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CP Symmetry Violation: The Search for Its Origin

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The greatest pleasure a scientist can experience is to encounter an unexpected discovery. I am always astonished when a simple apparatus, designed to ask the right question of nature, receives a clear response. Our experiment, carried out with James Christenson, Val Fitch, and René Turlay, gave convincing evidence that the long-lived neutral K meson (K_L) decays into two charged pions, a decay mode forbidden by CP symmetry. The forbidden decay mode was found to be a small fraction, $(2.0 \pm 0.4) \times 10^{-3}$, of all charged decay modes. Professor Fitch has described our discovery of CP symmetry violation. He discussed how it was preceded by brilliant theoretical insights and incisive experiments with K mesons. My lecture will review the knowledge that we have obtained about CP violation since its discovery (*1*). The discovery triggered an intense international experimental effort. It also provoked many theoretical speculations, which in turn stimulated a variety of experiments.

At present there is no satisfactory theoretical understanding of CP violation. Such understanding as we do have has come entirely from experimental studies. These studies have extended beyond the high energy accelerator laboratories into nuclear physics laboratories and research reactor laboratories. The experiments which have sought to elucidate the tiny effect have demanded both ingenuity and painstaking attention to detail.

Upon learning of the discovery in 1964, the natural reaction of our colleagues was to ask what was wrong with the experiment. Or, if they were convinced of the correctness of the measurements, they asked how the effect could be explained while still retaining CP symmetry. I remember vividly a special session organized at the 1964 International Conference on High Energy Physics at Dubna in the Soviet Union. There, for an afternoon, I had to defend our experiment before a large group of physicists who wanted to know every detail of the experiment—more details than could have been given in the formal conference session.

As the session neared a close, one of my Soviet colleagues suggested that, perhaps, the effect was due to regeneration of short-lived K mesons (K_S) in a fly unfortunately trapped in the helium bag. We did a quick estimate of the density of the fly necessary to produce the effect. The density required was far in excess of that of uranium.

More serious questions were raised at this session and by many other physicists who had thought deeply about our result. While we were confident that the experiment had been correctly carried out and interpreted, many sought reassurance through confirmation of the experiment by other groups. This confirmation came quickly from experiments at the Rutherford Laboratory (*2*) in England and at Centre Européen de Recherches Nucléaires (CERN) (*3*) in Geneva, Switzerland.

Another important issue was raised. In the original experiment, the decay to two pions was inferred kinematically, but no proof was given that these pions were identical to the ordinary pions or that the decay was not accompanied by a third light particle emitted at a very low energy. The direct proof that the effect was indeed a violation of CP symmetry was the demonstration of interference between the decay of K_S and K_L to two charged pions. This interference was first demonstrated in a simple experiment by my colleague Val Fitch with R. F. Roth, J. S. Russ, and W. Vernon (*4*).

Their experiment compared the rate of decay of a K_L beam into two charged pions in vacuum and in the presence of a diffuse beryllium regenerator. The density of the regenerator was adjusted so that the regeneration amplitude A_r was equal to the CP-violating amplitude η_{+-}. These amplitudes were defined by

$$\eta_{+-} = \frac{\text{amplitude } (K_L \rightarrow \pi^+\pi^-)}{\text{amplitude } (K_S \rightarrow \pi^+\pi^-)}$$

and

$$A_r = i\pi N\Lambda \left(\frac{f-\bar{f}}{k}\right)\left(i\delta + \frac{1}{2}\right)^{-1}$$

The yield of $K_L \rightarrow \pi^+\pi^-$ in the presence of the regenerator is proportional to

$$|A_r + \eta_{+-}|^2$$

In the expression for A_r, δ is given by $(M_S - M_L)/\Gamma_S$, where M_S and M_L are the K_S and K_L masses and Γ_S is the decay rate of the K_S meson; Λ is the mean decay length of the K_S meson; k is the wave number of the incident K_L beam; and f and $\bar{f}$ are the forward-scattering amplitudes for K and $\bar{K}$, respectively, on the nuclei of the regenerator. The regeneration amplitude is proportional to N, the number density of the material. The quantity $(f - \bar{f})/k$ was determined in an auxiliary experiment with a dense regenerator. Then a regenerator of appropriate density was constructed by using the formula for A_r (*5*). The actual regenerator was constructed of 0.5-millimeter sheets separated by 1 centimeter. Such an arrangement behaves as a homoge-

The author is professor of physics, University of Chicago, Chicago, Illinois 60637. This article is the lecture he delivered in Stockholm, Sweden, on 8 December 1980, when he received the Nobel Prize in Physics, a prize that he shared with Val L. Fitch. Minor corrections and additions have been made by the author. The article is published here with the permission of the Nobel Foundation and will be included in *Les Prix Nobel en 1980* as well as in the series *Nobel Lectures* (in English) published by Elsevier Publishing Company, Amsterdam and New York, Dr. Fitch's lecture appeared in the issue of 29 May.

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neous regenerator of 1/20 normal density if the separation of the sheets is small compared to the quantity $\delta\Lambda$.

In the earliest experiment, Fitch and his colleagues found that with $|A_r|$ chosen to be equal to $|\eta_{+-}|$, the rate of $\pi^+\pi^-$ decays was about *four times* the rate without the regenerator. This result showed not only that there was interference, but also that the interference was fully constructive. Complete analysis of this experiment (*6*) gave the $\pi^+\pi^-$ yield as a function of density (Fig. 1). The quantity α in the figure is the relative phase between the regeneration amplitude and the CP-violating amplitude.

The result of this experiment also permits the experimental distinction between a world composed of matter and a world composed of antimatter (*7*). Imagine that this experiment were performed in the antiworld. The only difference would be that the regenerator material would be antimatter. If we assume C invariance for the strong interactions, the forward scattering amplitudes for K and $\bar{K}$ would be interchanged so that A_r would have the opposite sign. Thus, an investigator performing the interference experiment in the antiworld would observe destructive interference similar to that shown by the dashed curve in Fig. 1, an unmistakable difference from the result found in our world. The interference experiment of Fitch and collaborators eliminated alternative explanations of the $K_L \rightarrow \pi^+\pi^-$ decay, since the effect was such that an experiment distinguishing a world of matter and antimatter was possible.

It was also suggested that the effect might be due to a long-range vector field of cosmological origin (*8*). Such a source of the effect would lead to a decay rate for $K_L \rightarrow \pi^+\pi^-$ which would be proportional to the square of the K_L energy in the laboratory. Our original experiment was carried out at a mean K_L energy of 1.1 GeV. The confirming experiments at the Rutherford Laboratory and CERN were carried out at mean K_L energies of 3.1 and 10.7 GeV, respectively. Since the three experiments found the same branching ratio for $K_L \rightarrow \pi^+\pi^-$, the possibility of a long-range vector field was eliminated.

