JUNE 1969

ENGINEERING AND SCIENCE

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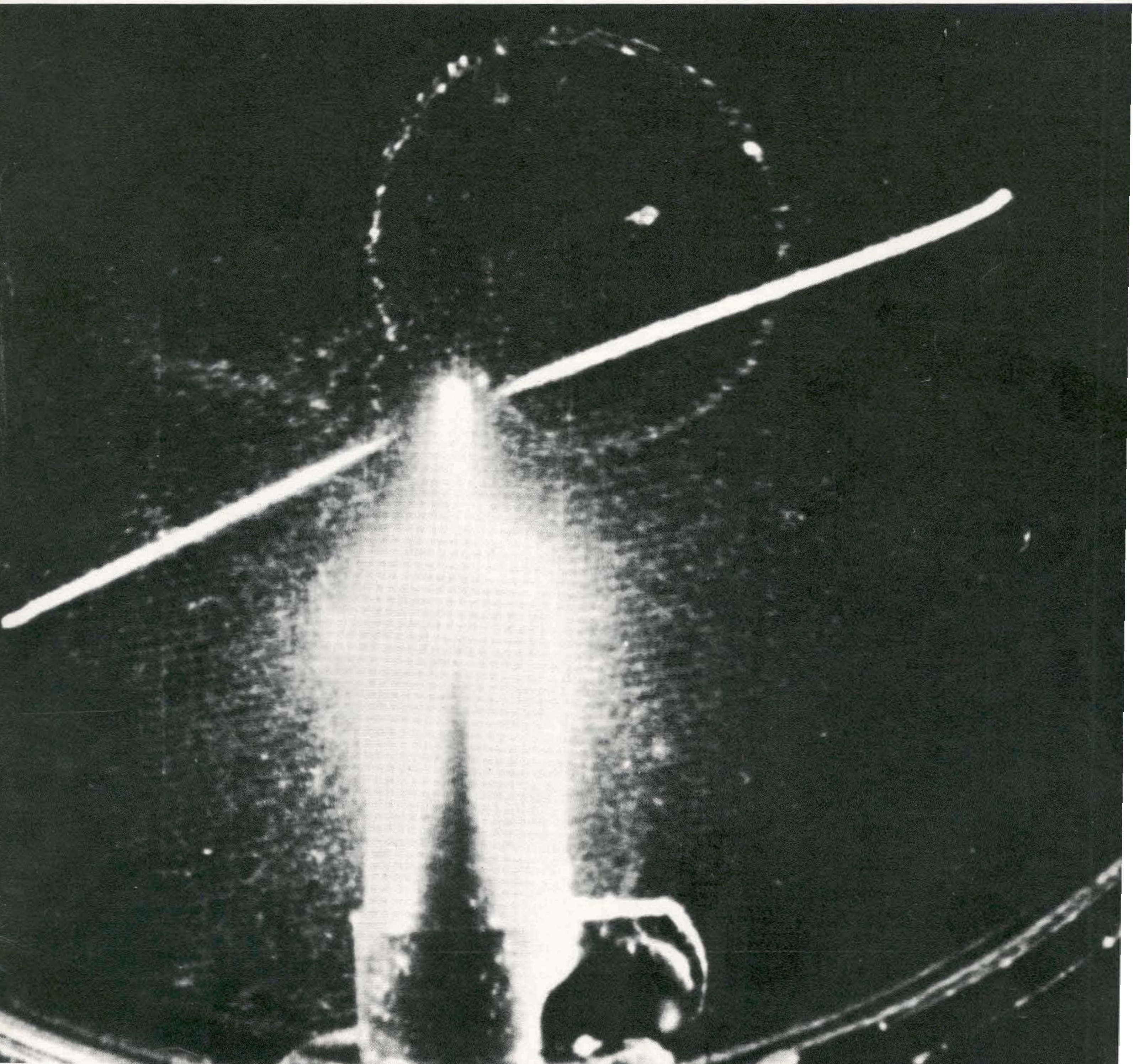

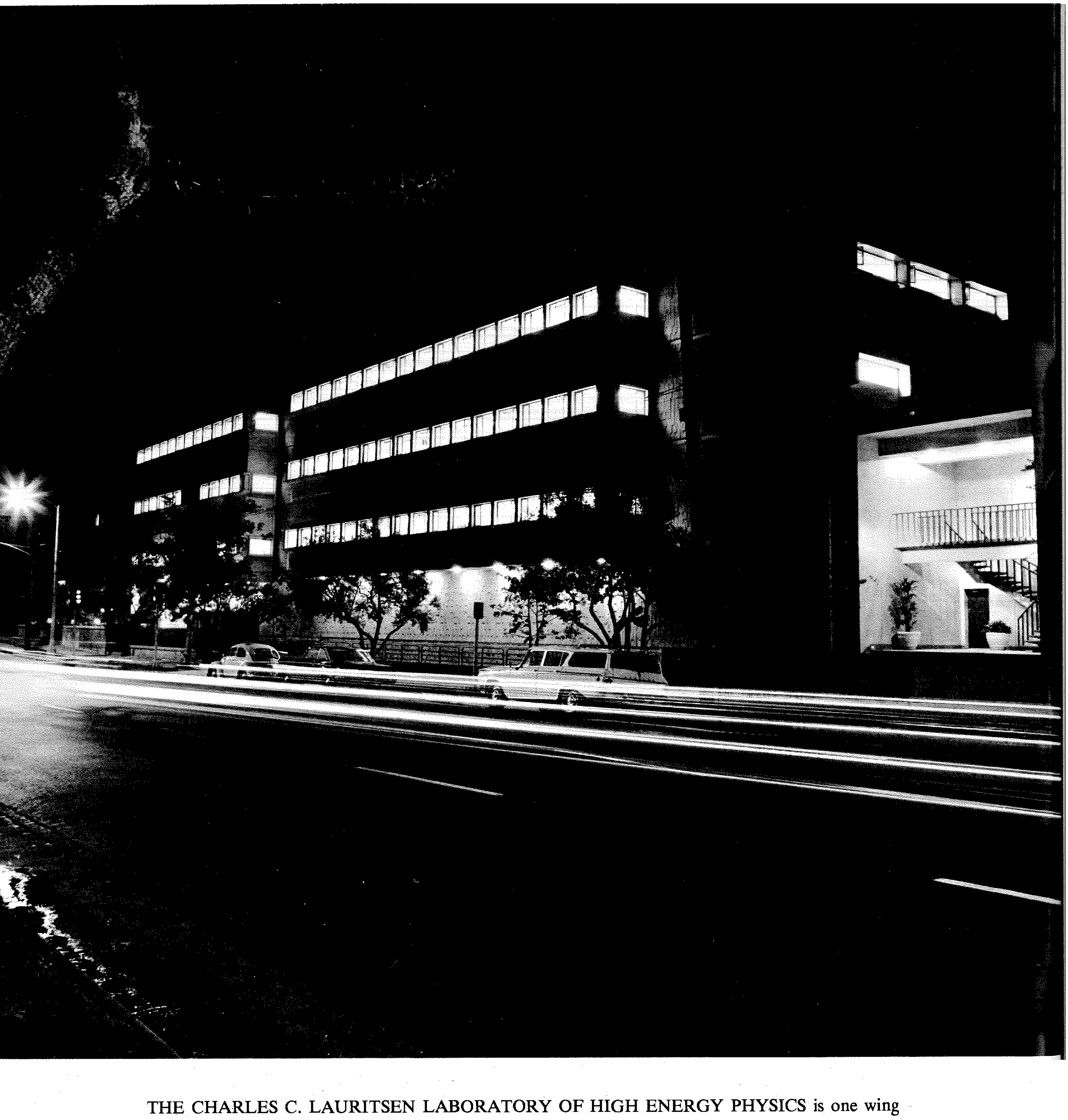

THE CHARLES C. LAURITSEN LABORATORY OF HIGH ENERGY PHYSICS is one wing (right) of Caltech's recently completed $3.5 million physics building. The George W. Downs Laboratory of Physics, the connecting wing (left), was erected with funds provided by the National Science Foundation and the late George Downs, a Caltech alumnus and an associate in engineering on the Institute staff. The Lauritsen wing was built with funds from the Atomic Energy Commission and is named in honor of Dr. Lauritsen, a member of the Caltech faculty from 1930 to 1968. The building is located on California Boulevard to the east of Kellogg Laboratory.

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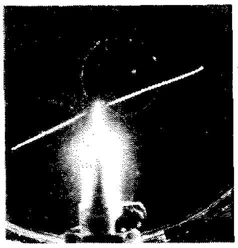
A SPECIAL ISSUE



ON THE COVER

A Wilson cloud chamber photograph of a lithium 8 decay. The nearly circular track was produced by a low-energy beta ray moving in an externally applied magnetic field. The two dense tracks are made by the alpha particles resulting from the fission of the resulting beryllium 8 nucleus. An anti-neutrino is also emitted, but makes no track in the chamber. Unraveling the beta-decay of lithium 8 has played an important role in our understanding of the weak interaction, as discussed by Charles Barnes on page 20. In turn, the beta-decay process, now well understood, has become a powerful tool for further studies of nuclear structure and nuclear astrophysics.

PHOTO CREDITS

All pictures in this issue by Floyd Clark except page 2—The Aerospace Corporation

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TO CHARLES

LAURITSEN AND HIS HERITAGE

This issue of *Engineering & Science* has been prepared as a tribute to Charles Lauritsen to coincide with the completion of the Institute's new Lauritsen Laboratory and the announcement of the Lauritsen Memorial Lectureship. The articles that follow give some indication of the flourishing and varied research that has grown out of his initial interest in high-voltage x-ray tubes 30 years ago.

The first article tells, in the words of Tom Lauritsen, how Charlie came to Pasadena and high-voltage research from a career in electrical engineering. Early investigations in the brand-new Kellogg Laboratory are described in William A. Fowler's account of the beginning of nuclear research and the way in which it quickly led to astrophysical applications. Stewart Harrison then describes radiation therapy in Kellogg—a relatively short and unfamiliar chapter in the history of the laboratory but one of Lauritsen's lifelong interests.

During the years in which he led the Kellogg and Sloan Laboratories to a position of eminence in nuclear physics, Lauritsen concentrated on two areas: the structure of light nuclei, and nuclear processes in stars. Tom Tombrello describes some of the highlights in this study of energy levels and reactions of light nuclei, and Charles Barnes describes noteworthy experiments on nuclear beta-decay in the context of the steadily increasing understanding of the weak interaction. In discussing nuclear processes in stars, Ralph Kavanagh describes a series of experiments extending over 20 years that have led to a fairly clear picture of energy production in the sun.

The next three articles deal with research that has developed out of this interest in nuclear astrophysics: Ward Whaling and George Lawrence describe atomic spectroscopy related to stellar composition; Kip Thorne discusses theoretical studies of relativistic cosmology and stellar evolution; and Gerry Wasserburg and Don Burnett report geochemical investigations of nuclear processes in our evolving solar system. In the last article Jim Mayer describes investigations in solid state physics that make use of the instrumentation and the methods that were developed in Kellogg Laboratory under Lauritsen's guidance.

All these articles reflect the influence of Charlie Lauritsen. We hope they convey some of his spirit of "having a good time" pursuing the challenging questions and fascinating puzzles that nature continually presents.

—Carl Anderson

Kellogg Laboratory: The Early Years

by Thomas Lauritsen

When C. C. Lauritsen came to Caltech in 1926, the stage was set for 40 years of enthusiastic and prodigious research in nuclear physics.

Like many ventures of its kind, the Kellogg Laboratory's entry into nuclear physics arose through a combination of serendipity and a favorable environment. In 1932, when Cockcroft and Walton announced that man-made machines could be used to disintegrate nuclei, Charlie Lauritsen was listening, and he had a laboratory ready to go. Of course it was luck. He just happened to be working with million-volt vacuum tubes, he just happened to see a future in this newborn field, and he just happened to know a way to put some junk together for an ion source and get in business. He also just happened to know R. A. Millikan.

C. C. Lauritsen came to Pasadena in 1926 after hearing a lecture by Millikan in, of all places, St. Louis. A graduate architect from Odense Technical School in Denmark, Charlie had emigrated in 1917 to find his fortune in America. After various undertakings, from designing naval craft in Boston to professional fishing off the Florida coast, he went to Palo Alto in 1921 to work on ship-to-shore radio for Federal Telegraph. There his interest turned to designing radio receivers, and, together with a couple of enthusiastic partners, he started producing them in a rented garage.

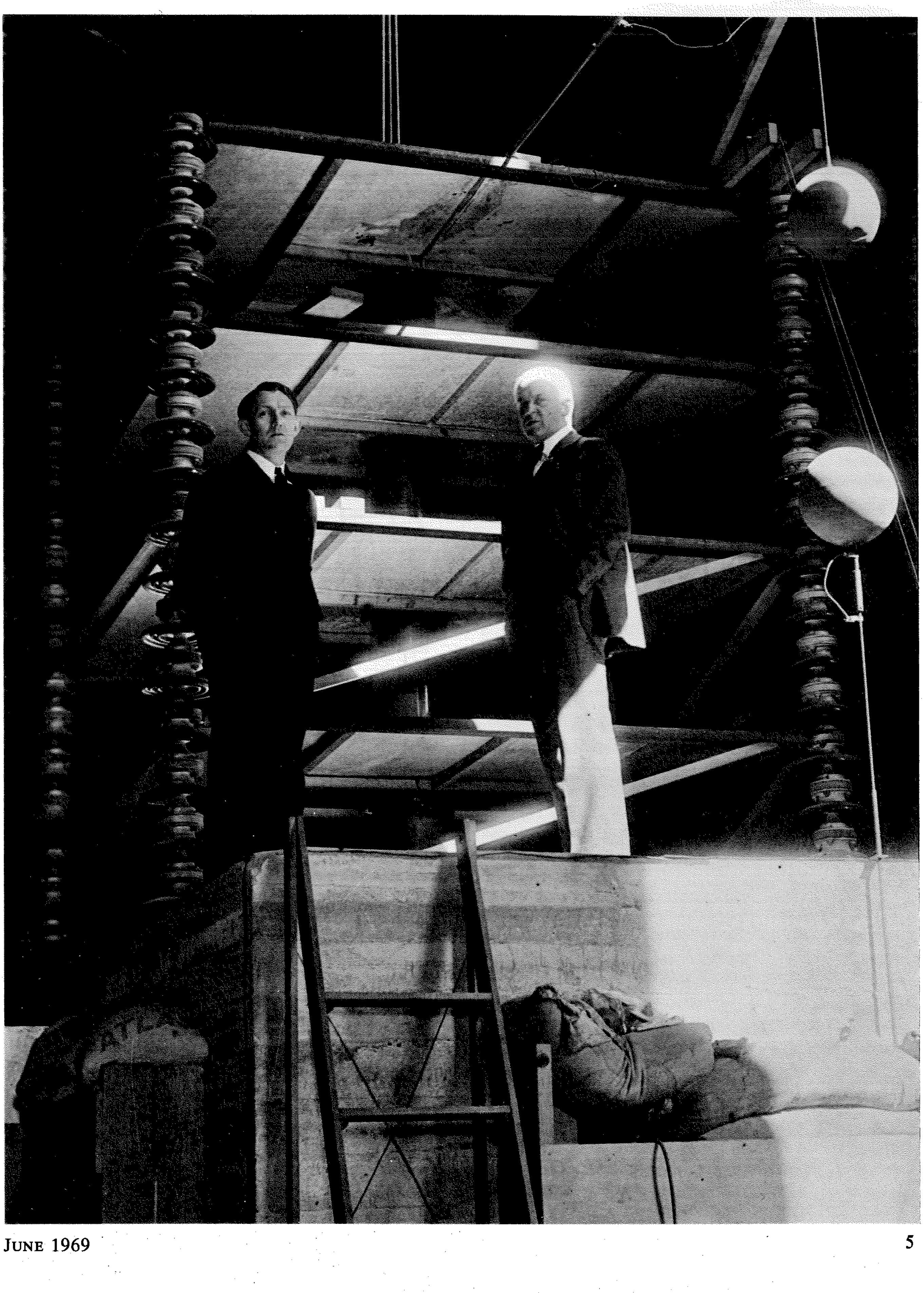
Radio receivers were pretty complicated in those days, with those great big blue tubes sticking out the top and a rat's nest of handmade components inside, and Charlie's had an especially sensitive regenerative circuit. In fact it would oscillate uncontrollably if a curious competitor took it out of the cabinet without noticing that half of a crucial condenser was imbedded in the woodwork. However, the recognition that nationwide companies were not buying his products two at a time for entertainment alone induced Charlie to patent his circuit and join the big operators. In 1923, then, he went off to St. Louis to become chief engineer for the Kennedy Corporation and started making those 50-pound, 10-tube monsters that brought music and status to tens of thousands of American households.

In 1928 the radio business was booming, but Charlie didn't like the noise. He thought he detected an instability in the frenetic maneuvering of the financial giants of industry who seemed to be trying to reap more than could be sown. A certain uneasiness about the future of this line of endeavor, together with the gentle reminder from Millikan that there was a more interesting world, led him to pick up his wife, chattels, and an unpromising 10-year-old offspring and head for Mecca.

In Pasadena, he found much to his surprise that you could get paid—though not handsomely—for working at a place like Caltech, and he settled down to work. He signed up for large chunks of Epstein and Smythe and Tolman and Bowen and Zwicky and Bateman, and started to rebuild his intellectual capital. More than that, he went to the Chief and asked for a project.

One of the most astonishing things about R. A. Millikan was his uncanny gift for knowing where the action was. On all of the crucially important experiments of the era—the measurement of e, the photo effect, x-ray spectroscopy, spectra of stripped atoms, cosmic rays—the Chief's intuition never failed. And he didn't disappoint Charlie, either. What was bothering him in the fall of 1926 was the cold-emission effect: pulling electrons out of metals by high electric fields. If you put in the experimental numbers, it appeared to be easier to get electrons out than the

The million-volt x-ray tube, developed and built at Caltech by C. C. Lauritsen (left) and colleagues in 1928, prompted R. A. Millikan (right) to interest W. K. Kellogg in financing a new laboratory to house the research.



theory would allow, considering that they had to be pulled over a quite formidable potential barrier at the surface. Would Charlie like to look into it? (Present-day graduate students might note that, in those days, such questions were entirely rhetorical.)

Look into it he did. With balls of wax and pieces of string and a joyously acquired skill in quartzblowing and microscopic fiddling, Charlie tracked the beast to its lair. As with many other experiments guided by Millikan, it developed that you had to work hard to get a really clear result, but when you did, it was pretty interesting. In the present instance, it was possible to show that the field emission was quite insensitive to temperature and displayed a simple exponential dependence on field strength that agreed very well with a theory developed by Oppenheimer on the basis of quantum-mechanical barrier penetration. This was 1928.

Field emission, vacuum tubes, and Sorensen's million-volt testing laboratory led Charlie to x-rays. No longer playthings to be stored in cigar boxes, his new tubes took on Brobdignagian proportions, with 6-inch vacuum plumbing and 12-inch glass gasoline pump cylinders (remember them?) for the tubes. With R. D. Bennett, B. Cassen, H. R. Crane, and others, Charlie built a series of these tubes in the old High Voltage Lab, operating up to 750 kilovolts.

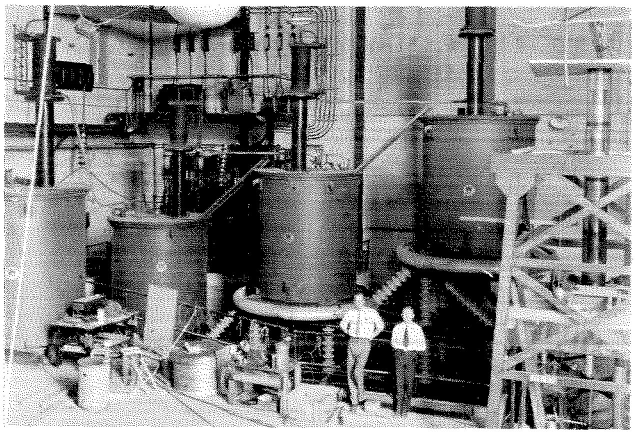
Three-quarters of a million volts was quite a step forward in the technology of 1928. The largest medical x-ray tubes then available were fragile overgrown glass bulbs rated for 200 kilovolts and worth their weight in gold. It seemed natural, then, to explore whether the bigger tubes offered any new opportunities in medicine, particularly in the treatment of deep-seated malignant tumors. This idea proved quite interesting to Albert Soiland, a distinguished radiologist in Los Angeles, and after some preliminary experiments with animals, treatment of patients with "super voltage" x-rays began in the Hi Volts lab in October 1930. In the following year, Millikan got W. K. Kellogg interested in improving the facilities, and the Kellogg Lab emerged from a dirt pile behind Hi Volts.

When the cataclysmic (to nuclear physicists) events of 1932 came along, the x-ray business was just moving out of Hi Volts and into Kellogg, and Charlie was working with Dick Crane to see how you would make a tube if you had money enough to have parts made to order. Came the news then that there was gold in positive ions, and they immediately got to work, converting an x-ray tube with a bottle of gas and a primitive ion source. One of the first projects, published in September 1933, was the artificial production of neutrons by bombarding beryllium targets with helium ions up to 950 kilovolts. The neutrons were detected with a simple quartz fiber electroscope that Charlie had developed for the x-ray work, now furnished with a lining of paraffin. Neutrons had been caught just the year before, after being chased all over Europe by people trying to understand the rare but potent radiations produced by bombarding beryllium with alpha particles from radium. The discovery that you could now make them in a machine by the tens of thousands instead of one at a time made quite a difference in their prospects for gainful employment.

Not very long after, G. N. Lewis supplied Charlie with a sample of heavy water which could be used to make deuterons to bombard lithium and beryllium for an even more copious source of neutrons. Heavy water turned out to be so useful that Dick Crane put together a big electrolytic cell that electrolyzed gallons of sparkling distilled water down to a few drops of repulsive, but heavy, mud. Do-it-yourself deuterons were the order of the day for a long time until some Norwegians made heavy water into a commercial enterprise.

Through all of this, there was Millikan, popping over from time to time with enthusiasm for the new discoveries and working like fury to keep the show on the road and the wolf from the door.

