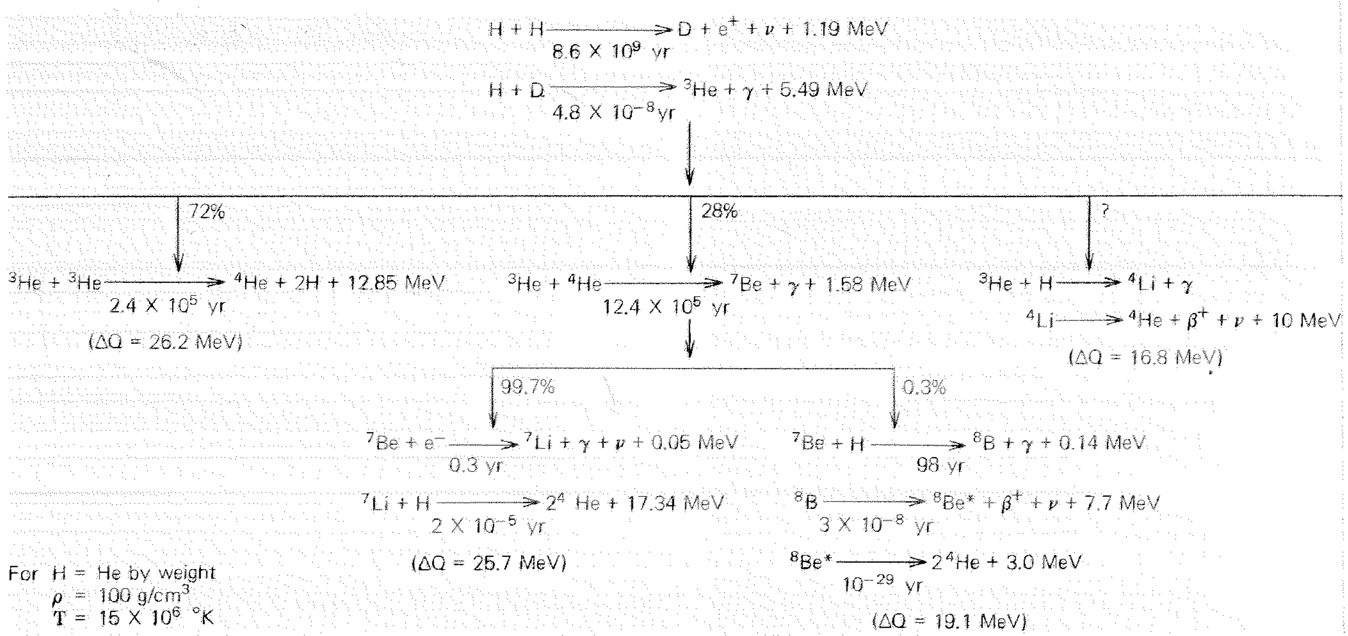
A by-product of this coup, illustrating one of the hazards of the profession, was related by Houtermans several years ago in a seminar he gave at Caltech. He told of walking with his best fraülein one evening just after he and Atkinson had concluded their work. She looked up at the stars and said, "Aren't they beautiful." He replied, "Yes, and now I know why!" and told her of their new ideas, modestly emphasizing Atkinson's role. Shortly thereafter she married Atkinson.

The following decade saw the discovery of the positron, neutron, and deuteron, the Fermi theory of β-decay, and much detailed information about nuclear-reaction cross sections—a good deal of it from C. C. Lauritsen's new Kellogg Radiation Laboratory. On the basis of these cross sections, Hans Bethe in 1939 published a study of the reactions that might be important to energy generation. Because he assumed a very large abundance of nitrogen and carbon in the sun, he arrived at the wrong conclusion that the most important solar source should be the so-called CN-cycle. We now know that this requires a larger, hotter star than the sun.

