CP VIOLATION AND $\bar{P}P$ EXPERIMENTS

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ABSTRACT

At present only one non-zero measure of CP violation is known, the parameter ϵ in the decay $K^o \rightarrow 2\pi$. This can be attributed to $K^o - \bar{K}^o$ mixing in the mass matrix. Searches for additional non-zero CP-violating quantities aim at finding direct evidence for CP-violating decay amplitudes. The pp annihilation as a source of tagged $K^o(\bar{K}^o)$ provides a new method of studying CP violation in $K^o \rightarrow 2\pi$, $K^o \rightarrow 3\pi$, and $K^o \rightarrow \gamma\gamma$.

Our present knowledge of CP violation is limited to the K^o system. In the strong and electromagnetic interactions K^o $(S = +1)$ and $\bar{K}^o(S = -1)$ must be produced in association because of the conservation of strangeness S. Since strangeness is violated in the weak interactions, eigenstates (with definite mass and lifetime) are not the strangeness eigenstates but rather linear combinations

$$K_s : \Gamma_s^{-1} = \tau_s = 0.89 \times 10^{-10} sec$$

$$K_L : \Gamma_L^{-1} = \tau_L = 5.2 \times 10^{-8} sec$$

$$\triangle M \equiv (M_L - M_s) = 3.5 \times 10^{-6} ev = 7 \times 10^{-15} M_K \qquad (1)$$

If CP were a good quantum number the eigenstates would be

$$K_1 = (K^o + \bar{K}^o)/\sqrt{2} \qquad CP = +$$

$$K_2 = (K^o - \bar{K}^o)/\sqrt{2} \qquad CP = -$$

where $\bar{K}^o = (CP)K^o$ Indeed this appeared to be true. K_s decays almost entirely to the CP-even $\pi\pi$ state whereas K_L decays primarily to the CP-odd 3π state. The observation[1] in 1964 that discovered CP violation was that K_L also decays sometimes into $\pi\pi$.

The violation of CP invariance has been observed in three decays of the K_L meson and nowhere else. These observations are summarized in two complex parameters η_{+-} and η_{oo} and the charge asymmetry δ defined by

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_s \to \pi^+\pi^-)} = |\eta_{+-}| e^{i\phi_{+-}}$$

$$\eta_{oo} = \frac{A(K_L \to \pi^o\pi^o)}{A(K_s \to \pi^o\pi^o)} = |\eta_{oo}| e^{i\phi_{oo}}$$

$$\delta = \frac{\Gamma(K_L \to \pi^- l^+ \nu) - \Gamma(K_L \to \pi^+ l^- \bar{\nu})}{\Gamma(K_L \to \pi^- l^+ \nu) + \Gamma(K_L \to \pi^+ l^- \bar{\nu})}$$

where A stands for amplitude and l is either e or μ. The experimental results are

$$|\eta_{+-}| = 2.274 \pm .022 \times 10^{-3}$$

$$\phi_{+-} = (44.6 \pm 1.2)^o \tag{2}$$

$$\phi_{oo} = (54 \pm 5)^o$$

$$|\eta_{+-}/\eta_{oo}| = .992 \pm .02$$

$$\delta = (3.30 \pm 0.12) \times 10^{-3}$$

These numbers come from the Particle Data Group averages[2] except for $|\eta_{oo}/\eta_{+-}|$ which is the average of two recent experiments.[3,4]

If we assume CPT invariance, unitarity, and the $\Delta Q = \Delta S$ rule for semileptonic decays it is possible to show[5] that to a good approximation the five measured numbers are reducible to two. We can write

$$\eta_{+-} = \epsilon + \epsilon'$$

$$\eta_{oo} = \epsilon - 2\epsilon'$$

$$Phase\ of\ \epsilon = tan^{-1}(2 \triangle M/\Gamma_s) = 43.7^o \tag{3}$$

$$Phase\ of\ \epsilon' = \delta_2 - \delta_o + \frac{\pi}{2} = 48 \pm 8^o$$

$$\delta = 2Re\epsilon$$

where δ_I are the final state $\pi\pi$ scattering phase shifts in states of isospin I. Thus the data can be summarized by

$$\mid \epsilon \mid = (2.27 \pm .02) \times 10^{-3}$$

$$\epsilon'/\epsilon = \mid \eta_{+-}/3\eta_{oo} \mid -1 = (-3 \pm 6) \times 10^{-3}$$

With these assumptions all the observations are summarized in a single measure of CP violation $|\epsilon|$. The CP-violating parameter ϵ' as well as any CP-violating parameters in any other experiment (such as nuclear beta decay, neutron electronic dipole moment, etc.) are consistent with zero.