One of the fun things that occurred during these first years of nuclear physics in Kellogg was the discovery that you could make radioactive substances by



Ralph Bennett (left) and C. C. Lauritsen were chiefly responsible for the building of the first million-volt x-ray tube (in the wooden tower at the right) at Caltech. Four cascade transformers supplied the power.

bombarding various things with deuterons. This was first published by Lauritsen, Crane, and Harper in early 1934. From carbon there was produced a 10.3 min activity ^{13}N which not only produced positrons—which weren't very old by then—but also annihilation radiation, the last agonized cry of a positron that has met its match. These experiments, and some others with boron, induced a brief flurry of controversy on this side of the ocean, which finally got resolved when experimental techniques got tightened up a bit. Something that always amused Charlie was that the ^{13}N, which ought to be a gas, stuck firmly in the targets, while ^{11}C usually escaped as CO or CO_2, falsifying the half-life.

Friendly controversies about new results in this fast-growing field were not infrequent. One of these had to do with whether protons could be captured by carbon, making nitrogen 13 and gamma rays. The resolution of this matter led to the discovery of resonance capture, a phenomenon that theorists were quite confident could not occur in nuclei. Niels Bohr's invention of the liquid drop model in 1936 cleared that up.

With the medical operations transferred to Kellogg Lab, Charlie had lots of space in Hi Volts. Together with his students, he built several positive ion accelerators on various concrete huts around the place and kept the million-volt transformer set buzzing day and night. But ac is not the best possible power supply for a nuclear physicist, especially if he's interested in resonances that occur at sharply defined voltages. In 1937 R. G. Herb at Madison had done beautiful things with a Van de Graaff generator enclosed in a pressure tank with a tube that really worked at high voltage. This seemed a good thing to get onto, so Charlie and his gang cleaned out a hut on the floor of Hi Volts and built a version of Herb's machine with some local modifications. Money was a little more plentiful by then, and the pressure tank was specially built for $1,500. That did it for the budget, however, and everything else was either scrounged or made to order by graduate students. Still it was a wonderful machine when it finally ran in late 1938, and it remains a thing of joy, if not beauty, to this day.

The x-rays were turned off in Kellogg in early 1939, when adequate commercial tubes became available in hospitals. Together with its gaggle of graduate students the Van de Graaff was moved in to replace them, along with some other nuclear enterprises just coming into being. Sadly, this promising effort had only just time to get going when the troubles of World War II intervened to shut down the lab for five long years. Charlie went off to Washington to join the fray in early 1940, and there was no more physics until the end of 1945.


Thomas Lauritsen (son of C. C. Lauritsen), professor of physics, has been at Caltech since student days, 1932.

These prewar years saw Caltech's first venture into the world of big accelerators and big projects. In today's terms, of course, neither the machine nor the budgets would be called big; in fact one would today characterize such budgets as an almost negligible perturbation on the poverty level. Still, there was enough money—Millikan saw to that—and more important, there was enthusiasm, and wonder and adventure, on a prodigious, boundless, all-encompassing scale—and this was Millikan, and Charlie, and four generations of horny-handed graduate students.

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.

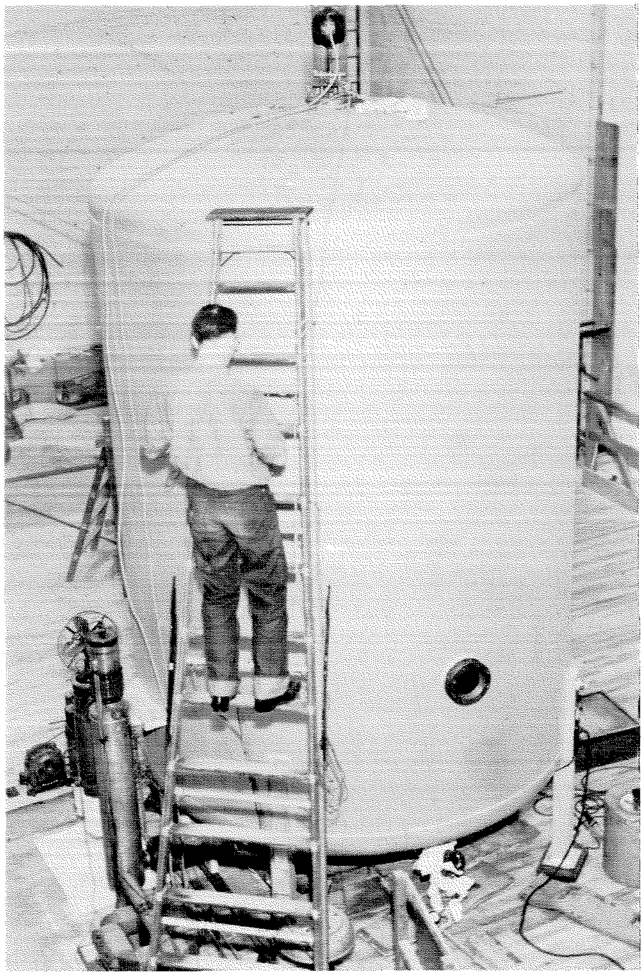
With Hiroshima, Nagasaki, and the end of the war Lauritsen had to decide the future direction of research in Kellogg. He did not really hesitate, and under his direction we all enthusiastically returned to the field of low-energy, light-element nuclear physics. We resolved to spend a good part of our 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.

By 1939 it was clear that problems in the application of nuclear physics to astronomy could only be solved by accurately measuring nuclear reaction rates. A start was made in this direction by the construction of Caltech's first electrostatic accelerator.

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.

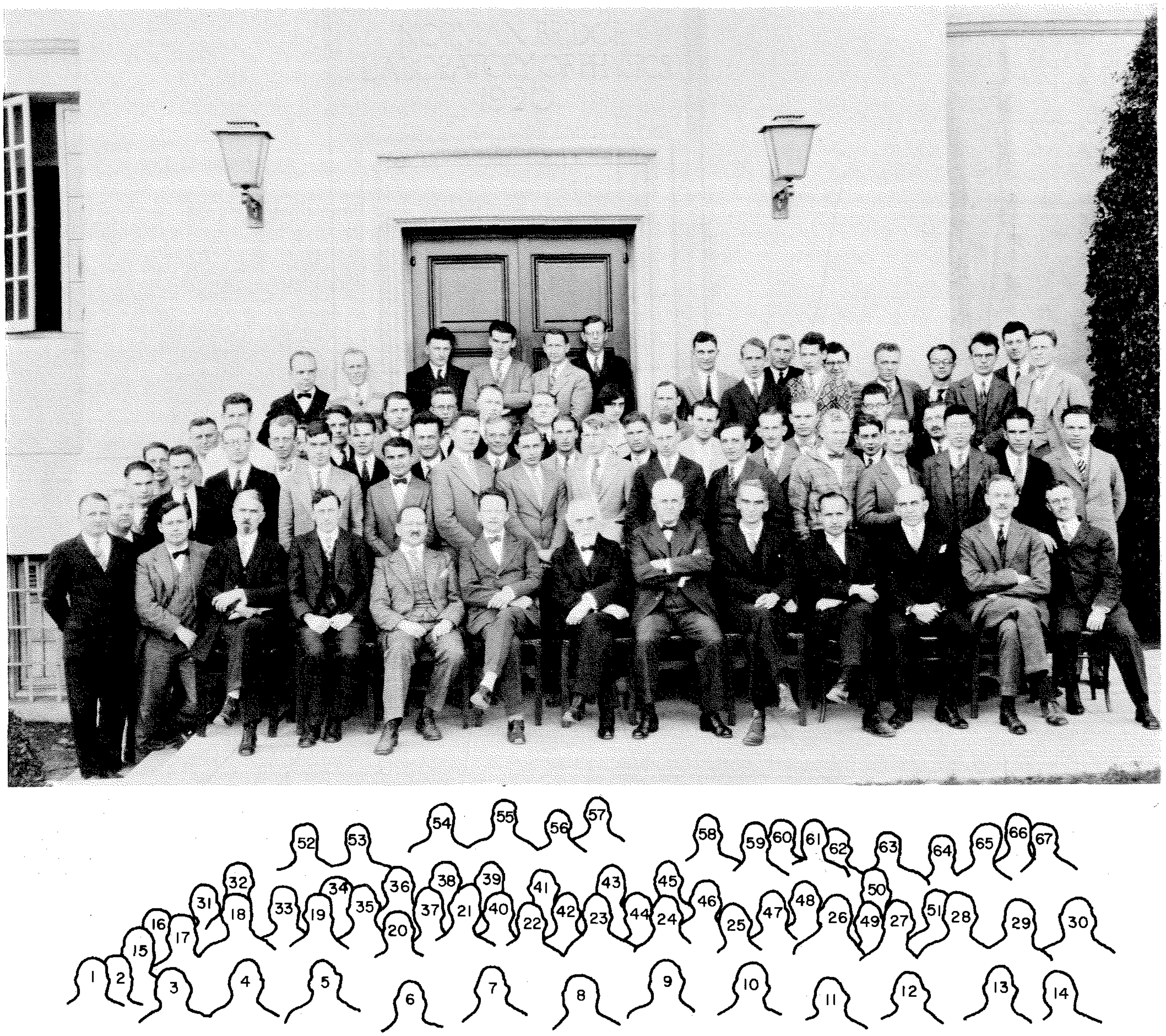
of Pennsylvania) had found an anomaly near 1 MeV bombarding energy in the scattering of neutrons by alpha particles, which are the nuclei of ordinary helium, ^{4}He. The anomaly consisted of a marked deviation from the theoretical predictions based on pure Coulomb scattering and corresponded to an unbound 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.

R. Stewart Harrison, MD, radiologist and director of radiation safety for the California Institute of Technology.

Radiation Therapy

by R. Stewart Harrison

During the depressed thirties there were at least three questions that confronted radiologists seeking to control or cure cancer below the surface of the skin:

(1) At that time the unit of ionizing radiation was based on the amount of ionization produced in air. Would one unit produce the same effect in tissue at all photon energies?

(2) Would the amount of ionization produced in a cubic centimeter of tissue n centimeters from the surface always bear a constant relation to the amount produced in the first cubic centimeter, regardless of photon energy? And, if there was a difference, would it be therapeutically useful?

(3) It was already known that some cancers were on the average somewhat more sensitive to ionizing radiation than surrounding or intermingled normal cells. Could this relative sensitivity be enhanced by increasing the energy of the photons?

These questions were answered within the decade by cooperative research undertaken at Caltech and elsewhere.

In 1928 C. C. Lauritsen built the world's largest x-ray tube—750,000 volts—for physics experimentation. In 1933 Albert Soiland, a prominent Los Angeles radiologist, documented the beginning of the medical use of radiation produced by this tube in an article published in *Radiology,* February 1933:

"During the summer of 1930 the writer was invited by Dr. R. A. Millikan and Dr. C. C. Lauritsen of the California Institute of Technology to inspect the high voltage x-ray tube installation at the Institute. Dr. Lauritsen, who had been experimenting with the 1,000,000-volt transformer set at the Institute, had succeeded in building a large x-ray tube of glass through which 5 milliamperes of current operated successfully at 750,000 volts. This equipment, which

A relatively short and unfamiliar chapter in the history of Kellogg Laboratory written by a member of the Caltech research team in radiology in the thirties who subsequently became director of the radiology department of the Huntington Memorial Hospital in Pasadena.

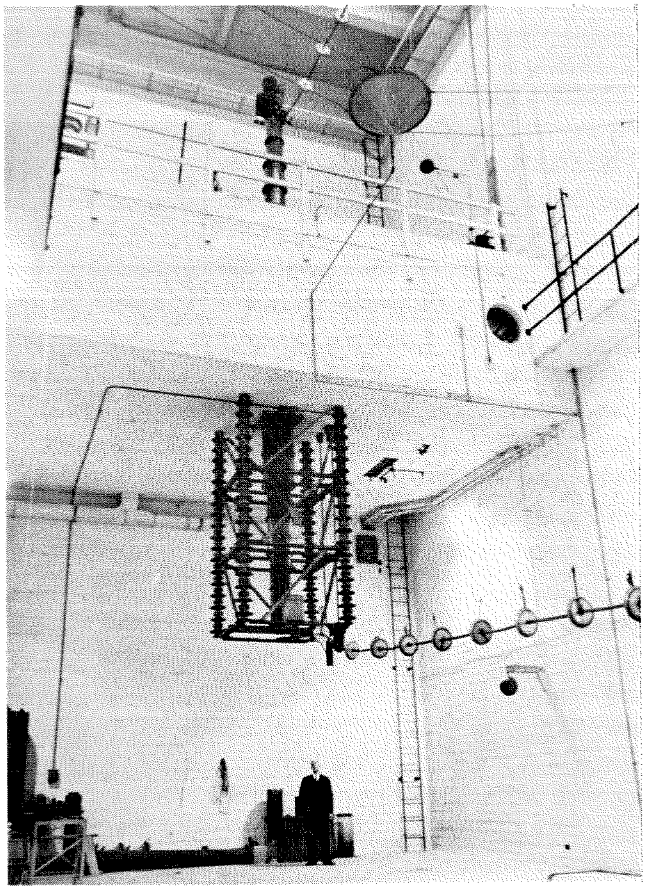
was designed for physical research purposes only, had been in successful operation for many months. It occurred to Dr. Lauritsen that the radiation produced by this tube might have some biologic effect which could be utilized in the treatment of disease. Because the writer was much impressed by Dr. Lauritsen's achievement, he suggested, after consultations with Dr. Millikan and Dr. Lauritsen, that he be permitted to put the tube to clinical tests. . . .

"Dr. Lauritsen has more recently constructed a tube with a capacity of 1,000,000 volts potential, and further research work is going on in the new Kellogg Laboratory. This department is under the immediate charge of Dr. Seeley G. Mudd, who has become greatly interested in the work and devotes his time and energy to the furtherance of the clinical experimentation. Dr. Mudd is assisted by Dr. Clyde K. Emery and by my clinical associates, Dr. William E. Costolow and Dr. Orville N. Meland as collaborators."

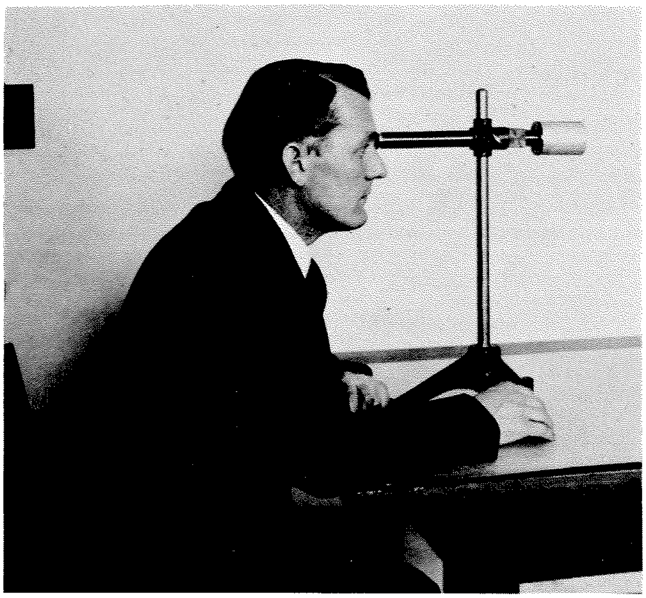
After the early 1930's Lauritsen was devoting his energy to physics, but admitted a primary duty, usually fulfilled during the night hours, of having the x-ray tube ready for an 8 a.m. starting time.

Seeley Mudd directed the clinical applications of the beam. Among those who participated in the work were Drs. Clyde Emery, George Sharp, Leo Levi, Melville Jacobs, Stewart Harrison, Henri Coutard, Mildred Wehrly (later to become an MD and radiation therapist at Orange County Hospital); and Virginia Johnson (later Kotkin). Among the graduate students who were engaged in the operation of the tube were Wilson Brubaker, H. Richard Crane, William A. Fowler, Thomas Lauritsen, and Louis Ridenour, Jr.

In his spare time, Lauritsen attacked the dose problem. The roentgen, which was proposed as a unit in 1926, measured the intensity of a beam of x-rays in air by counting the ion pairs produced. Its definition was ambiguous and the measurement doubtful or impossible at high energy. In September 1933 he wrote in the *American Journal of Roentgenology and Radiation Therapy*:



The upper and lower ends of the 30-foot x-ray tube—designed and built by C. C. Lauritsen and his associates in 1928—protrude from the concrete target enclosure in which patients were given radiation therapy at Kellogg.



C. C. Lauritsen takes readings of radiation intensity using an early model of the quartz fiber electroscope which he developed for measuring x-rays.

". . . This is satisfactory in practice as long as the problems dealt with are similar in nature and the quality of radiation is the same, but we have no right to expect that a given number of roentgens will produce the same effect regardless of the quality of the radiation. As a matter of fact, we can expect this to be so only in very special cases. It is much more reasonable to assume that equal effects are produced when equal quantities of energy are absorbed in a given volume."

"Obviously," he reported later in 1935, "any effect, whether physical or biological, is produced by that part of the energy which is truly absorbed in the volume under consideration. The energy which goes on through and the energy which is removed from the beam by scattering can have no effect within the volume. . . ."

The debate about dosage was vigorous, both here and in Europe. Professor Holfelder, a senior professor of radiology in Germany, claimed that "an increase in tube voltage above 200,000-volt peak is an illogical error that is accompanied by a completely unnecessary expenditure of money and results in a step backwards from what we already know." (I have tried to recapture in translation the professor's innate modesty.) Under Lauritsen's guidance, I showed that the more significant *depth* dose steadily increased with higher photon energy—a fact later confirmed experimentally. Such a phenomenon was of great interest to radiation therapists, who were concerned with possible damage to superficial tissues when treating deeper ones.

From 1930 to 1939 Mudd and his colleagues treated 746 patients with inoperable malignant lesions at the Kellogg Laboratory.

"It is obvious," they reported in 1938, "that it is too early to draw final conclusions regarding supervoltage irradiation. Fortunately, therapy of this type is being carried on in a number of laboratories in this country and abroad. It is to be hoped that cooperation between these clinics will result in a better understanding of the proper use of this agent."

In a final article that appeared in 1940, Mudd does not go beyond this, and it becomes apparent that the work of those days produced a clearer understanding of the problem, some improvement in the distribution of energy absorption when deep seated cancer is treated, but no evidence of a change in relative sensitivity; in short, "no breakthrough."

Early in 1939 the clinical studies were discontinued; all concerned were caught up in the steadily worsening world situation. After the war, by about 1950, cobalt 60 with a nearly monochromatic 1.3 MeV radiation was becoming available in sufficient quantity for clinical use in radiation therapy. With increasing energy of the primary photon (or particle) the absorption at deeper levels relative to the skin improved significantly. At these energies the roentgen fell into disuse and Lauritsen's workaday unnamed unit—100 ergs absorbed in 1 cubic centimeter of tissue—got its own name, the "rad," and, in 1956, became the official unit.

Cobalt 60 with its present known advantages of improved percentage depth dose, skin-sparing resulting from build up, decreased relative bone absorption, preferentially forward scatter—all predictable and predicted from the work in the thirties—is now used in the treatment of the vast majority of patients with deep cancer. (The machinery is also reliable and, for the energy and intensity available, not expensive.)

There is still no clear-cut evidence for a change in the relative sensitivity of normal cells and cancer cells, but a report from Louis Rosen at Los Alamos in December 1968 concludes *inter alia* that high energy negative pions, with high linear energy transfer on absorption, damage anoxic cells more readily than low L.E.T. radiation for the same damage to normal tissue. This will be a most interesting development if confirmed.

Mirror Nuclei and Charge Symmetry

by Thomas A. Tombrello, Jr.

Some highlights in the study of energy levels and reactions of light nuclei.

Soon after the nucleus was discovered, it became obvious that the mass of the atom was largely concentrated in its nucleus and that this mass was approximately an integral multiple of the mass of a hydrogen nucleus (proton). Since the nuclear charge was less than the charge on that number of protons, it was proposed by Rutherford in 1920 that one of the nuclear constituents would have about the same mass as the proton but with no electric charge (the neutron). The discovery of this object by Chadwick in 1932 led to a model of the nucleus consisting of neutrons and protons that is still in vogue today.

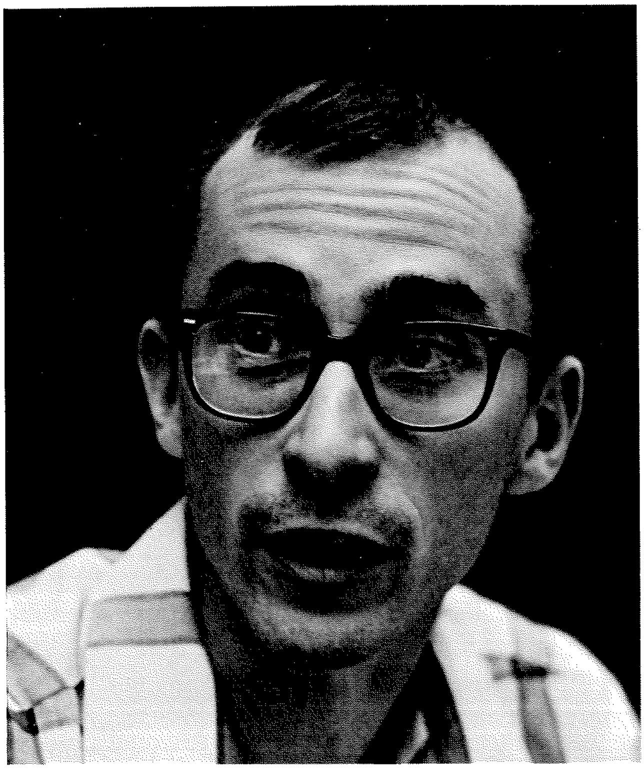
A particular nucleus of Z protons and N neutrons would then have a charge equal to Z (the atomic number) times the proton charge and have a mass approximately equal to that of Z protons and N neutrons. The mass equivalence is only approximate, because different nuclei have different binding energies —the effect of binding being to reduce the mass by $\triangle m$ according to Einstein's relation: binding energy $= \triangle mc^2$. Since the overall mass is still approximately $A = N+Z$ times the mass of a hydrogen atom, we call A the atomic mass number.

