Nuclear Astrophysics — Today and Yesterday

by William A. Fowler

"OK, Charlie, lend me one of your electroscopes and I'll check on the radioactivity from carbon-plus protons." The speaker was Merle Tuve, staff member of the Department of Terrestrial Magnetism at the Carnegie Institution of Washington, and later its director. The Charlie was Charles Lauritsen, who had recently found at Caltech that carbon bombarded by energetic protons produced radioactive nitrogen 13 (^{13}N).

William A. Fowler, professor of physics

The conversation took place at Berkeley, where the Pacific Coast Section of the American Physical Society was meeting. The time was June 1934. Earlier that same year Curie and Joliot had announced that natural alpha-particle bombardment produced artificial radioactivity such as that observed in positron emission by ^{13}N. I was a bystander, a first-year graduate student, wide-eyed and tongue-tied in the presence of the two great men.

The point at issue was a momentous one. In March of 1934 Lauritsen and his graduate student Dick Crane (now professor of physics at the University of Michigan) had detected a 10-minute activity from carbon targets bombarded by protons accelerated in the ac-powered tube in Caltech's old High Voltage Laboratory (rebuilt in 1960 as the Sloan Laboratory). Carl Anderson and his student Seth Neddermeyer (now professor of physics at the University of Washington) showed that the particles producing the activity were positrons. They did this using the same cloud chamber in which the positron had been discovered.

Lauritsen and Crane had previously found a much more copious activity of the same half-life in the bombardment of carbon targets by deuterons. Was the "proton activity" due to the natural contamination (1 part in 7,000) of deuterons in the ion-beam, or was it really induced by protons? In the deuteron (d) bombardment, neutrons (n) are produced on the light and most abundant isotope of carbon, ^{12}C, according to the reaction $^{12}C + d \rightarrow {}^{13}N + n$ followed by the beta-decay $^{13}N \rightarrow {}^{13}C + e^{+} + \nu$. In this decay process e^{+} represents the positron discovered by Anderson and ν represents the neutrino, first suggested

Nuclear research at the Institute dates back to 1934, when Willie Fowler was a first-year student. Here he reports on the development of this field and the Caltech men responsible.

by Pauli to conserve energy in beta-decays. The neutrino is now a well-established member, along with the antineutrino, of the hierarchy of elementary particles found in nature and in the laboratory.

Using the carbon-plus deuteron interaction, Crane and Lauritsen first produced neutrons with accelerated particles. Chadwick, the discoverer of the neutron, had used alpha particles from natural radioactivity. The yield of the activity produced in the reaction per incident deuteron was found to increase rapidly and smoothly with the deuteron energy, just as expected in the theory of the penetration of the Coulomb barrier between the positively charged ^{12}C and deuteron. On the other hand, the proton-induced activity showed a sharp increase above a bombardment energy of one-half million electron volts (0.5 MeV) which was indicative of "resonance" behavior. It was this marked difference in excitation curves that convinced Lauritsen and Crane that protons did indeed produce ^{13}N in carbon bombardment. The process involving ^{12}C which they suggested as a possible reaction was $^{12}C + p \rightarrow {}^{13}N + \gamma$ in which a gamma ray (γ) is emitted. This process, called radiative capture, was a matter of considerable controversy at the time.

To make a long story short, using the borrowed electroscope, Tuve and Larry Hafstad (now vice president of the General Motors Research Laboratories) confirmed Lauritsen's observation late in 1935. Subsequent work in Pasadena and elsewhere showed that the radiative capture of protons occurred for many other target nuclei.

Those were the herculean days in nuclear physics. The production of neutrons, gamma rays, electrons, and positrons by bombardment with positive ions accelerated to high velocities, the production of positron-electron annihilation radiation, the phenomenon of resonance in proton reactions—all these were discovered first or independently in Pasadena. Pasadena became one of the great centers of the nuclear world along with Cambridge (England), Berkeley, and Washington. Nuclear physics eventually died in Cambridge and Washington, while Berkeley went on to high-energy physics and nuclear chemistry. Classical nuclear physics continues to flourish in Pasadena but with an added dimension that sprang from Lauritsen's discovery of the radiative capture of protons by carbon.