Before continuing, it is necessary to state some of the phenomenology which describes the CP violation in the neutral K system. The basic notation was introduced by Wu and Yang (*9*). For this discussion, CPT conservation is assumed. Later, we shall refer to the evidence from K meson decays which shows that all data are consistent with a corresponding T violation. Any CPT violation is consistent with zero within the present sensitivity of the measurements.

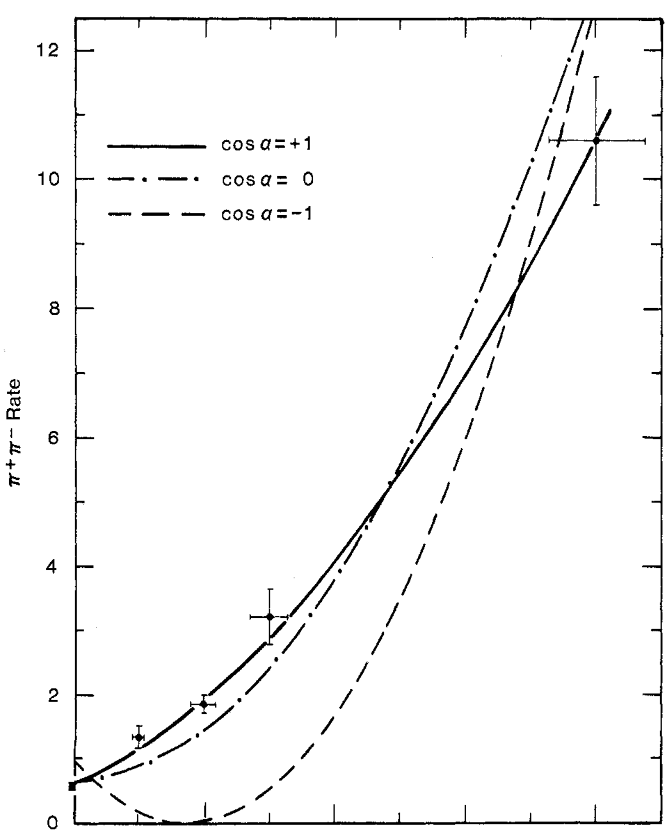

Fig. 1. Yield of $\pi^+\pi^-$ events as a function of the diffuse regenerator amplitude. The three curves correspond to the three stated values of the phase between the regeneration amplitude A_r and the CP-violating amplitude η_{+-}.

Two basic complex parameters are required to discuss CP violation as observed in the two pion decays of K_L mesons. The first quantity, ϵ, is a measure of the CP impurity in the eigenstates $|K_S\rangle$ and $|K_L\rangle$. These eigenstates are given by

$$|K_S\rangle = \frac{1}{\sqrt{2}\sqrt{1+|\epsilon|^2}}[(1+\epsilon)|K\rangle + (1-\epsilon)|\bar{K}\rangle]$$

and

$$|K_L\rangle = \frac{1}{\sqrt{2}\sqrt{1+|\epsilon|^2}}[(1+\epsilon)|K\rangle - (1-\epsilon)|\bar{K}\rangle]$$

The quantity ϵ can be expressed in terms of the elements of the mass and decay matrices which couple and control the time evolution of the $|K\rangle$ and $|\bar{K}\rangle$ states. It is given by

$$\epsilon = \frac{-\text{Im } M_{12} + i \text{ Im } \Gamma_{12}/2}{i(M_S - M_L) + (\Gamma_S - \Gamma_L)/2}$$

Limits on the size of Im Γ_{12} can be obtained from the observed decay rates of K_S and K_L to the various decay modes. If Im Γ_{12} were zero, then the phase of ϵ would be determined by the denominator, which is just the difference in eigenvalues of the matrix which couples K and $\bar{K}$. These quantities have been experimentally measured and give arg $\epsilon \sim 45°$.

The second quantity, ϵ', is defined by

$$\epsilon' = \frac{i}{\sqrt{2}} \text{Im} \left(\frac{A_2}{A_0}\right) e^{i(\delta_2 - \delta_0)}$$

Here A_0 and A_2 are the amplitudes for a K meson to decay to standing wave states of two pions in the isotopic spin 0 and 2 states, respectively. Time reversal symmetry demands that A_0 and A_2 be relatively real (*9, 10*). The quantities δ_0 and δ_2 are the s-wave π-π scattering phase shifts for the states $I = 0$ and $I = 2$, respectively. The parameters ϵ and ϵ' are related to observable quantities defined by

$$|\eta_{+-}|e^{i\Phi_{+-}} = \frac{\text{amp } (K_L \rightarrow \pi^+\pi^-)}{\text{amp } (K_S \rightarrow \pi^+\pi^-)}$$

$$|\eta_{00}|e^{i\Phi_{00}} = \frac{\text{amp } (K_L \rightarrow \pi^0\pi^0)}{\text{amp } (K_S \rightarrow \pi^0\pi^0)}$$

$$\delta_\ell = \frac{\Gamma(K_L \rightarrow \pi^-\ell^+\nu_\ell) - \Gamma(K_L \rightarrow \pi^+\ell^-\bar{\nu}_\ell)}{\Gamma(K_L \rightarrow \pi^-\ell^+\nu_\ell) + \Gamma(K_L \rightarrow \pi^+\ell^-\bar{\nu}_\ell)}$$

These experimentally measured quantities are related to ϵ and ϵ' by the following expressions (*11*):

$$\eta_{+-} = \epsilon + \epsilon'$$
$$\eta_{00} = \epsilon - 2\epsilon'$$
$$\delta_\ell = 2 \text{ Re}\epsilon$$

The magnitude and phase of the quantity η_{+-} have been most precisely measured by studying the time dependence of $\pi^+\pi^-$ decays from a K beam which was prepared as a mixture of K_S and K_L. This experimental technique was suggested by Whatley (*12*) long before the discovery of CP violation. If we let ρ be the amplitude for K_S at $t = 0$, relative to the K_L amplitude, then the time dependence of $\pi^+\pi^-$ decays will be given by (*13*)

$$N_{+-}(t) = |\rho \exp[(-i\Delta M - \Gamma_s/2)t] + \eta_{+-}|^2$$

The initial amplitude for the K_S component can be prepared by two different methods. In the first method, we pass a K_L beam through a regenerator. Then ρ is the regeneration amplitude. Here the interference term is $2|\rho|\,|\eta_{+-}|e^{-\Gamma_s t/2} \cos(-\Delta Mt + \phi_\rho - \phi_{+-})$. In the second method, we produce a beam which is pure K (or $\bar{K}$) at $t = 0$. In practice, protons of ~ 20 GeV produce at small angles about three times as many K as $\bar{K}$. The $\bar{K}$ dilution is a detail which need not be of concern here. In this case $\rho = +1$ and the interference term is $2|\eta_{+-}|e^{-\Gamma_s t/2}\cos(-\Delta Mt - \phi_{+-})$.