Early experiments showed that the low-energy scattering of protons from protons, and neutrons from protons, were virtually identical for the same angular momentum states, if one removed the effects produced by the electric repulsion of the charged protons. This led to the postulate that the nuclear force between proton pairs, neutron pairs, or a neutron and a proton were equal. This idea was called "charge independence" and was the first of the internal symmetries (exclusive of the space and time coordinates) proposed for the strong (or nuclear) interaction. To be slightly more precise, the equality of the proton-proton and neutron-neutron nuclear forces is called "charge symmetry," and the further equality with the appropriate part of the neutron-proton force is called "charge independence."

Soon after the proton-proton scattering measurements the Kellogg Laboratory became involved indirectly in this problem. W. A. Fowler, L. A. Delsasso, and C. C. Lauritsen had been using the early high-voltage machine to make radioactive nuclei that decayed by the emission of electrons (e^-) or positrons (e^+). The major part of their work reported in 1936 was concerned with what seemed to be a confirmation of the Konopinski-Uhlenbeck theory of nuclear beta-decay. As it turned out eventually, the theory was completely incorrect; the data contained unsuspected errors that were typical of all such experiments of that period. However, in the last few paragraphs of their paper the authors noted that in all the positron decays studied the mass difference (and hence the binding-energy difference) of the decaying nucleus and the nucleus it became after the decay could be explained by considering only the difference in the electric repulsion among the protons. The parent nucleus formed had Z+1 protons and Z neutrons; in the decay one proton becomes a neutron with the emission of a positron and a neutrino (ν). This is written schematically as:

$$ {}^{2Z+1}_{Z+1}X \rightarrow {}^{2Z+1}_{Z}Y + e^{+} + \nu $$

where ${}^{2Z+1}_{Z+1}X$ is the nucleus of the element X which has Z+1 protons (atomic number, Z+1) and an atomic mass of 2Z+1. We notice that the initial nucleus, X, has Z+1 protons and Z neutrons; the final nucleus, Y, has Z protons and Z+1 neutrons. Because of the equality of the neutron-neutron and proton-proton forces we see that the only difference in the binding forces in X and Y is produced by the



Thomas Tombrello, associate professor of physics.

electrostatic interaction of the extra proton with the rest. Thus, Fowler, Delsasso, and Lauritsen had shown that the neutrons and protons in nuclei also obeyed the same charge symmetry principle that had been observed for free neutrons and protons. One should not underestimate that result, because it provides not only a very strong confirmation of the symmetry principle itself but also reflects on the overall validity of the neutron-proton model of the nucleus.

Related pairs of nuclei like X and Y in our example have come to be known as "mirror nuclei," because the role occupied by neutrons in one nucleus is given to protons in the other, and vice versa. Thus, neutrons and protons could be thought of as mirroring one another in the structure of the two nuclei.

Following this discovery, theoretical work by Wigner indicated that such mirror pairs of nuclei would not only have similar binding energies, but all their excited states would be similarly located with virtually identical energy spacing. Not until after the war was this extended theory of mirror symmetry confirmed experimentally. Again, the lead in this area was in Kellogg, where the development of precise techniques of measuring particle energies with magnetic and electrostatic analyzers was actively pressed.

The key experimental example was the study of the lowest excited states of ^{7}Li (3 protons, 4 neutrons) and ^{7}Be (4 protons, 3 neutrons) by A. B. Brown, C. W. Snyder, W. A. Fowler, and C. C. Lauritsen. (It is worth noting that one of the techniques developed for this experiment was again put to use recently in the alpha-scattering experiment that was landed on the lunar surface.) The energy level diagrams for these mirror nuclei are below right. The excitation energies of the various states (in MeV), their angular momenta (J) and parities (±) are given. Also shown are the energies corresponding to the possible decay modes; e.g., all the excited states of ^{7}Be above 1.587 can decay into a ^{3}He nucleus plus a ^{4}He nucleus (alpha particle); states above 5.608 can also decay into a proton plus a ^{6}Li nucleus. The data shown are taken from the most recent and complete experimental work available, a PhD thesis from Kellogg by R. J. Spiger (1966).

Note that though the lower excited states have the same order and the same approximate spacing, the spacings are not reproduced in detail. This is not due in this case to any breaking of the mirror symmetry, but reflects the presence of nearby decay modes (channels). This effect was first explained in another PhD thesis from Kellogg by R. G. Thomas (1951) for another mirror pair, ^{13}N and ^{13}C.

In the past few years it has been of considerable interest to look for methods to test more precisely the limits of the validity of charge symmetry. This has taken two different routes in Kellogg; the first is closely akin to that used originally by Fowler, Delsasso, and Lauritsen.

The electrostatic energy of a nucleus is proportional to the number of pairs of charged particles present; if there are Z protons, then there are Z(Z-1) possible pairs. If we generalize slightly, we can say that the contribution from the interaction of the charges alone is a quadratic function of Z. Thus, we find within a set of mirror nuclei that for each nuclear mass, M:

$$M = cZ^2 + bZ + a$$

where c, b, and a are the same for all members of the set.

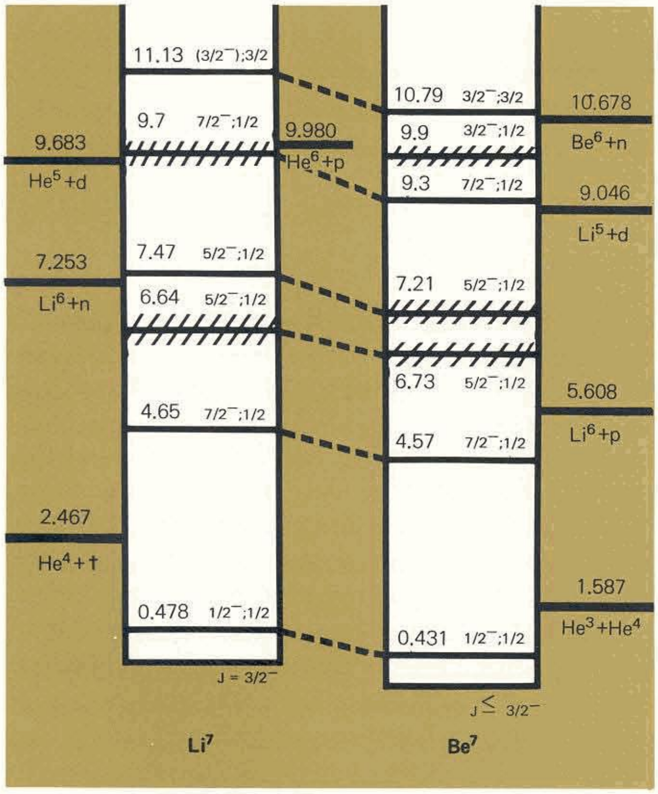
By our generalization we now have three parameters to determine, so that to check the validity of mirror symmetry we must have at least four pieces of data. Therefore, a mirror pair of nuclei will no longer be sufficient; we now need a mirror quartet. The only example that has been studied in sufficient detail—in Kellogg, of course—is composed of ^{9}Li, the corresponding excited states of ^{9}Be and ^{9}B, and ^{9}C. The masses of these nuclei and excited states were determined to about one part in two million, and they allow the only accurate check now available for the quadratic formula. The results show a definite breakdown of the formula, but this occurs at such a low level that it is impossible to say whether the discrepancy is due to a true violation of the symmetry or to higher order corrections to the electrostatic interaction itself.

The second approach to investigating charge symmetry attacks the foundations of the original postulate. Since the neutron is unstable, it has been impossible to actually observe the scattering of neutrons from neutrons. Thus the assumption of charge symmetry remains unchecked in its most fundamental form. It is just barely possible that the scattering could be studied directly using underground nuclear explosions, but the high cost together with the large chance of failure have so far prevented its serious consideration.

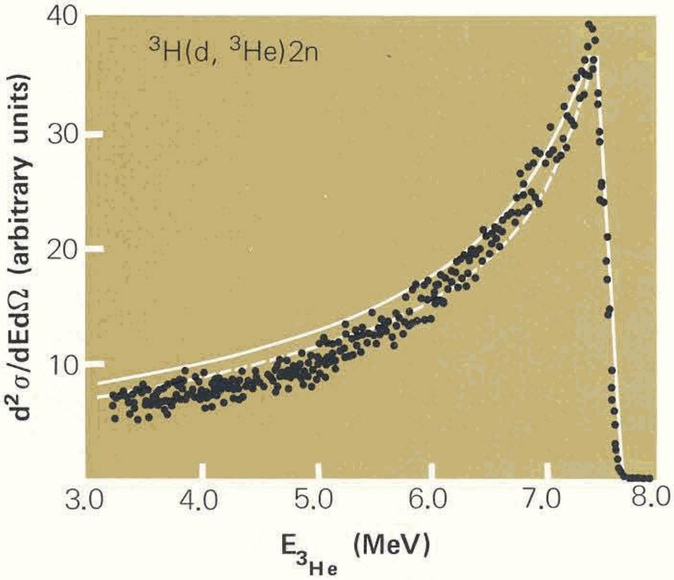
So we are forced to a less direct and less precise approach. We have considered reactions such as:

$$^{3}H + d \rightarrow {}^{3}He + 2n,$$

where two neutrons together with another particle occur as the products of a nuclear reaction. If experimental conditions can be found in which the neutrons do not interact with the other particle (in our example the ^{3}He), then perhaps the interaction of the two neutrons can be deduced.



Energy level diagram of the mirror nuclei ^{7}Li and ^{7}Be

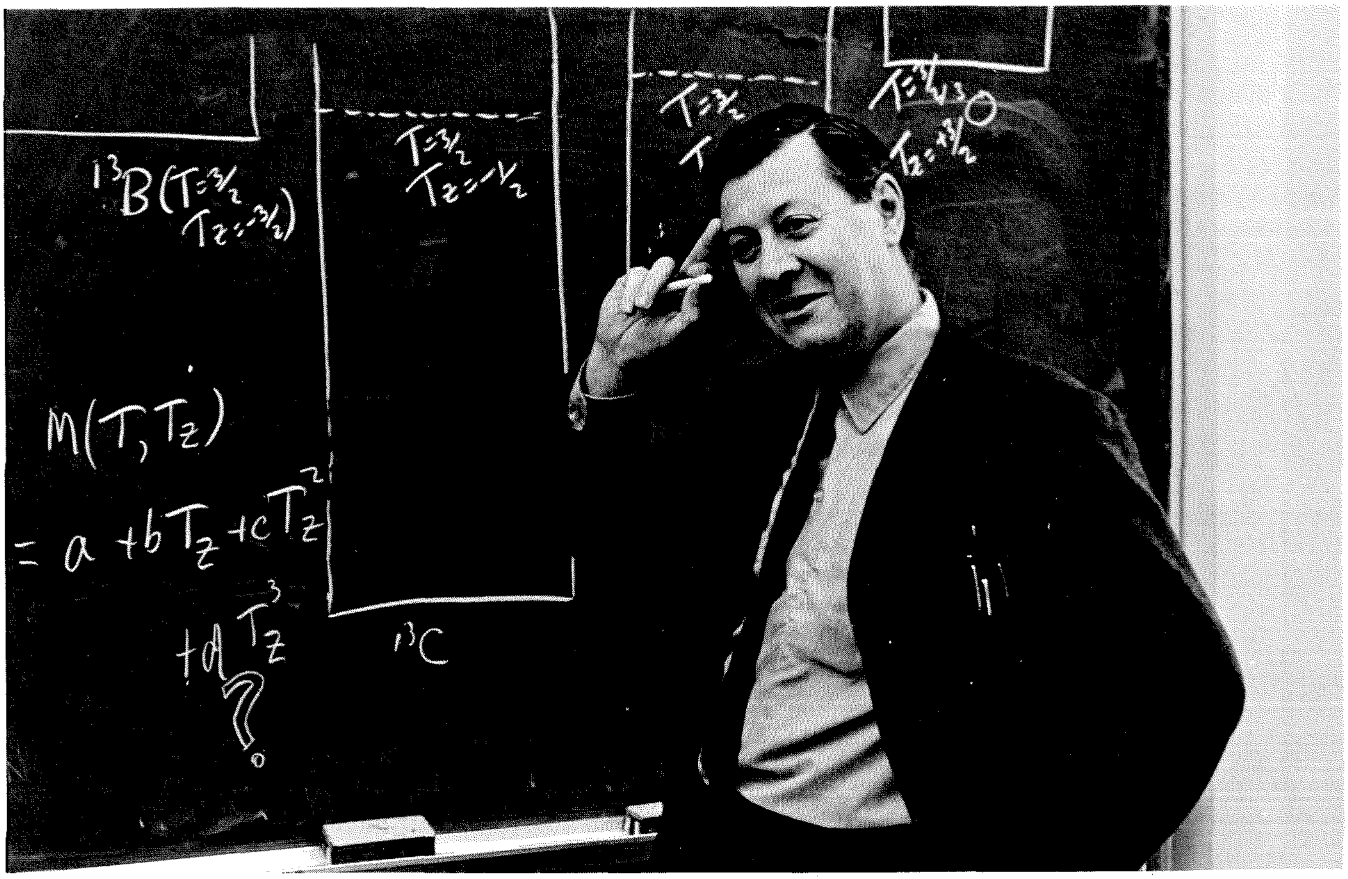


In the energy spectra of ^{3}He particles from the reaction $^{3}H(d, {}^{3}He)2n$, the pronounced peak shows the effect produced by the strong low-energy scattering of the two neutrons.

The criterion that the ^{3}He not be strongly involved with the neutrons can be fulfilled to a large extent. The chart above shows the energy spectrum of ^{3}He particles coming from the reaction. The lines give the simplest predictions one can make by assuming deviations of ±1 percent from charge symmetry. These data are from another Kellogg thesis project by H. T. Larson (1969), but similar data have been obtained elsewhere for other reactions.

However, one still has the problem of assigning an overall uncertainty because of the indirect nature of the process. Larson's analysis has gone quite far in this direction, at least for the reaction he has considered. Unfortunately, the news is not promising; we seem to be limited to a minimum theoretical uncertainty of about ± 2 percent. Since this is not really good enough to say anything definite about the breakdown of charge symmetry, we are blocked in this direction for the moment.

So, the study of mirror nuclei and charge symmetry remains a significant challenge to our ingenuity. We have made progress, but in some areas we are in need of new ideas and techniques. We can safely predict that these studies begun over 30 years ago will be with us for some time to come.



Charles Barnes, professor of physics.

Nuclear Beta-Decay Studies

by Charles A. Barnes

A report on the continuing development of nuclear weak-interaction research in Caltech's Kellogg and Sloan Laboratories, stemming from the original work of C. C. Lauritsen.

The study of nuclear β-decay and, indeed, the study of the physics of the atomic nucleus date back to the accidental discovery by Henri Becquerel in 1896 that photographic plates stored in close proximity to chemical compounds containing uranium were blackened by an unknown kind of radiation. We know now that the effects observed by Becquerel were mainly due to the β-rays emitted by the naturally occurring daughter nuclei resulting from the radioactive decay of uranium; in fact, Becquerel discovered that this obscure radiation could be deflected in a magnetic field, and was capable of ionizing matter—two phenomena which form the basis of all later experimental investigations of the properties of nuclear β-decay.

Progress in unravelling the characteristics of this new radiation seems leisurely by modern standards, but it was clearly recognized by the late 1920's that nuclear β-decay posed a serious challenge to the classically well-established laws regarding the conservation of mass and energy, and the conservation of angular momentum. The first of these laws was called into question by the observation that the β-rays from a given kind of radioactive nucleus have a continuous distribution of kinetic energies, ranging from zero to a maximum value equal to the difference in mass of the parent and daughter atoms (multiplied by the square of the velocity of light).

The difficulties with angular momentum conservation arose when it was discovered that the parent and daughter nuclei both had an *integral* number of units of spin (or, alternatively, both had a half-integral number of units), while the emitted β-ray had a spin of *one-half* unit. Rather than abandon these two cherished conservation laws, a step advocated by many physicists of the era, Pauli proposed in 1930 that each emitted β-ray was accompanied by a very light, electrically neutral, spin one-half particle, which carried away an energy equal to the difference between the observed β-ray energy and the maximum possible β-ray energy. This elusive particle, whose direct detection was accomplished only after 30 years of further technical development, was shortly named the neutrino (Italian for "the little neutral one") by Enrico Fermi, who in 1934 gave the first outlines of the present theory of β-decay.

Early in the same year, Irene Curie and Frederick Joliot reported the first *artificial* production of radioactive nuclei by bombarding boron and other chemical elements with α-particles from the naturally occurring radioactive element polonium. Less than two months later, C. C. Lauritsen, H. R. Crane, and W. W. Harper at Caltech reported the first production of a radioactive nucleus by *artificially-accelerated* particles, and identified the radioactive nucleus as being nitrogen 13, one of the nuclei produced by Joliot and Curie. The nuclear reactions used by these two groups of investigators to produce nitrogen 13 were:

^{10}B + alpha particle → $^{13}N + n$ (Curie and Joliot)
^{12}C + deuteron → $^{13}N + n$ (Lauritsen, Crane, and Harper)

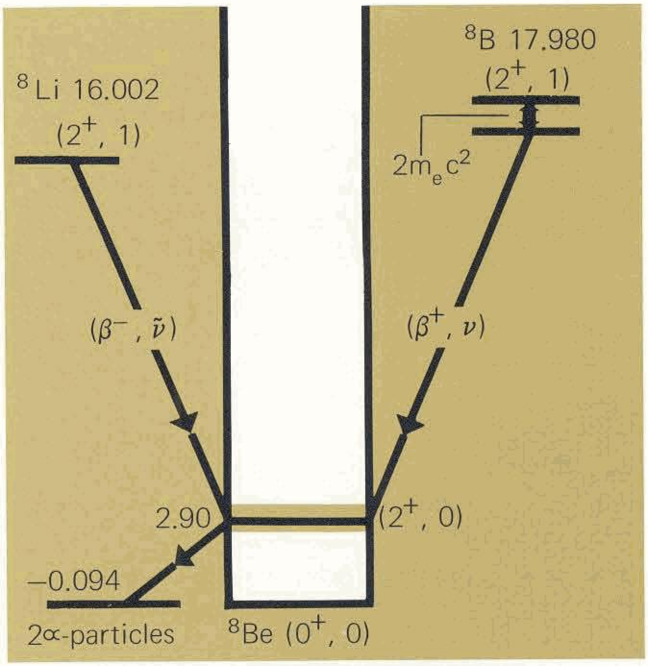
The nitrogen 13 decays, with a half-life of about ten minutes, by emitting a positron (the positive electron discovered by Carl Anderson at Caltech in 1932) and a neutrino, according to the equation,

$$^{13}N \rightarrow e^{+} + \nu + {}^{13}C.$$

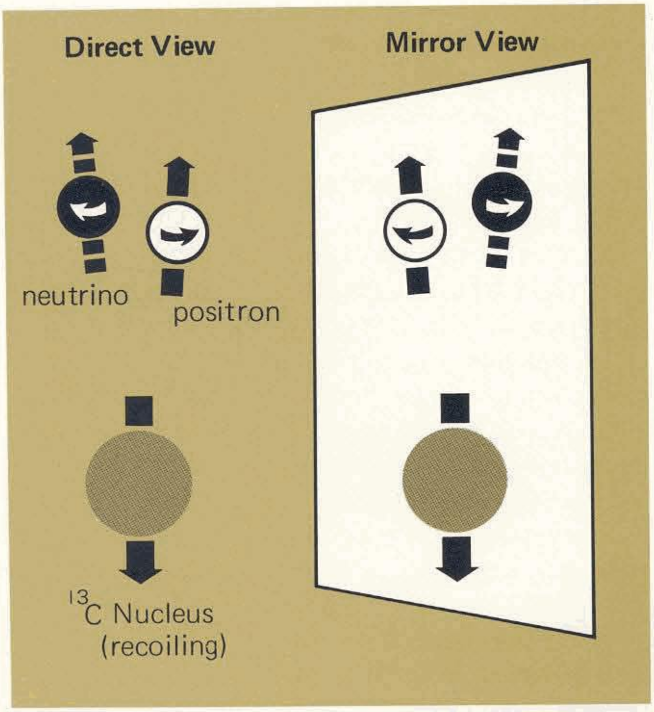
A rapid flurry of publications followed from many laboratories, especially from Caltech and the experimental groups at the University of California at Berkeley and at the Carnegie Institution in Washington, as a large number of new radioactive elements were discovered. Among others, the radioactive nuclei boron 12 and lithium 8 were reported in 1935 by Crane, Delsasso, Fowler, and Lauritsen; and the energy distributions of the electrons from these high-energy β-decays were studied by observing the curvature of the electron tracks in a Wilson cloud chamber with a superimposed magnetic field.

During the next few years many important refinements were made in the experimental techniques available for studying nuclear β-decay. Also during this period, the generalization of Fermi's β-decay theory showed that there are only five possible forms for the interaction producing β-decay which are consistent with the relativistic velocities of the emitted β-rays and neutrinos and which, at the same time, do not require a more complicated form of interaction than originally postulated by Fermi. These alternative forms of the theory were named Scalar, Vector, Tensor, Axial-Vector, and Pseudo-Scalar. The question of which, if indeed any, of these interactions gives a true description of the β-decay process continued to be a major goal of both experimental and theoretical research, and it remained unresolved when World War II intervened.

At the close of the war this problem was taken under study once more in many laboratories. At Caltech, C. C. Lauritsen, together with R. F. Christy, W. A. Fowler, T. Lauritsen, and E. R. Cohen, undertook a more detailed cloud chamber study of the decay of the nucleus lithium 8. Shown below is a simplified energy-level diagram of the decay of this



This energy-level diagram shows how the beta-decays of the radioactive nuclei lithium 8 and boron 8 lead to the 2.90-MeV excited state of beryllium 8, which disintegrates into two alpha particles within about 10^{-21} seconds.



