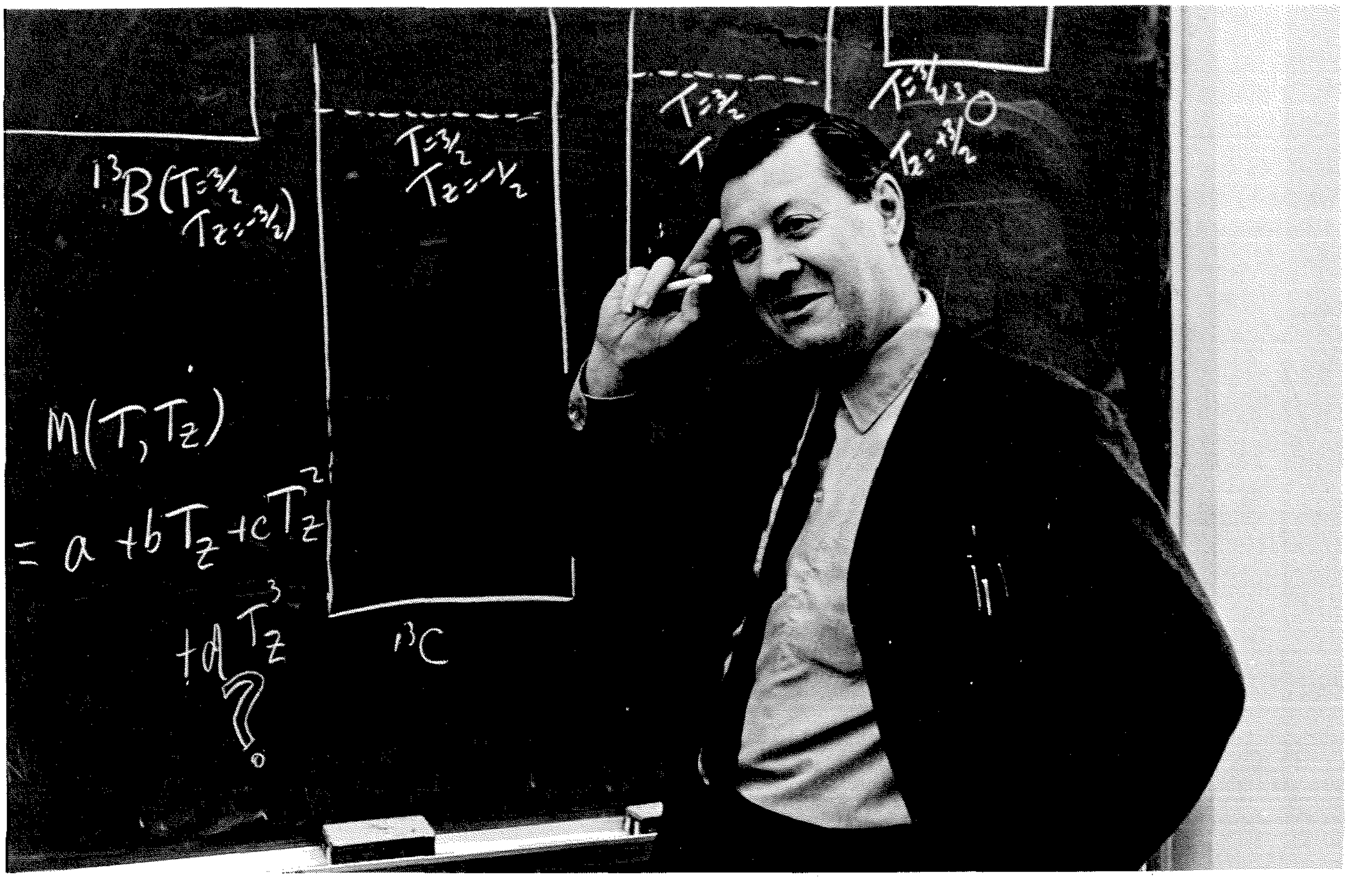


Charles Barnes, professor of physics.

