CP VIOLATION: STATUS AND PROSPECTS*

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Our current knowledge of CP violation and of the limits of CPT violation is reviewed: The only positive evidence for CP violation comes from studying the neutral K meson system. Also the new initiatives to study CP violation are discussed, in particular the electric dipole moment of the neutron.

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1. Status

In this lecture I would like to review our current knowledge of CP violation and also our knowledge of the limits of CPT violation. The only positive evidence for CP violation comes from our study of the neutral K meson system.

I will begin with a phenomenological analysis of the neutral K meson system which includes the possibility of CP violation with CPT conservation, and CPT violation with the retention of T invariance. Here C, P, and T refer to the symmetries of charge conjugation, parity, and time reversal, respectively.

The time evolution of the state of a neutral K meson system can be described to a very high degree of accuracy by the Wigner-Weisskopf approximation [1]. It is given by:

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

where a and $\bar{a}$ are the time dependent amplitudes for the states $|K^0\rangle$ and $|\bar{K}^0\rangle$ respectively. Conservation of probability (unitarity) requires that the matrices M and Γ are each separately Hermitian. We can write the two matrices M and Γ explicitly as

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} \quad \text{and} \quad \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}.$$

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The Γ matrix has elements of the form

$$\Gamma_{ij} = 2\pi \sum_f \langle i|H_w|f\rangle \langle f|H_w|j\rangle \varrho_f,$$

where H_w is the interaction Hamiltonian for the decay and f denotes a particular final state with density of states ϱ_f. The M_{ij} have a similar structure involving integrals over "off shell" matrix elements. It is this structure which demands that each matrix be separately Hermitian, if the interaction Hamiltonian is itself Hermitian [2].

CPT symmetry requires that $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$, a well known statement that the mass and lifetime of K_0 and $\bar{K}_0$ must be equal. The off diagonal elements are present only because of a decay interaction which leads K and $\bar{K}$ to the same final state. CP symmetry requires that Γ_{12} and M_{12} be real. This requirement can be traced to the well known requirement of T invariance that all decay amplitudes in the absence of final state interactions be relatively real.

We define two quantities (assumed to be small) ε and Δ given by,

$$\varepsilon = -\frac{\operatorname{Im} M_{12}+i \operatorname{Im} \Gamma_{12}/2}{\gamma_S-\gamma_L} \quad \text{and} \quad \Delta = \frac{i(M_{11}-M_{22})+(\Gamma_{11}-\Gamma_{22})/2}{\gamma_S-\gamma_L}.$$

Here γ_S and γ_L are the two eigenvalues of the matrix $M+i\Gamma/2$. The quantity ε is non-zero if CP and T symmetries are violated with CPT symmetry preserved. The quantity Δ is non--zero if CPT symmetry is not preserved. In all the analysis that follows we remind the reader again that probability conservation (unitarity) is assumed.

With these definitions the eigenvectors of the matrix are

$$|K_S\rangle = [2(1+|\varepsilon+\Delta|^2)]^{-1/2}[(1+\varepsilon+\Delta)|K^0\rangle+(1-\varepsilon-\Delta)|\bar{K}^0\rangle],$$
$$|K_L\rangle = [2(1+|\varepsilon-\Delta|^2)]^{-1/2}[(1+\varepsilon-\Delta)|K^0\rangle+(1-\varepsilon+\Delta)|\bar{K}^0\rangle]$$

with the corresponding eigenvalues

$$\gamma_S = iM_S+\Gamma_S/2,$$
$$\gamma_L = iM_L+\Gamma_L/2.$$

The time evolution of an arbitrary state at time $t = 0$ given by

$$|K(0)\rangle = a_S|K_S\rangle+a_L|K_L\rangle$$

becomes

$$|K(t)\rangle = a_S e^{-iM_S t} e^{\frac{-\Gamma_S t}{2}} |K_S\rangle + a_L e^{-iM_L t} e^{\frac{\Gamma_L t}{2}} |K_L\rangle.$$