The important CP parameters are $|\eta_{+-}|$ and ϕ_{+-}. We see, however, that a knowledge of the auxiliary parameters Γ_S and ΔM is also required. In the first method one measures $\phi_{+-} - \phi_\rho$, and one must also have a technique to independently measure ϕ_ρ. In both cases the $\pi^+\pi^-$ yield is most sensitive to the interference term when the two interfering amplitudes are of the same size. For the second method we require observation at 12 K_S lifetimes. (We want $e^{-\Gamma_s t/2} \approx |\eta_{+-}| \approx 2 \times 10^{-3}$.) As a consequence, a small error in ΔM can lead to a large uncertainty in ϕ_{+-}, and, more importantly, a systematic error in ΔM can lead to an incorrect value for ϕ_{+-}. A 1 percent error in ΔM corresponds to an error in ϕ_{+-} of about 3°. The measurement of ΔM with satisfactory precision has required an effort as formidable as the interference experiments themselves (*14*).

Time and space do not permit a survey which does justice to the many groups at CERN, Brookhaven, Argonne, and the Stanford Linear Accelerator Center (SLAC) who made the meticulous measurements leading to the following parameters (*15*):

$$\eta_{+-} = [(2.27 \pm 0.02) \times 10^{-3}] \exp[i(44.7^\circ \pm 1.2^\circ)]$$

$$\Delta M = M_S - M_L = -(0.535 \pm 0.002) \times 10^{10}\ \text{sec}^{-1}$$

$$\Gamma_S = (1.121 \pm 0.003) \times 10^{10}\ \text{sec}^{-1}$$

As an example of the quality of the measurements mentioned above, Fig. 2 shows a time distribution of $\pi^+\pi^-$ decays following the passage of a K_L beam of 4 to 10 GeV/*c* momentum through an 81-cm-thick carbon regenerator (*16*). The destructive interference is clearly seen. If the experiment were carried out with a regenerator of anticarbon, then constructive interference would have been observed.

Measurements of the charge asymmetry δ_ℓ for K_L decays began in 1966. This asymmetry is found in the abundant semileptonic decay modes $K_L \rightarrow \pi^\pm\ell^\mp\nu$, where ℓ is either an electron or muon. It basically measures the difference in amplitude of K and $\bar{K}$ in the eigenstate of the K_L. It does so by virtue of the $\Delta S = \Delta Q$ rule, which states that all semileptonic decays have the change in charge of the hadron equal the change in strangeness. Thus, K mesons decay to $\pi^-\ell^+\nu$ and $\bar{K}$ mesons decay to $\pi^+\ell^-\bar{\nu}$. The validity of the $\Delta S = \Delta Q$ rule was in doubt for many years, but it has finally been established that the $\Delta Q = -\Delta S$ transitions are no more than about 2 percent of the $\Delta Q = +\Delta S$ transitions (*17*). The size of the charge asymmetry expected is $\sim \sqrt{2}|\eta_{+-}| \approx 3 \times 10^{-3}$. Millions of events are required to measure δ_ℓ accurately, and excellent control of the symmetry of the apparatus and understanding of charge-dependent biases are needed to reduce systematic errors.

Again, we must omit a detailed review of all the asymmetry measurements. These have been carried out at CERN, Brookhaven, and SLAC. The net result of these measurements gives (*15*)

$$\delta_e = (3.33 \pm 0.14) \times 10^{-3}$$

and

$$\delta_\mu = (3.19 \pm 0.24) \times 10^{-3}$$

We expect these two asymmetries to be equal, since they both are a measure of 2 Re ϵ. These asymmetries are measured for a pure K_L beam. For a beam which is pure K at $t = 0$, the charge asymmetry shows a strong oscillation term with angular frequency ΔM. Figure 3 (*18*) shows the time dependence of the charge asymmetry. The small residual charge asymmetry of the K_L decays after the oscillations have died out is clearly resolved.

The charge asymmetry is a manifest violation of CP, and as such also permits an experimental distinction between a world and an antiworld. In our world we find that the positrons in the decay are slightly in excess. The positrons are leptons which have the same charge as our atomic nuclei. In the antiworld the ex-

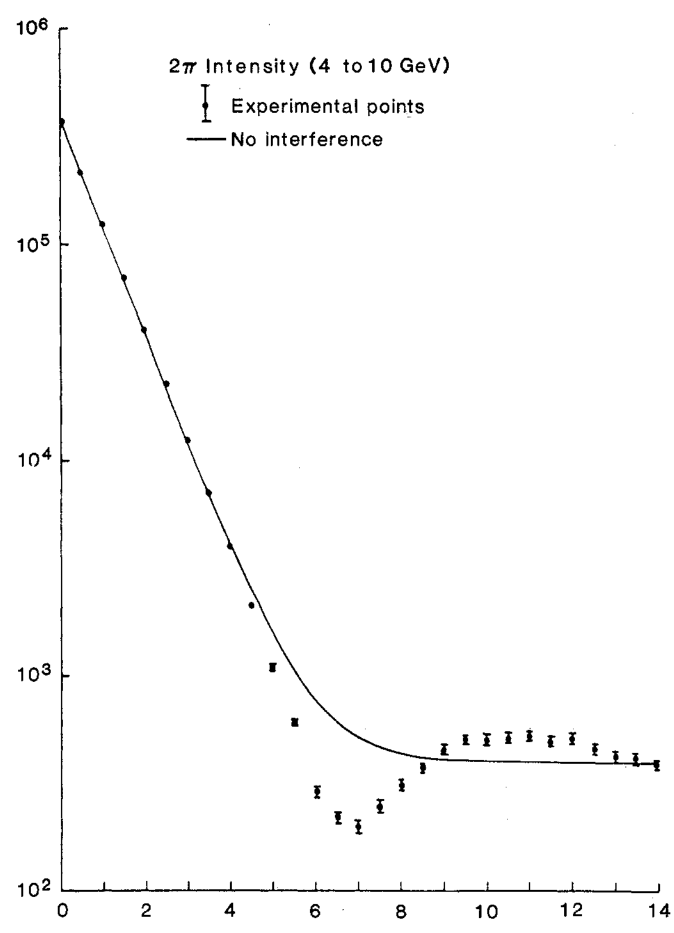

Fig. 2. Yield of $\pi^+\pi^-$ events as a function of proper time downstream from an 81-cm carbon regenerator placed in a K_L beam.

perimenter would find that the excess leptons have a charge opposite to that of his atomic nuclei; hence, he would report a different result for the same experiment.