The series of reactions now known as part of the "proton-proton chain," that Bethe considered most probable, were:

$$\begin{aligned} {}^1H + {}^1H &\rightarrow {}^2D + e^+ + \nu \\ {}^2D + {}^1H &\rightarrow {}^3He + \gamma \\ {}^3He + {}^4He &\rightarrow {}^7Be + \gamma \\ {}^7Be + e &\rightarrow {}^7Li + \gamma + \nu \\ {}^7Li + {}^1H &\rightarrow 2\,{}^4He \end{aligned}$$

The only important reaction which he overlooked, and which remained unnoticed until it was suggested in 1951 by C. C. Lauritsen, was ${}^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H$. It is especially significant in that it requires no previously existing catalyst such as ${}^4He$ or ${}^{12}C$



This series-parallel group of reactions, making up the solar proton-proton chains, has as its net result the fusion of four protons to make one ^{4}He nucleus, with liberation of heat varying from $\Delta Q = 16.8$ to 26.2 MeV per ^{4}He, depending on the particular path. The differences are due to the energy loss carried off by the elusive non-interacting neutrinos. The partial life expectancy of the first particle written in each reaction is stated under the arrow, for a representative choice of temperature and density in the sun.

to permit the fusion chain to be completed, so that it works in stars initially composed of pure hydrogen.

The chart above shows, according to our present knowledge, some of the competing possible routes for burning four protons to make one helium nucleus. The basic experimental problem is to determine the cross section, σ, for each reaction, and thus its relative importance from the relation,

$$\text{REACTION RATE} = n_1 n_2 <\sigma v>_{12}.$$

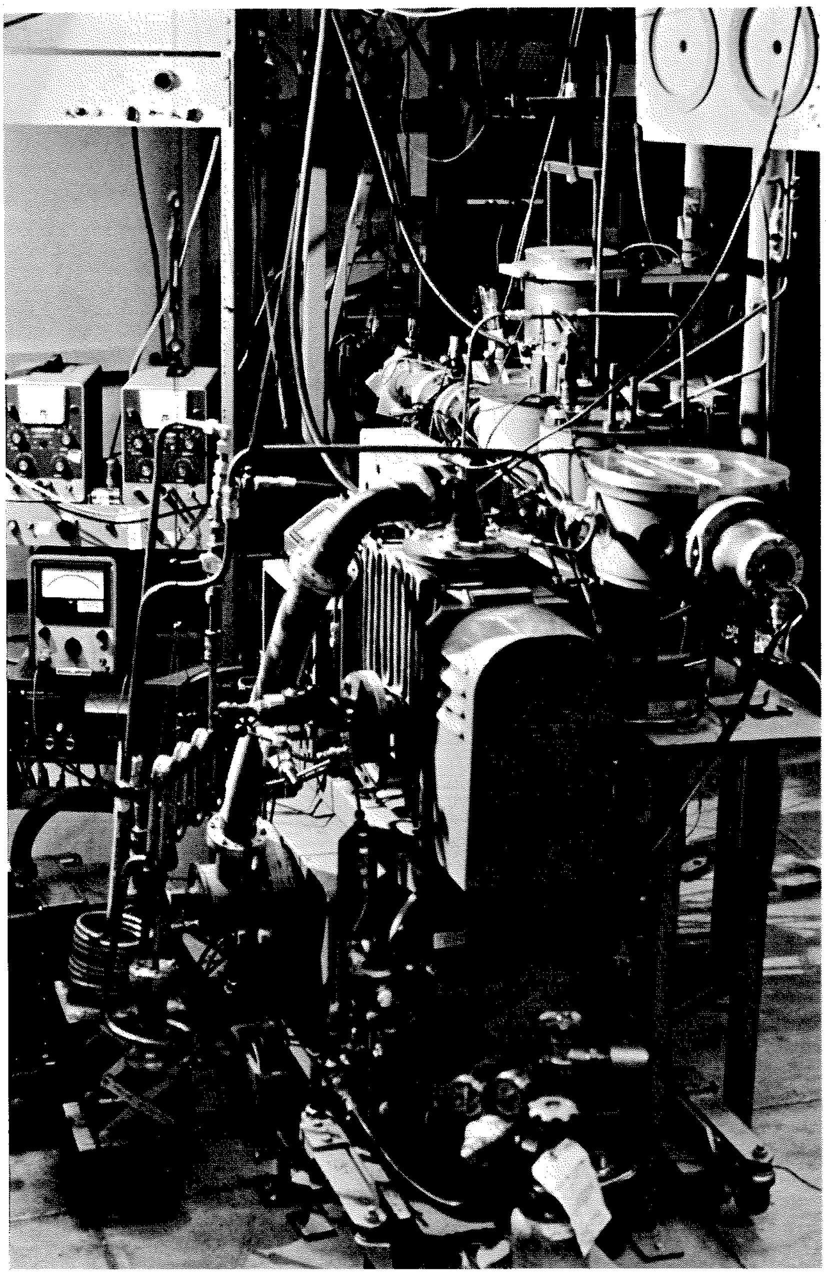
Here n_1, n_2 are the number densities of the reacting particles and v their relative velocity; the bracket denotes an average over the M-B distribution. The life expectancy of a particle in each reaction is inversely related to this rate, and the chart of the proton-chain reactions shows such lifetimes under the arrows, for conditions typical near the center of the sun, e.g., temperature 15 million degrees, density 100 g/cm^3.