The physical constants which control the evolution of the system are the K_S-K_L mass difference, $\Delta M = M_S-M_L$, and the K_S and K_L lifetimes Γ_S and Γ_L. The Particle Data Group [3] give the following values:

$$\Delta M = -(0.5349\pm0.0022)\times 10^{10}/\text{sec}$$
$$\Gamma_S = (1.1206\pm0.0027)\times 10^{10}/\text{sec}$$
$$\Gamma_L = (1.929\pm0.015)\times 10^{7}/\text{sec}.$$

The condition of unitarity can be carried further by equating the time rate of change of the norm of an arbitrary neutral K meson state with the rate of accumulation of the final states. The essential consequences of this relation were pointed out by Wu and Yang [4]. The explicit relation has been given by Bell and Steinberger [5]. In our notation it becomes

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

Explicit evaluation of the expression yields the result,

$$[-i(M_S - M_L) + (\Gamma_S + \Gamma_L)/2]\langle K_S|K_L\rangle = \sum [\operatorname{amp}(K_S \to f)]^* [\operatorname{amp}(K_L \to f)].$$

If ε and/or Δ are non-zero, the states $|K_S\rangle$ and $|K_L\rangle$ are not orthogonal. One finds,

$$\langle K_S|K_L\rangle = (2\operatorname{Re}\varepsilon - 2i\operatorname{Im}\Delta).$$

We can combine this relation with the more well known relations between experimentally measured quantities and suitable phenomenological parameters. This procedure may appear to the reader to be unnecessarily complicated, but it is necessary (1) to find explicit values for ε and Δ which are measures of the symmetry violations of CP and CPT, and (2) to provide insight into new experiments within the neutral K meson system.

We will review the definitions and give the results without derivation. There are two complex amplitude ratios and a charge asymmetry which have been measured, and are indicative of CP violation. These are:

$$\eta_{+-} = \frac{\operatorname{amp}(K_L \to \pi^+\pi^-)}{\operatorname{amp}(K_S \to \pi^+\pi^-)},$$

$$\eta_{00} = \frac{\operatorname{amp}(K_L \to \pi^0\pi^0)}{\operatorname{amp}(K_S \to \pi^0\pi^0)},$$

and

$$\delta_l = \frac{\Gamma(K_L \to \pi^- l^+ \nu_l) - \Gamma(K_L \to \pi^+ l^- \bar{\nu}_l)}{\Gamma(K_L \to \pi^- l^+ \nu_l) - \Gamma(K_L \to \pi^+ l^- \bar{\nu}_l)}.$$

Experimental values for these quantities are [6]

$$\eta_{+-} = (2.27 \pm 0.02)\exp[i(44.7^0 \pm 1.2^0)] \times 10^{-3},$$

$$\eta_{00} = (2.31 \pm 0.09)\exp[i(55^0 \pm 6^0)] \times 10^{-3},$$

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

With these data, derived quantities are introduced given by [7],

$$\varepsilon_0 = 2/3\eta_{+-} + 1/3\eta_{00}$$

$$\varepsilon_2 = \sqrt{2}/3(\eta_{+-} - \eta_{00}).$$

Also a host of other definitions and parameters must be introduced. These are:

$$A_0 = \text{amp}\,(\mathrm{K}^0 \to \pi\pi, \quad I = 0),$$

$$\bar{A}_0 = \text{amp}\,(\bar{\mathrm{K}}^0 \to \pi\pi, \quad I = 0),$$

$$A_2 = \text{amp}\,(K^0 \to \pi\pi, \quad I = 2),$$

$$\bar{A}_2 = \text{amp}\,(\bar{\mathrm{K}}^0 \to \pi\pi, \quad I = 2),$$

$$r_0 = (A_0 - \bar{A}_0)/(A_0 + \bar{A}_0).$$

The amplitudes are defined as transitions to standing wave states. The amplitude for a transition to an outgoing state of two pions is given by $A_I e^{i\delta_I}$ where δ_I is the s wave $\pi\pi$ scattering phase shift in the isotopic spin state I. CPT symmetry provides a relation between A_I and $\bar{A}_I$, namely $\bar{A}_I = A_I^*$.
We choose a phase convention where r_0 is a real quantity. We also define quantities,

