At Last We Have an Undisputed Observation of 'Direct' *CP* Violation in Kaon Decay

A long-awaited experimental result, recently announced by the KTeV collaboration at the Fermilab Tevatron,[1] does much to clarify the mechanism by which the decay of the neutral K mesons violates *CP* symmetry. Despite 35 years of painstaking investigation since the discovery of *CP*-violating K^0 decay by James Cronin, Val Fitch, James Christenson, and René Turlay, the important issue of what causes this asymmetry in nature had remained disturbingly unsettled. *CP* denotes the combined operation of charge conjugation (*C*), that is to say, the replacement of particles by their antiparticles, and parity inversion (*P*). After the rude overthrow of parity conservation in 1957, *CP* offered a refuge for believers in mirror symmetry, but only until the next rude overthrow, by Fitch, Cronin and company, in 1964.

Aside from the neutral kaon system, the only other clear manifestation of *CP* violation we have thus far is, of course, the overwhelming predominance of matter over antimatter in the visible universe. It's not yet clear how these two manifestations are related. Nor was there any undisputed evidence, before the new KTeV result, as to how neutral-kaon *CP* violation fits into the spectacularly successful "standard model," which had accounted for almost everything else in particle physics.

The essential manifestation of *CP* violation in kaon physics is the occasional decay (about twice in a thousand) of K^0_L, the longer-lived of the two neutral-kaon eigenstates of lifetime and mass, into a pair of pions. One can show that the two-pion decay state must be an eigenstate of *CP* with eigenvalue +1.

Mixing

Before the Fitch–Cronin experiment, it had been assumed that K^0_L was a pure −1 eigenstate of *CP*, namely

$$(K^0 - \overline{K}^0)/\sqrt{2} \equiv K_2\,,$$

where K^0 and $\overline{K}^0$ are the two eigenstates of strangeness. But the 1964 experiment began to make it clear that K^0_L contains a small admixture of the +1 *CP* eigenstate $(K^0 + \overline{K}^0)/\sqrt{2} \equiv K_1$, which had been presumed to be identical with the shorter-lifetime eigenstate K^0_S. So K^0_L is really $K_2 + \varepsilon K_1$, with the small *CP*-violating mixing parameter $\varepsilon \approx 0.0023$.

> Exquisitely careful comparison of different decay charge states tells us that the kaon's violation of *CP* symmetry is, at least in part, attributable to standard-model mechanisms rather than to some hypothetical superweak interaction.

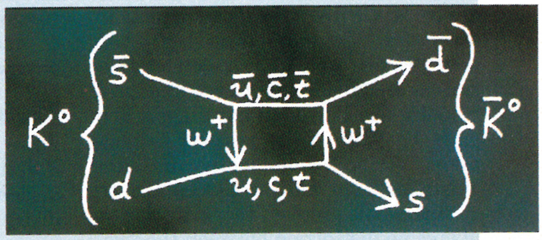
A decade before the unanticipated discovery of *CP* violation, Abraham Pais and Murray Gell-Mann had pointed out that the weak interactions, which do not conserve strangeness, permit K^0 and $\overline{K}^0$ to metamorphose into each other, essentially because they share common two-pion decay states. After Fitch–Cronin, this well-established oscillatory metamorphosis offered a ready phenomenological description of the observed *CP* violation: Because of the small wrong-*CP* component in each of the neutral-kaon lifetime eigenstates, the $K^0 \leftrightarrow \overline{K}^0$ metamorphosis makes possible the process $K_2 \rightarrow K_1$. If that's all there is to it, then the *CP* violation is restricted to the mixing of neutral-kaon states, described by the single parameter ε. Once the K_2 has become a K_1, its subsequent decay to two pions is strictly *CP* conserving. Hence the appellation "indirect *CP* violation" for this two-step process.

Standard or superweak?

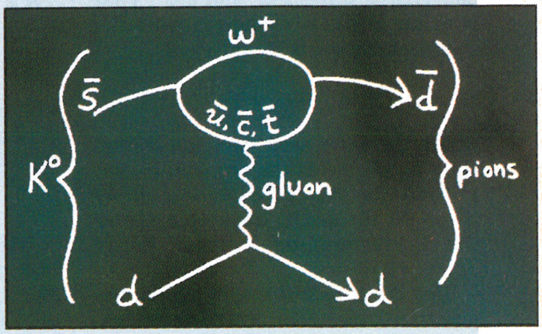
What's the fundamental physics that causes this mixing of neutral-kaon *CP* eigenstates? In 1964, Lincoln Wolfenstein suggested that it might be a manifestation of a previously unknown "superweak" interaction. Such an interaction would be beyond the purview of the standard model, which crystallized in the 1970s. But what does the standard model have to say about *CP* violation? In 1973, before there was any hint of a third generation of quarks (the bottom and the top), Makoto Kobayashi and T. Maskawa made the prescient observation that a third generation could provide a natural mechanism for *CP* violation. Once there are three generations, they pointed out, the mixing matrix that relates the quark mass eigenstates to their weak-interaction eigenstates can have an