A schematic presentation of the situation following the beta-decay of a nitrogen 13 nucleus into a positron, a neutrino, and a residual carbon 13 nucleus—in direct view (left) and as viewed in a mirror (right). In the direct view, the positron is right-handed, while the mirror view shows a left-handed positron. Parity conservation would require these two alternatives to be equally probable, contrary to what is found experimentally.

nucleus, and that of its mirror nucleus boron 8. An unusual feature of these β-decays is that an unstable excited state of beryllium 8 is produced by the beta and neutrino emission, and within about 10^{-21} seconds the beryllium 8 disintegrates into two alpha particles. The various possible interactions listed above yield different predictions for the distribution of angles between the emitted β-rays and neutrinos. If the β-ray and neutrino are emitted preferentially with a small angle between them, their momenta add together. If, on the other hand, the interaction causes the emission of the β-ray and neutrino most frequently with large angles between them, their momenta will largely cancel one another. The combined electron and neutrino momentum will show up in the departure of the two alpha particles from co-linearity, when the beryllium 8 nucleus subsequently breaks up. In this landmark experiment, published in 1947, it was not possible to achieve sufficient precision to resolve the question of the nature of the β-decay interaction, but the experiment did provide convincing confirmation that a neutrino was indeed emitted along with each β-ray, since the departure from co-linearity of the two breakup α-particles was quantitatively different from that predicted from the momentum of the observed β-ray alone. In the photograph from that experiment shown on the cover of this issue, a large departure from co-linearity is shown by the two α-particles—far larger than can be explained by the small momentum of the observed β-ray.

The suggestion in 1956, by C. N. Yang and T. D. Lee, that the interaction causing nuclear β-decay might not conserve parity triggered a new surge of activity in investigating the nature of the β-decay interaction. In simplest terms, parity conservation means that the mirror image of any observed submicroscopic process would be an equally acceptable way for the process to occur. That parity might not be conserved was a bold prediction. How could one possibly expect that nature, in submicroscopic processes, would exhibit an inflexible preference for either right-handedness or left-handedness, instead of expressing a disdainful indifference to the question?

Nevertheless, Yang and Lee's prediction was strikingly confirmed in a celebrated experiment carried out jointly by investigators from Columbia University and the National Bureau of Standards and reported in 1957. In this experiment it was found that more β-rays were emitted from polarized cobalt 60 nuclei at large angles from the polarization direction ($\Theta > 90°$) than at small angles ($\Theta < 90°$), whereas parity conservation would predict the emission of equal numbers into both hemispheres.

In collaboration with our Caltech colleagues, F. Boehm, B. Stech, A. Winther and T. Novey, we were shortly able to show that the positrons emitted in the β-decay of nitrogen 13 are essentially right-handed polarized; i.e., their spin axis is oriented parallel to their direction of motion. This is also a clear violation of parity conservation, since a reflection of the β-ray in a mirror (above left) gives us a positron with its spin antiparallel to its motion. Our experiment showed clearly that the emission of a positron with its spin axis antiparallel to its motion is *not* an equally likely way for the β-decay of nitrogen 13 to occur.

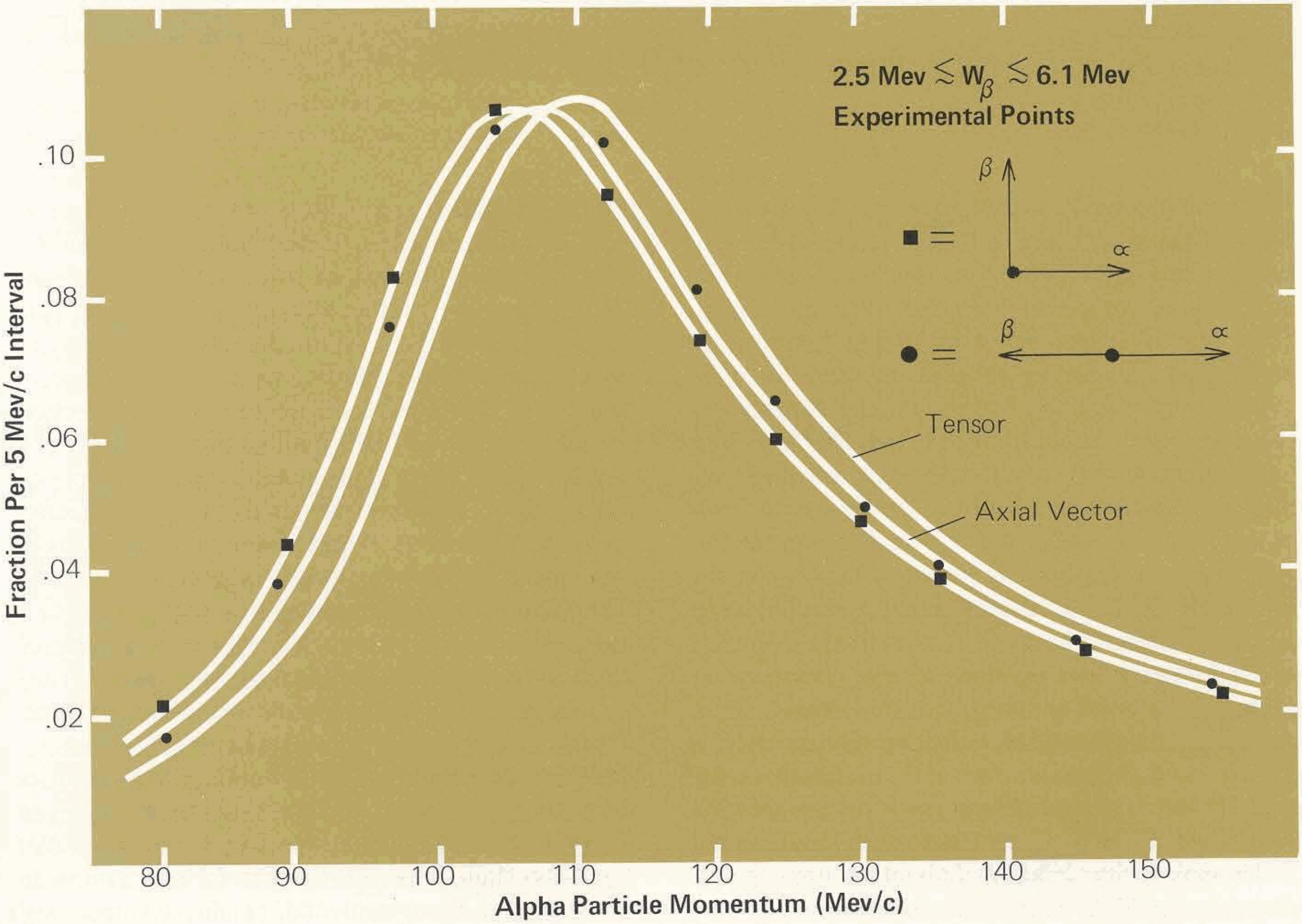
In 1958 Caltech theorists Richard Feynman and Murray Gell-Mann published what is still today the most elegant theoretical description of nuclear β-decay (and other weak interaction processes). Their theory not only explained the parity violation in a very direct and ingenious way, but it also led to the prediction that those β-decay processes in which the electron spin and the neutrino spin are antiparallel should be the result of the Vector interaction, while those in which the electron spin and neutrino spin are parallel should proceed by the Axial-Vector interaction.

This theory, the so-called V-A theory, was quickly verified in many laboratories. In Kellogg, Lauritsen, Fowler, T. Lauritsen, and I, working with Emory Nordberg and Howard Greenstein, were able to show that, of the two alternative interactions possible for the β-decay of ^{8}Li (Tensor or Axial-Vector), the correct form of the interaction was indeed Axial-Vector, as predicted by the V-A theory. This experiment was similar in concept to the earlier experiment reported in 1947; however, with the greatly enhanced precision made possible by technical advances in the intervening ten years, it was possible to pin down the explicit form of the β-decay interaction, as shown below.

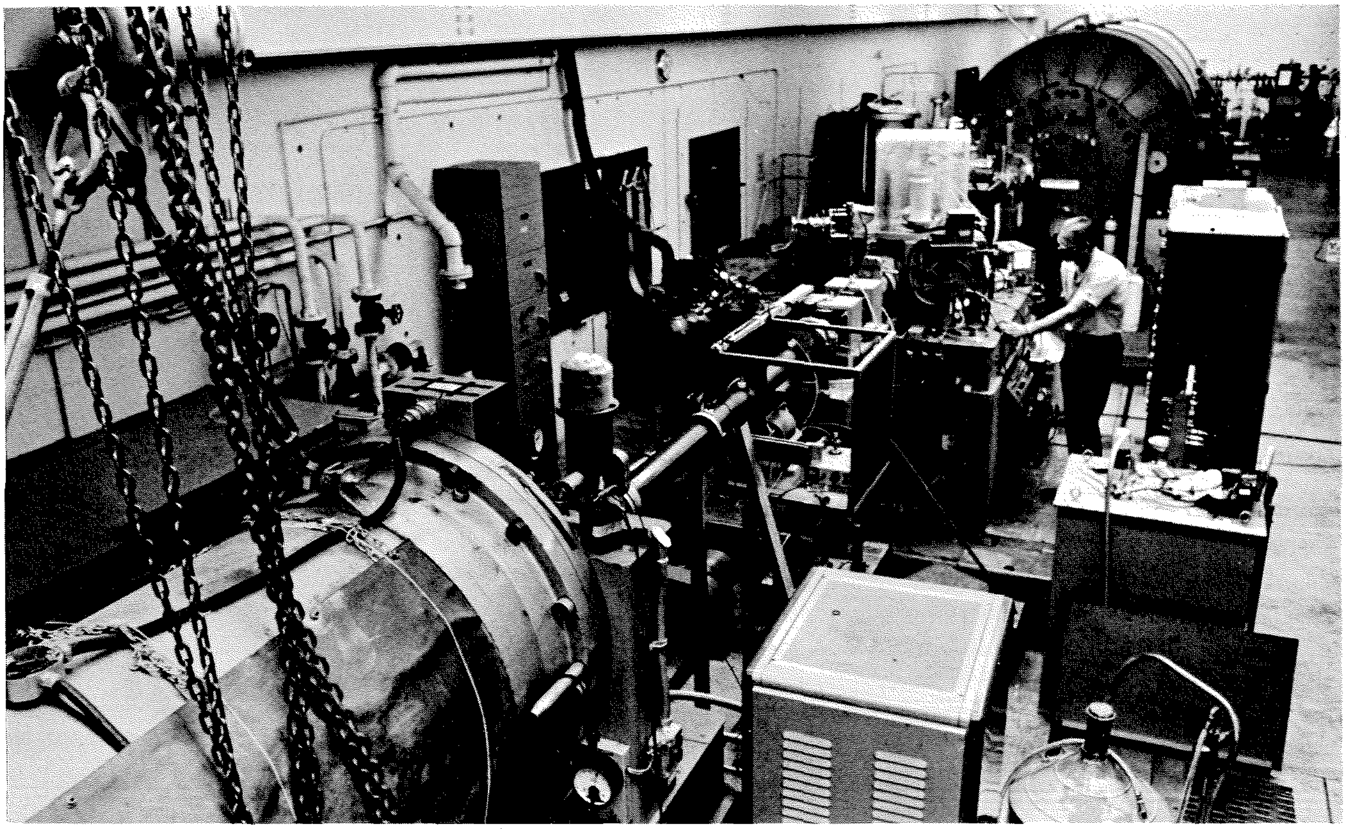
The V-A theory of β-decay also made several other important predictions. One of these was that the strength of the Vector β-decay interaction is a universal constant, so that the β-decay of the nucleus ^{14}O, for example, should occur with the same intrinsic strength as the β-decay of the muon, an apparently quite different process. That this prediction is correct we verified in 1962, working with Keith Bardin and Philip Seeger.

Another prediction of the V-A theory was that there should be small corrections to β-decay processes, which bear the same relation to β-decay that magnetism does to electricity. This weak-interaction magnetism was first verified in our laboratory, also in 1962, by T. Mayer-Kuckuk and Curtis Michel, who compared the energy spectra of the β-rays from the radioactive nuclei boron 12 and nitrogen 12. Further experimental confirmation of the weak magnetism prediction was provided by a comparison of the angular correlations between β-rays and subsequent α-particle emission in the decays of the nuclei lithium 8 and boron 8, which we studied with Nordberg and Fernando Morinigo.

These experiments, and those in other laborato-



Experimental demonstration that the beta-decay of lithium 8 is caused by the Axial-Vector interaction.

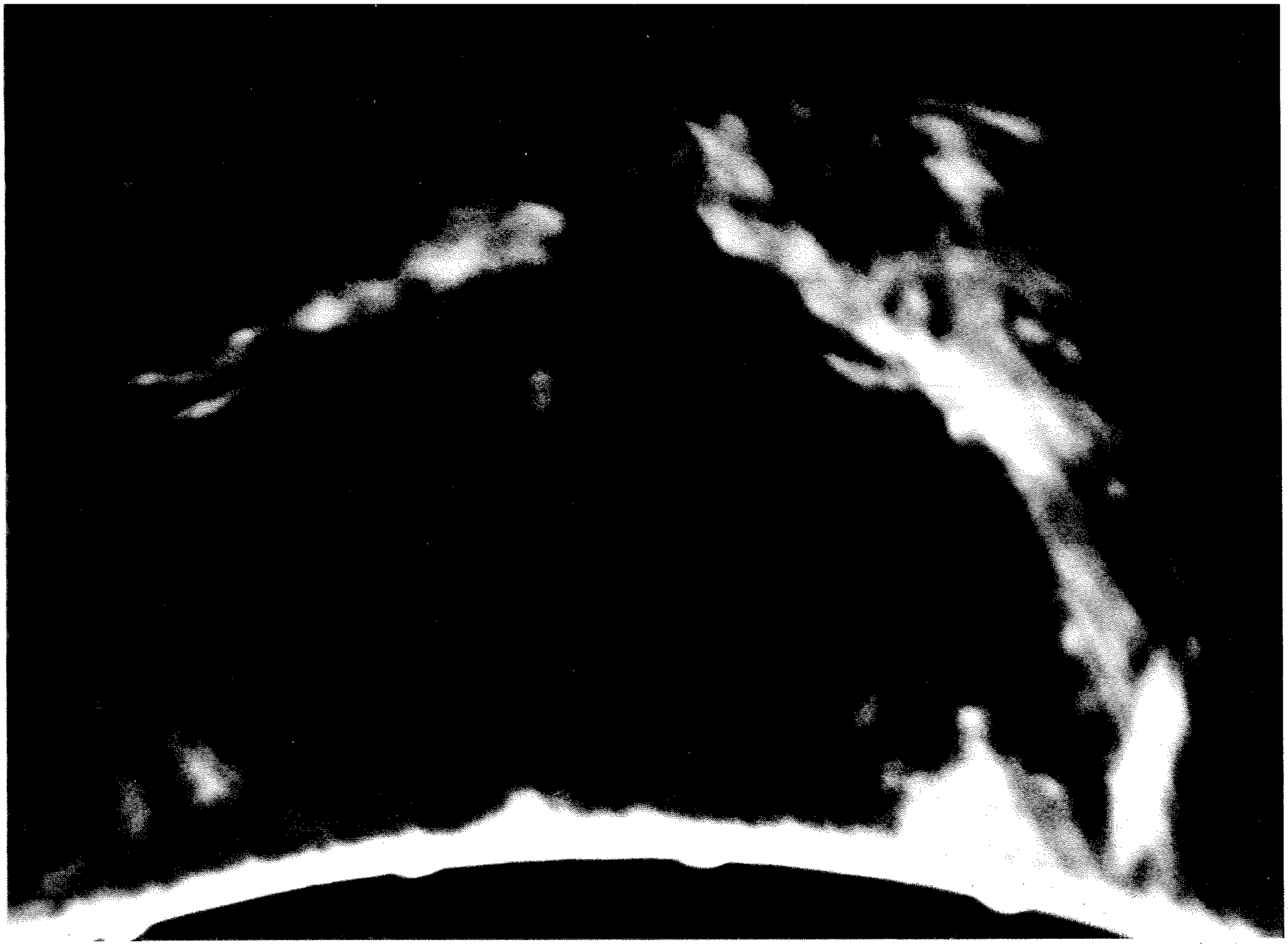


The Caltech-Office of Naval Research tandem accelerator, installed in 1960, produces the beams of very fast particles used in much of the Institute's nuclear and astrophysical research. In the foreground is the alpha particle injector; in the center, a technician works on the proton injector; in the rear—the 40-foot-long pressure tank containing the accelerator.

ries, have provided such strong evidence for the validity of the V-A theory of the weak interaction that one might easily suppose that this is the end of the trail for nuclear research on the weak interaction. Each established element of knowledge, however, inevitably challenges us to seek answers to more sophisticated questions. In 1964, Michel investigated the theoretical implications of applying the V-A weak-interaction theory to the neutrons and protons which constitute the atomic nucleus. As a result of this study, he predicted that a small component, at least, of the force binding nucleons together in the nucleus should exhibit the same parity-violating property seen in β-decay. This question is currently under intensive investigation in many laboratories. Preliminary results obtained here with Alan Moline, Anthony Adams, and John Morris, were reported in 1968 at the Pasadena meeting of the National Academy of Sciences. Although we found no evidence for a large violation of parity by the nuclear force, we did find a weak parity violation of about the strength predicted by the V-A theory. This experiment was only feasible on the newest and largest of Caltech's Van de Graaff particle accelerators (above).

The failure of parity conservation on the submicroscopic level has led us to question our preconceived ideas about other symmetries which we, perhaps naively, expect nature to exhibit. The symmetry of the physical laws governing the submicroscopic world with respect to a reversal of the direction of time has recently come under serious scrutiny, as a result of some anomalous results obtained by physicists at Princeton University, in a study of the decays of neutral K-mesons. Whether similar breakdowns of time-reversal-invariance occur in nuclear physics—and, if so, with what strength—are tantalizing questions. We are currently studying the feasibility of various experiments which might be capable of revealing a failure of time-reversal-invariance in nuclear phenomena, should such a breakdown exist.

Where our quest for understanding the mysteries of the submicroscopic world will ultimately lead can only be the subject of fascinating speculation. We can be certain, however, that the Charlie Lauritsen tradition for thoughtful and careful research will continue to be an essential guide in our future studies.



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

Ralph Kavanagh, associate professor of physics.

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.

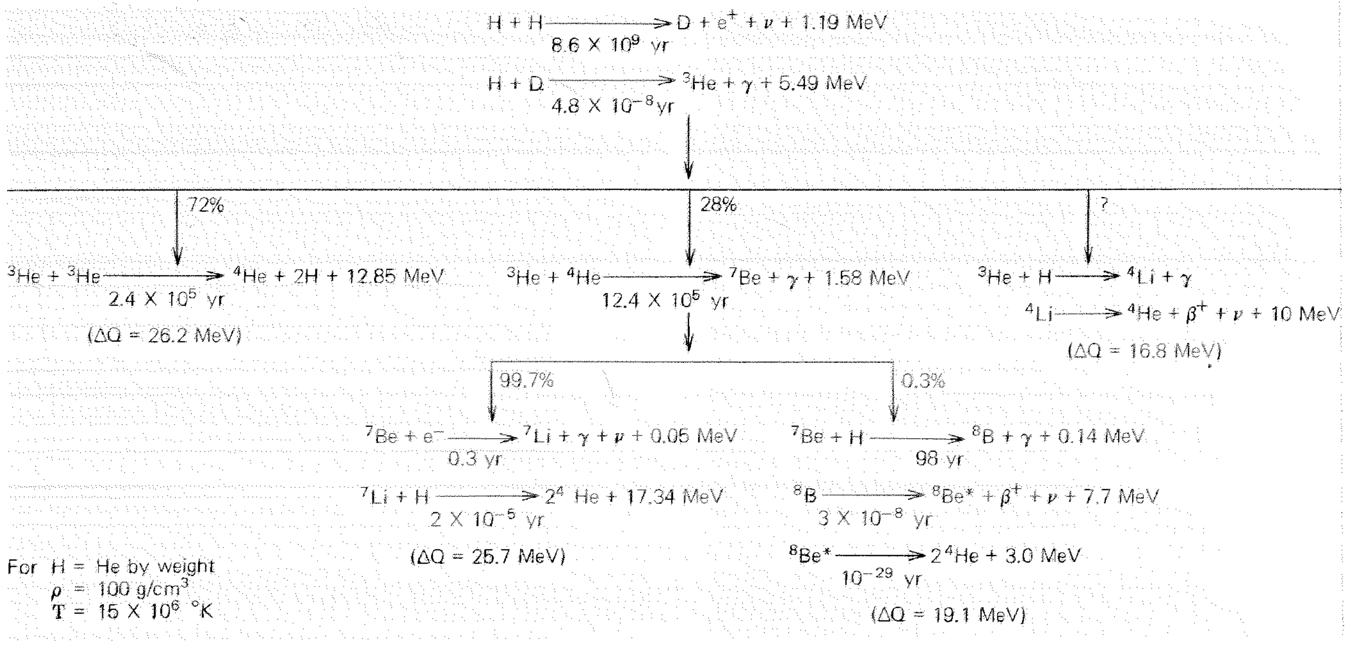
A by-product of this coup, illustrating one of the hazards of the profession, was related by Houtermans several years ago in a seminar he gave at Caltech. He told of walking with his best fraülein one evening just after he and Atkinson had concluded their work. She looked up at the stars and said, "Aren't 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:

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

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



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 $\triangle Q = 16.8$ 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,

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

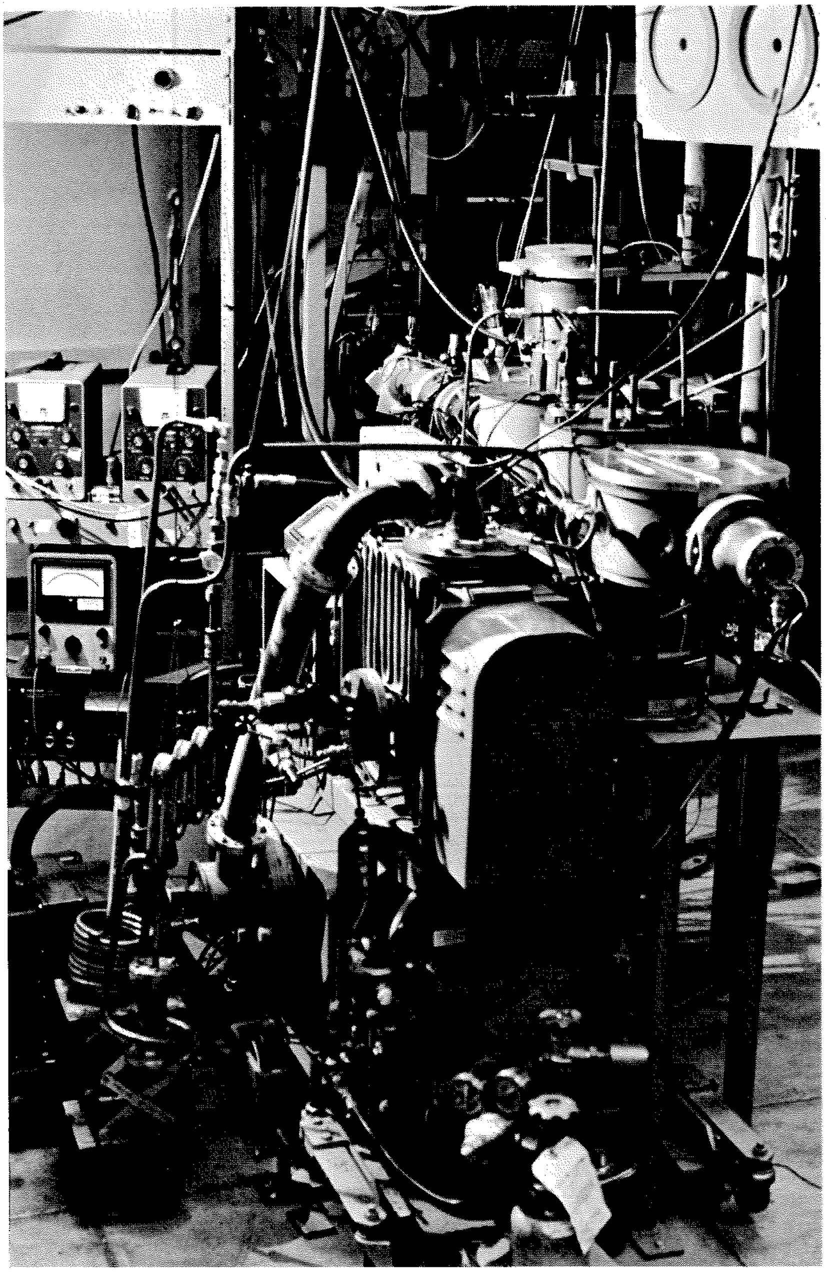
Here n_1, n_2 are the number densities of the reacting particles and v their relative velocity; the bracket denotes an average over the M-B distribution. The life expectancy of a particle in each reaction is inversely related to this rate, and the chart of the proton-chain reactions shows such lifetimes 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 ^{3}He + ^{3}He fusion.