$$\alpha(f) = (1/\Gamma_S)\,[\text{amp}\,(\mathrm{K_S} \to f)]^*[\text{amp}\,(\mathrm{K_L} \to f)], \qquad \tilde{\alpha} = \sum_f \alpha(f),$$

where the sum excludes the $I = 0$, $\pi\pi$ state. In terms of experimentally measured quantities, the $\alpha(f)$ are given by,

$$\alpha(\pi\pi, I = 2) = \sqrt{2}\,\omega^* \varepsilon_2$$

$$\alpha(\pi^0\pi^0\pi^0) = \frac{\Gamma(\mathrm{K_L} \to \pi^0\pi^0\pi^0)}{\Gamma_S}\,\eta^*_{000}$$

$$\alpha(\pi^+\pi^-\pi^0) = \frac{\Gamma(\mathrm{K_L} \to \pi^+\pi^-\pi^0)}{\Gamma_S}\,\eta^*_{+-0}$$

$$\alpha(\pi e\nu) = -2i\,\frac{\Gamma(\mathrm{K_L} \to \pi e\nu)}{\Gamma_S}\,\mathrm{Im}\,X_e$$

$$\alpha(\pi\mu\nu) = -2i\,\frac{\Gamma(\mathrm{K_L} \to \pi\mu\nu)}{\Gamma_S}\,\mathrm{Im}\,X_\mu.$$

Remaining undefined quantities in the above expressions are,

$$\omega = \left(\frac{A_2 + \bar{A}_2}{A_0 + \bar{A}_0}\right) e^{i(\delta_2 - \delta_0)},$$

$$\eta_{000} = \frac{\text{amp}\,(\mathrm{K_S} \to \pi^0\pi^0\pi^0)}{\text{amp}\,(\mathrm{K_L} \to \pi^0\pi^0\pi^0)},$$

$$\eta_{+-0} = \frac{\text{amp}\,(\mathrm{K_S} \to \pi^+\pi^-\pi^0, \text{CP odd})}{\text{amp}\,(\mathrm{K_L} \to \pi^+\pi^-\pi^0)},$$

$$X_l = \frac{[\text{amp}\,(\mathrm{K_L} \to \pi l\nu), \Delta Q = -\Delta S]}{[\text{amp}\,(\mathrm{K_L} \to \pi l\nu), \Delta Q = +\Delta S]}.$$

With these definitions we can write three equations which relate the CP and CPT violating parameters ε and Δ to experimentally measurable quantities [7]

$$(-i\Delta M/\Gamma_S+1/2)(2\,\mathrm{Re}\,\varepsilon-2i\,\mathrm{Im}\,\Delta) = \varepsilon_0+\tilde{\alpha}, \quad \text{(I)}$$

$$\varepsilon_0 = \varepsilon-\Delta+r_0, \quad \text{(II)}$$

$$r_0 = \mathrm{Re}\,\varepsilon_0-\delta/2. \quad \text{(III)}$$

These equations are solved for ε and Δ most conveniently if we write ε and Δ as components with respect to a "natural direction" given by

$$\phi_n = \arctan(-2\Delta M/\Gamma_S) = 43.7°\pm0.2°.$$

Then, one finds,

$$\varepsilon_{\parallel} = \varepsilon_{0\parallel}+\cos\phi_n\,\mathrm{Re}\,\tilde{\alpha},$$

$$\varepsilon_{\perp} = -\cos\phi_n\,\mathrm{Im}\,\tilde{\alpha},$$

$$\Delta_{\parallel} = \cos\phi_n\left[\mathrm{Re}\,\tilde{\alpha}+\mathrm{Re}\,\varepsilon_0-\frac{\delta}{2}\right],$$

$$\Delta_{\perp} = -\varepsilon_{0\perp}-\cos\phi_n\,\mathrm{Im}\,\tilde{\alpha}-\sin\phi_n\left[\mathrm{Re}\,\varepsilon_0-\frac{\delta}{2}\right].$$

If one refers to the definitions of ε and Δ, one observes that each quantity has a simple physical interpretation. $\varepsilon_{\parallel}$ is non-zero if a source of CP violation comes from the mass matrix M. $\varepsilon_{\perp}$ is non-zero if there is a contribution to CP violation from the decay matrix. $\Delta_{\perp}$ is non-zero if there is a CPT violation corresponding to a difference in mass of K and $\bar{\mathrm{K}}$. $\Delta_{\parallel}$ is non-zero if there is a difference in "lifetime" of the K and $\bar{\mathrm{K}}$.

