

Fitch and Cronin share Nobel prize for CP violation

"For the discovery of violations of fundamental symmetry principles in the decay of neutral K mesons," the Royal Swedish Academy of Sciences has awarded the 1980 Nobel Prize in Physics to James W. Cronin of the University of Chicago and Val L. Fitch of Princeton University. This year the prize is worth \$210 000.

Cronin and Fitch led a group from Princeton University that in 1964 reported that in the decay of the K_L^0 meson, one out of 500 K_L^0 decays produces a π^+ and a π^- , a process forbidden under CP invariance.

History. In 1956 T. D. Lee and C. N. Yang had proposed a solution to the θ - τ puzzle. It had been known that $\theta \rightarrow \pi + \pi$ and $\tau \rightarrow \pi + \pi + \pi$, the final state in the first reaction having even parity and the final state in the second odd. They conjectured that both θ and τ were identical K mesons and that parity might not be conserved in this weak interaction. Lee and Yang suggested a number of tests to check this conservation law, and within a few months experiments showed that parity is not conserved in weak interactions. These observations also showed that charge conjugation invariance is violated in the weak interactions.

Before the experiments were finished, a number of theorists suggested that even if C and P were not con-

served, T might be conserved. That is, the fundamental laws don't change when all motions are reversed. If T is conserved, it follows from the CPT theorem (which assumes little more than quantum mechanics and special relativity) that the product of C and P is conserved. In other words, right-left symmetry will still hold if one switches all particles into antiparticles while taking a mirror image. However, as Lee and Yang noted in their 1957 Nobel lectures, no experimental test of CP conservation had been made.

Like the test of P conservation, the test of CP conservation was to come from the K particle. In the early 1950's, it was known that both the K^0 and its antiparticle, the $\bar{K}^0$ exist, the former with positive strangeness, the latter with negative.

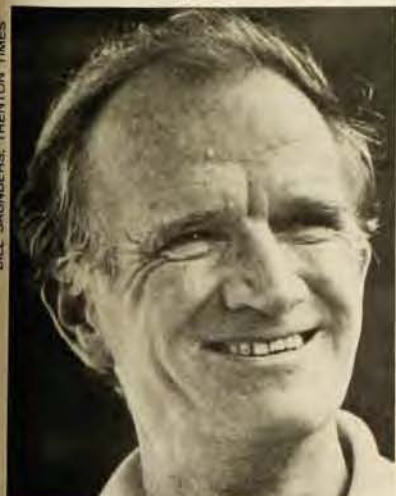
In 1955 Murray Gell-Mann and Abraham Pais had, on the basis of C invariance, argued that one can consider a beam of neutral kaons as linear combinations of K^0 and $\bar{K}^0$. Although their paper was based on C conservation, the same argument applies if CP conservation holds: In decaying, the kaon should be considered as having two states, the K_S^0 (short-lived) and K_L^0 (long-lived); the $K_S^0(K^0 + \bar{K}^0)$ is even under CP, the $K_L^0(K^0 - \bar{K}^0)$ is odd. If CP were conserved, the decay of one of the neutral components (K_S^0) into π^+ and π^- would be allowed, the decay of K_L^0 into π^+ and π^- would not. (Hence K_L^0 would have a longer lifetime.)

The prediction of a long-lived neutral kaon was verified the following year, by Kenneth Lande, Eugene Booth, Leon Lederman and William Chinowsky, who found the K_L^0 making a three-body decay 30 meters away from the Brookhaven Cosmotron target. In 1958 Marcel Bardon, Martin Fuchs, Lande, Lederman, Chinowsky and John Tinlot set an upper limit of about 1% on the CP-violating decay of K_L^0 into $\pi^+\pi^-$. A variety of other experiments studied the lifetime of the K_L^0 and the mass difference between K_L^0 and K_S^0 . In 1961 D. Neagu, E. O. Okonov, A. M. Rosanova, and V. A. Rusakov set an upper limit of 1 in 300 for the CP-violating decay.

