1980 Nobel Prize in Physics to Cronin and Fitch

A textbook-perfect experiment led to 1964 discovery that the laws of physics do not always operate the same when time is reversed

Science textbooks are punctuated with descriptions of certain classic experiments with which every researcher in the field is expected to remain familiar. One such revered experiment in high energy physics has won James W. Cronin of the University of Chicago and Val L. Fitch of Princeton University the 1980 Nobel Prize in Physics. Cronin and Fitch's 1964 experiment at Brookhaven National Laboratory showed that certain elementary particle reactions violated a then deeply held belief in a fundamental symmetry principle of physics. The simplest statement of their results is that the laws of physics operative in the reactions differ slightly when time is reversed.

Violation of time reversal invariance is a consequence of the failure of another symmetry principle called (in the jargon of physics) charge conjugation-parity (CP) conservation, which is what Cronin and Fitch's experiment actually measured. Although there are several theoretical models to explain the origin of CP nonconservation, none has been confirmed as yet. One theorist summed up the situation with "CP violation has been a bone in our throats for a long time. We don't know the true explanation, but when we do it will be damn interesting."

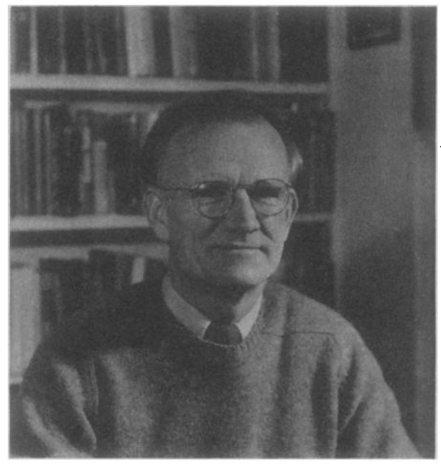
Symmetries play a most important role in modern physics. Some symmetries such as the homogeneity and isotropy of space and time (which give rise to laws of conservation of energy, momentum, and angular momentum) constitute the edifice on which all else is built. Other symmetry principles arise from elementary particle theories. No reasonable theory of the electromagnetic force can be constructed, for example, that does not conserve electric charge. Still other conservation laws seem, insofar as can be determined by experiment, always to hold, but theories that do or do not contain the associated symmetry principle can equally well be concocted.

An important outcome of experiments like that of Cronin and Fitch, which test conservation laws and find them to be wanting, is that physicists' attitudes about symmetry principles have slowly done a flip-flop. "The old [prejudice in favor of symmetry] is dying out. You used to have to explain why when it fails. Now you have to explain why it is respected," explained one theorist.

The elementary particles studied by Cronin and Fitch were the neutral K mesons, particles with masses about one-half that of the proton. K mesons were discovered in cosmic-ray experiments in 1947 and their history has been bound up in breaking conservation laws. For example, K mesons were involved in the 1956 prediction by T. D. Lee of Columbia University and C. N. Yang of the State University of New York at Stony Brook of nonconservation of parity in reactions governed by the weak force (for which they won the 1957 Nobel Prize). (There are two nuclear forces. The weak force is involved in interactions such as the beta decay of nuclei, whereas the strong nuclear force is primarily responsible for binding protons and neutrons together in nuclei.) Parity has to do with mirror images. The symmetry principle is that physical laws are identical in a given coordinate system and its mirror image. Elementary particles also have a property called parity that relates to the behavior of the particles in mirror-image coordinate systems and that must be conserved in any reaction.

As it happened, the several experiments published in 1957 that demonstrated nonconservation of parity also showed the violation of charge conjugation invariance. Charge conjugation is the replacement of a particle with its antiparticle, an electron with a positron, for example. The symmetry requires that a world made entirely of antimatter would have exactly the same physical laws as the matter world. Again, only the weak force gives rise to interactions that do not obey this symmetry principle.