It is a sad fact that none of the reaction cross sections can be directly measured at energies pertinent to the solar interior. Because of the Coulomb barrier, they are all far too small, and we must rely on a combination of measurement at higher energies and extrapolation guided by theory. In many cases, it is possible to justify factoring the cross section as $\sigma = S(E)E^{-1} \exp(\text{const}/\sqrt{E})$ and expect the factor S(E) to be nearly independent of energy, as we shall see presently in an example.

Even at typical laboratory energies, the first reaction, $H + H \rightarrow D + e^+ + \nu$, is so weak that no attempt has been made to measure it. Rather we rely on the well-tested validity of β-decay theory to compute the cross section, treated as an inverse β-decay. At 1-MeV proton energy, we find $\sigma_{pp} \sim 10^{-47}$ cm^2, which accounts for the absence of experimental effort. It is by far the slowest reaction and therefore governs the overall power. The remarkable interrelatedness of nature is here exemplified in that the critical experimental datum in the calculation is the half-life of the neutron, recently remeasured in Denmark and found to be about 8 percent shorter than the previous Russian result. It enters here because it involves the same fundamental interaction constant (the "axial vector") as the p-p reaction.

There are three possible ways to consume the accumulated ^{3}He. Each of these three has been investigated experimentally in our laboratories. Other energetically permitted reactions have also been checked and found to be at least 1,000 times slower than the $^3He + {}^3He$ fusion.

It often happens in nuclear physics that laboratory



The gas-recirculation system used for measuring the $^3He + {}^3He \rightarrow {}^4He + 2^1H$ reaction, with the ^3He targets contained in the flat-topped cylinder (right of center). The beam from the accelerator in the room above is deflected into the target chamber by the magnet at the rear.