In 1963 Robert Adair, Chinowsky, Raymond Crittenden, Lawrence Leipuner, Brain Musgrave and Frank Shively had been studying regeneration of kaons in a hydrogen bubble chamber and found anomalous regeneration of K_S^0 . The regeneration effect had been pointed out by Pais and Oreste Piccioni in 1955. In pion-nucleon collisions, K^0 is created, and after a while the K_S^0 component dies out. The remaining K_L^0 beam is allowed to pass through matter, and differential scattering eventually produces K_S^0 particles again. This regeneration effect is analogous to the rotation of the plane of polarization of light in optically active organic compounds. Adair and his collaborators found too many $\pi^+\pi^-$ pairs being produced by the regenerated K_S^0 particles.

Fitch-Cronin experiment. Fitch recalls that he and Cronin wanted to check Adair's results and study regeneration phenomena in general. At that time spark chambers were relatively new and offered higher spatial resolution than bubble chambers. Cronin had such a spark-chamber arrangement, which he had been using to study $\rho^+ \rightarrow \pi^+\pi^-$. The two decided to collaborate on a study of K decay, along with James W. Christenson, a grad student (now at New York University), and Rene Turlay, a postdoc from Saclay.

FITCH



CRONIN



They ran their experiment at the Brookhaven Alternating Gradient Synchrotron in June and July 1963, recording their data on photographic film. Fitch told us they were looking at several things: a systematic study of regeneration phenomena and also a version of a two-slit interference experiment to measure the $K_S^0 - K_L^0$ mass difference. As an added attraction, they knew their experiment could also set a new limit on CP conservation.

To produce the K_L^0 mesons, the experimenters bombarded an internal beryllium target with 30-GeV protons and allowed the neutral kaon beam to pass through a helium bag, where the K_S^0 particles would all die out. The bag provides a decay region without much background. Unlike the Adair experiment, which had the detector as an intrinsic part of the target, the Princeton experiment could separate the decay volume and the target. After leaving the helium bag, the K_L^0 beam was collimated. The decay products were detected by a two-arm spectrometer, each with two spark chambers separated by a magnetic field.

After analyzing their data for the mass difference and for regeneration properties, the Princeton group started looking at the two-pion decay of K_L^0 . They had also taken data on the two-pion decay of K_S^0 by inserting 5 cm of tungsten in the K_L^0 beam. In either case, each spectrometer arm would detect a charged pion. The group calculated the momentum of the charged reaction products and the angle the vector sum made with the K^0 beam. For the expected K_L^0 decay into three pions, the angle in general would be nonzero. For the CP-violating decay, the angle would be zero.

Fitch recalls, "We had indications of a funny peak in the forward direction in October and spent the next six months trying to kill the effect." Their first measurements were crude and rapid, Cronin said. Then they improved their measuring equipment. "We wondered if we could have been fooled by regeneration in the helium." But the event rate the group found in liquid hydrogen was just as expected and extrapolation to helium gas gave no measurable effect. The yield of regeneration from hydrogen was a factor of about 10 smaller than would have been expected from a simple CP-violation interpretation of the Adair anomaly. Or perhaps there was a crazy distribution in three-body decays, in which a neutrino came out in a narrow energy band and in the direction of the beam. But that was too crazy.

"We kept everything quiet until we were sure," Fitch told us, and then sent their paper to *Physical Review Letters*, which published it 17 days later (27 July 1964). The projected background

in the forward peak was 11 events, whereas 56 were observed. The Princeton group reported that the branching ratio of K_L^0 decaying into two pions to the decay into all charged modes was $(2.0 \pm 0.4) \times 10^{-3}$.

The 17 August issue of *Phys. Rev. Letters* carried a paper by Alexander Abashian, R. J. Abrams, D. W. Carpenter, G. P. Fisher, B. M. K. Nefkens and J. H. Smith on K_L^0 decay. They, too, found a forward peak indicating two-pion production, but with far fewer events. They said the peak constituted 0.2-0.3% of all K_L^0 decays, and said this placed an upper limit on CP violation "with at least a suggestion that CP may actually be violated by this amount."

Over the next six or eight years "experiments of exquisite beauty were done," Cronin told us, "and there was a wonderful camaraderie during that period." A series of experiments by several groups determined the amplitude ratios, η_{+-} and η_{00} and their phase angles. Cronin and Fitch, as they had in the past, worked separately. The original experiment did not identify pions as such, simply inferring their production from the kinematics. Fitch and his collaborators in 1965 showed that the pions produced are the same as those produced by the decay of the K_S^0 —they obtained fully constructive interference between K_S^0 and K_L^0 .