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)

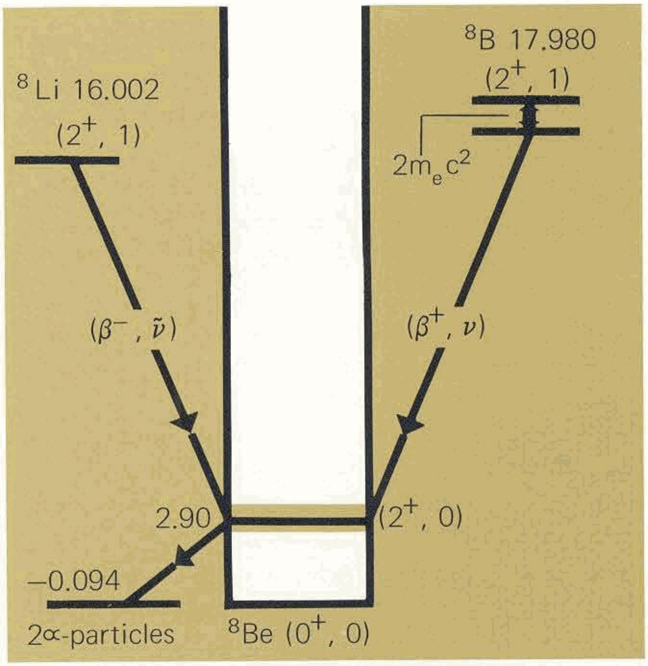
The nitrogen 13 decays, with a half-life of about ten minutes, by emitting a positron (the positive electron discovered by Carl Anderson at Caltech in 1932) and a neutrino, according to the equation,

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

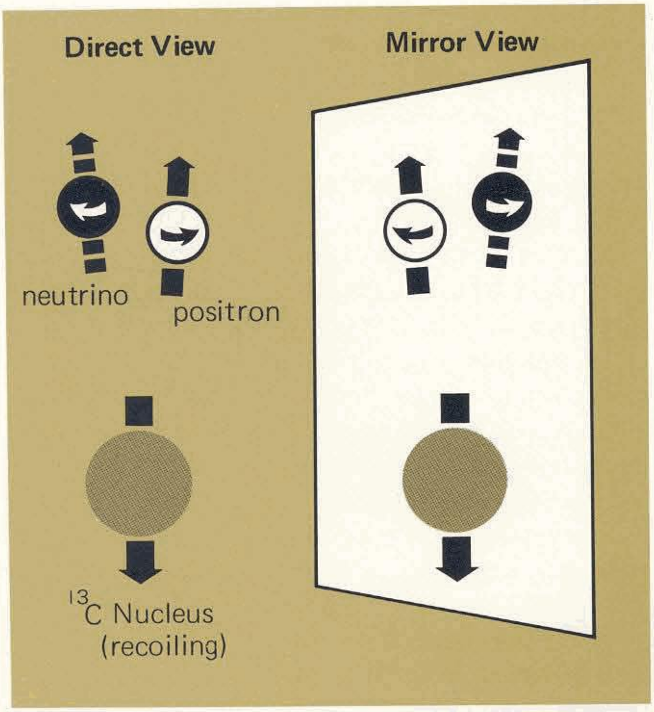
A rapid flurry of publications followed from many laboratories, especially from Caltech and the experimental groups at the University of California at Berkeley and at the Carnegie Institution in Washington, as a large number of new radioactive elements were discovered. Among others, the radioactive nuclei 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.