A simple class of model, called superweak, predicted this state of affairs. The suggestion was that CP violation in the K^o system occurred in the mass matrix that mixes K^o and $\bar{K}^o$. In the K_1 - K_2 representation we write

$$M = \begin{pmatrix} M_s & im' + \delta' \\ -im' + \delta' & M_L \end{pmatrix} \tag{4}$$

The term m' violates CP and T, whereas δ' is T-invariant and violates CPT. Assuming CPT invarinace we set $\delta' = 0$. In the superweak model the term m' is associated with a new interaction that changes S by two units ($\triangle S = 2$) and also violates CP. The eigenstates are

$$K_s \approx K_1 + \tilde{\epsilon} K_2$$

$$K_L \approx K_2 + \tilde{\epsilon} K_1 \tag{5}$$

$$\tilde{\epsilon} = \frac{im'}{\triangle m + i\Gamma_s/2} \tag{6}$$

The decay $K_L \rightarrow \pi\pi$ is simply due to the admixture of K_1 in the K_L eigenstate. As a result $\epsilon = \tilde{\epsilon}$ and $\epsilon' = 0$. The model is superweak in the sense that m' can be very small; from Eqs. (1) and (6) $m' \sim 10^{-8} ev$ in order to get $\epsilon \sim 10^{-3}$. The search for some other non-zero CP-violating observable such as ϵ' has as an important goal ruling out the superweak model.

The alternative models of interest I classify as milliweak. CP violation may occur in the weak interactions which allow $\triangle S = 0$ or $\triangle S = 1$ but not $\triangle S = 2$. The prefix milli indicates that the effective CP-violating term (at least for K^0 physics) is down by a factor 10^{-3}. There may, of course, be effective $\triangle S = 2$ contributions to the mass matrix but these are higher-order. As a result one expects in these models that some CP-violating decay amplitudes will be observable.

The standard electroweak model with six quarks allows for milliweak CP violation, as first pointed out by Kobayashi and Maskawa[6] (KM), by the presence of a complex quantity in the quark mixing matrix. The KM model is consistent with present data but problems may arise in the future. The model requires that the decay $b \to u + e + \nu$ be allowed where b is the third $Q = -\frac{1}{3}$ quark. So far this decay has not been seen and it should be found not too far below its present limit. The parameter ϵ' which demonstrates a $\Delta S = 1$ CP-violating amplitude should be non-zero. Unfortunately quantitative predictions are uncertain because of the difficulty of going from quarks to mesons. The range of predictions for ϵ' are

$$7.0 \times 10^{-3} > | \epsilon'/\epsilon | > 1.0 \times 10^{-3}$$

with probably a positive sign. Thus prospective experiments should have a good chance of finding a non-zero ϵ'.

There are many other alternative milliweak models that require an extension of the standard electroweak theory. I shall refer to two examples to illustrate possibilities.

(1) *Weinberg Higgs Model*

In the standard model there is a single Higgs doublet and only one physical Higgs scalar, a neutral particle with flavour-diagonal interactions proportional to mass. Weinberg[7] suggested the possibility of three Higgs doublets in which case there exist physical charged scalar Higgs $H^{\pm}$ as well as neutrals. The model was designed so that the neutral Higgs bosons did not change flavour; otherwise the model becomes a version of the superweak. CP violation in the K^0 system arises from the $\Delta S = 1$ interactions of $H^{\pm}$, which contribute to m' in second order due to diagrams in which one $H^{\pm}$ and one $W^{\pm}$ are exchanged or two $H^{\pm}$. The $H^{\pm}$ bosons must be considerably lighter than $W^{\pm}$ in order to cause a large enough value for ϵ. It was pointed out by Deshpande and Sanda[8] that ϵ'/ϵ in this model should be approximately equal to (-0.05), a value which is clearly ruled out by experiment. Recently, Donoghue and Holstein[9] have pointed out an error in previous calculations and say the value could be as low in magnitude as $-.006$.