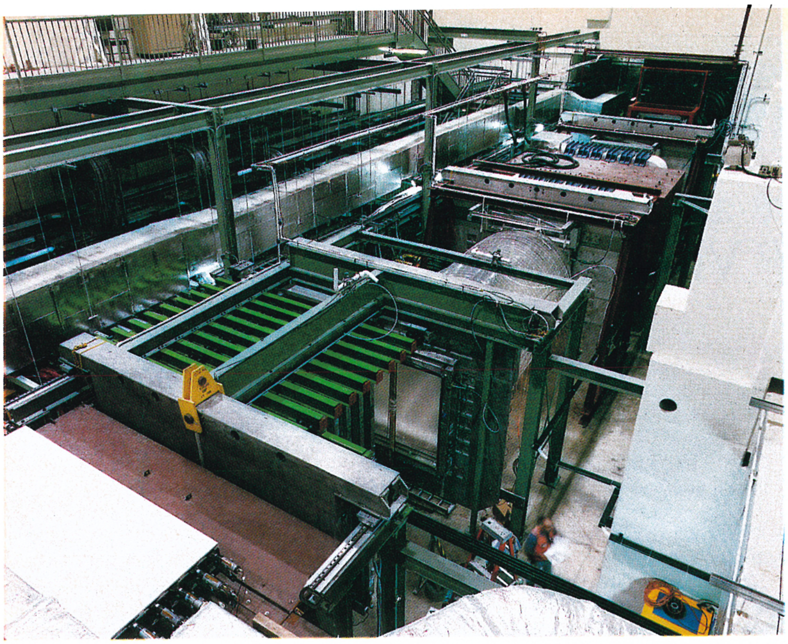
Contributions to *CP* violation in kaon decay

BOX DIAGRAM, exchanging two weak vector bosons (W), changes a K^0 into its antiparticle. (s and d are the strange and down quarks, with charge $-\frac{1}{3}$). This permits $K_2 \rightarrow K_1$ and therefore *indirect CP* violation, if the kaon lifetime eigenstates are not pure *CP* eigenstates. In superweak models, the only *CP* violation is indirect. But the standard model, ascribing *CP* violation to a phase in the quark mixing matrix, requires both this indirect mechanism and direct *CP* violation. Note that all three generations of charge $+\frac{2}{3}$ quarks (up, charmed, and top) contribute to the intermediate state.



PENGUIN DIAGRAM, required in standard-model *CP* violation, describes the *direct decay* of the K_2 into the *CP*-forbidden two-pion state, without prior metamorphosis to K_1. It introduces the parameter ε', which distinguishes between different two-pion charge states and thus distinguishes standard-model *CP* violation from putative superweak interactions.





AT FERMILAB, downstream of KTeV's evacuated decay region, we see the first tracking drift chamber (top right with red frame) beyond the vacuum window, followed by the spectrometer magnet and more tracking chambers and veto counters. Then comes a large helium bag to minimize scattering of decay pions and gammas, followed by more drift chambers and a transition-radiation chamber (under green slats) that is used only in KTeV's rare-decay experiments. Finally (bottom left) we see a calibration hodoscope array on the brown roof of the sealed blockhouse that protects the cesium iodide calorimeter from atmospheric moisture.

irreducible overall phase that would dictate *CP* violation.

One determines the elements of this unitary Kobayashi-Maskawa-Cabibbo matrix by measuring decay rates from one quark flavor to another. In practice, however, hadronic complications make it impossible to predict ε from the measured matrix elements. The Kobayashi–Maskawa *CP*-violating phase might, in fact, be zero. So how would we know whether the observed neutral-kaon *CP* violation is simply dictated by the standard model or requires some sort of superweak interaction beyond the physics we already understand?

Direct *CP* violation

There is a way, and that's what the Fermilab collaboration and the rival group at CERN have been trying to accomplish for more than ten years now. The principal mechanism for neutral-kaon *CP* violation in the standard model is the Feynman box diagram on page 17. This is the *indirect* mechanism, phenomenologically indistinguishable from what would happen in a superweak process. In particular, it makes no distinction between the two-pion charge states $\pi^+\pi^-$ and $\pi^0\pi^0$. That is to say, if the box diagram were the sole mechanism, it would yield

$$\eta_{+-} = \eta_{00} = \varepsilon,$$

where the η for each two-pion charge state is defined as the probability amplitude for the *CP*-violating decay $K^0_L \to \pi\pi$ divided by the amplitude for the corresponding normal decay $K^0_S \to \pi\pi$.