Simple examination of the relations between the experimentally measurable parameters and the complex quantities ϵ and ϵ' show that measurements of $|\eta_{00}|$ and ϕ_{00} are essential to finding ϵ and ϵ'. The path to reliable results for $|\eta_{00}|$ and ϕ_{00} has been torturous. This statement is based on personal experience; 6 years of my professional life have been spent on the measurement of $|\eta_{00}|$.

Measurement of the parameters associated with $K_L \rightarrow \pi^0\pi^0$ is complicated by the fact that each π^0 decays rapidly (10^{-16} second) into two photons. For typical K_L beams used in these experiments, the photon energies are in the range of 0.25 to 5 GeV. It is difficult to measure accurately the direction and energy of such photons. In addition to that difficulty, the CP-conserving decay $K_L \rightarrow 3\pi^0$ occurs at a rate which is about 200 times as frequent, and presents a severe background.

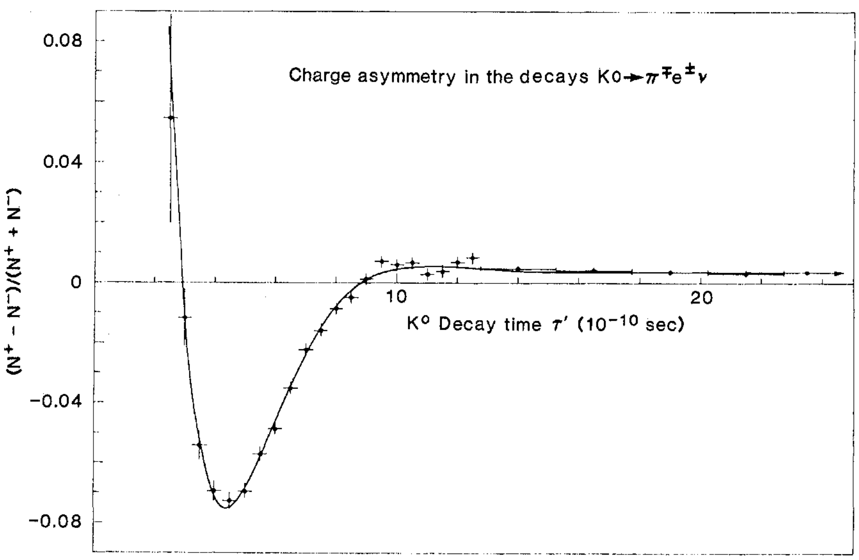

Fig. 3. Time dependence of the charge asymmetry of semileptonic decays.

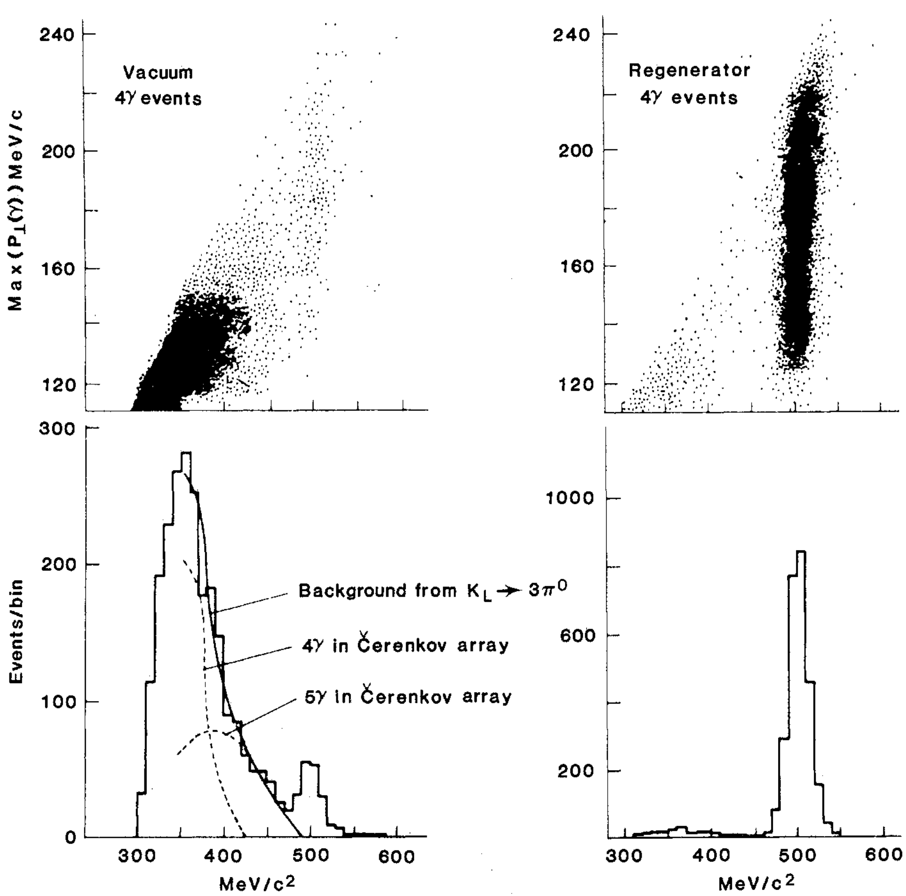

Fig. 4. Distributions of reconstructed $K_L \rightarrow \pi^0\pi^0$ events, and regenerated $K_S \rightarrow \pi^0\pi^0$ events.

Early results suggested that $|\eta_{00}|$ was about twice $|\eta_{+-}|$, with the consequence that ϵ' was a large number. By 1968, however, an improved experiment in which spark chambers (*19*) were used and a painstaking heavy-liquid bubble chamber experiment from CERN (*20*) showed that $|\eta_{00}|$ was rather close in value to $|\eta_{+-}|$. Figure 4 shows the results from the most accurate measurement of $|\eta_{00}|/|\eta_{+-}|$ (*21*). Shown are reconstructed events from free K_L decays as well as a sample of $K_S \rightarrow \pi^0\pi^0$ from a regenerator used to determine the resolution of the apparatus. The serious background from the $3\pi^0$ decays is clearly seen. The result, $|\eta_{00}|/|\eta_{+-}| = 1.00 \pm 0.06$, is based on only 167 events. The equality of $|\eta_{00}|$ and $|\eta_{+-}|$ means that the ratio of charged 2π decays to neutral 2π decays is the same for CP-violating K_L decays as for CP-conserving K_S decays. This result implies that ϵ' is very small, provided ϕ_{00} is close to ϕ_{+-}.