In 1967 J. J. Sakurai and Albert Wattenberg pointed out that one can use this interference pattern from the decay of $K_L^0 \rightarrow \pi^+ \pi^-$ and $K_S^0 \rightarrow \pi^+ \pi^-$ to distinguish between matter and antimatter in an absolute sense. As Cronin explained to us, the interference experiment of Fitch and his collaborators in 1965 was an almost "manifest demonstration of CP violation. In the antiworld, you'd get totally destructive interference." An even simpler way of making the distinction is from the decay of K_L^0 into an electron, pion and neutrino. The K_L^0 decays preferentially to $e^+ \pi^- \nu$, as first shown in 1967 by Jack Steinberger and his collaborators at Brookhaven and by Melvin Schwartz and his collaborators at SLAC. So one can use this CP violation to define positive charge without invoking mirrors or screws.

Despite many observations of CP violation and the concomitant violation of time-reversal invariance, Cronin told us no one has convincingly shown T violation directly. However, he noted,

The 1980 Nobel prize in chemistry was awarded to Paul Berg, Walter Gilbert and Frederick Sanger. A story about their work on the biochemistry of DNA will appear in our January issue.

further experiments provided the details from which one can infer that time reversal symmetry was indeed violated. A number of groups found that the phase of $\eta_{+-} = +45^\circ$. From unitarity arguments, if time reversal were invariant (and consequently the CPT theorem didn't hold), the phase of η_{+-} would be 90° different from the observed phase. Thus, the phase analysis is another way of showing that T is violated in the decay of K_L^0 .

Theory. In the early exciting period after the K_L^0 decay into two charged pions was discovered, many theoretical explanations were proposed. By the early 1970's, the strongest possibility appeared to be the superweak theory of Lincoln Wolfenstein, which said the interaction would be so weak it could only be observed in the mixing of K^0 and $\bar{K}^0$.

Interest in CP violation revived a few years ago because various gauge theories made different predictions for η_{+-} , η_{00} and the electric dipole moment of the neutron. The simplest version of the Weinberg-Salam model with two or four quarks and Higgs bosons cannot violate CP. In 1973 M. Kobayashi and T. Maskawa had found that with at least six quarks and ordinary intermediate vector boson processes, the CP violation occurs naturally, with some mixing between the old quarks (up, down, strange and the as-yet-undiscovered charm) and the new quarks (now known as top and bottom). In 1977 Lederman and his collaborators at Fermilab discovered the upilon particle near 10 GeV, providing evidence for the bottom quark. The top quark is still missing.

In a second possibility, which came from T. D. Lee (in 1974) and was later developed (in 1976) by Steven Weinberg, the Weinberg-Salam model is complicated by introducing several Higgs boson multiplets. This model relates the weakness of CP violation to the large mass of Higgs bosons and involves a "milliweak" interaction, 10^{-3} as large as the weak interaction.

A third possibility adds heavier intermediate vector bosons to the ordinary one involved in the Weinberg-Salam model; these heavier particles lead to an effective interaction that varies as the square of the weak interaction and violates strangeness by two units. Wolfenstein's superweak theory is of this variety.

In 1975 Gerard 't Hooft realized that in SU(3) gauge theories, even though P and CP are conserved, effects due to "instantons" would produce P and CP noninvariance and that residual effects should occur in the strong interaction. This mechanism provides much too large a value for the electric dipole moment of the neutron.

Future experiments. So far CP viola-

tion has only shown up in the K^0 meson, which has two states separated by 10^{-5} eV. Such a nearly degenerate system is expected to be sensitive to extremely weak effects. The B^0 meson is a similar system, and one might expect to see mixing between B^0 and $\bar{B}^0$, just as in K^0 and $\bar{K}^0$. By colliding-beam experiments in the vicinity of $\Upsilon(4S)$ one can manufacture pairs of B mesons and hope to find CP violation in this system, perhaps with a charge asymmetry.

Another object of intense interest is the putative electric dipole moment of the neutron. It is expected to be nonzero if time reversal is violated. Over the past three decades, Norman Ramsey and his collaborators, using cold neutrons, have set ever better limits on the electric dipole moment of the neutron. More recently V. M. Lobashov and his collaborators have done similar experiments.