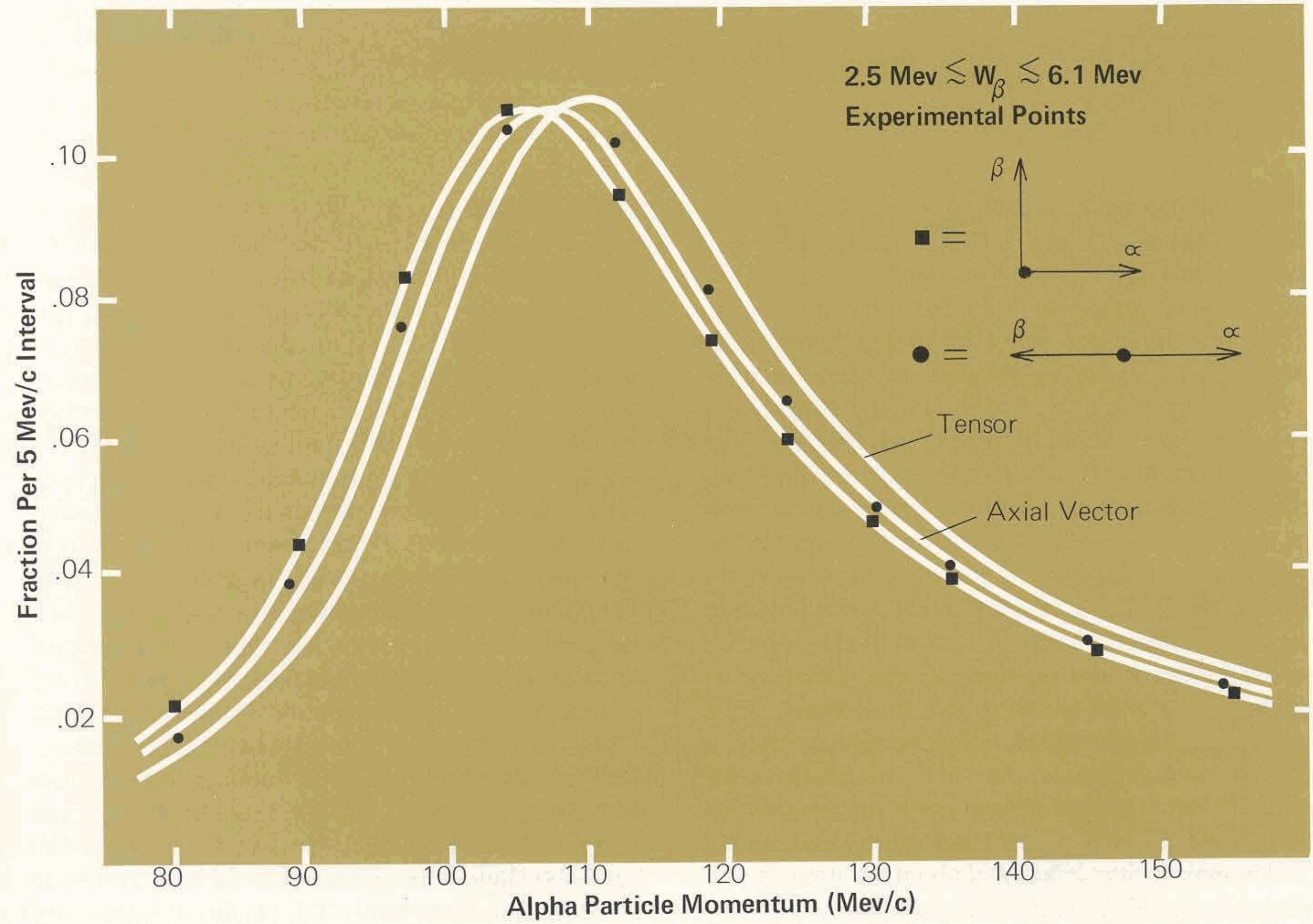
In 1958 Caltech theorists Richard Feynman and Murray Gell-Mann published what is still today the most elegant theoretical description of nuclear β-decay (and other weak interaction processes). Their theory not only explained the parity violation in a very direct and ingenious way, but it also led to 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.