It often happens in nuclear physics that laboratory



The gas-recirculation system used for measuring the $^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,{}^{1}\mathrm{H}$ *reaction, with the* $^{3}\mathrm{He}$ *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.*

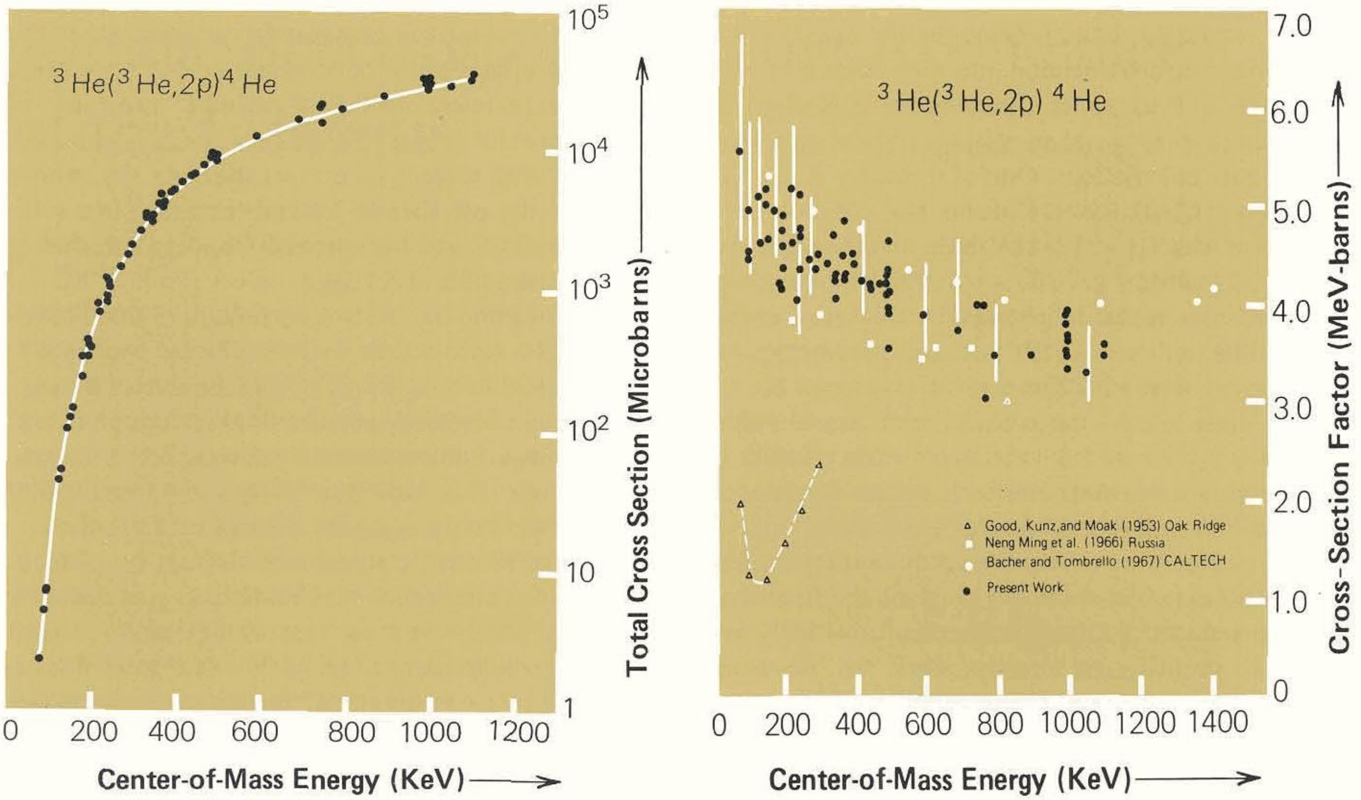
measurement of some interesting reaction is stymied or complicated by the nature of the necessary beam or target material. In the present cases, ^{3}He is needed for one or both. This stable isotope of helium occurs in atmospheric helium in the ratio of about $1/10^{6}$, and much less in helium separated 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 $^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,{}^{1}\mathrm{H}$ 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 $^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$, a "direct-capture" reaction, which, like the preceding $^{2}\mathrm{D} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma$, 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, $^{3}\mathrm{He} + {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{Li} + \gamma$, 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 ^{4}Li. 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 ^{4}He 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 ^{3}He 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 ^{4}Li. 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 ^{4}Li. Evidence against such low-mass ^{4}Li has also been deduced from the absence of analogous, or "mirror," states in ^{4}He and ^{4}H. 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 ^{7}Be produced by $^3He + {}^4He$ fusion, we again find two competitors. One is the decay of ^{7}Be 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 ^{7}Li 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 ^{4}He 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 x 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.

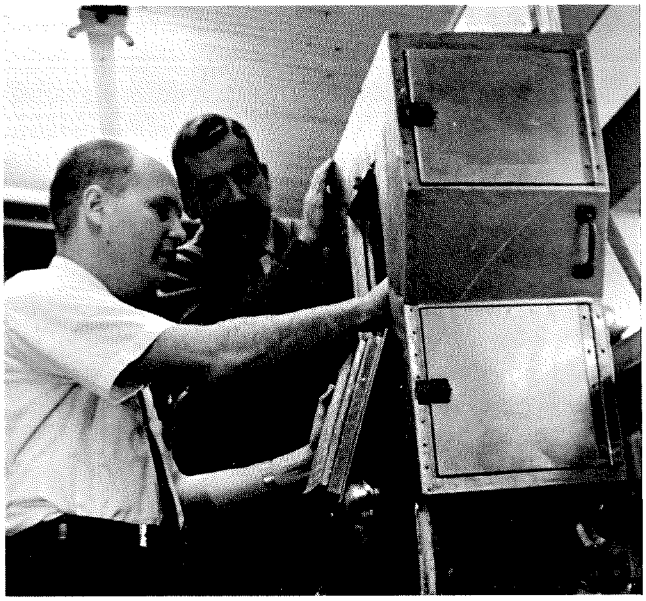
Atomic Spectroscopy and the Abundance of the Elements

by Ward Whaling and George M. Lawrence

The Kellogg Laboratory is bringing some of the techniques of nuclear physics to bear on problems in the optical spectroscopy of atoms. This activity is a natural development of our longstanding interest in nuclear physics and nuclear astrophysics, and stems from the fundamental role that atomic spectroscopy plays in present-day astrophysics.

Astronomers learned long ago how to analyze the wavelengths of starlight to identify the elements present in a star, an amazing accomplishment that has made possible the modern science of astrophysics. As soon as they were able to make qualitative analyses of a star's composition, the next step was inevitable and immediate: to make a *quantitative* analysis to find *how much* of each element is present.

As might be expected, quantitative analysis has turned out to be more difficult, but for reasons that are not widely known outside the ranks of professional astronomers. Whereas the identification of an element requires only the measurement of a characteristic wavelength in the starlight, quantitative analysis requires the measurement of the number of photons of the characteristic wavelength, plus a knowledge of certain properties of the radiating atom, properties that can be measured in the laboratory.

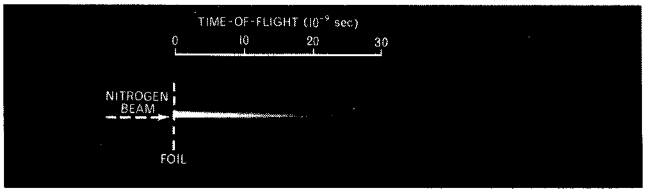


George M. Lawrence, visiting associate in physics from the Douglas Advanced Research Laboratories, and Ward Whaling, professor of physics.

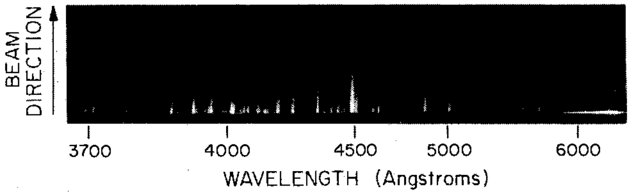
As astronomers have tried to measure elemental abundances, they have found that the accuracy and reliability of their results is limited not by the difficulty of the astronomical observations but frequently by our meager knowledge of atomic physics. Except for the simplest atoms, we don't know enough about how atoms radiate and, in particular, how fast they radiate, and it is this barrier which our experiments seek to overcome. Since much of the research in Kellogg attempts to discover those nuclear processes that can account for the elemental abundances in stars, efforts to improve our knowledge of these abundances are clearly in keeping with our overall goals.

In spite of this motivation, it is not likely that we would have been diverted from the familiar field of nuclear research had not two other circumstances favored this diversion. First, a new and promising method of measuring the needed atomic properties was discovered by Stanley Bashkin, at one time a research fellow in the Kellogg Laboratory and now at the University of Arizona. His method makes use of high-velocity atomic beams that we can produce with the accelerators originally built for nuclear research. We had on hand the expensive facility needed to exploit this new technique. Second, and equally important, we had the collaboration of R. B. King, professor of physics, who had been measuring atomic properties of astrophysical interest and, in particular, atomic radiation rates ever since he came to Caltech in 1948 and even before that at the Mount Wilson Observatory. Without his patient introduction into the unwritten know-how of atomic spectroscopy, our first efforts in this unfamiliar field would have been slow and painful.

What is this new technique of measuring atomic radiation rates, and what do we mean by radiation rates? If an atom is raised to an excited level (for example, in a collision with another atom), it will remain in this excited level for a short time interval before it drops to a lower level, radiating a photon in the process. In atomic systems, this interval is typically 10^{-8} seconds—seemingly instantaneous by human standards—and it may be helpful to recall the analogous process in nuclear physics, i.e., radioactivity, where the time scale is more familiar. If we start with $N(O)$ atoms at time $t = O$, all in the same excited level, the number that will survive for a time t is given by $N(t) = N(O)e^{-t/\tau}$ where τ is called the mean life of the level. The more familiar quantity, half-life, is just 0.69τ, and is the time in which one-half of the original number of atoms will decay. The mean life τ is characteristic of the particular level, and it is this quantity that we want to measure, since it determines how fast an atom will radiate once it has been raised to an excited level.



An invisible beam of nitrogen ions (N^+_2) approaches from the left with a velocity of about 10^8 cm/sec. and strikes a thin carbon foil. Collisions in the foil break up the molecule and excite the nitrogen atoms and ions into excited levels. Photons from the decay of these levels make the beam glow after it emerges from the foil. The gradual decay of this light is a measure of the lifetime of the excited level in the atom.



A spectrogram of the same nitrogen beam shown above. The beam now travels upward, and the time scale has been reduced. Each wavelength radiated by the beam appears as a separate image; the longer images signify longer lifetimes for the radiating level.

To measure these short time intervals, we use the distance traveled by the high-velocity beam as a clock. We excite the atom by shooting it through a thin foil, then see how far it travels before it decays, that is, how far from the foil the atom moves before the excited level radiates. The light that the atom radiates is the signal that tells us where the atom decayed, how far it went, and thus how long it lived, since we know how fast the atoms are moving.

Atoms are accelerated to high velocity (about 10^8 cm/sec) in our 2-million-volt electrostatic accelerator. After passing through magnetic and electrostatic deflectors which tell us the velocity of the beam, the atoms strike a thin carbon foil. The foil is only a few hundred atoms thick, and the energetic atoms pass through easily, but not without making many hundreds of collisions with atomic electrons in the foil, collisions in which the moving atom may absorb energy and be raised to an excited level. When the beam finally gets through the foil, each atom emerges in the level in which the last collision left it. Some will be in one level, some in another, and almost all of the atomic levels are represented in the emerging beam.

Once through the foil and into the vacuum where no more collisions take place, the excited atoms begin to decay. In each decay process a photon is emitted, and if these photons are collected in a camera, one obtains a photograph of the glowing beam (left). As more and more atoms return to the ground level, there are fewer and fewer atoms remaining that can radiate, and hence there are fewer photons, less light, and the beam becomes darker as it moves away from the foil. The finite lifetime of the atomic levels is clearly evident in the photograph; the time scale drawn on the photograph indicates the order of magnitude of the time interval.

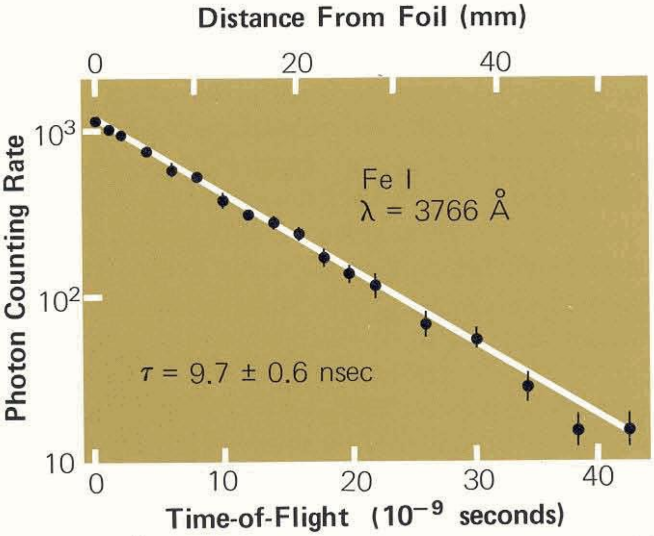
In order to measure the lifetime of a particular level, we need only isolate the characteristic wavelength radiated by atoms in that particular level. This separation can be achieved by photographing the glowing beam through a spectrograph. Different wavelengths appear at different positions in the spectrogram, and the beam is pictured over and over again. Each image corresponds to a different wavelength radiated by the beam, hence a different transition in the atom, and usually a different radiating level. The different lifetimes of different levels are quite evident in the spectrogram at the left.

In principle, it is possible to read the lifetimes of the different levels directly from the spectrogram by the standard methods of photographic photometry. We have found that we can achieve better precision by replacing the photographic plate with a photomultiplier tube which enables us to count the individual photons that enter the spectrometer. We restrict the field of view of the spectrometer so that it sees photons emitted only from a short segment of the glowing beam, and measure the counting rate as a function of distance from the foil. On the semilogarithmic plot, the exponential radioactive decay function becomes a straight line, with slope $(-1/\tau)$ that can be read directly from the graph.

We have chosen to look first at the iron spectrum and the lifetimes of levels in the iron atom. Iron recommends itself for several reasons: Except for the very lightest elements, iron is the most abundant element. Furthermore, its spectrum is unusually rich in lines, and iron lines are prominent features of nearly all astrophysical spectra. In the sun, more than 5,000 of the 13,000 identified lines are attributed to iron, and iron lines outnumber those of any other element by a factor of five. Because of this astrophysical interest, the iron spectrum has been extensively studied, and a great wealth of information already exists. Even a relatively few accurate lifetime measurements can make this existing information more valuable. Finally, there are interesting peculiarities in the observed iron abundance that have long perplexed astronomers. For example, the iron abundance in the sun is apparently about five times less than it is in meteorites, whereas other similar metals are about equally abundant in both. And there is disagreement, or surprising variation, even in the sun itself: The glowing disc (photosphere) appears to contain 10 to 15 times less iron than the corona, the halo around the sun that is visible when the disc is blanked out in a total eclipse. These and other longstanding problems put iron at the top of our list.

Our first results appear to justify our hopes and expectations. Light decay curves similar to the one shown in the graph (above right) have now been measured for six different levels in the iron atom. Our measured lifetimes differ from the previously accepted values by a factor of 4.7 ± 1.1, and, happily, this factor is in the right direction to make the meteoritic and solar abundance agree and to reduce the discrepancy between the chromospheric and the photospheric measurements.

Another phase of this research is now under way, although it is too early to tell what the results will be. As the iron atom shoots through the foil, colliding with electrons along its path, not only will the outer electrons be raised to excited levels, but, if the beam velocity is high enough, some collisions are so violent that electrons are shaken loose from the moving atom. As a result, the atoms emerge missing one or more electrons as charged iron ions, Fe^+, Fe^{++}, etc. These iron ions also have a characteristic spectrum, just as neutral atoms do, and in astrophysical applications these ionic spectra may be more interesting than the neutral atomic spectra. For example, on the sun's surface, more than 99 percent of the iron is in the form of singly charged ion Fe^+. In our high-velocity atomic beam we can produce ions of any desired charge by varying the beam velocity—the higher the velocity the higher the charge. We hope to be able to measure the lifetimes of levels in the singly and doubly charged iron ion, and it is reasonable to expect that these ionic lifetimes will provide another way of getting at the iron abundance in the sun.



The 3766Å transition in neutral iron observed with a 500 keV ion beam. The photon counting rate is shown at different distances from the foil. In this logarithmic graph, the exponential decay function appears as a straight line with a slope determined by the lifetime of the level which radiates this wavelength.

Some of the results of these experiments may have interest quite apart from the abundance problem. More than half of the spectral lines that we see in the light from the glowing iron beam do not correspond to any known transition in the iron atom. These lines have never been seen before, and this is in spite of the fact that the iron spectrum has been more extensively studied than any other. The violent collisions in the foil excite levels that cannot be excited in the usual laboratory arc and spark, perhaps levels in which two or more electrons in the same atom are lifted into excited levels at the same time. Of course, it may turn out that such multiple excitation occurs nowhere else in nature, and our new lines are simply exotics of interest only to other atomic physicists. But it is our hope that these new wavelengths may lead to the identification of some of the many unknown lines observed in stellar spectra. Even in the sun, there are still 5,000 lines whose origin is unknown. It would be lots of fun to find in our beam spectra some of these unidentified lines, and it seems reasonable to expect that we will.

Relativistic Astrophysics at Caltech: 1923-1969

by Kip S. Thorne

A report on Caltech's contributions to theoretical studies of relativistic cosmology and stellar evolution

One of the greatest triumphs of pre-twentieth century physics was Newton's law of gravitational "action at a distance," $F = Gm_1m_2/r^2$. This simple law explained the complicated motions of the planets and their satellites in the solar system, as well as the effects of gravity in earthbound laboratories. Despite its success, by 1905 it was known to be wrong.

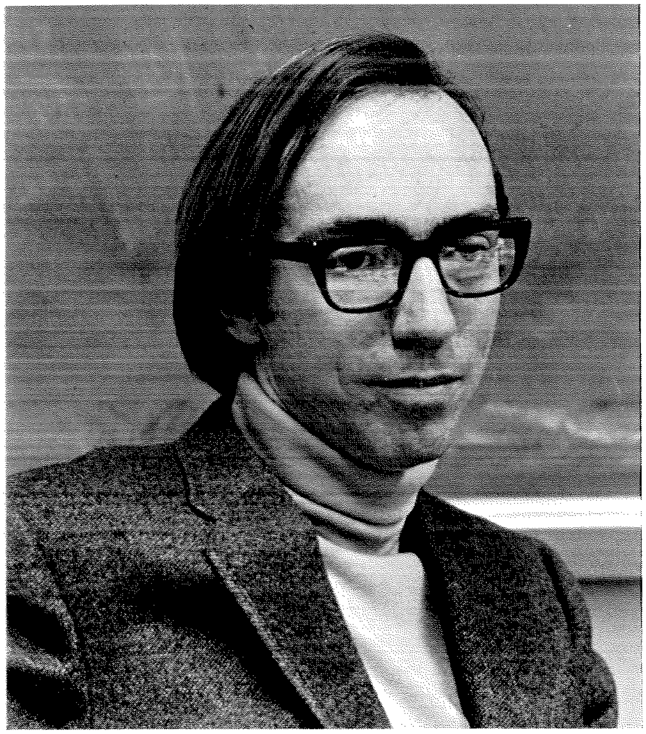
The disproof of Newton's law came from both experiment and theory. On the experimental side, it could not account for an excess precession of the perihelion of Mercury's elliptical orbit amounting to 43 seconds of arc per century. On the theoretical side, it was incompatible with Einstein's special theory of relativity—the theory which Einstein developed in 1905 to describe the relationships between observers moving with large relative velocities.