The full significance of this discovery did not come until 1939 when Bethe at Cornell and Von Weizsäcker in Germany independently suggested that hydrogen could be converted into helium in stars by means of a catalytic process involving the isotopes of carbon and nitrogen which they called the CN-cycle. The first reaction in the cycle is the radiative capture of protons by ^{12}C. The second and third reactions involve similar capture by ^{13}C and ^{14}N. The capture by ^{13}C produces the ^{14}N while the capture by ^{14}N produces ^{15}O, which decays by positron and neutrino emission to ^{15}N, just as ^{13}N decays to ^{13}C. The ^{15}N reacts with protons according to $^{15}N + p \rightarrow {}^{12}C + \alpha$ so that the cycle is closed with the reappearance of the ^{12}C and the overall result is the conversion of four protons into an alpha particle, two positrons, and two neutrinos. Much later it was discovered that ^{15}N also captures protons with gamma-ray emission to form ^{16}O. In turn, the ^{16}O captures protons to form ^{17}F which decays to ^{17}O. The ^{17}O reacts with protons according to $^{17}O + p \rightarrow {}^{14}N + \alpha$, thus feeding back into the CN-cycle. The two cycles have come to be called the CNO bi-cycle.

Bethe and Critchfield suggested another process, the proton-proton chain, by which hydrogen could be converted directly into helium in stars. Bethe thought that the CN-cycle was the dominant process in the sun and that the pp-chain predominated only in somewhat cooler stars than the sun. We now know from our measurements that the pp-chain dominates in the sun and that the CNO bi-cycle takes over in stars somewhat hotter than the sun. Even so, it was quite clear in 1939 that problems in the application of nuclear physics to astronomy could only be solved by detailed and accurate measurements of nuclear reaction rates.

A start was made in this direction, mainly the construction of a 2-MeV electrostatic accelerator capable of high resolution dc operation, but World War II put a stop to all nuclear work in Kellogg. Lauritsen and Richard Tolman went to Washington early in 1940 to form the Armor Division of the National Defense Research Committee, and in the last few days of that year the majority of the laboratory group joined Lauritsen in Washington to work on proximity fuses. These fuses were being designed not only for bombs and shells but also for ordnance rockets. On a visit to England in 1941 Lauritsen found that the British were producing solid propellants for rockets of much greater size than were then being produced in the United States. He decided that there was a need for expanded rocket development in this country and moved us all back to Pasadena late in 1941 to set up a rocket project under what came to be called Section L (for Lauritsen) of the NDRC. On December 7, 1941, at Pearl Harbor it all became very real.

The story of Kellogg during the war has been told elsewhere (*Scientists Against Time,* by James Phinney Baxter, Chapter XIII, and *Rockets, Guns, and Targets,* by John E. Burchard). The greater part of the work was for the United States Navy, and by late 1944 we had started to turn the rocket work over to the Naval Ordnance Test Station at China Lake, California, near Inyokern, which we had helped the Navy build. Lauritsen was called to Los Alamos by Robert Oppenheimer, and Kellogg became involved in the production of atomic bomb components in 1944 and 1945.

With Hiroshima, Nagasaki, and the end of the war Lauritsen had to decide the future direction of research in Kellogg. He did not really hesitate, and under his direction we all enthusiastically returned to the field of low-energy, light-element nuclear physics. We resolved to spend a good part of our effort on the study of those nuclear reactions thought to take place in stars. We were encouraged in this by Ira Bowen, who had directed all the photographic measurements on the rocket range at Goldstone Dry Lake in the Mojave Desert. After the war Bowen became director of the Mount Wilson and Palomar Observatories, and early in 1946 he held a series of informal seminars in his home, where we discussed problems of mutual interest with the astronomers over beer and pretzels. In 1948 Jesse L. Greenstein came to Caltech to lead the work in astronomy, and his interests, particularly in the abundances of the elements in stars, stimulated —and continue to stimulate—much of our work.