(2) $SU(2)_L \times SU(2)_R \times U(1)$ *Models*

It was first suggested by Mohapatra and Pati[10] that CP violation could be explained if the gauge interactions were extended to include bosons $W_R^{\pm}$ interacting with right-handed currents. In a two-generation model, in which the phase convention is chosen so that all W_L couplings are real, CP violation is associated with the effective complex couplings of W_R. Because W_R is somewhat heavier than W_L, the CP violation occurs only at the level of parts per thousand. A highly constrained model of this sort based on spontaneous CP violation has been developed by Chang[11] and extended to three generations. For masses of W_R between 2 and 15 Tev, it turns out that most of the value of ϵ is due to W_R and only a little due to pure W_L exchanges. The value of ϵ'/ϵ is roughly calculated[12] to be of the order $\pm 5 \times 10^{-3}$ but could be lower.

Let me say a word about CPT. First it is important to note that CPT invariance is a very fundamental principle. While it is easy to write down theories that violate CP it is almost impossible to write down Lorentz-invariant field theories that violate CPT. Nevertheless it is obviously important to search for CPT violation since such a discovery would be of truly great significance. If we assume CPT invariance then CP violation implies T violation even though we have no direct observation of T violation. Thus it is important to ask whether the observed CP violation might be consistent with T invariance. Detailed analyses of K^o decays allowing for CPT violation exist in the literature, most recently by Barmin et al[13]. The conclusion is that the agreement of the phase of η_{+-} with the theoretical phase of Eq. (3) assures that T violation occurs.

In my opinion the most reasonable place to look for CPT violation is to search for a non-zero value of δ' in Eq. (4). This is because a very small value of δ' would still have a significant effect. It is easy to see that a non-zero δ' shifts the phase of ϵ from that given by Eqs. (3) and (6). The experimental value of the phase of η_{+-} then puts a strong limit on δ'. This corresponds to a limit on the difference of the masses (diagonal mass terms) of K^o and $\bar{K}^o$

$$| m(K^o) - m(\bar{K}^o) | < 3 \cdot 10^{-10} ev$$

So far in my discussion I have omitted the value of ϕ_{oo} because of its limited experimental accuracy derived from a single experiment[14]. Given the formulas of

Eq. (3) together with the empirical value of $|\eta_{+-}/\eta_{oo}|$ it is clear that ϕ_{oo} should equal ϕ_{+-} within about 0.1^o. Thus if ϕ_{oo} were really 54^o we would have to modify our assumption of CPT invariance. What would be required is a simultaneous violation of CPT violation in the mass matrix (non-zero δ') and in the decay amplitude (a roughly 90^o shift in the phase of ϵ') which conspire together to give the correct phase for ϕ_{+-}. While this seems extremely unlikely it is obvious that a better determination of ϕ_{oo} is needed. To be more precise one needs to measure $(\phi_{oo} - \phi_{+-})$. The best experiment that has measured both ϕ_{oo} and ϕ_{+-} yields $(\phi_{oo} - \phi_{+-}) = (14 \pm 7)^o$. The LEAR proposal[15] aims at an error on $(\phi_{oo} - \phi_{+-})$ of 0.2^o. It is also important to measure ϕ_{+-} more precisely. While the quoted result $(44.6 \pm 1.2)^o$ has a fairly small error and agrees with the CPT prediction, the most precise single measurement[16] is $46.5^o \pm 1.6^o$. Measurements of ϕ_{+-}(*or* ϕ_{oo}) are extremely sensitive to the value of $\triangle m$ so that the difference $(\phi_{oo} - \phi_{+-})$ might be measured more accurately than either individually.