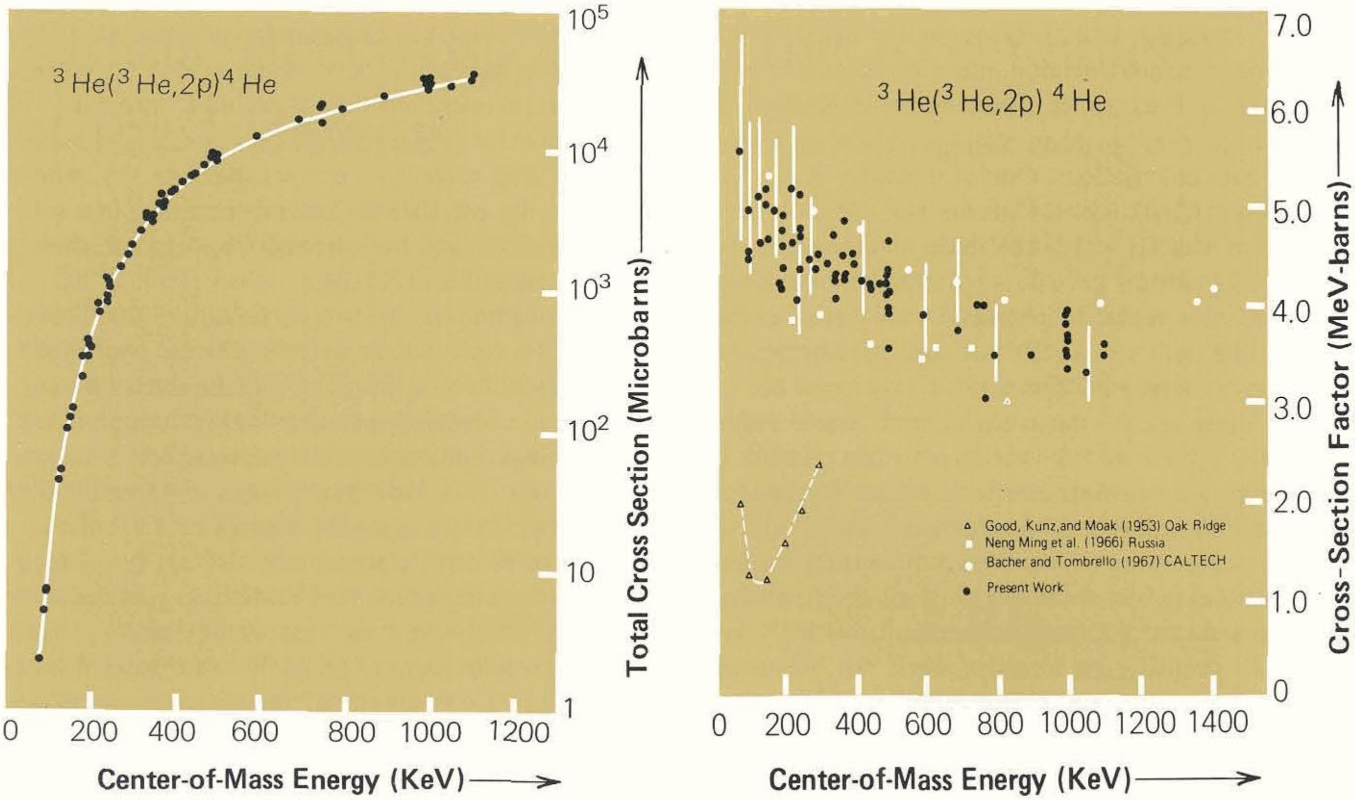
measurement of some interesting reaction is stymied or complicated by the nature of the necessary beam or target material. In the present cases, ^{3}He is needed for one or both. This stable isotope of helium occurs in atmospheric helium in the ratio of about $1/10^6$, and much less in helium separated from natural gas. But it is one of the fortunes of no war that the nation's stockpile of tritium for fusion bombs decays on the shelf to ^{3}He by 50 percent every 12 years, providing a cheap source (about $1,000/gram) of the pure gas for peaceful laboratory fusion studies.

The $^3He + {}^3He \rightarrow {}^4He + 2^1H$ reaction has been recently remeasured here by Winkler and Dwarakanath (now staff members at Cal State, Los Angeles, and Tata Institute, Bombay, respectively), who built for this purpose the impressive gas-recirculating system shown at the left. Such a system is superior to the only practical alternative, for noble permanent gases, of gas retention by thin foils. In the recirculating system, the energy loss and straggling of the incident beam are much less, permitting measurements (right) to be made to lower energies—in this case down to 160 keV. Measurements through foils have also been made here, by A. D. Bacher and T. A. Tombrello, down to about 300 keV. Earlier (1953) Oak Ridge results, obtained with a rather tricky target of helium gas embedded in a metal plate, are evidently seriously in error.

The competing reaction at this stage is $^3He + {}^4He \rightarrow {}^7Be + \gamma$, a "direct-capture" reaction, which, like the preceding $^2D + {}^1H \rightarrow {}^3He + \gamma$, involves the relatively weak electromagnetic interaction. It has a comparable rate in the sun only because of the large ratio of ^{4}He to ^{3}He nuclei, after five billion years of solar helium production. In the Kellogg Laboratory there have been two studies of this process, the first (PhD thesis of P. Parker, 1963) using a small gas cell with a thin nickel entrance foil, and the second by Nagatani, Dwarakanath, and Ashery last year using the recirculation system mentioned above. In both cases, sodium-iodide scintillation counters detected the reaction gamma rays. The two studies are in complete agreement, and give a value of the cross section about three times smaller than a 1958 measurement at the Naval Research Laboratory in Washington and 1,000 times larger than Bethe's guess in 1939. The theoretical extrapolation taken from the recent work is the basis for the branching fractions calculated for the p-p chain.