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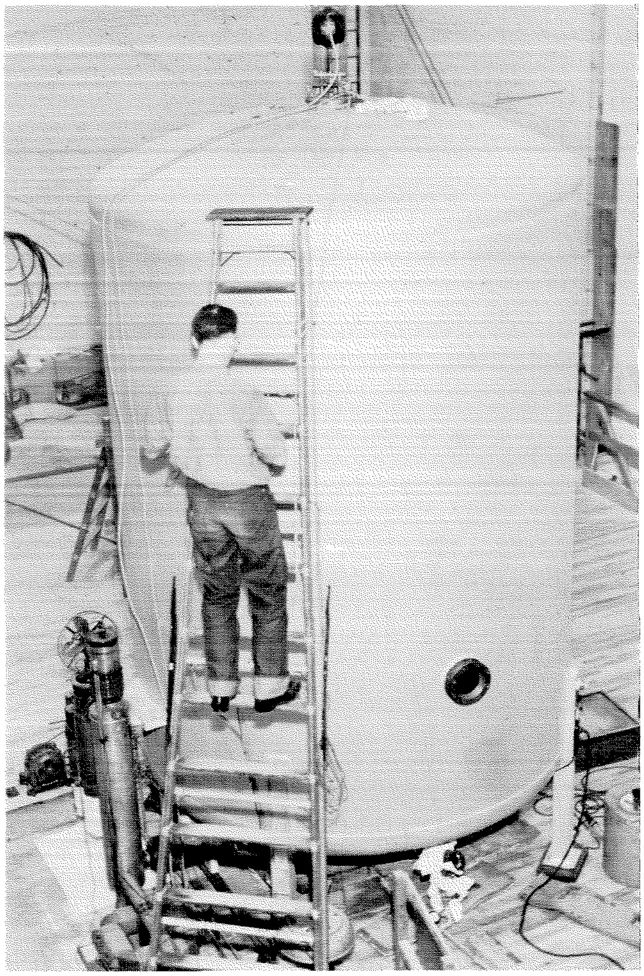
Lauritsen realized that Caltech had to move into high-energy physics as well as continue nuclear physics in Kellogg. He plumped for an electron synchrotron and persuaded R. V. Langmuir to come from Schenectady to start design and construction. Then Robert Bacher came from Cornell as new head of the division of physics, mathematics and astronomy, and within a few years there was a large and enterprising group working with Caltech's new billion-volt synchrotron.

Studies of the hydrogen-burning processes in main sequence stars began in earnest in 1946 and are still proceeding. In this context, burning means nuclear burning, not chemical atomic burning. But hydrogen burning produces helium and the question naturally arises: When the hydrogen is exhausted, what happens to the helium? When energy generation stops at the center of a star, the temperature does not decrease, which may seem paradoxical. Instead, gravitational forces, no longer balanced by sufficient internal pressures, bring about a quasi-static contraction and compression which raises the temperature of the stellar material. This continues until ignition of a new fuel supplies the energy requirement set by the luminosity of the star under hydrostatic equilibrium.

In the early 1950's the big question was: How does helium burn? Even as early as 1939 work in Kellogg had pinpointed this problem. In that year research fellow Hans Staub (now professor of physics at the University of Zurich) and graduate student William Stephens (now professor of physics at the University



A graduate student works on Caltech's first 2-MeV electrostatic accelerator, built in 1940.