Up to this time all K^o results have come from two types of experiments[17]. In both types the K^o beams are produced by the interaction of protons on a target such as beryllum. At low energies (such as the 30 Gev beam at the CERN PS) the production process yields K^o+ hyperons plus some associated $K^o + \bar{K}^o$ pairs. Thus the beam is predominantly K^o with some admixture of $\bar{K}^o$. In most early experiments observations were made far away from the target in a pure K_L beam. By inserting a hadronic target such as carbon a small K_s component can be added by regeneration. In many of the most precise experiments, particularly those of the CDHS group at CERN, the detectors are close to the target and the time evolution of decays from a pure (or almost pure) K^o beam is studied. The experiments proposed[15] at LEAR introduce a new method of studying K^o decays. The basic production processes of interest are

$$p + \bar{p} \begin{cases} \rightarrow \bar{K}^o \pi^- K^+ \\ \rightarrow K^o \pi^+ K^- \end{cases}$$

By observing the $K^+(K^-)$ it is possible to tag in a symmetrical way emerging $\bar{K}^o(K^o)$. Thus it is possible to study the time evolution of decays from K^o and $\bar{K}^o$. The CP-violating interference effects are equal and opposite for K^o and $\bar{K}^o$.

The comparison of K^o and $\bar{K}^o$ provides a graphic demonstration of CP violation and also provides a control on various systematic errors. However as far as the measurement of CP-violating parameters are concerned the use of $\bar{p}p$ provides no qualitatively new possibilities. Any observation of interference between K_s and K_L decays is evidence for CP violation; it is not necessary to use both K^o and $\bar{K}^o$ beams. Some proposed tests[18] for CPT vioaltion may require the use of both K^o and $\bar{K}^o$.

We turn now to possible experiments designed to find a CP-violating decay amplitude in non-leptonic K^o decays; this means a CP-violating effect which cannot be attributed to $K^o - \bar{K}^o$ mixing. In thinking about such experiments it is important to note that ϵ' provides an excellent limit on such amplitudes. The present limit on $\mid \epsilon' \mid$ is about 2×10^{-5}. Prospective experiments at CERN and Fermilab[19] using conventional methods aim at reducing the error on ϵ' close to 3×10^{-6}. The proposed LEAR experiment aims at similar accuracy. In some sense all K^o non-leptonic decays (and more generally hyperon non-leptonic decays as well) probe the same decay amplitudes $\bar{d} + s \rightarrow (u + \bar{u})$ or $(d + \bar{d})$. It is hard to imagine that any other experiment can rival the accuracy of a few parts per million that can be achieved for ϵ'. Thus we first ask if there are some reasons why ϵ' may be suppressed. The first point, which is well-known, is that ϵ' would vanish if the $\triangle I = \frac{1}{2}$ rule were exact. In that case there would be only one final $\pi\pi$ state, the $I = 0$ state, and only one CP-violating parameter $\eta_{\pi\pi} = \eta_{+-} = \eta_{oo}$. In fact we know that for the CP-conserving amplitude there is a $\triangle I = \frac{3}{2}$ piece of .045 times the $\triangle I = \frac{1}{2}$ piece. In many models (such as the KM model) the CP violation is pure $\triangle I = \frac{1}{2}$. The result is a natural suppression of ϵ' by the factor .045. Thus a prospective measure of ϵ' to a few parts per million is equivalent to a measurement at the level of 10^{-4} for quantities not subject to this suppression.

It is also possible to envisage a class of models in which ϵ' vanishes. These are models in which the CP-violating Hamiltonian has the form[20]

$$H(CP - odd) = H_+ + H_- e^{i\alpha} \qquad (7)$$

where $H_+ (H_-)$ are even (odd) under parity. It follows that CP violation can only be seen when comparing (or beating) a parity-even with a parity-odd transition. This occurs in the virtual transitions contributing to the mass matrix M but this is the only way CP violation can show up in $K \to 2\pi$. As far as $K \to 2\pi$ is concerned the model seems superweak and so $\epsilon' = 0$. However when we look at other decays the model can be distinguished from superweak. An example of such a model is the $SU(2)_L \times SU(2)_R \times U(1)$ model with two generations[10].