A third reaction at this stage, $^3He + {}^1H \rightarrow {}^4Li + \gamma$, has often been proposed as a possibly dominant route to the ^{4}He end, but depends on the mass of the ground state of ^{4}Li; this path would be overwhelming if the ^{4}Li mass were less than or about equal to the combined masses of ^{3}He and ^{1}H.

In a way, this possibility is fraught with significance, in that if the reaction goes, the sun is relatively near to the "heat death" described in *E&S* (January 1957) by Allan Sandage. The difference is due to the



A summary of measurements of the $^3He + {}^3He \rightarrow {}^4He + 2{}^1H$ reaction taken from the PhD thesis of M. R. Dwarakanath (1968). The "present-work" points on the right are the same as the data on the left after the strongly varying exponential is factored out. One effect of the higher cross section established by these recent results has been to substantially decrease the predicted flux of high-energy neutrinos from the sun.

substantial energy loss in the form of neutrinos released in the β-decay of ^4Li. These neutrinos interact so weakly with matter that they penetrate clear through the sun, carrying off about half the heat of reaction. Thus, the solar core must run hotter and produce ^4He at a higher rate, about 60 percent faster than in the case for the path via $^3He + {}^3He$. Translated into solar longevity, this implies we would have a mere billion years left to strut and fret instead of some five or six billion.

A test of this possibility was carried out in Kellogg in 1959, using the proton beam from the original 2-MV generator to bombard ^3He in a cell. Except for the beam-entrance tube, the gas cell was completely surrounded by a plastic scintillator to intercept with high probability the penetrating positron that would follow the production and decay of ^4Li. Since such decays are known to be slower than about one millisecond, the beam was remotely interrupted and the detector turned on in a cyclic fashion to avoid the strong background from the direct beam in the cell. No positrons were found in several long runs. The upper limit deduced for the production rate was about 25 times less than a theoretical estimate by R. F. Christy of the rate assuming the hypothetical ^4Li. Evidence against such low-mass ^4Li has also been deduced from the absence of analogous, or "mirror," states in ^4He and ^4H. So we assert with some confidence that the sun is in its prime, and with some relief that "no ν's is good news."

Returning now to the fate of the ^7Be produced by $^3He + {}^4He$ fusion, we again find two competitors. One is the decay of ^7Be by capture into the nucleus of one of its orbital electrons, and simultaneous emission of a 0.86-MeV neutrino, a well known radioactivity that has a laboratory lifetime of 77 days. However, at 15 million degrees ambient temperature, the atomic electrons spend less time near the nucleus and the lifetime is about doubled, according to a calculation by John Bahcall (1962). The ^7Li formed by the electron capture quickly combines with a proton to form two helium nuclei, completing the chain with a net heat generation of 25.7 MeV per new ^4He produced (here "net" means excluding neutrino losses). One of the two helium nuclei in the last step is merely recovered from its catalytic use in an earlier reaction.

The remaining branch through ^7Be involves the proton-capture cross section into the nucleus: $^7Be + p \rightarrow {}^8B + \gamma$. Prior to its measurement in Kellogg in 1959, there were two theoretical estimates on which to base rate calculations. One of these, by A. G. W. Cameron at Chalk River, Ontario, said the cross-section factor was $S_{1,7} = 1.5$ keV-barn and the other, by Christy at Caltech, gave $S_{1,7} = 0.005$ keV-barn. At the time, interest was heightened by the fact that the $^3He + {}^3He$ and $^3He + {}^4He$ reaction parameters, as then known, were such that a value as large as $S_{1,7} = 20$ keV-barn would mean that the ^8B route might dominate in the sun. Like the hypothetical ^4Li, ^8B is a high-energy neutrino emitter, and its dominance would similarly shorten the solar life span.