The $K_L \rightarrow \pi^0\pi^0$ events cannot be collected at the rate of the $\pi^+\pi^-$ decays, nor can they be separated so cleanly from backgrounds. As a consequence, the precision with which we know the parameters $|\eta_{00}|$ and ϕ_{00} is much less than that with which we know the charged parameters. A weighted average of all the data presently available gives (*15*)

$$|\eta_{00}|/|\eta_{+-}| = 1.02 \pm 0.04$$

and

$$\phi_{00} - \phi_{+-} = 10° \pm 6°$$

The results are quoted with reference to the charged decay mode parameters because the most accurate experiments have measured the quantity $|\eta_{00}|/|\eta_{+-}|$ directly. The result for ϕ_{00} is principally due to a recent experiment by Christenson *et al.* (*22*).

The phase of the quantity ϵ' is given by the angle $\pi + \delta_2 - \delta_0$. Information concerning the pion-pion scattering phase shifts comes from several sources (*23*). A compendium of these sources gives $\delta_2 - \delta_0 = -45° \pm 10°$. The phase of ϵ is naturally related to $\phi_n \equiv \arg\,[i(M_S - M_L) + (\Gamma_S - \Gamma_L)/2]^{-1} = 43.7° \pm 0.2°$. This is the phase ϵ would have if there were no contributions from Im Γ_{12}. The measured phase of η_{+-}

(44.7° ± 1.2°) is, within measurement precision, equal to ϕ_n.

The measured parameters are plotted on the complex plane in Fig. 5a. The size of the box for η_{+-} and η_{00} and the width of the bar for δ_ℓ correspond to 1 standard deviation. The derived quantities ϵ and ϵ' are plotted in Fig. 5b. Boxes corresponding to both 1 and 2 standard deviations are shown. Also plotted is the constraint coming from the π-π scattering phase shifts, which defines the phase of ϵ' to be 45° ± 10°. With this constraint we find that ϵ, ϵ', η_{00}, and η_{+-} lie nearly on a common line. There is a mild disagreement between the π-π phase shift constraint and the result of Christenson *et al.* for ϕ_{00}.

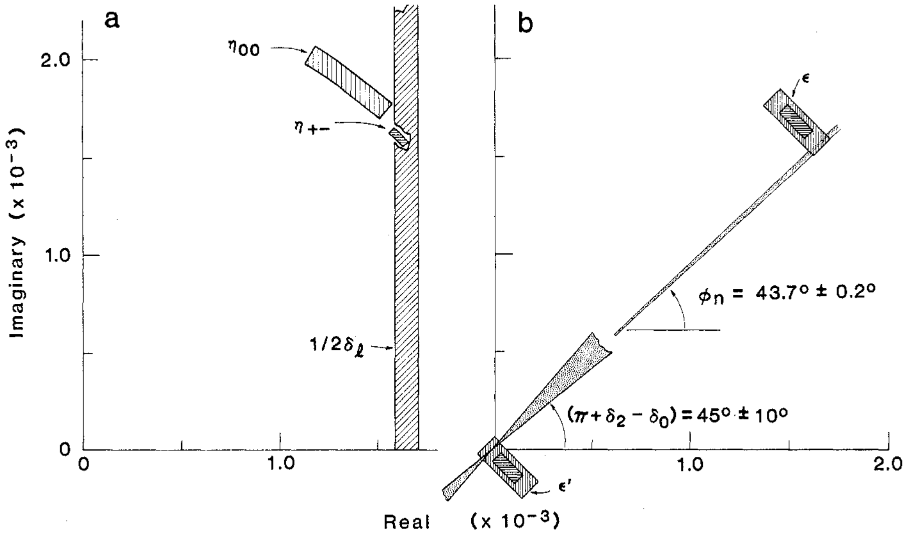

Fig. 5. Summary of CP-violating parameters in the neutral K system. (a) Measured quantities; (b) derived quantities.

A more general analysis of the neutral K system, which includes the possibility of violation of CPT with T conservation as well as CP violation with CPT conservation, has been given by Bell and Steinberger (*24*). The analysis does depend on the assumption of unitarity, which requires that the M and Γ matrices remain Hermitian. The Bell-Steinberger analysis has been applied to the data with the conclusion that while a small CPT violation is possible, the predominant effect is one of CP violation. All experiments are consistent with exact CPT conservation (*25*) and, hence, imply a violation of time reversal symmetry. The conservation or nonconservation of CPT remains, however, a question that must be addressed by experiment. A brief discussion of the unitarity analysis is given in the appendix.

The essential point of this analysis rests on the measurement of the phase of η_{+-}. Limits on the contribution of Im Γ_{12} can be estimated from measured decay rates to all modes of decay of the neutral K mesons. The absence, within present experimental limits, of CP violation in the decay modes other than the 2π modes limits the contribution of Im Γ_{12} to ϵ to $\leq 0.3 \times 10^{-3}$, a value small compared to $|\eta_{+-}|$. Thus the phase of ϵ and hence η_{+-} is expected to be close to ϕ_n. We can examine the other extreme, namely, that CP and CPT symmetry are both violated while time reversal symmetry remains valid. Under these conditions we would find the natural phase ϕ_n to be ~ 135° and would expect ϕ_{+-} to be close to 135°. The fact that this is not the case is the essence of the argument that CPT is not violated.

We note that the natural phase depends on the sign of the mass difference. We have assumed that $\Delta M = (M_S - M_L) < 0$. If the sign of ΔM were the opposite, we would expect the phase of ϵ to be equal to 135° or −45° for CP violation with CPT symmetry. The phase of ϵ' would remain the same, however, since it does not depend on ΔM in any way. Thus, the conclusion that the phase of ϵ and ϵ' are approximately the same is a consequence of the fact that K_L is heavier than K_S. The sign of ΔM has been measured by several groups with complete agreement (*26*).

Independent of any particular theory, we would expect results similar to those observed. The constraint of unitarity and π-π scattering phase shifts force $\phi_{00} \approx \phi_{+-}$ for $\epsilon' \ll \epsilon$. Under these circumstances, a measurement of the ratio $(|\eta_{00}|/|\eta_{+-}|)^2$ is a direct measurement of the quantity ϵ' by means of the relation $\epsilon'/\epsilon \approx [1 - (|\eta_{00}|/|\eta_{+-}|)^2]/6$. Applying this relation to the present data, we have $\epsilon'/\epsilon = -0.007 \pm 0.013$. New experiments at Fermilab and Brookhaven will attempt to increase the sensitivity of the measurement by a factor of 10.

As we have shown, detailed analysis of the CP violation in the neutral K meson system leads to the conclusion that time reversal is also violated. Table 1 gives a representative set of experiments which have searched for T violation, CP violation, and C violation (in nonweak interactions). None of these experiments has led to a positive result. Many of the experiments are approaching a sensitivity for the violation of 10^{-3}, but few have attained this value. A strength of 10^{-3} in amplitude or relative phase is what we might expect for the CP violation based on the results of K decay. For experiments involving decays with electromagnetic interactions in the final states, an apparent T-violation effect is usually expected at the 10^{-3} level. An example of this is the result for the ^{191}Ir decay, in which a significant effect is found, but it is of the size expected on the basis of the final-state electromagnetic interaction.