In analogy with η_{+-} and η_{oo} we can define CP-violating parameters for 3π final states

$$\eta_{ooo} = \frac{A(K_s \to 3\pi^o)}{A(K_L \to 3\pi^o)}$$

$$\eta_{+-o} = \frac{A(K_s \to \pi^+\pi^-\pi^o)}{A(K_L \to \pi^+\pi^-\pi^o)}$$

While the decay $K_s \to 3\pi^o$ is direct evidence for CP violation there does exist a CP-conserving decay $K_s \to \pi^+\pi^-\pi^o$ but it is inhibited by angular-momentum barriers and the $\triangle I = \frac{1}{2}$ rule. In any case as long as the parameter η_{+-o} is measured in an interference experiment (which assures that K_L and K_s go to the same final state) this is an unambiguous measure of CP violation. For either η_{+-o} or η_{ooo} one can write assuming CPT invariance

$$\eta_{3\pi} = \eta + i\left(\frac{Im\ A_{3\pi}}{Re\ A_{3\pi}} - \frac{Im\ A_o}{Re A_o}\right) = \epsilon + \epsilon'_{3\pi}$$

Here we assume a single dominant 3π final state so that $\epsilon'_{3\pi}$ is purely imaginary[21]. The quantity $(Im\ A_{3\pi}/Re\ A_{3\pi})$ represents the CP-violating phase in the decay to 3π while $(Im\ A_o/Re\ A_o)$ represents the CP-violating phase in the decay to the $I = 0$ 2π state. In many models, including the KM model[22] and the Weinberg Higgs model[23], one expects $\epsilon'_{3\pi}$ to be the same order as ϵ'. A very difficult ongoing experiment[24] aims at measuring η_{+-o} to an accuracy of $\pm.003$ corresponding to obtaining limits on $\mid \epsilon'_{+-o}/\epsilon \mid$ of order unity. The LEAR experiments[15] aims to measure $(\epsilon'_{3\pi}/\epsilon)$ to an error of ± 0.2. In models in which H satisfies Eq. (7) and

$\epsilon' = 0$ we have $\epsilon'_{3\pi} = \alpha$. For the particular case of the $SU(2)_L \times SU(2)_R \times U(1)_L$ model, even if we can neglect the third generation, there is an enhancement of ϵ due to special features of the left-right box diagram; as a result we expect $\epsilon >> \alpha$ and so $| \epsilon'_{3\pi}/\epsilon |$ is still expected to be very small[11].

A number of recent papers[25] have discussed the decay $K^o \rightarrow \gamma\gamma$. The observed decay $K_L \rightarrow \gamma\gamma$ with a branching ratio of 5×10^{-4} presumably goes to the CP-odd state $(\gamma\gamma-)$, the same final state as in π^o decay. It is expected, but not yet observed, that K_s decays to the CP-even state $(\gamma\gamma+)$ with a compaable rate. A study of interference effects in $K^o(\bar{K}^o) \rightarrow \gamma\gamma$ could then measure

$$\eta_- = \frac{A(K_s \rightarrow \gamma\gamma-)}{A(K_L \rightarrow \gamma\gamma-)} = \epsilon + \epsilon'_{\gamma\gamma}$$

A rough estimate[25] give $\epsilon'_{\gamma\gamma} \approx 30\epsilon'$ thus illustrating that in this case there is not the suppression factor present for ϵ'. The possibility of measuring η_- at LEAR has been discussed by Pavlopoulos and collaborators[26].

In conclusion, $\bar{p}p$ annihilation at rest now provides an alternative method of measuring CP violation in K^o decays. This method appears to be competitive with the standard older methods. Only a very careful analysis of the systematic errors in different experiments can yield the conclusion whether this method has distinctive advantages. At the moment it seems that the most precise measurement of a CP-violating decay amplitude in K^o decay will continue to be the measurement of $| \epsilon' |$. For this measurement it is not clear that any $\bar{p}p$ experiment can do better than the conventional type experiments now being carried out. Nevertheless given the difficulty of finding new results on CP violation one must welcome the introduction of a new class of experiments now proceeding at LEAR.

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