Below we list the values of the experimental inputs to the evaluation of ε and Δ. Comments concerning these data are given where appropriate.

$$\omega = 0.045\pm0.001.$$

This result comes from a comparison of $K^+ \to \pi\pi$ and $K^0 \to \pi\pi$ decay rates. We assume $\Delta I \leqq 3/2$ for K^+ decay to obtain this result. We will not assume $\Delta I \leqslant 3/2$ holds for possible CP violating interactions which are at most a small fraction of the CP conserving modes. Since we do not know the nature of CP violation, it is unwise to assume anything about its nature.

$$\delta_2-\delta_0 = -45°\pm10°.$$

This result is an average of values determined from three sources (1) the ratio $\Gamma(K_S \to \pi^0\pi^0)/\Gamma(K_S \to \pi^+\pi^-)$, (2) K_{e4} decay [8], and (3) Chew-Low extrapolation from pion production by pions [9].

$$\eta_{+-0} = 0.05\pm0.07+i(0.26\pm0.13)\ [10],$$

$$\eta_{000} = -0.08\pm0.18-i(0.05\pm0.27)\ [11].$$

This result is a new measurement carried out at ITEP with a large liquid xenon bubble chamber. The experiment contains 632 events and replaces an old experiment which contained only 23 events.

$$X_{\mu} = 0.04 \pm 0.12 + i(0.12 \pm 0.16)\ [12],$$
$$X_{e} = 0.023 \pm 0.020 - i(0.0015 \pm 0.025)\ [13].$$

With the above input and the values for ε_0 and ε_2 derived from η_{+-} and η_{00} we find,

$$\tilde{\alpha} = [-0.01 \pm 0.07 - i(0.14 \pm 0.18)] \times 10^{-3}.$$

For Re $\tilde{\alpha}$ the error is dominated by η_{000}, while for Im $\tilde{\alpha}$ the error comes equally from η_{000} and X_{μ}. While it might be reasonable to assume $X_{\mu} = X_{e}$, we do not make such an assumption.

We then find

$$\varepsilon_{\parallel} = (2.24 \pm 0.06) \times 10^{-3},$$
$$\varepsilon_{\perp} = (0.1 \pm 0.12) \times 10^{-3},$$
$$\Delta_{\perp} = (0.03 \pm 0.19) \times 10^{-3},$$
$$\Delta_{\parallel} = (-0.09 \pm 0.10) \times 10^{-3}.$$

One can conclude that there is no evidence for a CPT violation, and any CPT violation is less than $\sim 10\%$ of the CP violation (with CPT conserved). Further, the CP violation is dominated by the mass matrix, while the contribution from the decay matrix is consistent with zero.

We can also use these results to obtain CPT limits that can be compared with other measurements on mass and decay rate differences between particle and anti-particle. We find,

$$\frac{M_{11} - M_{22}}{\Delta M} = \frac{\Delta_{\perp}}{\sin \phi_n} = (0.04 \pm 0.27) \times 10^{-3},$$

$$\frac{\Gamma_{11} - \Gamma_{22}}{\Gamma_S} = \frac{\Delta_{\parallel}}{\cos \phi_n} = (-0.13 \pm 0.14) \times 10^{-3}.$$

Mass differences are generally normalized to the mass of the particle itself. We can compare our result with others in the tables below.