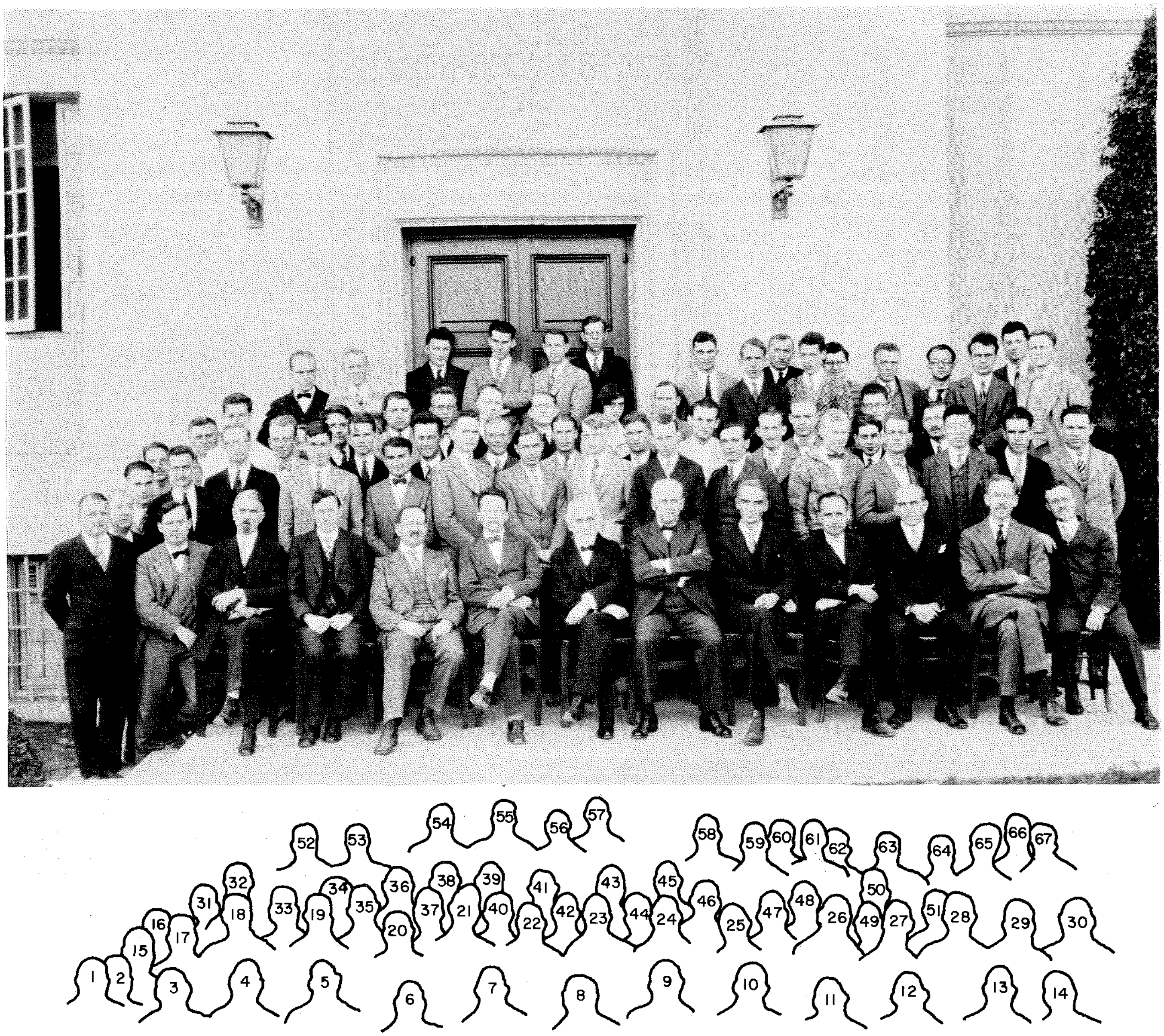
of Pennsylvania) had found an anomaly near 1 MeV bombarding energy in the scattering of neutrons by alpha particles, which are the nuclei of ordinary helium, ^{4}He. The anomaly consisted of a marked deviation from the theoretical predictions based on pure Coulomb scattering and corresponded to an unbound state in the nucleus ^{5}He, and it confirmed work done with other reactions elsewhere. Subsequent work has never revealed a lower state. Thus this state is now known to be the ground state of ^{5}He so that ^{4}He cannot radiatively capture neutrons into a stable configuration with the release of energy. Because of repulsive electrostatic forces it was realized that the ground state of ^{5}Li would be still more unstable with respect to a proton and an alpha particle, and in fact the state has been found to be unbound with respect to $^5\mathrm{Li} \rightarrow {}^4\mathrm{He} + \mathrm{p}$ by approximately 2 MeV compared to 1 MeV in the $^5\mathrm{He} \rightarrow {}^4\mathrm{He} + \mathrm{n}$ case. ^{4}He scatters neutrons and protons but does not capture them.

There is thus a mass gap—no stable nucleus—at mass five. This constituted a formidable barrier to George Gamow's theory of nucleosynthesis by neutron capture in "big bang" cosmology. It meant too that protons did not combine with ^{4}He in stars to produce mass five and perhaps heavier elements.