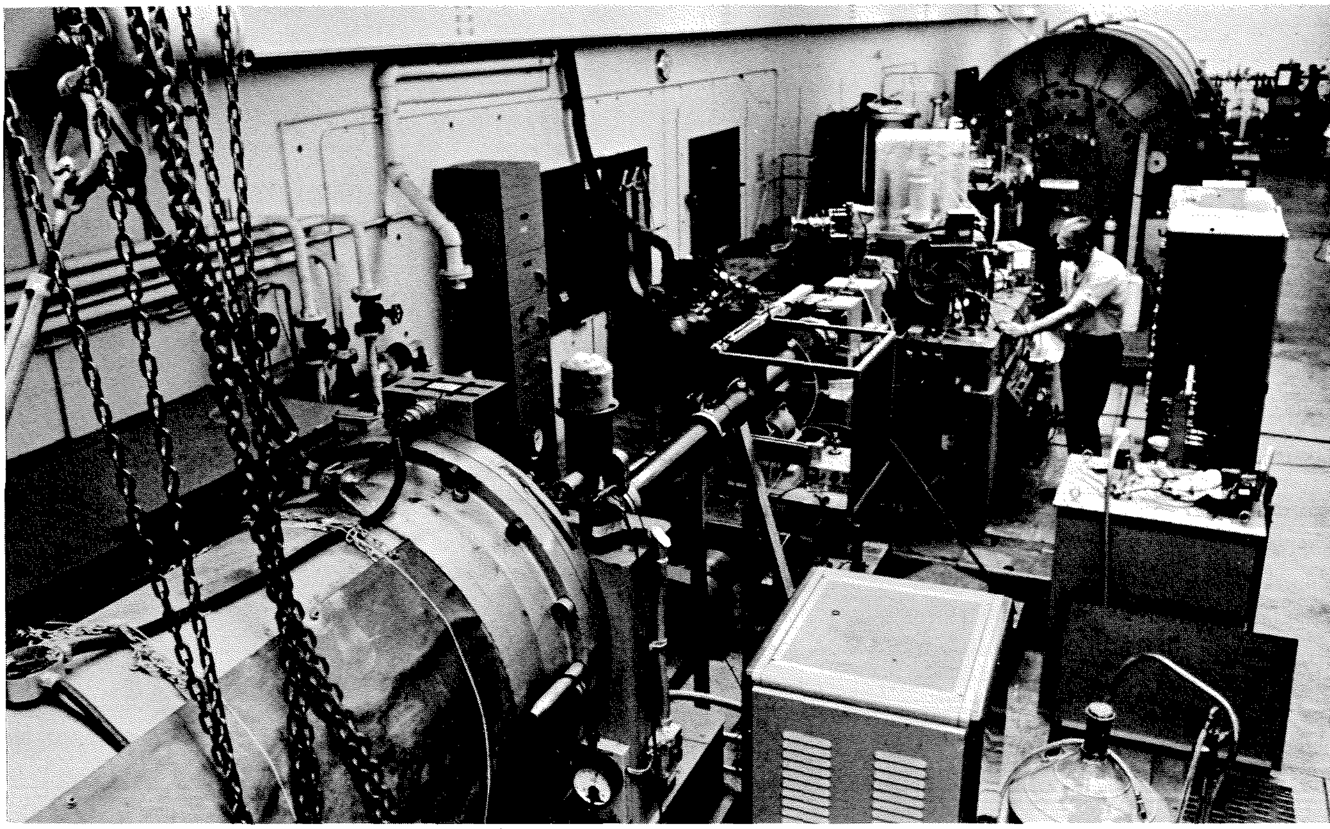
The V-A theory of β-decay also made several other important predictions. One of these was that the strength of the Vector β-decay interaction is a universal constant, so that the β-decay of the nucleus ^{14}O, for example, should occur with the same intrinsic strength as the β-decay of the muon, an apparently 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.