Particle pair	$\delta M/M$	Ref.
$e^- - e^+$	$(0.0 \pm 1.3) \times 10^{-7}$	[14]
$\pi^+ - \pi^-$	$(0.2 \pm 0.5) \times 10^{-3}$	[15]
$K - \overline{K}$	$(0.2 \pm 2.3) \times 10^{-18}$	this analysis
$K^+ - K^-$	$(-0.3 \pm 0.9) \times 10^{-3}$	[16]
$p - \overline{p}$	$(0.7 \pm 0.4) \times 10^{-4}$	[17]

Particle pair	$\delta\Gamma/\Gamma$	Ref.
$\mu^- - \mu^+$	$(0\pm 1)\times 10^{-4}$	[18]
$\pi^+ + \pi^-$	$(-5\pm 7)\times 10^{-4}$	[3]
$K-\overline{K}$	$(-1.3\pm 1.4)\times 10^{-4}$	this analysis
$K^+ - K^-$	$(-9\pm 8)\times 10^{-4}$	[19]

The neutral K meson analysis gives extraordinary sensitivity for the mass difference, and is comparable in sensitivity to other measurements of decay rate differences. Since we do not have any idea about how CPT might be violated we cannot assess the relative importance of the measurements, in rejecting a CPT violation.

We will now assume that CPT is not violated and examine the consequence of the unitarity constraint on the observed CP violation. If CPT is valid, then one can choose a phase convention for which $r_0 = (A_0-\overline{A}_0)/(A_0+\overline{A}_0) = 0$ since CPT requires $\overline{A}_0 = A_0^*$, and one is free to choose A_0 real. As a consequence, Re $\tilde{\alpha}$ is also required to be zero. The unitarity conditions become $\varepsilon = \varepsilon_0$, $\varepsilon_\perp = -\mathrm{Im}\,\tilde{\alpha}\cos\phi_n$.

The perpendicular component of ε, which is the part coming from the decay matrix is constrained to be quite small, and hence the direction of ε is expected to lie quite close to the natural angle ϕ_n. Since the CP violation effect is largely given by $|\varepsilon_0|$, we find that the angle that ε makes with the natural axis is given by $\phi_\varepsilon - \phi_n = -\dfrac{\mathrm{Im}\,\tilde{\alpha}\cos\phi_n}{\varepsilon_0}$. To establish Im $\tilde{\alpha}$ the various experiments have been evaluated with the constraint that Re $\tilde{\alpha} = 0$. We now compute ϕ_ε for a series of assumptions concerning the physics that governs CP violation. For example, if the CP violation is a part of the weak interaction of quarks there are only interactions with $\Delta Q = \Delta S$ and $\Delta I \leqslant 3/2$. These results are given in the table below.

Assumption	Im α	$\phi_\varepsilon - \phi_{+-}$
No additional assumptions	$(-0.10\pm 0.17)\times 10^{-3}$	$1.8°\pm 3.1°$
Violation of $\Delta Q = \Delta S$. Rule same for e and μ	$(0.02\pm 0.09)\times 10^{-3}$	$0.3°\pm 1.7°$
$\Delta Q = \Delta S$ rule valid. $\Delta I \leqslant 3/2$	$(0.1\pm 0.06)\times 10^{-3}$	$0.2\pm 1.1°$
$\eta_{000} \lesssim 0.01$; $\eta_{+-0} \lesssim 0.01$	$(<\|0.006\|)\times 10^{-3}$	$<\|0.35°\|$

The conclusion is that the direction of the CP violating parameter ε, which represents the "CP impurity" in the state representing the K_L is a complex quantity whose phase must be very close to the natural direction $\phi_n = 43.7°$. Furthermore, if the CP violation in the 3π modes is less than five times larger than the CP violation in the 2π mode we would expect ϕ_ε to deviate from ϕ_n by less than 0.35°. These same general conclusions were anticipated by Wu and Yang [4].

The quantities actually measured are the amplitude ratios η_{+-} and η_{00}. An observation of a difference between these two ratios depends on a second parameter. The second parameter is related to the fact that the K can decay to $\pi\pi$ in final states of $I = 0$ or $I = 2$. If the two amplitudes A_0 and A_2 are not relatively real, then a CP violation is implied. States of $I = 0$ and $I = 2$ when decomposed into observable pions, give different ratios of neutral to charged pions. Hence this second source of CP violation is observable in the comparison of η_{00} and η_{+-}. The explicit relations between the two CP violating parameters are,

$$\eta_{+-} = \varepsilon + \varepsilon'/(1+\omega), \qquad \eta_{00} = \varepsilon - 2\varepsilon'/(1-2\omega),$$

with

$$\varepsilon' = \frac{i}{\sqrt{2}} \frac{\operatorname{Im} A_2}{A_0} e^{i(\delta_2-\delta_0)}, \qquad \omega = \frac{1}{\sqrt{2}} \frac{\operatorname{Re} A_2}{A_0} e^{i(\delta_2-\delta_0)}.$$

With CPT conservation ε' is identical within a factor $\sqrt{2}$ with the quantity ε_2 defined before.