Among the many measurements listed in Table 1, we would like to single out the electric dipole moment of the neutron. The first measurement of this quantity was made in 1950 by Purcell, Ramsey, and Smith (*27*) with the avowed purpose of testing the assumptions on which one presumed that the electric dipole moment would be zero. Today, outside the K system, the search for an electric dipole moment of the neutron is the most promising approach to the detection of T violation. At present the upper limit is $\sim 10^{-24}$ e-cm. New experiments using ultracold neutrons give promise of an increase in intensity by 100-fold in the next several years. The significance of a negative result for the electric dipole moment, or for any of the measurements in Table 1, is difficult to assess without a theory of CP violation (*28*).

Up to now our discussion has been entirely experimental. In the analysis of the CP violation in the neutral K system, general principles of quantum mechanics have been used. The manifest charge asymmetry of the K_L semileptonic decays requires no assumptions at all for its interpretation. The literature abounds with theoretical speculations about CP violation. One of these speculations, by Wolfenstein (*29*), is frequently referred to. He hypothesizes a direct $\Delta S = 2$ superweak interaction which is constructed to produce a CP violation. This direct interaction interferes with the second-order weak interaction to produce the CP-violating $\Delta S = 2$ coupling between K and $\bar{K}$. Since the hypothesized superweak transition is first-order, it need have only $\sim 10^{-7}$ of the strength of the normal weak interaction. As such, the only observable consequence is a CP violation in $K \rightarrow 2\pi$ decay characterized by a single number, the value of Im M_{12} in the mass matrix.

At present, the data are in agreement with this hypothesis, which leads to predictions that $|\eta_{00}| = |\eta_{+-}|$, and $\phi_{00} = \phi_{+-} = \phi_n$. However, the relation $\phi_{00} = \phi_{+-} = \phi_n$ to a good approximation follows from the constraints of unitarity and the π-π scattering phase shifts with no further assumptions. On the other hand, the relation $|\eta_{00}| = |\eta_{+-}|$ has not been tested to very high accuracy, especially considering the difficulty of experiments which attempt to measure the properties of $K_L \rightarrow \pi^0\pi^0$. These experiments are more prone to systematic errors, and in truth $|\eta_{00}|$ and $|\eta_{+-}|$ could differ considerably more than the experiments appear to allow. Thus, while the superweak hypothesis is in agreement with the present data, the data by no means make a compelling case for it.

In 1973, Kobayashi and Maskawa (*30*) pointed out that with the (then) current understanding of weak interactions, CP violation could be accommodated only if there were three or more pairs of strongly interacting quarks. The paper was remarkable because at that time only three quarks were known to exist experimentally. Since then, strong evidence has been accumulated to support the existence of a charmed quark and a bottom quark. It is presumed that the sixth quark, top, will eventually be found. With six quarks the weak hadronic current involving quarks can be characterized by three Cabibbo angles and a phase δ. This phase, if nonzero, would imply a CP violation in the weak interaction.

In principle, the magnitude of δ which appears in the weak currents of quarks can be related to the CP violation observed in the laboratory. Unfortunately, all the experimental investigations are carried out with hadrons, which are presumed to be structures of bound quarks, while the parameter one wants to establish, δ, is expressed in terms of interactions between free quarks. The theoretical "engineering" required to relate the free-quark properties to bound-quark properties is difficult and, as a consequence, not well developed. A balanced view of this problem is given by Guberina and Peccei (*31*). Even if the CP violation has its origin in the weak currents, it is not clear whether the experimental consequences with respect to K decay can be distinguished from the superweak hypothesis. If we are successful in establishing the fact that CP violation is the result of a phase in the weak currents between quarks, we will still have to understand why it has the particular value we find.

There are, however, new systems on the horizon which have some promise of giving additional information about CP violation. These are the new neutral mesons D^0, B^0, and B_s^0 (composed of $c\bar{u}$, $b\bar{d}$, and $b\bar{s}$ quarks) and their antiparticles $\bar{D}^0$, $\bar{B}^0$, and $\bar{B}_s^0$. These mesons have the same general properties as K mesons. They are neutral particles that, with respect to strong interactions, are distinct from their own antiparticles and yet are coupled to them by common weak decay modes. While we may not expect any stronger CP impurities on the eigenstates (the parameter analogous to ϵ), we might expect stronger effects in the decay amplitudes (the parameter analogous to ϵ'). We might expect this since the CP violation comes about through the weak interactions of the heavy quarks c, b, and t, which participate only virtually in K decay, but can be more influential in heavy neutral meson decay. At present, D mesons can be made rather copiously at the e^+e^- storage ring SPEAR at SLAC (*32*) and B mesons are beginning to be produced at the e^+e^- storage ring CESR at Cornell (*33*).

It is conceivable that the effect of CP violation may become stronger with energy. Soon collisions of protons with antiprotons with a total center-of-mass energy greater than 500 GeV will be observed at CERN. It will be most interesting to look for C violations in the spectra of particles produced in those collisions. Also, improvements in detector technology over the next several decades may permit sensitive searches for time reversal–violating observables in high energy neutrino interactions.

Recently, much attention has been given to the role of CP violation in the early stages of the evolution of the universe (*34*). A mechanism has been proposed, with CP violation as one ingredient, which leads from matter-antimatter symmetry in the early universe to the present small excess of matter. To my knowledge, the first published account of this mechanism was made by Sakharov (*35*) in 1967. He stated the three ingredients which form the foundation of

Table 1. Searches for CP, T, and C violation.