During the same year, Lee and Yang discussed the possibility that the combination of charge conjugation and parity would continue to be conserved in weak interactions, even if separately they were not; that is, that physical laws would not change in mirror-image coordinate systems, provided that all particles were replaced by their antiparticles. And, in another paper, Lee, Yang, and Reinhard Oehme of the University of Chicago specifically examined the neutral K mesons and pointed out the signatures for violations of several symmetries. "It was all there," says Cronin. Up to the time of the Cronin-Fitch experiment, no CP nonconservation had been observed, although a number of experiments (including one published in the same issue of *Physical Review Letters* as



Val L. Fitch

Cronin and Fitch's) had set an upper limit on how big such an effect could be. With the help of a much more sensitive detector than previously available, Cronin and Fitch were able to see what their predecessors had not.

The two investigators did not start out with a test of CP invariance primarily in mind, however. The immediate stimulus was a 1963 experiment by Robert Adair of Yale University, Lawrence Leipuner of Brookhaven, and their colleagues that turned up some unusual behavior by neutral K mesons, which come in pairs. The effect seen by the Yale-Brookhaven collaboration was called anomalous regeneration.

Regeneration itself is a well-understood quantum mechanical phenomenon. A beam of neutral K mesons from an accelerator consists of short-lived particles (K_S) that decay into two pi mesons and long-lived particles (K_L) that

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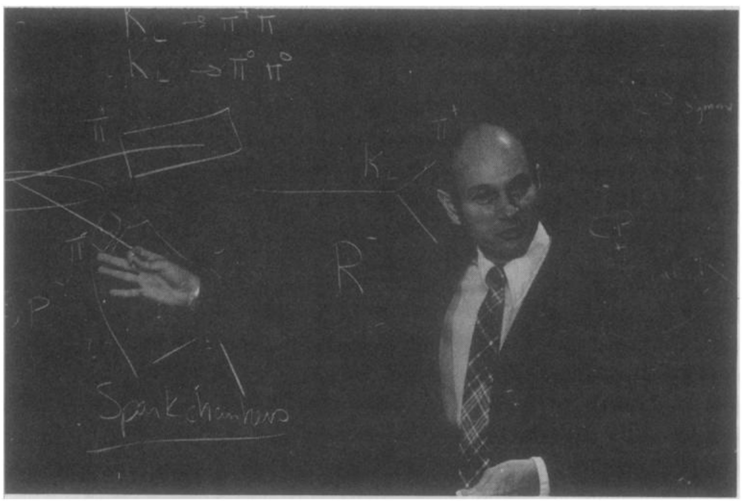
decay into three pi mesons. After a certain distance, mainly K_L particles remain in the beam passing through a vacuum, as signaled by the disappearance of decays consisting of two pi mesons. But, if the beam then passes through a material such as the liquid hydrogen in a bubble chamber, K_S particles are regenerated, as indicated by the detection of decays consisting of two pi mesons. The Yale-Brookhaven experiment found an anomalously high number of regenerated K_S particles.

Cronin recalls talking over regeneration with Adair and Fitch. In the course of the discussion, the physicists realized that an ideal detector for a more detailed examination of the phenomenon already existed in Cronin's laboratory at Brookhaven. Cronin and Fitch, who had generally worked independently as heads of their own groups, decided to collaborate on a study of regeneration in the neutral K mesons. James Christenson of New York University, who was a graduate student at Princeton under Cronin at the time, and René Turlay, who had come to Princeton as a postdoctoral associate from the Center for Nuclear Studies in Saclay, France, also worked on the project.



James W. Cronin

Once the decision to do the experiment was made, things moved swiftly. A new beam line from which neutral K mesons could be extracted was just opening up on Brookhaven's then new Alternating Gradient Synchrotron, a machine that accelerates protons to energies of 30 billion electron volts. Christenson remembers that Cronin's detector was moved "lock, stock, and barrel" from an older Brookhaven accelerator (the Cosmotron) to the larger machine and set up "in record time." Fitch admits that much of this work was done even before Brookhaven authorities had formally approved the experiment, although not without their knowledge and cooperation. The proposal to Brookhaven called for checking the Yale-Brookhaven group's anomalous regeneration result, carrying out a detailed examination of the regeneration phenomenon in condensed media, and testing for CP violation. The expectation for the third objective was that a tighter limit would be placed on the magnitude of any CP-violating effect, not that it would be observed, according to Christenson.