But the standard model, unlike the putative superweak interactions, requires the participation of a second mechanism, described by the fancifully named "penguin" diagram in the figure. This is *direct CP* violation: The K_2 decays directly to the *CP*-forbidden two-pion state without first having to become a K_1. Unlike the indirect box-diagram mechanism, the penguin diagram does introduce a distinction between the two-pion charge states, characterized by an additional parameter ε', at least a hundred times smaller than ε. One gets

$$\eta_{+-} \approx \varepsilon + \varepsilon' \text{ and } \eta_{00} \approx \varepsilon - 2\varepsilon'.$$

Standard-model predictions of the real part of ε'/ε have ranged in recent years from about 1×10^{-4} to 2×10^{-3}. If, on the other hand, the observed *CP* violation were due to Wolfenstein's superweak interaction or some more modern but phenomenologically equivalent excursion beyond the standard model, ε' would vanish or be too small to observe.

The long search

Since the mid-1980s, the CERN and Fermilab groups have been looking for evidence of a nonvanishing ε' by measuring the ratio of ratios

$$R \equiv |\eta_{+-}/\eta_{00}|^2 = \frac{\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(K^0_S \to \pi^+\pi^-)}{\Gamma(K^0_L \to \pi^0\pi^0)/\Gamma(K^0_S \to \pi^0\pi^0)},$$

where the Γ's are the rates for the various *CP*-allowed and forbidden decays. Then

$$\mathrm{Re}(\varepsilon'/\varepsilon) \approx \tfrac{1}{6}(1 - R).$$

This is a daunting experimental task. R is very close to unity, and the four different decay processes make very different demands on detectors: The K^0_L lives about 600 times longer than the K^0_S; the *CP*-forbidden K^0_L decays to two pions are vastly outnumbered by their normal decays to three pions; and the neutral pions are much harder to track down than the charged pions. So any search for a nonzero ε' must deal exhaustively with the issue of systematic errors.

In 1988, the CERN collaboration, then under the leadership of Heinrich Wahl, was the first to be heard from. (See PHYSICS TODAY, October 1988, page 17.) They reported $\mathrm{Re}(\varepsilon'/\varepsilon) = (33 \pm 11) \times 10^{-4}$. But with only this three-standard-deviation result on the record, the Fermilab collaboration, led by Bruce Winstein (University of Chicago), was not yet ready to declare the superweak models dead. "At that time," Winstein recalls, "the CERN experiment didn't have the magnetic spectrometer and two-beam setup we thought was essential for such a difficult measurement." After several more years of data taking,[2] the CERN group, having almost halved its quoted uncertainty, reported $(23 \pm 6.5) \times 10^{-4}$. But the Fermilab group, at that point, reported $\mathrm{Re}(\varepsilon'/\varepsilon) = (7.4 \pm 5.9) \times 10^{-4}$, quite compatible with zero.[3] Given this impasse in 1993 on such an important question, both groups undertook major upgrades in their experimental facilities.

KTeV at Fermilab

The new Fermilab facility, dubbed KTeV, began taking data in 1996. KTeV is headed by Winstein and Fermilab's Yee Bob Hsiung. At KTeV's upstream end, an intense beam of 800 GeV protons from the Tevatron is directed at a target to produce a profusion of all sorts of hadrons. Neutral kaons from this profusion are formed into two identical beams, about 20 cm apart, and directed toward a vacuum decay region that begins about 100 meters downstream. After such a journey, just about all of the K^0_S mesons will have decayed away, leaving a pure beam of their long-lived siblings.

Therefore a 1.7 m long regenerator target, designed to convert a few percent of the K^0_L mesons coherently to K^0_S, is inserted into one of the two beams at the beginning of the decay region. To minimize biases due to unintended asymmetries in the beams or detectors, the regenerator is flipped back and forth between the two beams once a minute. Downstream of the vacuum decay volume, $\pi^+\pi^-$ pairs are analyzed by a spectrometer magnet bracketed between tracking drift chambers. (See the photo on page 18.)

Further downstream is KTeV's most crucial new element—an array of 3100 blocks of crystalline cesium iodide scintillator, each one 50 cm deep and attached to its own photomultiplier tube. This is the electromagnetic calorimeter that records the positions and energies of the two gammas into which each π^0 decays within a micron of its birth. For both the neutral and charged pions one must, of course, be able to recognize and then discard the *CP*-allowed decays of the K^0_L to *three* pions (or to a pion and two leptons).

From a global fit to almost 10 million two-pion decays recorded by KTeV in 1996 and 1997, the collaboration arrives at

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (28.0 \pm 4.1) \times 10^{-4},$$

almost seven standard deviations from zero. Statistical and systematic uncertainties contribute about equally to the quoted error. This first KTeV announcement is based on less than a quarter of the data that the collaboration already has in hand, and a new run is scheduled to begin in a few months.