Between 1905 and 1915 Einstein worked hard to create a theory of gravity that would be compatible with special relativity and would explain all the experimental facts, including the perihelion shift of Mercury. In 1915 his efforts bore fruit, and he published his general theory of relativity.

General relativity theory and Newton's law of gravity are entirely different conceptually. According to general relativity, space and time make up a four-dimensional "space" (or *manifold*) called spacetime, which is curved. The curvature of spacetime is produced by its material content (galaxies, stars, planets, people). Experimentally, the curvature of spacetime shows up as gravity. In effect, gravity and spacetime curvature are one and the same thing.

Despite its completely revolutionary formulation, general relativity gives the same predictions as Newtonian theory when applied to the solar system, the galaxy, and the structures of normal stars—or almost the same predictions. General relativity always predicts tiny "post-Newtonian" corrections to the Newtonian results. In the solar system these corrections amount to less than one part in a million of the dominant Newtonian behavior; nevertheless, a number of them have been detected. These include the perihelion shift of the planet Mercury and of the asteroid Icarus, the gravitational redshift of light and of gamma rays, the gravitational deflection of starlight and of quasar radio waves, and an anomalous time delay for radar signals bounced off planets.

Although relativistic gravitational effects are miniscule in the solar system, in normal stars, and in the galaxy, they are of crucial importance elsewhere in the universe: (1) The large-scale structure and evolution of the universe itself (*cosmology*) is governed by relativistic effects; Newtonian theory is useless there. (2) Highly relativistic objects may be responsible for quasars and for explosions in the nuclei of galaxies. (3) Neutron stars, with relativistic deviations from Newtonian gravity of up to 200 percent, are probably formed in supernova explosions and are probably the recently discovered pulsating radio



Kip S. Thorne, associate professor of theoretical physics

sources which have come to be known as *pulsars*.

The study of systems such as these, with highly relativistic gravitational fields, is called *relativistic astrophysics*. Research in relativistic astrophysics is a major activity in the Kellogg Laboratory today. In fact, Kellogg's involvement in this research goes back to the infancy of Einstein's theory itself.

In 1915 Einstein had no idea that relativistic gravitational effects might one day prove crucial for finite astronomical objects such as pulsars and quasars. However, he did know that they would be crucial for cosmology, so this was where he turned his attention as soon as he had formulated general relativity. He soon discovered, to his dismay, that general relativity does not admit static cosmological models. The universe would have to be expanding or contracting, and this was in contradiction to the beliefs of the day. In semi-panic at this discovery, Einstein modified his theory in 1917 to include a cosmological constant, which would produce a pressure to keep the universe static.

Not so repelled by the idea of a dynamical universe was a young man named H. P. Robertson. From 1918 to 1923 Robertson was a student at the University of Washington, where he developed an interest in general relativity. In 1923 he came to Caltech to study for the PhD under Harry Bateman and Paul Epstein. His PhD thesis in 1925, "On the Dynamical Space-Times which Contain a Conformal Euclidean 3-Space," was one of the first theoretical studies to take seriously the possibility that the universe might be dynamical. (The metric for the geometry of such dynamical spacetimes has been called the "Robertson-Walker metric" ever since.)

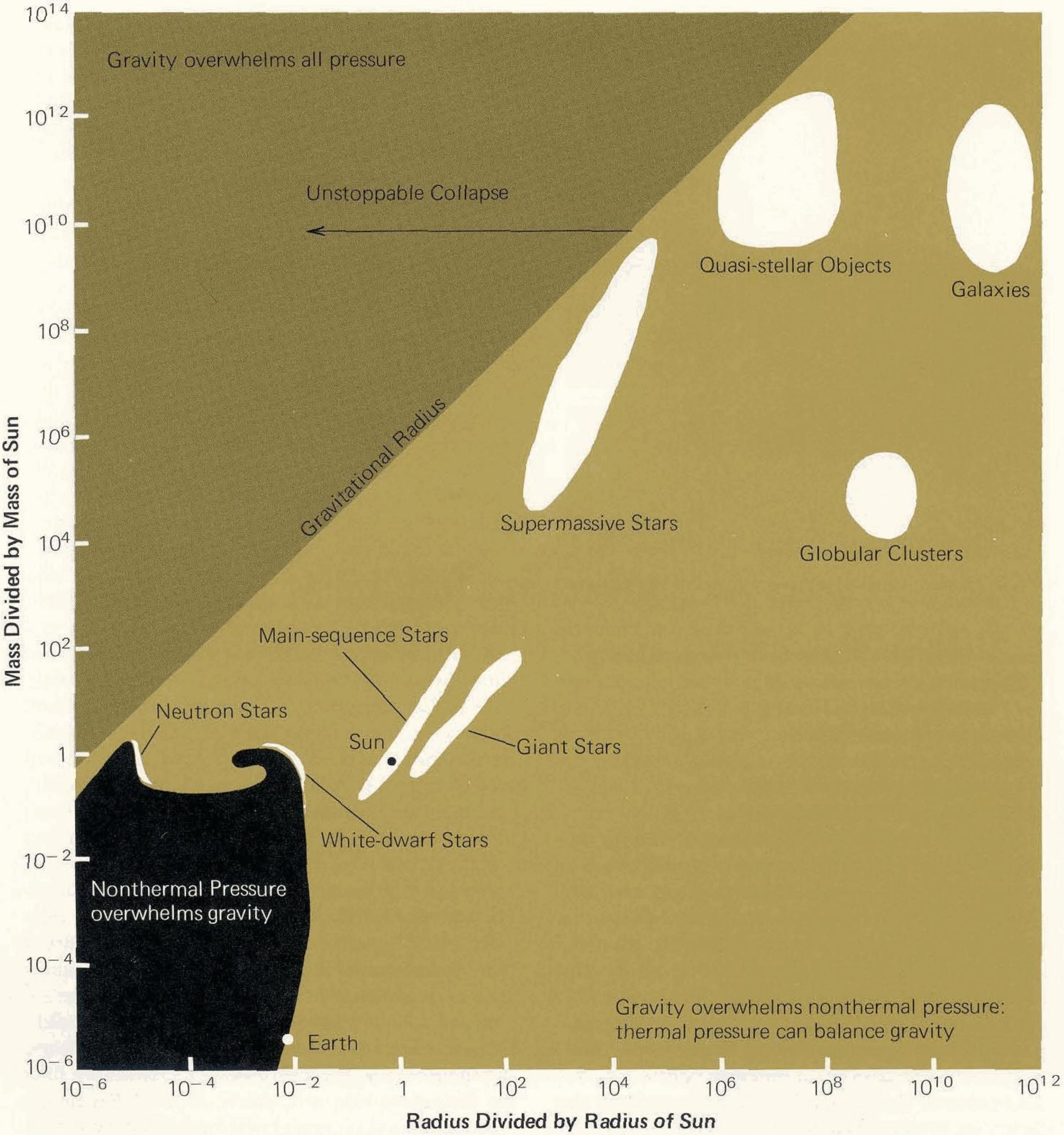
In 1930 the Caltech astronomer Edwin Hubble rocked the foundations of cosmology by showing that the universe is *not* static; it is expanding. Suddenly Robertson's work was of the utmost relevance.

Although Robertson had left Caltech for Princeton in 1929, this did not leave Caltech bereft of relativistic astrophysicists. The discoveries being made at Mount Wilson in 1930 were too exciting to be ignored by theorists. Richard Chace Tolman, who had come to Caltech in 1923, and J. Robert Oppenheimer, who had arrived in 1927, made fundamental contributions to theoretical cosmology and relativistic astrophysics throughout the subsequent decade. (Tolman's contributions were immortalized in his classic book *Relativity, Thermodynamics, and Cosmology*; Oppenheimer's contributions, we shall return to shortly.)

The old guard of the Kellogg faculty still tell the tales of those exciting days: Tolman, "Oppie," and Charlie Lauritsen were inseparable friends. When they got together in the lab or under the arcades, the conversation ranged all the way from Charlie's newest experimental results to Tolman's latest ideas on cosmology and Oppenheimer's latest calculations on neutron stars.

After World War II, in 1948, Oppenheimer left Caltech for Princeton, Robertson returned from Princeton to Caltech, and Tolman died.

The 1950's were slow years for relativistic astrophysics throughout the world. Caltech's 200-inch Hale telescope on Mount Palomar went into operation, and with it Allan Sandage and others produced significant improvements in the cosmological data. But there were no great surprises, no revolutions. On the theoretical side at Caltech, Richard Feynman made significant progress toward the quantization of general relativity; Jon Mathews, with his student Philip Peters, developed the theory of gravitational waves from binary-star systems; and Mathews, with Robert Kraft and Jesse Greenstein, investigated a particular binary system (WZ Sagitae) for which the energy losses due to gravitational radiation might eventually be detectable. In the fifties the action was elsewhere in physics and astronomy; so Robertson,



Mass-radius diagram depicting the dimensions of various astrophysical objects: Relativistic astrophysics is concerned with objects near their gravitational radii—collapsing objects, neutron stars, supermassive stars, perhaps quasi-stellar objects, and the universe as a whole (which sits near its gravitational radius, far off in the diagram in the upper right). Whether quasi-stellar objects actually lie in the relativistic region is not clear.

Sandage, Feynman, and Mathews dabbled only occasionally in general relativity and relativistic astrophysics.

All of this changed quite suddenly in the early sixties. On the cosmological scale (10^{10} light years), groups at Bell Laboratories and Princeton discovered the cosmic microwave radiation. On a smaller scale (10^6 to 10^9 light years from the earth), Caltech's astronomers discovered quasars and explosions in the nuclei of galaxies. On the theoretical front, work on stellar evolution—much of it performed in Kellogg Laboratory—began to suggest strongly that neutron stars and perhaps even "black holes" might be formed at the endpoint of stellar evolution. Finally, in 1967 came the discovery of pulsars, which seems to have verified the existence of neutron stars.

In response to these discoveries, the Kellogg Laboratory has had a vigorous program in theoretical relativistic astrophysics since 1963. Research during this period has concentrated on cosmology, on quasars and the nuclei of galaxies, and on the endpoint of stellar evolution.

COSMOLOGY

The cosmic microwave radiation has revolutionized cosmology. The observations, carried out with radiometers in the wavelength range from one millimeter to one meter, are just what one would expect if the earth were enclosed in a box whose walls had a temperature of 2.7 degrees Kelvin. Of course, nobody believes that such a box is out there. Rather, nearly everyone believes that the radiation was formed in the big-bang creation of the universe ten billion years ago and that it has bathed the entire universe ever since. The original temperature of the radiation was billions of degrees, but the expansion of the universe has cooled it by now to 2.7 degrees.

From the present temperature of the radiation and the mean density of matter in the universe, we can (in principle) reconstruct the entire history of the universe. This is possible if we assume that, on a large-scale average, the universe is homogeneous and isotropic. Much of the effort of our Caltech group since 1963 has concentrated on the following reconstruction of the history of the universe:

1. The formation of primordial helium in the big bang, when the universe was only a few minutes old, has been calculated in Kellogg by William A. Fowler and Robert V. Wagoner, and at Princeton by P. J. E. Peebles, who is working in our group this year. They have found that approximately 25 percent of the mass of the primordial matter should have been converted from hydrogen to helium in the big bang—a figure much higher than astronomers had previously believed. Most subsequent astronomical observations have tended to agree with this new figure.

2. Peebles has been delineating the processes by which globular clusters and galaxies probably condensed out of the interstellar medium when the universe was several hundred million years old.

3. Vahé Petrosian, a research fellow in Kellogg, has been studying the effects of the cosmological constant on the history of the universe.

Into all these studies goes the assumption that the universe is homogeneous and isotropic, when one ignores the lumpiness due to clumping of matter into galaxies and clusters of galaxies. How good is this assumption? The cosmic microwave radiation again is the key to the answer: Its intensity is measured to be isotropic to within 0.1 percent. To gauge the significance of such measurements, Kenneth Jacobs and I have investigated anisotropic, general-relativistic cosmological models. The result of comparing the Princeton measurements of isotropy with our theory is that the universe, on a large-scale average, is now expanding at the same rate in all directions to an accuracy of one part in ten thousand or better. This amounts to a three-thousand-fold improvement on our previous knowledge of the isotropy of the expansion! The microwave isotropy also implies an impressive degree of large-scale homogeneity for the universe.

QUASARS AND EXPLOSIONS IN THE NUCLEI OF GALAXIES

The energy released in quasars and in explosions in the nuclei of galaxies is so enormous that theoreticians have been forced to invoke esoteric processes to explain it. Thus far none of the explanations has been successful enough to gain wide acceptance, so work on the theory continues along many fronts. One of the first proposals, made in our laboratory by William A. Fowler and Fred Hoyle in 1963, was based on violent activities of a supermassive star—a star of more than a million solar masses. (No stars more massive than 100 solar masses have ever been observed, but Fowler and Hoyle present cogent arguments why supermassive stars might form in the nuclei of galaxies or in quasars.) A key facet of supermassive stars is an instability against gravitational collapse due to general-relativistic effects. This relativistic instability was discovered independently in 1963 by Feynman at Caltech and by S. Chandrasekhar at the University of Chicago, and it has played an important role in the subsequent theory of supermassive stars. Today the supermassive-star theory is still a vigorous competitor in the quasar marketplace; it is particularly popular in the Soviet Union.

Another 1963 proposal to explain the quasar energies was gravitational collapse, which general relativity predicts should destroy supermassive stars and other massive objects when the relativistic instability sets in. Gravitational collapse was first discovered and studied as a general-relativistic phenomenon by J. Robert Oppenheimer and his student, Hartland Snyder, at Caltech and the University of California in 1939. From then until 1963 gravitational collapse remained in the backs of peoples' minds as a vaguely possible phenomenon in astrophysics. In 1963, however, with the discovery of quasars and of the relativistic instabilities in stars, it came roaring into the focus of attention. In principle, collapse could convert 100 percent of the mass of a body into high-energy radiation and particles; this was an implication of Oppenheimer's work. Is this the key to the quasar energy? Perhaps so, according to 1963 calculations by Curtis Michel in our laboratory; probably not, according to subsequent, more refined calculations by others in the laboratory; quite uncertain, according to current thought.

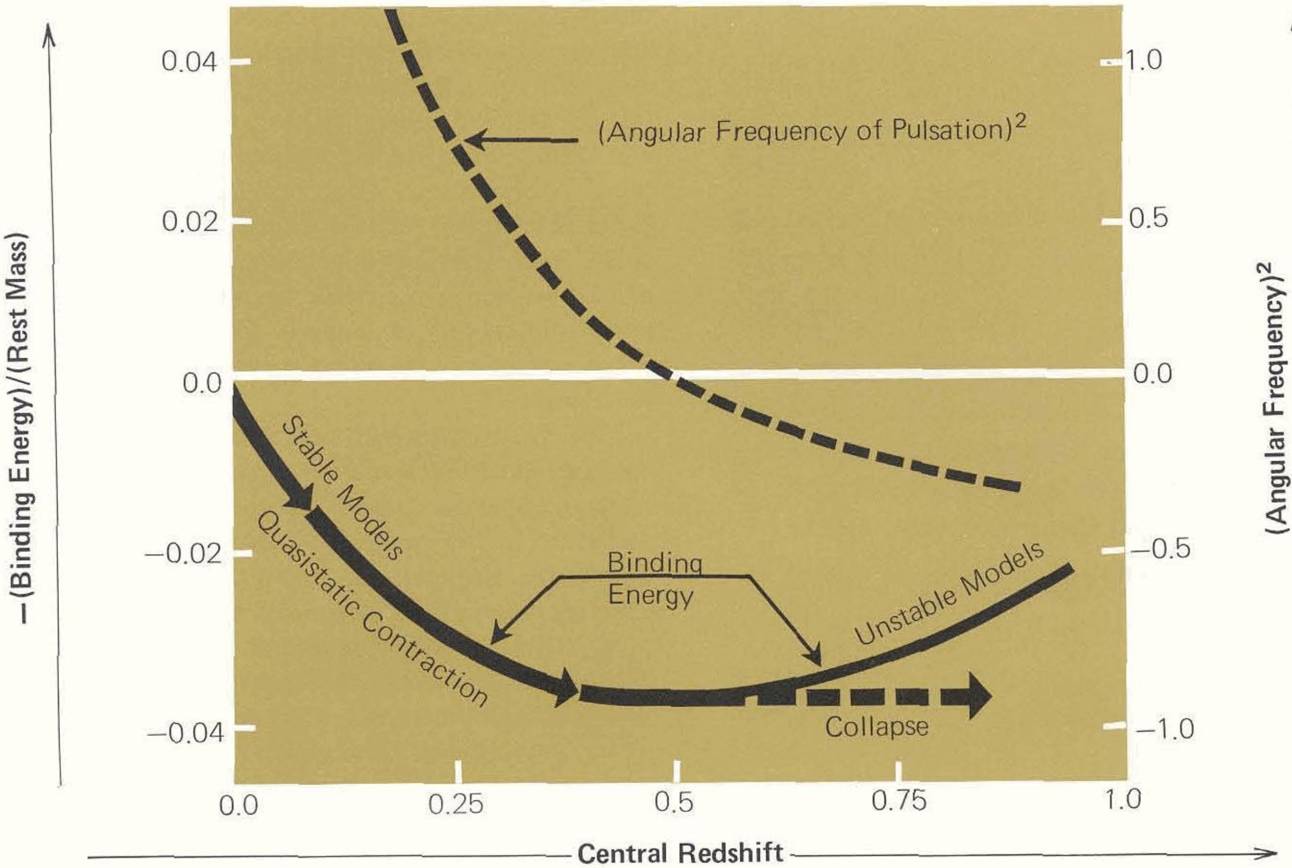
Before we can say anything definitive about the role of gravitational collapse, we must understand it better. All pre-1968, general-relativistic studies of it assumed spherical symmetry. But spherical symmetry may be a terribly bad approximation for realistic collapse. For example, in the spherical case no energy, or light, or anything else can escape from a star after it has collapsed through its "gravitational radius"; the star leaves behind a gravitating black hole in space. "But," prominent relativity theorists have argued, "perhaps small deviations from spherical symmetry will completely change this; perhaps there will be no black hole; perhaps it will always be possible to get the energy of collapse back out."

To evaluate this and other speculations requires extensive mathematical studies of general relativity theory. Such studies are now under way in our group and elsewhere. Preliminary results obtained by Richard Price, one of our students, constitute a strong case against the above speculation. It appears very likely that nonspherical collapse is qualitatively like spherical collapse. The results of this study and others like it will be the foundation for future applications of the theory of collapse to astronomical phenomena.

A third proposal to explain the energy outputs of quasars and of galactic nuclei relies upon star-star collisions and supernova explosions in superdense star clusters (clusters with more than a billion stars per cubic light year). A variant of this idea, due to Fowler and Hoyle at Caltech in 1967, makes the cluster so dense that general-relativistic effects produce a huge gravitational redshift of the spectral lines emitted by matter near its center. This could account for most of the redshift of the light from quasars, permitting them to be much nearer the earth than we had previously thought (no cosmological shift needed!), and partially alleviating the difficulties with the apparently huge energy output.

Whether this theory is right or not, it has suddenly forced astrophysicists to realize that relativistic effects could be important in clusters of stars as well as in individual stars. What would those relativistic effects be, besides the gravitational redshift? Some preliminary answers had been given, before the work of Fowler and Hoyle in 1967, by Zel'dovich and Podurets in Moscow (1965) and by Fackerell in Australia (1966). But these groups were unaware that their work was anything more than a mathematical exercise—i.e., that it could be significant for astrophysics—so they did not pursue it far. Here was a major subject for theoretical research, virtually untouched, and of potentially great significance for astrophysics. James Ipser, one of our students, launched eagerly into it in the spring of 1967; a year later Fackerell came from Australia to work with Ipser, and in the summer of 1969 Donald Lynden-Bell—an expert on Newtonian star clusters—will come from England for a year, in part to work with Ipser and Fackerell.

One of the most exciting results of our star-cluster work is that clusters, like individual stars, are subject to a relativistic instability. As time goes on, star-star collisions and stellar evaporation cause a cluster to contract to higher and higher density. When its density becomes so large that the redshifts of photons emitted from its center are $\Delta\lambda/\lambda = 0.5$, the cluster begins to collapse. All of its stars spiral in toward the center, leaving behind a black hole. At least this is the case for spherical clusters whose stars have isotropic velocity distributions. If it is also true for more general clusters, then the Hoyle-Fowler star-cluster model cannot produce redshifts as large as those observed for some quasars ($\Delta\lambda/\lambda$ up to 2.4).



The structure and evolution of a relativistic star cluster with a truncated Maxwellian velocity distribution. The cluster initially contracts slowly, becoming more and more tightly bound. When the binding reaches a maximum, relativistic collapse begins, and all the stars spiral inward through the gravitational radius.

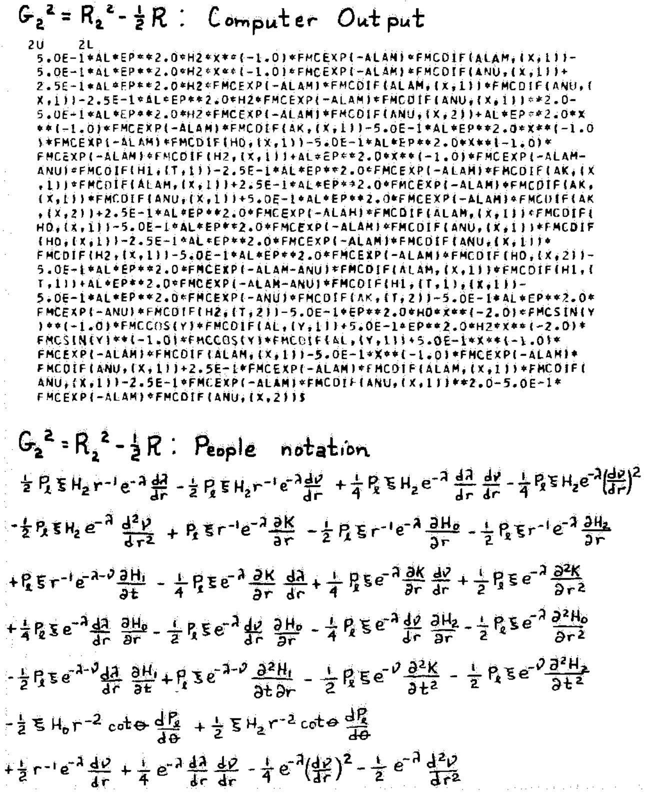
Nevertheless, collisions and collapses in relativistic star clusters might still be a key to the outbursts of quasars, and to explosions in some galaxies.