The guts of the detector were devices called spark chambers, which produce flashes of light that trace the paths of the pi mesons produced in the decay events as they pass through a magnetic field. Photographs are taken of the paths delineated by the sparks and later analyzed. Nowadays it would all be done by computer, but in 1964 the physicists had to carry the film ("rolls and rolls and rolls," says Christenson) back to Princeton to be examined by a laborious process.

Not expecting CP violation, says Cronin, the investigators scanned films pertaining to the more interesting anomalous regeneration first. When they did get around to looking at the CP conservation test 6 months later, they were shocked to find 45 events in a total of almost 23,000 that were clear and unmistakable indications of CP violation, or about 1 in 500. The 45 events were those in which K_L particles decayed into two pi mesons instead of three. The beam had passed through no liquids or solids in this part of the experiment, so regeneration of K_S particles could not provide the answer. Fitch says the group then spent 6 months analyzing their data in a variety of different ways "to try to kill the effect," but that each new cut through the data only enhanced it. In the end, he says, the outcome was sharp and clear with no fuzziness.

Theorists, though greatly surprised by the finding, were not too startled to begin devising models for CP violation. For a long time, the most successful of these was that constructed by Lincoln Wolfenstein of Carnegie-Mellon University almost immediately after publication of the Cronin-Fitch experiment. Wolfenstein theorized that it was not the weak force that was responsible for the effect but a heretofore undetected fifth force, a so-called superweak force. Wolfenstein's proposal had several things going for it. It correctly accounted for the magnitude of several quantities that were measured in the original and in subsequent experiments. And it correctly (so far) predicted that CP violation would only be seen in decays of the neutral K mesons. Cronin and Fitch observed the K_L to decay into two charged pi mesons. In later experiments, Cronin and several others also found the K_L to decay into two neutral pi mesons. A more complicated test of CP violation carried out by numerous groups, including Fitch's, involves the K_L decay into a pi meson, an electron, and a neutrino. The main problem with the superweak force model derives from this same prediction. If CP violation is small and only seen in neutral K meson decays, it would not affect the rest of physics very much. "For a long time, CP violation was a phenomenon looking for an application," says Frank Wilczek of the University of California at Santa Barbara.

Interest in CP violation revived in the 1970's, which for elementary particle physics was the decade of quarks and of gauge theories. Quarks are the entities now believed to be the "true" elementary particles, the constituents of particles like the proton, the neutron, and the mesons. In 1964, quarks were just beginning to be talked about and no one was sure whether they were actual particles or just mathematical constructs. Gauge theories are a special kind of quantum field theory. In 1964, the only gauge theory relevant to elementary particles was quantum electrodynamics, the theory of the electromagnetic force. By 1973, a unified gauge theory that tied the electromagnetic and weak forces together had taken shape, and a separate gauge theory of the strong nuclear force was being taken seriously.

In that year, Makoto Kobayashi and Toshihide Maskawa of Kyoto University showed that if there were at least six types of quarks, then the weak force could violate CP conservation "naturally" without the need for ad hoc postulates. Probably because only three varieties of quarks were widely accepted then, Kobayashi and Maskawa's proposal did not immediately attract a lot of attention. But the following year, evidence for a fourth quark was unearthed, a watershed event in quark history because from then on the particles were taken increasingly seriously. And in 1977, physicists reported on the possibility of a fifth quark. Since the unified theory has quarks coming in pairs, physicists suspect that a sixth variety is also waiting to be found, and Kobayashi and Maskawa's model has become a serious contender.

Another explanation for CP violation by way of gauge theories was made by Columbia's Lee, also in 1973. Although the particles are as yet unobserved, the unified theory as developed by Steven Weinberg of Harvard University and Abdus Salam of Imperial College, London, requires the existence of an altogether new type of particle called a Higgs boson. Lee suggested that if there were at least four such particles, another mechanism for CP violation would be opened up. Weinberg later worked out a more realistic model of this type.

Among the differences between the models stemming from gauge theories (which are often called milliweak theories of CP violation) and the superweak theory is that the former predict the observation of larger CP violating effects in more places than does the latter. Several extremely sensitive experiments are planned or under way to try to distinguish between the various models.