The phase of ε' is also constrained. Its phase is $(\pi+\delta_2-\delta_0)$. Since $\delta_2-\delta_0 = -45° \pm 10°$, the direction of ε' is very closely constrained to be along the direction of ε. Since η_{00} and η_{+-} are very close in magnitude, one expects the phases of η_{+-} and η_{00} to differ very little from one another and from the natural direction ϕ_n.

In figure 1 we plot on the complex plane the measured and derived quantities. The derived quantities are given by,

$$\begin{aligned}
\varepsilon_{\parallel} &= (2.27 \pm 0.03) \times 10^{-3}, \\
\varepsilon_{\perp} &= (0.18 \pm 0.08) \times 10^{-3}, \\
\phi_\varepsilon - \phi_n &= (4.6° \pm 2°), \\
\varepsilon'_{\parallel} &= (0.0 \pm 0.035) \times 10^{-3}, \\
\varepsilon'_{\perp} &= (-0.13 \pm 0.08) \times 10^{-3}.
\end{aligned}$$

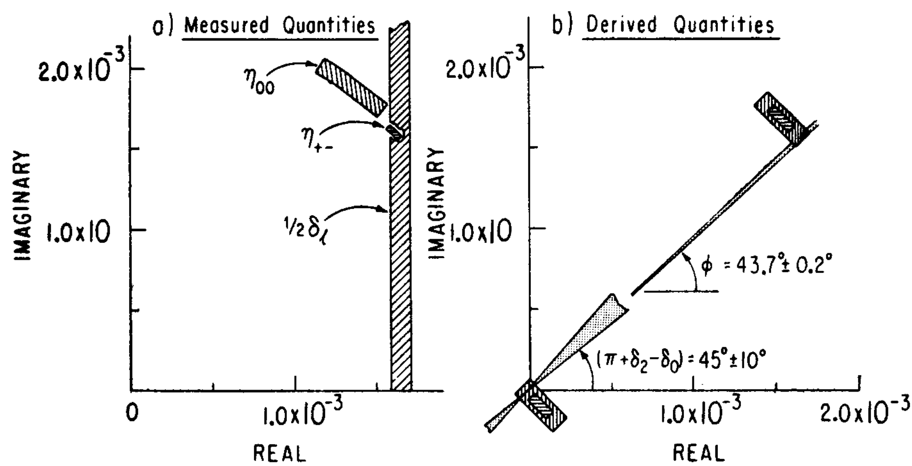

Fig. 1. Summary of CP-violating parameters in the neutral K system. (a) Measured quantities. (b) Derived quantities, boxes show one and two standard deviation limits

rrors for ε' are too large to quote an angle $\phi_{\varepsilon'}$. However, one does not expect : perpendicular component, since ε' should point along ϕ_n within $\pm 10°$. Also the ie of ϕ_ε deviates from ϕ_n more than would be expected by the unitarity analysis. culties are immediately traced to the large deviation of the phase of η_{00} from unt $11.3 \pm 6°$. If on further measurement this discrepancy remained, a violation uld be indicated. This can be seen in the generalized expression for ε_2 which is,

$$\varepsilon_2 = \frac{A_2 - \bar{A}_2}{A_0 + \bar{A}_0} e^{i(\delta_2 - \delta_0)}.$$

ie CPT constraint, $A_0 + \bar{A}_0$ can no longer be chosen real and A_2 and $\bar{A}_2$ bear to one another. Hence the phase of ε_2 is no longer determined by the $\pi\pi$ scatter- shifts alone. It has been pointed out that the magnitude of the effect, if the glected, can be related to a $K^+ - K^-$ lifetime difference, assuming $\Delta I = 3/2$, onsiderably larger than the present upper limit on the lifetime difference [20]. ll assume for the following discussion that the large phase of η_{00} is a fluctuation, measured more precisely, will be in better agreement with expectations. If the e confirmed, it would be a sensational discovery!