ENDPOINT OF STELLAR EVOLUTION

Theoretical work in the 1930's by Oppenheimer and his students at Caltech and the University of California, and by Chandrasekhar, then in Cambridge, England, suggested that three types of objects should be the endpoints of stellar evolution: white-dwarf stars (radius ~ 6000 kilometers, density ~ 10^6 g/cm^3), neutron stars (radius ~ 10 kilometers, density ~ 10^{14} g/cm^3), and black holes (radius ~ 5 kilometers). Subsequent theoretical work in the late 1950's and early 1960's firmed up these predictions. Particularly important was the theoretical work on supernova explosions by Hoyle, Fowler, and Geoffrey and Margaret Burbidge, and subsequent work by others, which predicted that neutron stars should be formed in supernova explosions.

By 1963 observational astronomers, particularly Jesse Greenstein at Caltech, had produced extensive data on white-dwarf stars, data which meshed well with the theory. But nobody had ever found any observational evidence for the existence of neutron stars or black holes. Nevertheless, the theoretical case for neutron stars was so compelling that the group here in Kellogg Laboratory and John Wheeler's group in Princeton (of which I was then a member) embarked on vigorous studies of them.

What observational handle might one get on neutron stars? This was the crucial question. One possibility, of course, was thermal radiation from the surface of a neutron star. Because of the extreme smallness of its surface area (a few hundred square miles) a neutron star would be very dim. But it might not be hopelessly dim. How hot should a neutron star's surface be? A few million degrees, if the star was only a few thousand years old, according to calculations by Hong-Yee Chiu in New York City in 1963. In this case, young neutron stars should produce primarily x-rays, not light! Several months after