Measurement	Result	Test	Reference
$\dfrac{\Gamma(K^+ \rightarrow \pi^+\pi^+\pi^-) - \Gamma(K^- \rightarrow \pi^-\pi^-\pi^+)}{\text{average}}$	$(0.8 \pm 1.2) \times 10^{-3}$	CP	(*37*)
$\dfrac{\Gamma(K^+ \rightarrow \pi^+\pi^0\pi^0) - \Gamma(K^- \rightarrow \pi^-\pi^0\pi^0)}{\text{average}}$	$(0.8 \pm 5.8) \times 10^{-3}$	CP	(*38*)
$\dfrac{a_{\tau+} - a_{\tau-}}{\text{average}}$, where $a_{\tau\pm}$ is the slope of the odd pion in the $K^\pm \rightarrow \pi^\pm\pi^\pm\pi^\mp$ Dalitz plot	$(-7.0 \pm 5.3) \times 10^{-3}$	CP	(*37*)
Muon polarization transverse to decay plane in $K_L \rightarrow \pi^-\mu^+\nu_\mu$	$(2.1 \pm 4.8) \times 10^{-3}$	T	(*39*)
Coefficient of T odd correlation $\langle \mathbf{J} \cdot \mathbf{P}_e \times \mathbf{P}_\nu \rangle$ in the β decay of polarized ^{19}Ne	$(-0.5 \pm 1.0) \times 10^{-3}$	T	(*40*)
Coefficient of T odd correlation $\langle \sigma_n \cdot \mathbf{P}_e \times \mathbf{P}_\nu \rangle$ in the β decay of the neutron	$(-1.1 \pm 1.7) \times 10^{-3}$	T	(*41*)
Asymmetry in distribution of $(T_{\pi^+} - T_{\pi^-})$ in the decay of $\eta \rightarrow \pi^+\pi^-\pi^0$	$(1.2 \pm 1.7) \times 10^{-3}$	C	(*42*)
Electric dipole moment of the neutron	$(0.4 \pm 1.5) \times 10^{-24}$ *e*-cm $(0.4 \pm 0.75) \times 10^{-24}$ *e*-cm	T	(*43*) (*44*)
Angular correlation in γ decay of polarized iridium, $^{191}Ir^* \rightarrow {}^{191}Ir + \gamma$. Measure phase angle between E_2 and M_1 decay amplitudes	$(4.7 \pm 0.3) \times 10^{-3}$	T	(*45*)
Result expected on basis of electromagnetic interaction in final state	4.3×10^{-3}		(*46*)
Detailed balance in nuclear reactions, such as $^{24}Mg + \alpha \rightleftarrows {}^{27}A\ell + p$ Measure: $\dfrac{\text{amplitude T-violating}}{\text{amplitude T-conserving}}$	$\leq 3 \times 10^{-3}$	T	(*47*)

the mechanism as it is presently conceived: baryon instability, CP violation, and appropriate lack of thermal equilibrium. The recent intense interest in this problem has arisen because baryon instability is a natural consequence of the present ideas of unification of the strong interactions with the successfully unified electromagnetic and weak interactions. This latter unification was discussed in the 1979 Nobel lectures of Glashow, Salam, and Weinberg (*36*).

A very simplified explanation of the process which leads to a net baryon number can be given with the aid of Fig. 6a. Quarks and leptons are linked by a very heavy boson X and its antiparticle $\bar{X}$. While the total decay rates of X and $\bar{X}$ may be equal, with CP violation the fractional partial rates r and $\bar{r}$ to $B = -1/3$ and $B = +1/3$ decay channels of X and $\bar{X}$, respectively, can differ. At an early stage, when the temperature is large compared to the mass of X, the density of X and $\bar{X}$ may be equal. On decay, however, the net evolution of baryon number is proportional to $(r - \bar{r})$. The excess can be quite small since the ratio of baryons to photons today is $\sim 10^{-9}$. Figure 6b shows how such an X boson can mediate the decay $p \rightarrow e^{+} + \pi^{0}$. If nucleon decay is discovered it will give strong support to these speculations.

Whether the CP violation that we observe today is a "fossil remnant" of these conjectured events in the early universe cannot be answered at present. That is to say, does the CP violation we observe today provide supporting evidence for these speculations? We simply do not know enough about CP violation. Our experimental knowledge is limited to its observation in only one extraordinarily sensitive system that nature has provided us. We need to know the theoretical basis for CP violation and we need to know how to reliably extrapolate the behavior of CP violation to the very high energies involved.

Our experimental understanding of CP violation can be summarized by the statement of a single number. If we state that the mass matrix which couples K and $\bar{K}$ has an imaginary off-diagonal term given by

$$\mathrm{Im}\, M_{12} = -1.16 \times 10^{-8}\ \mathrm{eV}$$

then all the experimental results related to CP violation can be accounted for. If this is all the information nature is willing to provide about CP violation, it is going to be difficult to understand its origin. I have emphasized, however, that despite the enormous experimental effort, punctuated by some experiments of exceptional beauty, we have not reached a

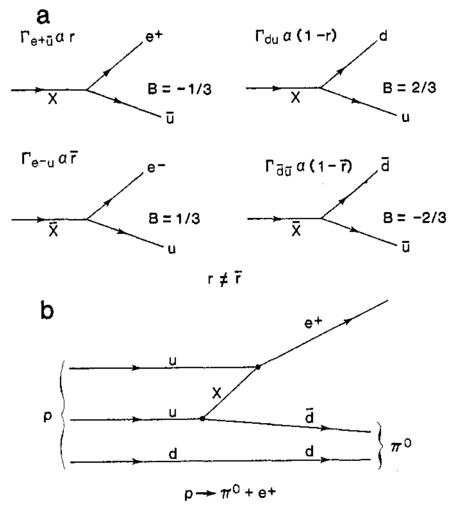

Fig. 6. (a) Simplified diagrams of baryon number nonconserving X boson decays. (b) A proton decay mediated by an X boson.

level of sensitivity for which a single-parameter description should either surprise or discourage us.

We must continually remind ourselves that CP violation, however small, is a very real effect. It has been used almost routinely as a calibration signal in several high energy physics experiments. But more importantly, the effect tells us that there is a fundamental asymmetry between matter and antimatter and that, at some tiny level, interactions show an asymmetry under the reversal of time. We must continue to seek the origin of the CP symmetry violation by all means at our disposal. We know that improvements in detector technology and accelerator quality will permit even more sensitive experiments in the coming decades. We are hopeful then, that at some epoch, perhaps distant, this cryptic message from nature will be deciphered.

Appendix

The evolution of a neutral K system characterized by time-dependent amplitudes a and $\bar{a}$ for the $|K\rangle$ and $|\bar{K}\rangle$ components, respectively, is given by

$$-\frac{d}{dt}\begin{pmatrix} a \\ \bar{a} \end{pmatrix} = \left(iM + \frac{1}{2}\Gamma\right)\begin{pmatrix} a \\ \bar{a} \end{pmatrix}$$

where M and Γ are Hermitian matrices and t is the time measured in the rest system of the K meson. Expressed in terms of their elements, the matrices are

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^{*} & M_{22} \end{pmatrix} \text{ and } \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^{*} & \Gamma_{22} \end{pmatrix}$$

The matrix $iM + 1/2\ \Gamma$ has eigenvalues $\gamma_S = iM_S + 1/2\ \Gamma_S$ and $\gamma_L = iM_L + 1/2\ \Gamma_L$. We define small parameters $\epsilon = (-\mathrm{Im}\, M_{12} + i\mathrm{Im}\, \Gamma_{12}/2)/(\gamma_S - \gamma_L)$ and $\Delta = [i(M_{11} - M_{22}) + (\Gamma_{11} - \Gamma_{22})/2]/[2(\gamma_S - \gamma_L)]$. We can then express the eigenvectors as

$$|K_S\rangle = \frac{1}{\sqrt{2}}\frac{1}{\sqrt{1 + |\epsilon + \Delta|^2}}\,[(1 + \epsilon + \Delta)\,|K\rangle + (1 - \epsilon - \Delta)\,|\bar{K}]$$

and

$$|K_L\rangle = \frac{1}{\sqrt{2}}\frac{1}{\sqrt{1 + |\epsilon - \Delta|^2}}\,[(1 + \epsilon - \Delta)\,|K\rangle - (1 - \epsilon + \Delta)\,|\bar{K}\rangle]$$

The parameter ϵ represents a CP violation with T nonconservation. The parameter Δ represents a CP violation with CPT nonconservation.