The only serious difficulties in measuring the required cross section in the lab hinge on the facts that the target material is radioactive and not easily acquired in quantity. As already noted, the ^7Be mean life is 77 days. It is most easily made by proton bombardment of lithium metal ($^7Li + {}^1H \rightarrow {}^7Be + n$), and for the early measurement about one-tenth microgram was obtained in this way from a 25-hour irradiation at the old Crocker cyclotron at Berkeley. About half survived carrier-free separation and deposition by vacuum evaporation onto a platinum target disc.

Again, as in the case of ^4Li, a search was made (with the same plastic scintillator) for a short-lived, high-energy positron emitter formed by bombardment of the target with protons from the 2-MeV electrostatic accelerator. ^8B activity was in fact found, and the yield led to the value, $S_{1,7} = 0.03 \pm 0.01$ keV-barn, nearly as low as Christy's calculation.

About three years ago at Brookhaven, a former student (P. Parker, now assistant professor of physics at Yale University) repeated and improved upon the measurement, taking advantage of the new semiconductor detectors to observe the 1.5-MeV alpha particles that also follow the ^8B decay. The results are in fair agreement, and we currently use $S_{1,7} = 0.035$ keV-barn. With this value we find that the proton capture is only 0.3 percent as strong as the electron capture under our standard solar conditions.

Despite this small fraction, the $^7Be + p$ branch is of great interest because of the high-energy neutrinos (up to 14 MeV) that accompany the decay of ^8B. There is a distinct possibility that they may be detectable in a massive experiment now in process by a Brookhaven group under R. Davis, involving the neutrino-induced reaction, $^{37}Cl + \nu \rightarrow {}^{37}Ar + e^- - 0.8$ MeV, which has a rate strongly dependent on the excess neutrino energy over the 0.8-MeV threshold.

The experiment consists of periodic "sweeping" of a *large* tankful (some 670 tons) of C_2Cl_4, a chlorine-rich cleaning solvent, to extract the ^{37}Ar gas, whose radioactivity can then be leisurely counted, in a sufficiently delicate and background-free detector, during the ^{37}Ar mean life of 50 days.

The outstanding and unique feature of this experiment is the fact that the detection of the neutrinos is equivalent to "seeing" directly into the core of the sun, something allowed by no other known radiation, and thus we anticipate a relatively direct test of the validity of our ideas. How much ^{37}Ar should we expect? For our standard conditions, we can readily calculate the flux of ^8B neutrinos at the earth from the product of our branching ratios (0.28 x 0.003) and the solar constant (0.134 watt per cm^2 at the earth) divided by the pp-chain energy (26 MeV = 4.2×10^{-12} watt-sec). This gives about 27 million neutrinos per square centimeter per second reaching the earth; the currently preferred model of the sun, taking into account the strong temperature dependence of the ^8B production over the active part of the solar core, gives about 3.8 million. Combining this flux with the $^{37}Cl + \nu$ cross section calculated by Bahcall, we find that ^{37}Ar is produced in the tank at the rate of 0.9 atoms per day. Further contributions from low-energy neutrinos from the ^7Be decay and from the occasional CN-cycle raises this to 1.2 per day.

Needless to say, it came as a shock when Davis reported his experimental limit from the past year's counting to be equivalent to a production of only 0.6 ± 0.5 per day! There may yet be enough flexibility in our model to meet this requirement. For example, a reduction of the central abundance of heavy elements to about half to two-thirds of its surface measured value is sufficient, because the opacity and hence the radial temperature distribution depend strongly on this feature. Davis is continuing to refine his measurements to lower his probable error, and if his improved results turn out much lower, we will be hard-pressed to resolve the conflict. We are currently planning a remeasurement this summer of the $^7Be + p$ cross section, with extension to lower energies, in an attempt to improve our knowledge of the important $S_{1,7}$ parameter, to which the calculated neutrino flux is sensitive. Though there is still no reason to push the panic button on our theories of nuclear energy generation in the sun, the coming year is a critical one.