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  FMCEXP(-ALAM)*FMCDIF(ALAM,(X,1))-5.0E-1*X**(-1.0)*FMCEXP(-ALAM)*
  FMCDIF(ANU,(X,1))+2.5E-1*FMCEXP(-ALAM)*FMCDIF(ALAM,(X,1))*FMCDIF(
  ANU,(X,1))-2.5E-1*FMCEXP(-ALAM)*FMCDIF(ANU,(X,1))**2.0-5.0E-1*
  FMCEXP(-ALAM)*FMCDIF(ANU,(X,2))$
```

$G_2{}^2 = R_2{}^2 - \frac{1}{2}R$: People notation

$$\frac{1}{2}P_\ell \xi H_2 r^{-1} e^{-\lambda}\frac{d\lambda}{dr} - \frac{1}{2}P_\ell \xi H_2 r^{-1} e^{-\lambda}\frac{d\nu}{dr} + \frac{1}{4}P_\ell \xi H_2 e^{-\lambda}\frac{d\lambda}{dr}\frac{d\nu}{dr} - \frac{1}{4}P_\ell \xi H_2 e^{-\lambda}\left(\frac{d\nu}{dr}\right)^2$$

$$-\frac{1}{2}P_\ell \xi H_2 e^{-\lambda}\frac{d^2\nu}{dr^2} + P_\ell \xi r^{-1} e^{-\lambda}\frac{\partial K}{\partial r} - \frac{1}{2}P_\ell \xi r^{-1} e^{-\lambda}\frac{\partial H_0}{\partial r} - \frac{1}{2}P_\ell \xi r^{-1} e^{-\lambda}\frac{\partial H_2}{\partial r}$$

$$+P_\ell \xi r^{-1} e^{-\lambda-\nu}\frac{\partial H_1}{\partial t} - \frac{1}{4}P_\ell \xi e^{-\lambda}\frac{\partial K}{\partial r}\frac{d\lambda}{dr} + \frac{1}{4}P_\ell \xi e^{-\lambda}\frac{\partial K}{\partial r}\frac{d\nu}{dr} + \frac{1}{2}P_\ell \xi e^{-\lambda}\frac{\partial^2 K}{\partial r^2}$$

$$+\frac{1}{4}P_\ell \xi e^{-\lambda}\frac{d\lambda}{dr}\frac{\partial H_0}{\partial r} - \frac{1}{2}P_\ell \xi e^{-\lambda}\frac{d\nu}{dr}\frac{\partial H_0}{\partial r} - \frac{1}{4}P_\ell \xi e^{-\lambda}\frac{d\nu}{dr}\frac{\partial H_2}{\partial r} - \frac{1}{2}P_\ell \xi e^{-\lambda}\frac{\partial^2 H_0}{\partial r^2}$$

$$-\frac{1}{2}P_\ell \xi e^{-\lambda-\nu}\frac{d\lambda}{dr}\frac{\partial H_1}{\partial t} + P_\ell \xi e^{-\lambda-\nu}\frac{\partial^2 H_1}{\partial t\,\partial r} - \frac{1}{2}P_\ell \xi e^{-\nu}\frac{\partial^2 K}{\partial t^2} - \frac{1}{2}P_\ell \xi e^{-\nu}\frac{\partial^2 H_2}{\partial t^2}$$

$$-\frac{1}{2}\xi H_0 r^{-2}\cot\theta\frac{dP_\ell}{d\theta} + \frac{1}{2}\xi H_2 r^{-2}\cot\theta\frac{dP_\ell}{d\theta}$$

$$+\frac{1}{2}r^{-1}e^{-\lambda}\frac{d\nu}{dr} + \frac{1}{4}e^{-\lambda}\frac{d\lambda}{dr}\frac{d\nu}{dr} - \frac{1}{4}e^{-\lambda}\left(\frac{d\nu}{dr}\right)^2 - \frac{1}{2}e^{-\lambda}\frac{d^2\nu}{dr^2}$$

Calculations in general relativity involve tedious manipulations of algebraic expressions—since 1967 performed on computers. Above is one component of the Einstein tensor for the simple problem of a star in nonradial pulsation, produced by the computer and translated into "people language."

Chiu's prediction came the discovery of x-ray "stars" by telescopes flown in rockets. Great excitement ensued for about a year, until two new developments cooled the enthusiasm: John Bahcall and Richard Wolf in Kellogg Laboratory recalculated the cooling of neutron stars due to the emission of neutrinos, and they found a much more rapid cooling than had Chiu—too rapid to leave sufficient x-rays to account for the observations. At the same time, refinements in the observations revealed that some of the x-ray sources were much larger than neutron stars and had nonthermal spectra.

In what other ways might neutron stars make themselves known? Any observational features would have to result from the release of stored energy. The energy could be stored in heat (already investigated by 1963), vibrations (unstudied in 1963), or rotation (also unstudied). Thus it was that, at Princeton in 1964, we turned our attention to the theory of the pulsation and rotation of neutron stars.

Because relativistic deviations from Newtonian theory are as great as 200 percent in some neutron-star models, we had to use general relativity, in its full nonlinear glory, in this work. By the time I came to Caltech in 1965, David Meltzer, a student of mine, and I had worked out the properties of radial pulsations of neutron stars. Since then James Hartle (UC Santa Barbara), Alfonso Compolattaro (UC Irvine), Richard Price (a student in our laboratory), and I have worked together to develop the general relativistic theory of neutron stars which rotate, which pulsate nonradially, and which emit gravitational waves.

This five-year project, now essentially complete, has been great fun; and it has produced a payoff for astronomy, which came much sooner than we had dreamed. In February 1968 radio astronomers in Cambridge, England, announced their discovery of a class of pulsating radio sources with intervals between pulses of about one second. The only kinds of objects which could have characteristic periods so short are highly compact white dwarfs, where relativistic gravitational effects are important, and neutron stars, where relativity is crucial. And the only reasonable "clock mechanisms" for governing the pulses are the pulsation and the rotation of such stars. Consequently, our theory of the pulsation and rotation of relativistic stars has become a foundation on which models of pulsars are constructed these days.

As a result of the most recent observations, it seems highly likely that the pulsars are rotating, magnetic neutron stars.

A second payoff for our studies is the recent detection, by Joseph Weber (University of Maryland), of vibrations in an isolated aluminum cylinder, vibrations which may well be due to bursts of gravitational waves from neutron stars in the process of formation. If Weber has indeed detected gravitational waves, then our work on the emission of such waves by pulsating neutron stars may play an important role in the interpretation of his data.

Despite the crucial role played by relativistic gravitational effects in cosmology, pulsars, and (perhaps) quasars, we do not know for certain yet whether general relativity is the correct relativistic theory of gravity. Fortunately, solar-system experiments using, among other things, JPL space probes should give the answer within the next five or ten years. To facilitate the planning for these experiments, the Caltech relativistic-astrophysics group may turn its attention next to the theory of relativistic celestial mechanics.

Gerald Wasserburg, professor of geology and geophysics; Don Burnett, assoc. professor of nuclear geochemistry.

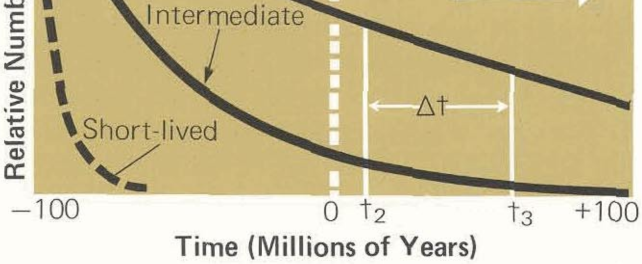
The Time Scales of Nucleosynthesis

by Donald S. Burnett and Gerald J. Wasserburg

The nuclei of the atoms of elements heavier than hydrogen are generally believed to have been synthesized in a variety of stars, more or less continuously, throughout the history of the galaxy. The matter ejected from these stars at various stages in their evolution is mixed into the interstellar gas and, in turn, portions of this gas become isolated from the remainder of the galaxy and form later-generation stars such as the sun. The times required for the various stages in the evolution of the matter of our solar system are of interest, both from an astrophysical and a philosophical point of view. We will discuss how relatively definitive information can be obtained on the times for at least the latter stages in this evolution through the measurement of the isotopic composition of those elements in meteorites which contain the daughter products of radioactive decay.

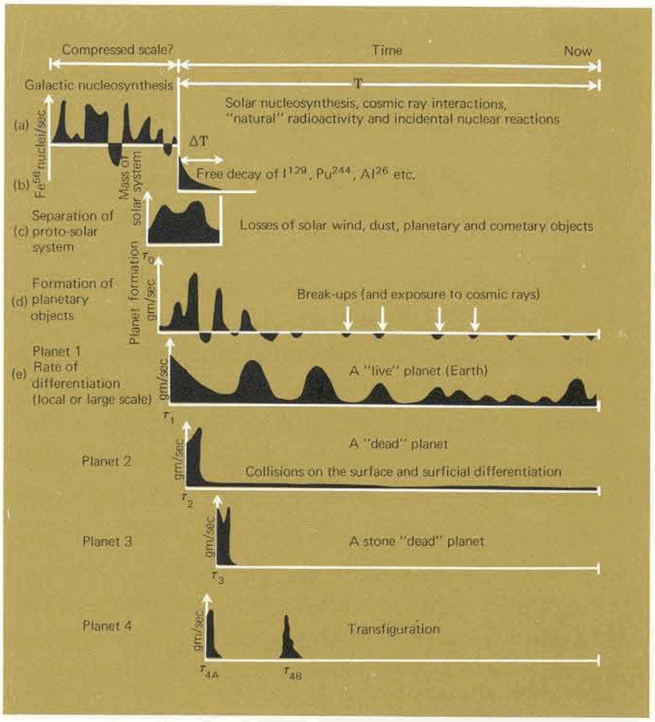
Information on the order of magnitude of the time that has elapsed since the matter in our solar system was "seriously" involved in nucleosynthetic activity is obtained from the simple observation of the presence or absence of certain radioactive species. All of the radioactive isotopes observed on the earth either have half-lives greater than about 10^9 years, or are the decay products of such elements. (Radioactive nuclei diminish in amount by a factor 2 in a time equal to the half-life of a nucleus.) This ignores the feeble level of nuclear reactions due to cosmic rays. Thus the matter which makes up our planet (also meteorites and the moon) has been removed from nucleosynthetic activity for times greater than 10^9 years. The absence of the shorter lived radioactivities is a consequence of the age of the solar system—about 4.7×10^9 years.

It is of considerable interest to seek evidence for the existence of element formation processes near the time of formation of the solar system. The diagram below illustrates the effect of a *hypothetical* event of nucleosynthesis occurring 100 million years before the formation of the first solid bodies in the solar system. Those nuclei which are short-lived (compared to 100 million years in this example) have completely decayed by the time solid objects are formed. For a half-life of 10 million years the exponential decay factor is 2^{-10}. Those "intermediate"



Addition of nuclei to the first solid bodies formed in the solar system from an event of nucleosynthesis at —100 million years. Simple exponential decay curves are shown for stable and radioactive nuclei with lifetimes long, intermediate, and short—compared to 100 million years.

nuclei whose lifetimes are comparable to the time interval between the event of nucleosynthesis and the formation of solid bodies will be incorporated into these bodies then, but will have completely decayed by the present time. Pu^{244} (82 million years half-life) is an example. The experimental upper limit for the ratio of Pu^{244} to U^{238} in modern terrestrial materials is about 10^{-14}, while it was almost certainly present in meteorites when they formed with $Pu/U \sim 1/30$. The hypothetical event shown on page 41 may be considered to be only one of a large number of galactic events which contributed matter to our solar system. This segment of the time scale should be considered in the broader context of the generalized chronology for the solar system above. The period of nucleosynthetic activity is indicated in the topmost graph of the chart (a) which shows the rate of Fe^{56} production. This is terminated at the time marked by a vertical bar T years ago. Line b corresponds to the decay of intermediate-lived radioactive elements resulting from the superposition of individual events as shown on the diagram on page 41.

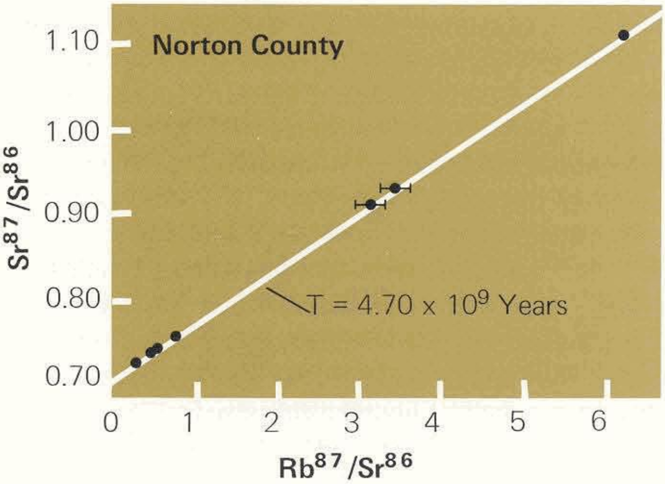


A generalized chronology for the solar system.

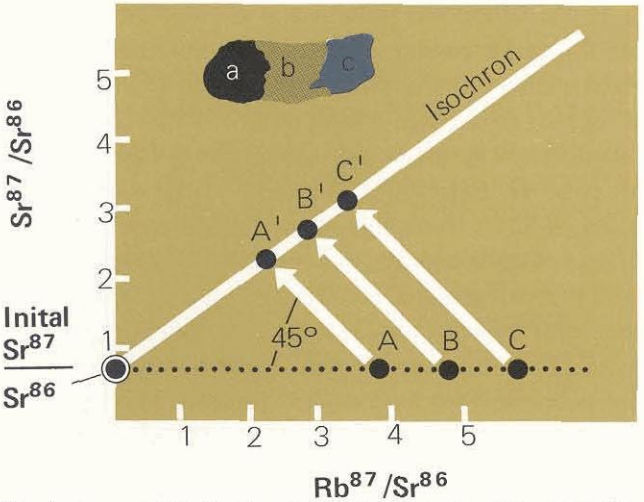
After the isolation and separation of nebular matter to form the solar system (c above), the sun and planetary objects start to condense. Subsequent to this, the solar system remains closed except for minor exchanges of matter with the remainder of the universe. All the planets probably formed during this early period. Subsequent to their initial formation, some of them (the asteroids) have been broken up by collision over the whole history of the solar system (d left). The small fragments are then exposed to cosmic ray bombardment. The effects of this bombardment allow us to calculate when these breakups took place. Four planetary bodies are shown forming at different times relative to the termination of nucleosynthesis. It is in fossil objects left over from these times that evidence of the intermediate-lived (10^7 to 10^9 years) nuclear products may be found which allow us to look back into presolar system processes.

The meteorites appear to be small fragments of such "planets" left over from the time of formation of the solar system. These planetary objects have undergone only a few changes since their formation, except to grow older and occasionally to be shattered into small pieces, some of which fall on the earth and other planets. They are thus fragments from "stone dead" planets (Planet 3, left). The dating of these objects either singly or in conjunction with the earth provides the basic time scale for the solar system. In contrast with the meteorites, the earth, which is a live planet, undergoes continuous rejuvenation both chemically and physically (Planet 1, left). Terrestrial material is constantly melted and recrystallized or weathered and is continuously mixed and transformed. Only the isotopic abundances reflect its original condition.

The ages of meteorites, as measured from the present, are obtained by the study of long-lived nuclei such as K^{40}, Rb^{87}, Th^{232}, U^{235} and U^{238}. The decay of



Sr^{87}/Sr^{86} evolution for the Norton County meteorite.



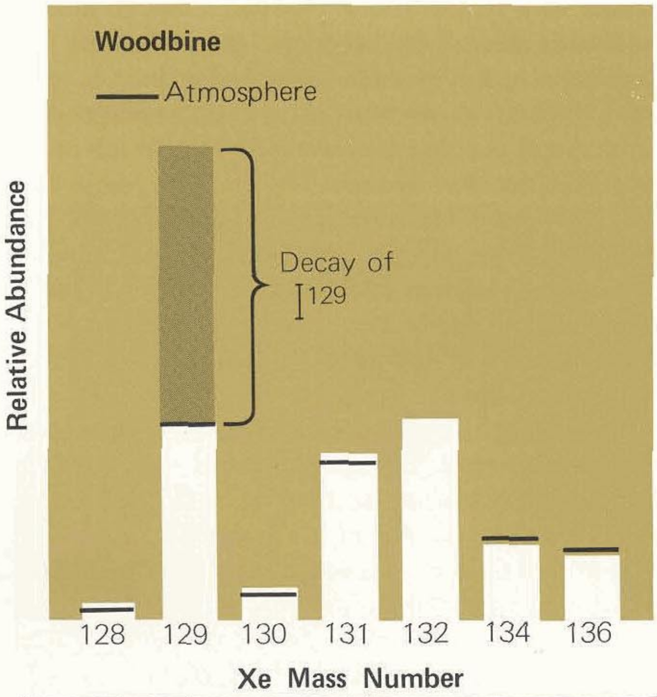
Evolution of Sr^{87}/Sr^{86} ratio in three parts of a meteorite.

Rb^{87} to Sr^{87} has proved to be particularly useful for this purpose. Generally speaking, Rb and Sr are inhomogeneously distributed in a meteorite, either due to the simple fact that a meteorite is a mixture of minerals of different chemical composition or, for more obscure reasons, due to variations in composition from one portion of the sample to another. Consider three parts of a meteorite (a, b, c, above) which formed with different ratios of Rb^{87}/Sr^{86}. However, the isotopic composition of the Sr (measured as Sr^{87}/Sr^{86}) will initially be the same in all three parts (points A, B, C). Sr^{86} is a stable isotope of Sr, and, barring chemical or thermal alteration, its concentration does not change with time. However, as time passes, the Sr^{87}/Sr^{86} ratio will increase as the result of the decay of Rb^{87} into Sr^{87} with larger increases occurring in those parts having a higher Rb^{87}/Sr^{86} ratio (above). Today, a plot of the measured Sr^{87}/Sr^{86} ratio vs. the measured Rb^{87}/Sr^{86} in each sample (A′, B′, C′) will give a straight line. The age can be calculated from the slope of this line, and the initial Sr^{87}/Sr^{86} ratio is given by the intercept. Such a plot for an actual meteorite (left) demonstrates that the simple evolutionary model (above) does, in fact, apply to many real situations, allowing accurate ages and initial Sr^{87}/Sr^{86} values to be obtained. Occasionally some meteorites are formed by a more recent (3.8×10^9 years) transfiguration (such as Planet 4 on page 42) and show us that other planets besides the earth have been subject to reformation since they were first made.

We can also obtain a more detailed view of the processes which took place at the termination of nucleosynthesis and planet formation. Those solid objects (planets, small fragments, grains) that formed during or immediately after nucleosynthesis will have the best chance of trapping the short- and intermediate-lived radioactive isotopes. The decay products of these radioactive isotopes, particularly when trapped in "stone dead" planetary objects, are a direct measure of the time ΔT between the formation of these objects and the termination of nucleosynthesis. Even more important, they tell us the time scale for the processes which produced the elements.

The simple existence of these intermediate-lived nuclei at the time of formation of most meteorites allows us to conclude with a high degree of certainty that the ages of these meteorites, as measured from the present, can be equated with the age of the solar system as a whole.

Evidence exists that I^{129} (17 m.y. half-life) and Pu^{244} (82 m.y. half-life) were present in meteorites when they formed. The presence of I^{129} (originally discovered by J. H. Reynolds of the University of California) in the early solar system is of great significance. At the present time, all of the I^{129} atoms



A portion of the mass spectrum of Xe from the Woodbine meteorite (linear scale). A comparison with atmospheric Xe, made by normalizing to mass 132, is shown by the dark lines. The dark area represents excess Xe^{129}, presumably from the decay of I^{129}. The small differences at mass numbers 128, 130, and 131 reflect primarily small deviations in the isotopic composition of primordial Xe in meteorites from that in the terrestrial atmosphere.

initially present in a meteorite will have been transformed into Xe^{129} by radioactive decay. Because Xe is a rare gas, most meteorites retain only about 5 x 10^9 "primordial" Xe atoms/gram when they form. Thus, because about the same number of I^{129} atoms were typically present, a pronounced Xe^{129} excess results in most meteorites compared either to the isotopic abundance of Xe^{129} in those unusual meteorites which contain large amounts of rare gases or to the Xe^{129} isotopic abundance in the earth's atmosphere (page 43). The initial existence of I^{129} in meteorites shows that they formed no later than about 100 million years after the last event of nucleosynthesis. However, other workers have shown that neither Pd^{107} (7 million years) nor Tc^{97} (3 million years) appear to have been initially present in meteorites. The experimental upper limits are relatively high; nevertheless, very large events of nucleosynthesis just prior to the formation of solid bodies can be ruled out.

Some heavy nuclei, such as U^{238}, occasionally decay by a relatively rare process known as spontaneous fission in which the U^{238} nucleus splits into two lighter nuclei (fission products). For example, Xe^{136} would be a typical fission product, although a wide variety of other fission products are also formed. The amount of energy given to the fission products is large (80-100 MeV); however, if the fission event occurs in a crystal, the distance travelled by the fission product is very small, only about 10^{-3} cm. This results in a large amount of radiation damage in the crystal along the path of the fission product. This damaged material is much more subject to chemical attack than the bulk material, and treatment with an appropriate etching agent produces a hole or "fission track" which marks the original fission event.

It has been demonstrated by Fleischer, Price, and Walker that many more fission tracks are present in crystals in meteorites than can be accounted for by U^{238} spontaneous fission. In conjunction with J. Huneke of Caltech, we have just shown that these same crystals contain a great excess of fission products (xenon). The isotopic spectrum of this fission Xe is different from that observed in any type of U fission. These results clearly show the existence of fissionable, transuranic elements during the beginning of the solar system, possibly Pu^{244}. From such observations we conclude that the solar system was not too removed in time from at least one of the "r" (rapid) type nucleosynthesis events in which neutrons were bountiful (a mole of neutrons per cc). (See article by William Fowler in this issue.)

In the future we plan to test the compatibility of the time information obtained from the intermediate-lived nuclei with that from the long-lived nuclei. Consider two meteorites whose parent bodies formed at two different times, t_2 and t_3 after $t = 0$ (the diagram on page 41 and Planets 2 and 3 on the diagram on page 42 left). Comparisons of the isotopic composition of many elements between meteorites and terrestrial samples make it very likely that all the matter in the solar system was isotopically homogeneous at $t = 0$. Thus, because isotopic fractionations in chemical processes are very small, the I^{129}/I^{127} ratio between two meteorites will differ only due to the decay of I^{129}, and comparison of the measured (excess Xe^{129})/I^{127} ratios allows the difference in formation times ($\triangle t$) to be calculated. No knowledge of the absolute I^{129}/I^{127} at $t = 0$ is required. Many meteorites were formed within two million years of each other, back at 4.6 x 10^9 years ago (as shown by Hohenberg, Podosek, and Reynolds at U. C. Berkeley).

In principle, $\triangle t$ can also be obtained by precise measurement of time differences with respect to the present using Rb^{87} - Sr^{87}. The accurate measurement of slopes of lines (page 42 bottom) can only resolve time differences of about 50 to 100 million years with present techniques except in very favorable cases. However, qualitative information about small age differences in meteorites can be obtained if a precise *direct* measurement of the initial Sr^{87}/Sr^{86} (intercept in the diagram at the top of page 43) can be made on a part of the meteorite with a low Rb^{87}/Sr^{86} ratio (e.g., a Sr-rich mineral). D. Papanastassiou, in our laboratory, has found that the initial Sr^{87}/Sr^{86} in Rb-poor meteorites can be measured with a precision of ± 6 parts in 10^5.

To illustrate the significance of this result, suppose that two meteorites representing Planets 2 and 3 (the diagram on page 42 left) formed from a common parent material having a $Rb/Sr = 0.6$ corresponding to the spectroscopically estimated value for the atmosphere of the sun. Then, regardless of changes in the value of the chemical abundance ratio of Rb/Sr during their formation, it would be possible to measure a value of $\triangle t = 2$ m.y. This time resolution corresponds to the first week in the life of a 60-year-old man. With such high time sensitivity, both from intermediate and long-lived radioactivities, an understanding of the details of the infancy of the solar system is now possible, particularly when measurements on lunar samples (and eventually on other planets, asteroids, and comets) are made.

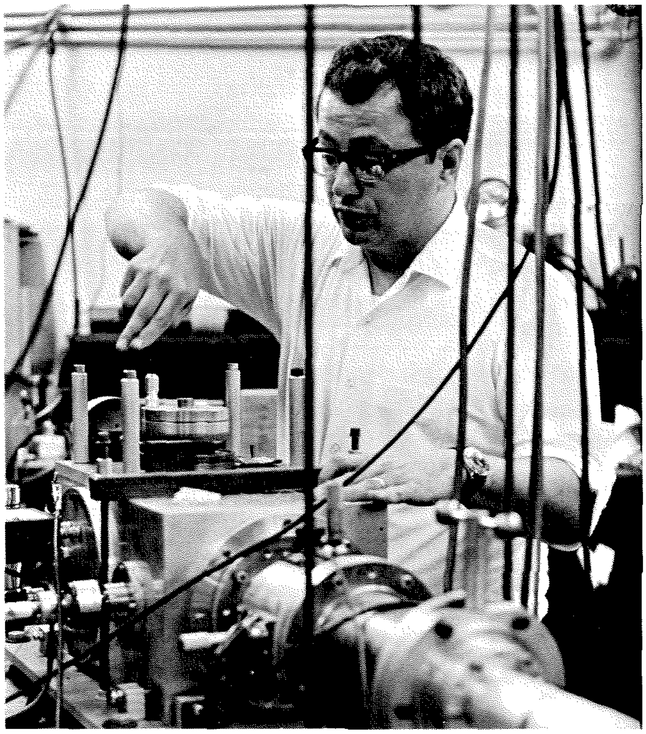
Accelerators, Channeling, and Solid State Physics

by James W. Mayer

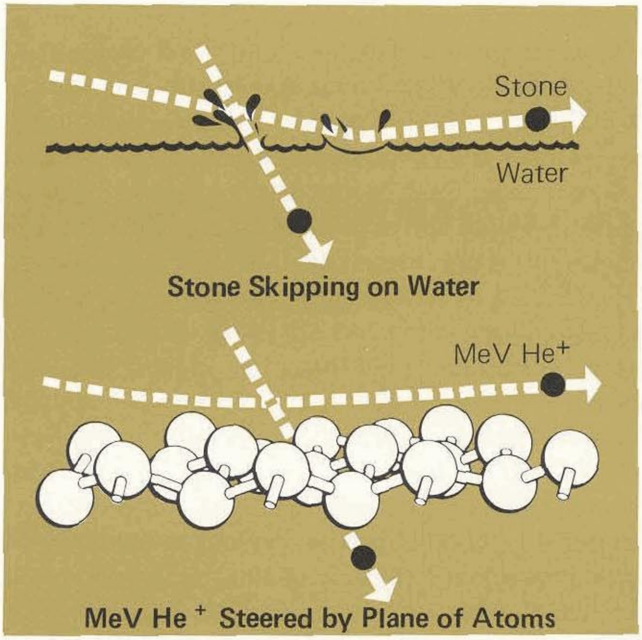
The activities of the Kellogg Laboratory are not entirely devoted to nuclear and atomic physics. Nuclear particles are extremely useful as probes to determine the properties of solids. These particles provide a simple and direct means of determining the composition of surface layers, the number and location of impurity atoms in crystalline materials, and the amount of disorder in a single crystal. Of course, using million-electron-volt (MeV) protons or helium ions produced in a two-story-high Van de Graaff accelerator to analyze a paper-thin region in a crystal might seem somewhat extreme. However, this information is relevant in many practical applications such as transistors, whose characteristics are entirely determined by the properties of the first few microns of material. Our work is based on the recent discovery that the interactions of energetic charged particles depend strongly on the alignment of the incident beam of particles with the crystal lattice. Under the right conditions the crystal atoms, even though they are held in place by only 10-electron-volt binding energy, can steer MeV charged particles along the "channels" in the crystal lattice structure.

In one sense channeling phenomena are like skipping a stone on water. If the stone approaches the water at a small enough angle, it will skip nicely. Similarly, if a fast-moving, positively charged particle, say a 1 MeV helium ion, is incident at a small angle to a close-packed atomic plane, it can be reflected by a succession of gentle collisions without making a violent impact with any of the lattice atoms. Since hundreds of lattice atoms in the plane may participate in steering the incident helium ion, one may visualize the plane of atoms as a sheet of charge rather than a set of individual scattering centers. On this basis the MeV ion can be considered as being reflected by a potential barrier. As long as the incident angle is small enough (one or two degrees for MeV particles) so that the component of the particle velocity normal to the plane is less than that needed to penetrate the potential barrier, the particle can easily be steered or channeled. At larger incident angles, the particle can easily penetrate through the planes. After all, when skipping stones, a flat trajectory is required for best results.

In a single crystal, steering can also be achieved by rows of atoms. In this case the rows can be treated as a "string of charge," a concept introduced by Jens



James Mayer, assoc. professor of electrical engineering.



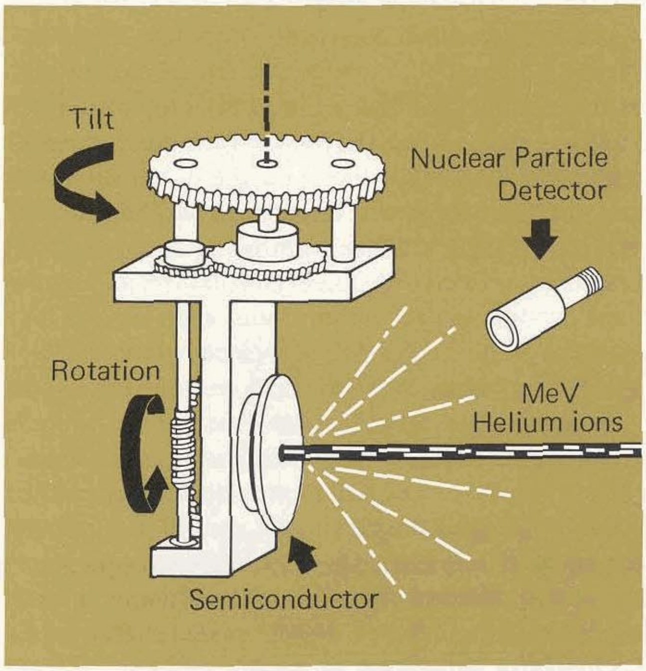
Skipping a stone on water is analogous to steering fast-moving particles (e.g. million-electron-volt helium ions) by planes of atoms. The steering is accomplished by a series of gentle pushes given to the ion by each of the many atoms it passes over.

Lindhard at Aarhus University in Denmark. In his elegant and simple theory, channeling is described as a classical steering process arising from the Coulomb repulsion between the screened nuclear charges of the projectile and lattice atoms. In measurements both at Caltech and the Chalk River Nuclear Laboratories in Canada, we have found that the approximation of strings and planes of charge describes very well the dependence of the steering process on both the characteristics of the incident ion and the lattice. We are particularly interested in the steering aspects of semiconductor lattice structures in order to use channeling effect techniques as a tool to investigate these materials.

Since the collisions during channeling are gentle ones rather than the normal violent collisions, channeling can influence particle ranges and particle energy loss, yields of nuclear reactions, in fact almost all the standard charged particle interactions studied in nuclear laboratories. Different aspects of these effects have been demonstrated at many laboratories over a wide range of particles (protons to xenon ions), energies (10 keV to 50 MeV), and crystals (diamond to tungsten). The effects are so large, one or two orders of magnitude in some instances, that it is hard to realize why channeling remained undiscovered until less than six years ago. To demonstrate the effect, one needs only a parallel beam of particles and a single crystal target.

The use of channeling techniques to determine the position of foreign atoms in a host lattice is based on the fact that the well-channeled particles do not approach closely to the atoms on lattice sites. In fact, the distance of closest approach is of the order of 0.1 to 0.2 angstroms for helium ions in the 1 MeV energy range. These distances of approach are orders of magnitude larger than those required for close impact processes such as nuclear reactions or backscattering (i.e., when the incident particle can interact strongly enough with one lattice atom to be scattered backwards through an angle from 120 to 180 degrees). In fact, the distances of approach are sufficiently large to exclude interactions with the inner shell electrons which for a nonchanneled beam give rise to the production of x-rays.

Measurement of the yield of any of these "close impact" processes provides a very sensitive means of determining the influence of channeling effects. A typical experimental setup in the Kellogg Laboratory

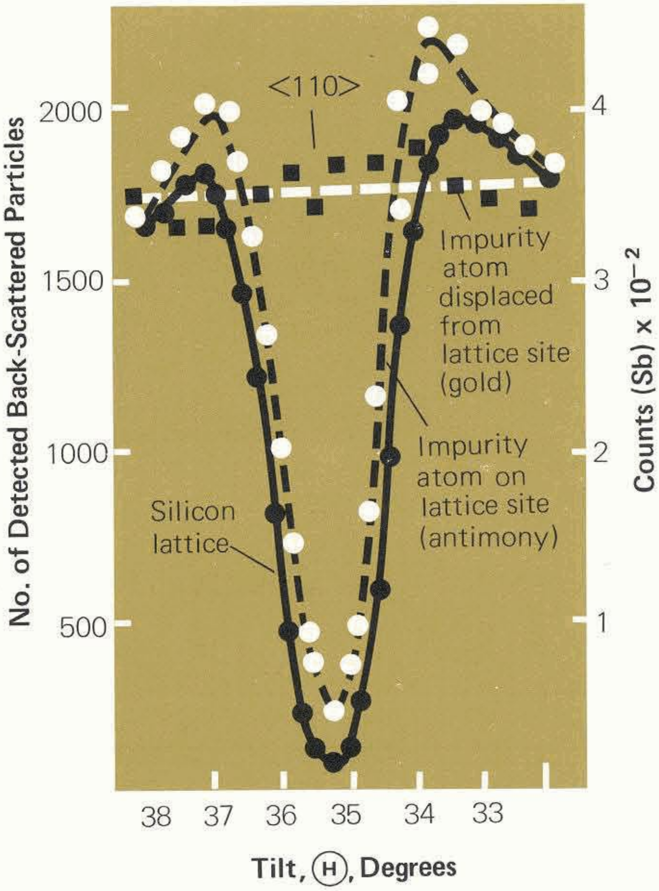


Schematic view of an experimental setup for determination of the lattice location of impurity atoms in a semiconductor. When the incident beam of helium ions strikes the sample, a small fraction are scattered back into the detector. The number and energy of these backscattered particles are measured as a function of sample tilt and rotation.

is to mount a single crystal of silicon on a goniometer so that the crystal can be tilted and rotated with respect to the incident beam of strongly collimated MeV particles. A nuclear particle detector is used to determine the number and energy distribution of backscattered particles. As the crystal is tilted in such a way that a crystallographic axis (a "string" direction) is aligned with the beam, a 10- to 100-fold decrease in the number or yield of backscattered particles is observed.

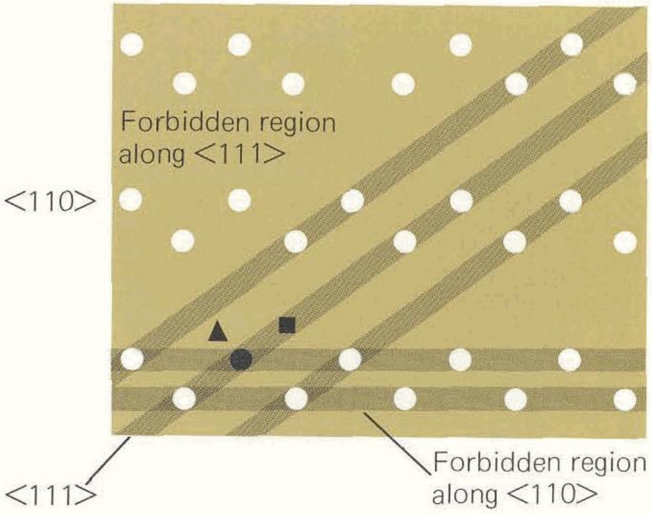
So far we have not considered how one can detect the presence of a small percentage of foreign atoms in a host crystal. This is a crucial point in semiconductor technology, where the properties of silicon transistors, for example, are determined largely by the presence of much less than one atomic percent of impurity atoms. It is the "doping" action of these atoms which determines to a large extent electrical behavior of the semiconductor. Fortunately, in channeling-effect measurements, there are several methods by means of which the interaction of the incident beam with dopant or impurity atoms gives rise to a signal that can be clearly distinguished from the more numerous interactions with the lattice atoms. For light dopant atoms such as lithium or boron, there are specific nuclear reactions that provide a clearly identifiable "signal." In other cases, the characteristic x-rays from the dopant atoms have an energy spectrum distinct enough that they can be distinguished from the x-ray emission from the host atoms. A particularly simple case arises when the mass of the impurity atom is heavier than that of the lattice atoms, such as antimony atoms in silicon. In this case the helium ion loses less energy scattering backwards off the heavy antimony atom than off the silicon lattice atoms. Energy analysis of the backscattered particles is sufficient to identify the scattering from the impurity atoms. Typical sensitivity levels achieved in these measurement techniques 10^{-1} to 10^{-2} atomic percent of dopant atoms to host lattice atoms.

In atom location studies one can treat the crystal as being composed of "allowed" and "forbidden" regions; that is, a well-channeled particle moving along an axial direction is "forbidden" to interact closely with atoms located inside a cylinder of about 0.2 angstroms radius stretched along the row of atoms. On the other hand, the beam can interact with atoms that are displaced from the rows by more than 0.2 angstroms. For example, in a silicon crystal containing impurity atoms on lattice sites, the yield of scattering interactions with impurity atoms will show nearly the same orientation dependence as the yield from the silicon lattice itself. If the impurity atoms are displaced from a lattice site, the scattering interactions with these atoms will not show such orientation effects.



This curve shows how the lattice location of impurity atoms can be determined by analysis of the interaction of MeV helium ions with the silicon host crystal and the impurities. As the sample is tilted so that the <110> crystallographic axis is aligned with the incident ion beam, a channeling condition, the number of backscattering interactions with the silicon lattice atoms decreases by a factor of 30. If the impurity atoms (antimony) are on lattice sites (substitutional location), there will be a similar decrease in the number of interactions. On the other hand, if the impurities (gold) are not on lattice sites, interaction with these atoms does not show orientation effects.

The diamond lattice of typical semiconductors such as silicon or gallium arsenide provides unique possibilities to study the lattice location of impurity atoms because of the existence of well-defined interstitial sites. These interstitial sites are positions along certain lattice rows that can be occupied by an impurity atom without taking the place of a host lattice



○ — Silicon Lattice Atoms

	Direction Effect		Impurity
	<111>	<110>	
●	yes	yes	substitutional
■	yes	no	"regular" interstitial
▲	no	no	off lattice site

The diamond lattice typical of semiconductors, such as silicon, provides a simple case for determining the lattice location of impurity atoms. Well-channeled energetic ions do not penetrate into the lattice rows (forbidden regions) and cannot interact with impurity atoms contained within these regions. Consequently, one may determine the lattice location of the impurities from directional effects in the yield of backscattered particles.

atom. (The latter is a substitutional position.) Along one set of rows the atoms are spaced evenly. But along another set of rows the atoms are spaced in groups of two. It is along this direction that the regular well-defined interstitial sites are located. If one then tilts the crystal so that the incident beam is swept through a lattice axis, in one case interstitial sites are in the "forbidden" region, and in the other case the interstitial sites are in the "allowed" region. Consequently, by measuring the scattering yield along the two directions, one can determine whether the impurity atoms are on regular interstitial sites or substitutional sites, or whether they are displaced by more than 0.1 to 0.2 angstroms from either of these two well-defined sites.

Channeling-effect measurements have been applied systematically to solid state problems only in the past three years. One of the first major applications was the analysis of lattice disorder and atom location in semiconductors which had been implanted with dopant elements. That is, we use one type of heavy-ion accelerator to introduce (implant) the impurity atoms at keV energies and another accelerator to analyze the implanted structure by using lighter particles (protons, helium ions, carbon ions) at MeV energies. This work was started by a group at Chalk River Nuclear Laboratories and continues as a collaboration between Chalk River, Caltech, and the Research Institute for Physics in Stockholm.

As a result of channeling investigations, we have found that implanted impurity atoms can be on substitutional lattice sites in concentrations orders of magnitude above those found in thermal diffusion studies. Also there are certain classes of elements which are located on both substitutional and the regular interstitial sites. We have observed the motion of these elements from substitutional to interstitial and then to precipitation sites. In measurements carried out in collaboration with the Hughes Research Laboratories, we have found that the electrical characteristics of the dopant atoms are strongly dependent on their lattice position. As an example, a column III element, thallium, which captures an extra electron when substitutional (an acceptor), gives up one of its electrons (becomes a donor) when on interstitial sites.

We started our investigations with implantation in semiconductors because this technique offers some unique advantages in fabrication of semiconductor devices. From a more general viewpoint, the solid state aspects of ion implantation are particularly broad because of the range of physical properties that are sensitive to the presence of foreign atoms in solids. The mechanical, electrical, optical, magnetic, and superconducting properties of a solid are affected and indeed may be dominated by the properties of implanted layers. Implantation makes it possible to obtain impurity concentrations and distributions which are of particular interest and which are otherwise unobtainable.

The application of channeling effects is not restricted, of course, to semiconductors or implantation. Studies of diffusion in metals, radiation damage effects, oxidation, corrosion, and others are possible. It only depends on the ingenuity of the investigator to choose the right conditions so that meaningful data can be obtained.

Charles C. Lauritsen

Memorial Lecture in Physics

Friends and associates of Charles Lauritsen have established a memorial fund in his honor to endow the Charles C. Lauritsen Memorial Lecture in Physics.

These lectures will be given annually to the students and faculty of Caltech and the interested public by an outstanding scientist on a subject of current interest in the field of nuclear physics and its applications in astrophysics and geophysics.

Contributions designated for the Lauritsen Memorial Fund may be made through the Division of Physics, Mathematics and Astronomy at the California Institute of Technology.