Interest in CP violation also revved up in the 1970's because of its implications for cosmology and the Big Bang model of the origin of the universe. The various conservation laws of physics had seemed to say that, in the Big Bang, equal amounts of matter and antimatter had to be created. Similarly, as the universe expanded and cooled, equal amounts of matter and antimatter would have to be annihilated, as in collisions between electrons and positrons where both are transformed into gamma rays. Yet, experimentally, the universe seems to be almost entirely matter, the only antimatter coming in cosmic rays and in accelerators. One consequence of CP violation is that particles and antiparticles do not have to decay by the same reaction at the same rates. Among the first published accounts of a way to incorporate CP violation into a model for a universe consisting of matter but not antimatter was that by Soviet dissident Andrei Sakharov in the mid-1960's.

In the mid-1970's, a number of grand unified gauge theories were proposed that attempted to encompass the strong nuclear, weak, and electromagnetic forces into one formalism. A fallout of some of these theories is that there is a new hyperweak force (even weaker than Wolfenstein's superweak force) that is responsible for the unequal decay of matter and antimatter. Several theorists have in the last 2 years constructed speculative models based on an assumed hyperweak force and CP violation that roughly account for the imbalance of matter over antimatter in the universe, provided that a period of thermodynamic nonequilibrium existed in the early hot universe when the imbalance was created.

Some physicists have speculated that the Royal Swedish Academy of Sciences placed considerable weight on the emergence of gauge theory models of CP nonconservation and on the cosmological connection in making the award to Cronin and Fitch. Physicists hope this is not true because the Cronin-Fitch experiment, they say, stands on its own. "It was such a beautiful and elegant experiment," said experimentalist Jack Sandweiss of Yale, "that it was the equivalent of listening to Rudolf Serkin play Beethoven."—ARTHUR L. ROBINSON

1980 Nobel Prize in Physiology or Medicine

Three immunologists win for their research on the identification and action of histocompatibility antigens

A story that began more than 40 years ago with the identification of the first transplantation antigen in mice has culminated in the award of the 1980 Nobel Prize in Physiology or Medicine to three immunologists. The Nobel Assembly of the Karolinska Institutet has cited Baruj Benacerraf, Jean Dausset, and George Snell for their work on "genetically determined structures of the cell surface that regulate immunological reactions."

The structures in question, called histocompatibility antigens, are best known for their role in triggering the rejection of transplanted organs by the immune system. Their discovery has helped transplant surgeons select for grafting organs that are more likely to be accepted by the recipient. But, in addition, the histocompatibility antigens determine whether an individual can mount an immune response to a given antigen. In this way, they can influence the individual's susceptibility to disease.

The early history of the discovery of histocompatibility antigens is intertwined with that of the Jackson Laboratory in Bar Harbor, Maine. The laboratory was founded in 1929 by C. C. Little as a center for the study of mammalian genetics. Snell, who at age 77 is the oldest of the three new laureates, went to Bar Harbor in 1935 and has spent his professional life there. He had previously worked at the University of Texas with Herman Muller, who won a Nobel Prize in 1946 for studies of the x-ray induction of mutations in the fruit fly.

After working for a time on the x-ray induction of mutations in mice, Snell decided in the mid-1940's to look for a new project, one consistent with his training as a geneticist and his location at Bar Harbor. And, he says, "I wanted in the long run for it to have a payoff."

He knew from the work of Little that a number of genes controlled the ability of mice to resist tumor transplants, but at that time the genes had not been isolated or identified. Snell decided to find a way to study the working of each transplant gene individually.

He proceeded, in the words of Elizabeth Russell, his longtime colleague at Bar Harbor, "to invent the idea of congenic mice." These are mice that are genetically identical except at the single locus or genetic region to be studied. They make it possible to follow the effects of a single gene in a constant genetic background, and today they are a mainstay of histocompatibility research. For this contribution, Frank Lilly, of Albert Einstein College of Medicine, describes Snell as "the father of modern immunogenetics."

Breeding congenic mice is a tedious business, requiring some 14 to 15 generations. Snell met with an immediate setback when the Jackson Laboratory was burned out in 1947. But, he says, "The thing did work. Over the years we identi-

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