2. *Prospects*

s lecture we will review the new initiatives to study CP violation and discuss r investigations, particularly the electric dipole moment of the neutron. nitarity analysis carried out in the first lecture, gives some insight into the proper for further research on the neutral K meson system. One can conclude that rate measurements on the phase of η_{+-}, ϕ_{+-}, are not worthwhile. This phase ction defined by the vector sum of ε and ε'. The unitarity analysis shows that reasonably deviate from ϕ_n by more than 1°. The magnitude of ε' is small to ε and further its direction is constrained to lie within 10° of ϕ_n. Thus ε' can a transverse component of η_{+-} of at most $0.2\,\varepsilon'$, so that $|\phi_{+-} - \phi_\varepsilon| \lesssim 0.2|\varepsilon'/\varepsilon|$. ta indicate that $|\varepsilon'/\varepsilon|$ is of the order of 0.01. If $|\varepsilon'/\varepsilon|$ were as large as 0.05 one pect $|\phi_{+-} - \phi_\varepsilon| \lesssim 0.6°$. Therefore, further measurements of ϕ_{+-} cannot give nformation. On the other hand our information on the magnitude of ε' is the in of the measured parameters in the neutral K meson system. There are three ts where the ratio $|\eta_{00}|^2/|\eta_{+-}|^2$ was measured. The results are given below.

	$\lvert\eta_{00}/\eta_{+-}\rvert$	Ref.
	1.03 ± 0.07	[21]
	1.00 ± 0.06	[22]
	1.00 ± 0.09	[23]
average	1.01 ± 0.04	

t ε and ε' have nearly the same phase, the ratio $|\eta_{00}/\eta_{+-}|$ measures directly the by the relation $\varepsilon'/\varepsilon = 1/3\ (1 - |\eta_{00}/\eta_{+-}|) = 0.003 \pm 0.013$.

Measurements involving the decay $K_L \to \pi^0\pi^0$ are much more difficult to perform than the companion charged mode because of intrinsic difficulties in the measurement of γ-ray energies, directions, and positions. Recently there has been renewed interest in the measurement of ε'. This interest rests on the general ground that η_{00} is so much more poorly known than η_{+-}. New developments in detectors now permit much better measurement of γ-rays.

In addition there is renewed interest in the measurement of ε'/ε because limits on its value can be predicted from estimates based on the six quark model. Kobayashi and Maskawa [24] pointed out (even before a fifth quark was discovered), that the unitary matrix that rotates the strong interaction quark states into the weak interaction states, allows the possibility of a single CP violating phase, in addition to three Cabbibo-like angles. Numerous authors [25] have made calculations of the possible range of ε'/ε within the framework of the K–M model. These calculations involve the passage from weak interactions of quarks to the weak interactions of hadrons, a regime where the calculational techniques of Quantum Chromodynamics are poor. The authors make conservative estimates which now suggest that the value of ε'/ε should have a lower limit of $\sim$0.01. Such a value will produce a 6% deviation of $|\eta_{00}{}^2/\eta_{+-}{}^2|$ (the quantity measured) from unity.

As a consequence of these developments there is a strong experimental effort in Europe and the United States to improve the measurement of $|\eta_{00}/\eta_{+-}|$. The table below gives a summary of the experiments which are underway or planned during the next few years.

$|\eta_{00}/|\eta_{+-}|$ experiments

Laboratory	Exp. no. [26]	Error expected for $\left\|\frac{\varepsilon'}{\varepsilon}\right\|$ (std dev)	Number of $K_L \to \pi^0\pi^0$ events expected	Result expected
FERMILAB	617	4×10^{-3}	3000*	1983
BNL	749	10^{-2}	$\sim$ 2000	1984
CERN	NA31	0.5×10^{-3}	100,000	1986
FERMILAB	731	1×10^{-3}	100,000	1986

* Data already taken.

All of these experiments plan to measure $|\eta_{00}/\eta_{+-}|^2$ directly and have schemes to eliminate systematic errors.