The present limit on the neutron

electric dipole moment is about 10^{-24} e-cm. The model due to Lee and Weinberg predicts the electric dipole moment to in fact be about 10^{-24} e-cm. Kobayashi and Maskawa predict a value of 10^{-30} – 10^{-31} . Ramsey's next experiment, scheduled to operate at Grenoble next year, might be able to check the Lee and Weinberg prediction.

Cronin earned a BS from Southern Methodist University in 1951, and an MS in 1953 and PhD in 1955 from the University of Chicago. After three years at Brookhaven, he joined the Princeton physics department, rising to professor. In 1971 he went to the University of Chicago, where he is now University Professor of Physics. Fitch earned a BE at McGill University in 1948 and a PhD at Columbia University in 1954. In that year he went to Princeton, where he is now Cyrus Fogg Brackett Professor and chairman of the physics department. —GBL

the chemical energy of the explosive (about 1 electron volt per atom) to muzzle velocities of one or two km/sec. One can't push the projectile in the gun barrel to speeds higher than those of the molecular combustion products. Rockets, though they are also driven by chemical combustion, do not suffer this velocity limitation, because the combustion takes place in the projectile itself. But one pays for this by having to carry aloft a great mass of propellant. The useful payload put into the Earth orbit turns out to be less than one percent of the launched weight, with a correspondingly horrific cost. Henry Kolm, head of the mass-driver group at MIT, looks forward to reducing the cost of putting payloads into Earth orbit to less than a dollar per pound—three orders of magnitude less than today's cost, and fifty times less than the early promises of the space-shuttle program.

The rail gun is conceptually the simplest electromagnetic launcher currently under consideration—and the one that has thus far achieved the highest velocities. It consists of two conducting rails mounted in a gun barrel. A pulsed dc current is sent down one rail and comes back along the other. In the original rail-gun design, the conducting bridge between the rails is a sliding metal conductor, analogous to the armature of a dc motor. The armature is propelled forward by the Lorentz force of the magnetic field generated by the current in the rails acting on the current in the armature. The propelling force is thus proportional to the square of the current. The problem is to achieve sufficiently high and steady currents—and to keep the armature from disintegrating.

Several important steps toward the solution of these problems were taken between 1968 and 1977 by Richard

Electromagnetic guns and launchers

While we accelerate elementary particles and ions by the most advanced electromagnetic means, our standard techniques for propelling macroscopic objects—from birdshot to interplanetary vehicles—are not very different from those in use since the introduction of gunpowder from China. But propulsion by chemical combustion suffers from severe limitations that are keenly felt by people interested in space travel, inertial-confinement fusion, and even such prosaic pursuits as artillery.

The Germans made an abortive attempt to use a "rail gun," a kind of linear dc motor, as an antiaircraft launcher during World War II. But for the next three decades very little was done about electromagnetic acceleration schemes for macroscopic projectiles. Now we are seeing a surge of interest and activity in this field, attested to by a DOD-sponsored conference on electromagnetic guns and launchers, held last month in San Diego.

Although such "guns" do have military applications, they are also of particular interest to solid-state physicists interested in the behavior of materials at extreme pressures, and to those thinking about initiating thermonuclear fusion with beams of "macroparticles." This latter was the subject of the DOE-sponsored Impact Fusion Workshop at Los Alamos last year.

Using rail guns a few meters long, groups at the Australian National University (Canberra), Los Alamos (in collaboration with Livermore), and Westinghouse have in the past few years succeeded in accelerating projectiles weighing a few grams to speeds ap-

proaching 10 km/sec—the escape velocity from the Earth. Attaining such a speed in so short a distance involves a steady acceleration on the order of a million g.

A Princeton-MIT collaboration is currently building a "mass driver," a 2½-meter-long travelling-magnetic-wave accelerator, intended to accelerate a 1-kilogram vehicle to about 110 meters/sec (250 miles/hr). Although this device is thought of as a prototype launcher for interplanetary transport, the same ac linear-synchronous-motor scheme is being considered for the ignition of thermonuclear fusion—by accelerating small superconducting projectiles to speeds in excess of 100 km/sec.

Conventional artillery is limited by



Livermore-Los Alamos rail gun at the Los Alamos firing site. Two 8-foot-long parallel copper strips (foreground) constitute the magnetic-flux-compression generator. Sheet explosive driving the upper strip down generates a megawatt current pulse in the 6-foot-long small-bore rail gun (background). The $\frac{1}{8}$ -inch plastic cube is launched at speeds up to 5.5 km/sec.