If we form a state $|K(t)\rangle$ which is an arbitrary superposition of $|K_S\rangle$ and $|K_L\rangle$ with amplitudes a_S and a_L at $t = 0$, we can compute its norm $\langle K(t)|K(t)\rangle$ as a function of time. At $t = 0$, by conservation of probability we have the relation

$$-\frac{d}{dt}\langle K(t)|K(t)\rangle\Big|_{t=0} = \sum_f |a_S\, \mathrm{amp}(K_S \rightarrow f) + a_L\, \mathrm{amp}(K_L \rightarrow f)|^2$$

where f represents the set of final states. Explicit evaluation of the expression gives

$$[-i(M_S - M_L) + (\Gamma_S + \Gamma_L)/2]\ \langle K_S|K_L\rangle = \sum_f (\mathrm{amp}\ (K_S \rightarrow f))^{*}\ (\mathrm{amp}\ (K_L \rightarrow f))$$

A number of definitions and a particular phase convention are used. We define $\tilde{\Delta} = \Delta - (A_0 - \bar{A}_0)/(A_0 + \bar{A}_0)$, where A_0 and $\bar{A}_0$ are the standing wave amplitudes for K and $\bar{K}$, respectively, to decay to the $I = 0$ state of two pions. A_0 and $\bar{A}_0$ are chosen real and define the phase convention used in the analysis. From the experimental parameters, we define

$$\epsilon_0 = \frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00},\ \epsilon_2 = \frac{\sqrt{2}}{3}(\eta_{+-} - \eta_{00}),\ \text{and}\ \alpha(f) = (1/\Gamma_S)\ (\mathrm{amp}\ (K_S \rightarrow f))^{*}\ (\mathrm{amp}\ (K_L \rightarrow f))$$

With these definitions, we find to a good approximation that

$$\left[-i\Delta M/\Gamma_S + \frac{1}{2}\right][2\ \mathrm{Re}\ \epsilon - 2i\ \mathrm{Im}\ \tilde{\Delta}] = \epsilon_0 + \sum_f \alpha(f) \qquad (1)$$

and

$$\epsilon - \tilde{\Delta} = \epsilon_0 \qquad (2)$$

The sum over f, which now excludes the $I = 0$ π-π state, consists of the following terms:

$$\alpha(\pi\text{-}\pi, I = 2) = (A_2/A_0)e^{i(\delta_2 - \delta_0)}\,\epsilon_2^*$$

$$\alpha(\pi^+\pi^-\pi^0) = (\Gamma(K_L \rightarrow \pi^-\pi^+\pi^0)/\Gamma_S)\eta^*_{+-0}$$

$$\alpha(\pi^0\pi^0\pi^0) = (\Gamma(K_L \rightarrow \pi^0\pi^0\pi^0)/\Gamma_S)\eta^*_{000}$$

$$\alpha(\pi e\nu) = (\Gamma(K_L \rightarrow \pi e\nu)/\Gamma_S)2i \text{ Im } x_e$$

and

$$\alpha(\pi e\nu) = (\Gamma(K_L \rightarrow \pi\mu\nu)/\Gamma_S)2i \text{ Im } x_\mu$$

where η_{+-0} = amp $(K_S \rightarrow \pi^+\pi^-\pi^0)$/amp $(K_L \rightarrow \pi^+\pi^-\pi^0)$, η_{000} = amp $(K_S \rightarrow \pi^0\pi^0\pi^0)$/amp $(K_L \rightarrow \pi^0\pi^0\pi^0)$, and x_ℓ is the ratio, amp$(\Delta Q = -\Delta S)$/amp$(\Delta Q = \Delta S)$ for $K \rightarrow \pi\ell\nu_\ell$. The quantities η_{+-0} and η_{000} are CP-violating ratios. (The final state $\pi^+\pi^-\pi^0$ can be CP even or odd. Here we refer only to the odd state.) The measurements of η_{000} and η_{+-0} are not at present very accurate and are consistent with zero. If we use the experimental limits (*15*), we find

$$\text{Re } \alpha = \text{Re} \sum_f \alpha(f) = (0.14 \pm 0.19) \times 10^{-3}$$

$$\text{Im } \alpha = \text{Im} \sum_f \alpha(f) = (-0.19 \pm 0.25) \times 10^{-3}$$

Equations 1 and 2 take a very simple form if we resolve the components of ϵ and Δ parallel and perpendicular to the direction which makes an angle ϕ_n with the real axis, where

$$\phi_n = \tan^{-1}\left[-\frac{2(M_S - M_L)}{(\Gamma_S - \Gamma_L)}\right]$$

We then find

$$\epsilon_\parallel = \epsilon_{0\parallel} + \cos\phi_n \text{ Re}\alpha$$
$$\epsilon_\perp = -\cos\phi_n \text{ Im}\alpha$$
$$\Delta_\parallel = \cos\phi_n \text{ Re}\alpha$$
$$\Delta_\perp = -\epsilon_{0\perp} - \cos\phi_n \text{ Im}\alpha$$

The experimental values of $\epsilon_{0\parallel}$ and $\epsilon_{0\perp}$ are, respectively $(2.27 \pm 0.03) \times 10^{-3}$ and $(0.16 \pm 0.09) \times 10^{-3}$. We then find

$$\epsilon_\parallel = (2.37 \pm 0.19) \times 10^{-3}$$
$$\epsilon_\perp = (0.14 \pm 0.18) \times 10^{-3}$$
$$\Delta_\parallel = (0.10 \pm 0.14) \times 10^{-3}$$
$$\Delta_\perp = (-0.02 \pm 0.20) \times 10^{-3}$$

Within the present experimental limits, we find that all the measurements are consistent with T violation and CPT conservation. In particular, we see that the limit on $\epsilon_\perp$ is very small, so we cannot expect ϕ_{+-} and ϕ_{00} to differ greatly from ϕ_n. Further, if the values of η_{000}, η_{+-0}, x_e, and x_μ were $< 10^{-2}$, then we would find $|\epsilon_\perp| \leq 10^{-5}$. Such an expectation is reasonable if the strength of the CP violation is roughly the same in all modes.

References and Notes

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