More to the point, when hydrogen was exhausted, would ^{4}He react with ^{4}He to form a stable nucleus, in this case ^{8}Be? The nucleus ^{8}Be does not occur in nature, and in all nuclear reactions in which it was produced it broke up very rapidly into two alpha particles, but there was considerable uncertainty in the breakup energy, estimates ranging from 40 to 120 keV. As part of his doctoral research in 1949 Alvin Tollestrup measured the breakup energy accurately for the first time, finding 89 ± 5 keV. The presently accepted value is 92.12 ± 0.05 keV. It was thus clear that the interaction of two helium nuclei would not supply nuclear energy. In 1951 E. E. Salpeter of Cornell spent the summer in Kellogg, and with the ^{8}Be instability energy as a basis he worked out the details of an old idea of Bethe's by which helium might burn in spite of the instability of ^{8}Be. Because of the relatively low value of the instability energy, ^{8}Be will have a small but significant equilibrium concentration in hot helium and in addition will act just like any other nucleus. In particular it will radiatively capture a third alpha particle to form ^{12}C with a substantial radiated energy release. Salpeter proposed that the $3\alpha \rightarrow {}^{12}\mathrm{C}$ process is the nuclear source of energy in red giant stars.

However, it was not until 1953 that we did anything experimentally about this new process. In that year Fred Hoyle came to Caltech for the first time. He walked into Kellogg and announced that there had to be a resonance in the reaction $^8\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + \gamma$ at an interaction energy near 0.3 MeV. This corresponds to an excited state in ^{12}C at 7.7 MeV excitation. He had come to this result on the basis of his idea that the elements beyond hydrogen are produced in stars and in particular that ^{4}He, ^{12}C, and ^{16}O are produced in red giant stars. This resonance was needed to make the production ratios agree with the abundance ratios of helium, carbon, and oxygen in the solar and other stellar systems.

Was there such a state in ^{12}C? The record was ambiguous. Prewar measurements at Cornell had found a state near 7.6 MeV but with considerable uncertainty in energy, though postwar measurements at MIT and elsewhere had failed to confirm these results. We believed the postwar results.



Caltech's math and physics group in 1926

(1) Bruno Merkel (2) W. H. Bressler (3) Robt. Burt (4) S. S. Barnett (5) Harry Bateman (6) Paul Epstein (7) Edwin Shroedinger (8) H. A. Lorentz (9) R. Millikan (10) Eric Temple Bell (11) Earnest Watson (12) F. C. Blake (13) J. B. Brinsmade (14) Norton Kent (15) H. M. Evjen (16) C. Millikan (17) H. E. Mendenhall (18) J. H. Bohn (19) Sidney Ingram (20) M. E. Brenner (21) Charles Daily (22) Lee DuBridge (23) A. L. Foster (24) K. K. Illingsworth (25) Jos. Mattauch (26) Lynn Howell (27) C. A. Cartwright (28) K. C. Fang (29) Ralph Winger (30) Arthur Klein (31) Julius Pearson (32) Dwight Taylor (33) Ralph Day (34) W. C. Bruce (35) Norris Johnston (36) A. Keith Brewer (37) F. L. Poole (38) A. C. Hodges (39) W. V. Houston (40) G. H. Palmer (41) Charlie Lauritsen (42) W. L. Bradway (43) Anna Van Tienhoven (44) J. H. Hamilton (45) Lars Thomassen (46) Claude Hayward (47) Richard Badger (48) Paul Richardson (49) Charles Richter (50) G. R. Jaffray (51) Vladimir Zaikowsky (52) Burt Richardson (53) R. M. Sutton (54) Willy Uyterhoven (55) Ray Kennedy (56) T. D. Yensen (57) Stuart Mackeown (58) Wm. Smythe (59) G. H. Dieke (60) Fritz Zwicky (61) Bruce Hicks (62) Boris Podolsky (63) Morgan Ward (64) J. A. Van den Akker (65) Ira Bowen (66) Otto Ritzman (67) W. N. Birchby

Ward Whaling and the group of graduate students and research fellows working with him finally succumbed to Hoyle's insistence and looked for the state in the reaction $^{14}N + d \rightarrow {}^{12}C + \alpha$. The results were loud and clear—the state was indeed produced in this process, albeit weakly compared to other states, but the experimental evidence for it stood out more than one hundred times over the inevitable background. The weakness compared to other states explained, in part at least, why it had been missed in some measurements. Most remarkable of all, the excitation energy came out to be 7.68 ± 0.03 MeV. We now know that the interaction energy is 0.28 MeV and the excitation energy is 7.653 ± 0.003 MeV, but Hoyle's prediction was and still is the closest ever for the value of a nuclear excited state. Nuclear theory then and now cannot do as well.