"This firmly establishes the existence of direct *CP* violation in a decay process," Winstein told us. "So now we can be sure that superweak processes, if there are such things, can't be the whole story." But whether the standard model is the whole story is not quite clear yet. The measured value of $\mathrm{Re}(\varepsilon'/\varepsilon)$ is somewhat higher than the theoretical estimates, most of which favor a value somewhat less than 10^{-3}.

"We, ourselves, were surprised at how big ε' turned out to be," Winstein recalls. "To keep from being unconsciously biased by the theoretical expectations, we hid the final result from ourselves by means of a secret offset until the data analysis and the evaluation of systematic errors were finished." Luis Alvarez used to advocate such blind analyses, to avoid what he called "intellectual phase lock."

The Fermilab group freely admits that the new result is closer to the old CERN results, albeit with smaller uncertainties, than to its own 1993 result. Indeed, shortly after KTeV announced its result, Konrad Kleinknecht (University of Mainz), a leader of the CERN collaboration, congratulated the Fermilab group, not without a touch of sarcasm, for its "brilliant confirmation of our 1988 observation of this new symmetry violation." The CERN group expects to report its own new results in a few months.

Also to be heard from before year's end is the group studying *CP*-violating kaon decays by a quite different technique at the new Frascati "ϕ factory" in Italy. The machine is an e^+e^- storage-ring collider designed to create, in abundance, the ϕ meson, a bound state of the strange quark and its antiquark that decays mostly into kaon pairs. Also expected soon are first results from the new "B factories" in the US and Japan. (See PHYSICS TODAY, January 1999, page 22.) B mesons, bound states of the heavy bottom quark and its antiquark, are expected to open important new vistas on *CP* violation.

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References

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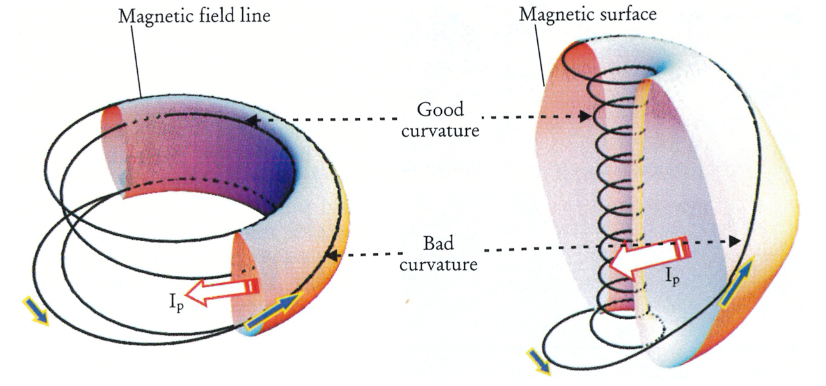
Spherical Torus May Improve Tokamak Cost and Performance

After the tokamak approach became fashionable three decades ago, other approaches to magnetic fusion were left withering on the vine or cut off at the roots. In the last few years, however, US participation in the International Thermonuclear Experimental Reactor (still being pursued by Europe, Japan, and Russia) has been cancelled, and Department of Energy funding for magnetic fusion suffered a major reduction. "The cost of developing tokamak-based fusion systems may be too expensive," according to Rob Goldston, director of the Princeton Plasma Physics Laboratory (PPPL). Fusion scientists both in the US and abroad have once again begun to explore the potential of other concepts. They have revived some old ideas and developed some new ideas, which build on the progress gained from tokamak studies.

Alternative approaches to magnetic fusion are moving ahead in many labs. One leading approach, the spherical torus, will be tested at two new facilities, just starting up at Princeton and Culham.

A conventional tokamak is shaped like a torus. It has both a strong toroidal field the long way around the torus and a weaker poloidal field the short way around. The poloidal field that surrounds the plasma is generated by a strong current in the plasma itself. If you just shrink the hole of the tokamak to a very small, but nonzero size, while maintaining a toroidal field strong enough to stabilize the plasma (thus decreasing the aspect ratio, which is the ratio of the major radius to the minor radius), you get the spherical torus (ST). An ST has produced values of β—the ratio of plasma pressure to magnetic pressure—as high as 40%, three times the value achieved by conventional tokamaks.

In the last few months, two new ST facilities have produced their first plasmas—the Mega-Amp Spherical



SPHERICAL TORUS (right) is designed to have a much higher safety factor than the advanced tokamak design (left) because the ST maximizes good curvature of the field lines. The plasma current is shown as I_p. (Figure courtesy of Martin Peng, PPPL.)