The state was well established, but whether its existence did any good was now the question. Did it have such properties that it could be formed from three alpha particles? Strict selection rules determine the states through which these three identical particles can interact to form ^{12}C. If the spin of the state is an even number (0, 2, 4 . . .), then its parity must be even (+). If the spin is an odd number (1, 3, 5 . . .), then its parity must be odd (−). The parity is determined by the behavior of the wave function under the operation of mirror reflection. Now it wasn't possible to produce the excited ^{12}C directly in the laboratory from three alpha particles. The lifetime of the intermediate ^{8}Be was much too short ($\sim 10^{-16}$ sec). Lauritsen and a group of us went about the problem indirectly. We produced the excited state in the radioactive decay of ^{12}B and showed that it broke up into three alpha particles as well as decaying to the ground state of ^{12}C. On very general physical grounds we then knew that it could be formed from three alpha particles and took part in the nuclear transformation of helium into stable ^{12}C. Helium burning did indeed occur and was sufficient to warm the hearts of red giant stars.

It became abundantly clear that there was something in Hoyle's idea of element building in stars, particularly since the experimental $3\alpha \rightarrow {}^{12}C$ reaction rate parameters showed that it could not occur at the temperatures and densities which occur in Gamow's big bang. In 1955 Geoffrey and Margaret Burbidge —both of whom are now professors at UCSD, La Jolla—came to Pasadena; Hoyle spent much time here; and eventually we developed together a comprehensive theory of nucleosynthesis in stars of all of the elements and their isotopes.

A key step in this development was the recognition that the abundance of the nuclear species beyond iron indicated that the major synthesis in this region involved the successive capture of neutrons. This was quite natural since charged-particle reactions with the heavier nuclei became very infrequent because of the relatively high Coulomb repulsions involved. In addition, Jesse Greenstein and A. G. W. Cameron (now professor of physics at Yeshiva University) independently pointed out that neutrons became available in helium burning through the $^{13}C + \alpha \rightarrow {}^{16}O +$ n reaction, the ^{13}C having been produced previously in the CN-cycle.

The neutron capture story took some unraveling since two processes are involved—one in which the neutrons are captured *slowly* compared to the intervening beta decays, called the *s*-process; and one in which the neutrons are captured *rapidly*, called the *r*-process. We did not have neutron sources intense enough to study these processes experimentally, but J. H. Gibbons and R. L. Macklin at the Oak Ridge National Laboratory were induced to undertake the long and arduous task of measuring neutron-capture cross sections by individual isotopes in the 10 to 100 keV bombardment range, and this by now they have largely completed. Their work has exhibited the many predicted correlations between individual abundances and neutron-capture cross sections. The observations of Greenstein and his collaborators on stellar abundances played a major role in this work.

It is fair to say that hydrogen and helium burning in stars are now, in principle, quite well understood even though there are still key quantitative measurements of great difficulty under way in Kellogg and Sloan. A major part of the investigations in nuclear astrophysics in the laboratories is now devoted to the study of carbon burning, oxygen burning, and silicon burning—the complicated nuclear processes which take place during the advanced stages of stellar evolution beyond the main sequence and red giant stages.

These burning processes lead in a variety of ways and at a variety of stages to instabilities in stellar structure. These instabilities lead to the ejection of the outer layers of the stellar material, and this ejection is observed in supernova explosions. This is one of the ways in which the debris of element-building processes in stars is ejected into the interstellar medium from which new stars and their planetary systems are formed. On the other hand, as a result of the instability, the inner core of the star collapses and survives as a remnant white dwarf or neutron star. White dwarfs have been observed for years while evidence has accumulated since the discovery of the pulsars, slightly over one year ago, that these puzzling celestial objects are probably rotating neutron stars.

The field is enlivened and stimulated by astronomical discoveries such as quasars, pulsars, and x-ray stars, and we have to work hard in Kellogg and Sloan to keep up with the nuclear aspects of these exciting situations. It is clearly recognized that no solution of the formation of supernova remnants can be reached until the nuclear problems are solved. It is clear that our business is the firm establishment of the *empirical* basis for stellar nucleosynthesis and stellar instability. In the tradition of Charles Lauritsen we are working hard at these problems, and are having a wonderful time as our five electrostatic accelerators turn out the results.