The Fermilab experiments use two beams produced from the same target to simultaneously measure $K_L \to \pi^0\pi^0$ and $K_S \to \pi^0\pi^0$, or $K_L \to \pi^+\pi^-$ and $K_S \to \pi^+\pi^-$. The K_S are produced by a carbon regenerator. A schematic view of the experiment is shown in figure 2. The mean energy of the K_L beam is 70 GeV/c. The charged decays are detected in a magnetic spectrometer, while the $\pi^0\pi^0$-decays are detected with a 800-block-Pb glass array. A single photon converted in a thin Pb sheet is used to trigger the neutral decay modes. The regenerator oscillates between the two beams to average out small fluctuations and small

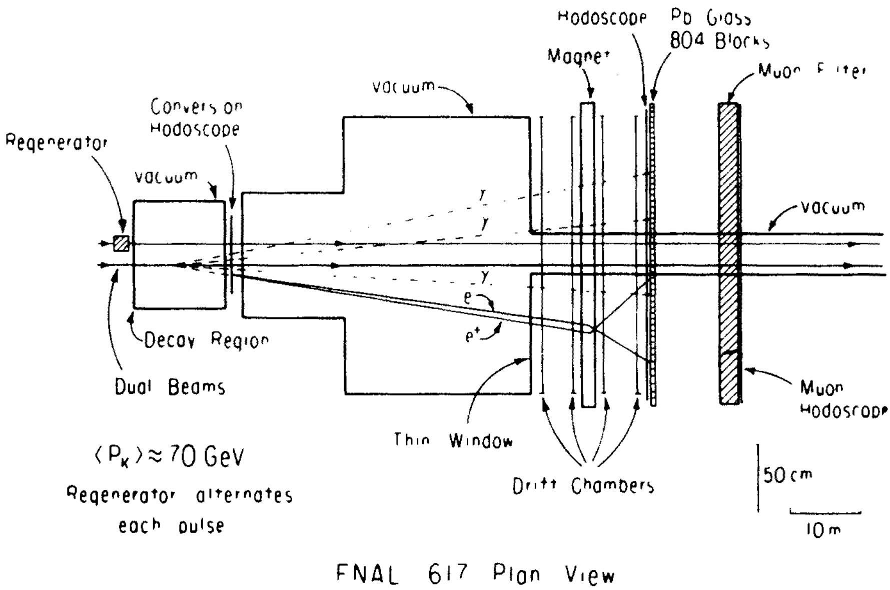

Fig. 2. Schematic arrangement at Fermilab for the measurement of $|\eta_{00}|^2/|\eta_{+-}|^2$

differences in the energy and intensity of the two beams. Also important is the fact that the losses due to beam and regenerator induced backgrounds are the same for regenerated events and free decay events, and the fact that no independent monitor is required.

Figure 3 shows a mass plot for a small sample of $K_L \to \pi^0\pi^0$ events. The separation from the $K_L \to \pi^0\pi^0\pi^0$ background is greatly improved with respect to former experiments. The desired ratio is given by,

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{(Y_L^{00}/\varepsilon_{00}^L)}{(Y_S^{00}/\varrho\varepsilon_{00}^S)} \cdot \frac{(Y_S^{+-}/\varrho\varepsilon_{+-}^S)}{(Y_L^{+-}/\varepsilon_{+-}^L)},$$

where Y is the measured yield for the designated mode, ε is the efficiency for the designated mode and ϱ is the regeneration amplitude. There are only small differences between ε_{00}^L and ε_{00}^S. The events are collected for ~ 3 K_S-mean decay lengths downstream from the regenerator, and the relative efficiencies differ by only a few percent. These corrections can be made by Monte Carlo or by appropriate weighting of the data itself.

The BNL and CERN experiments use a somewhat different arrangement. For these experiments the charged and neutral modes are measured simultaneously first for K_L and then for K_S. A single beam is used. The BNL derives the K_S from a regenerator while the CERN experiment uses a K_S beam. A very important consideration for this technique is to assure that the relative efficiency of neutral and charged decays remains unchanged between the K_S and K_L runs.

The new experiments at CERN and Fermilab which will yield results in a few years will give results sensitive to $|\varepsilon'/\varepsilon| \geqq 10^{-3}$. Even with the uncertainties in the K–M model,

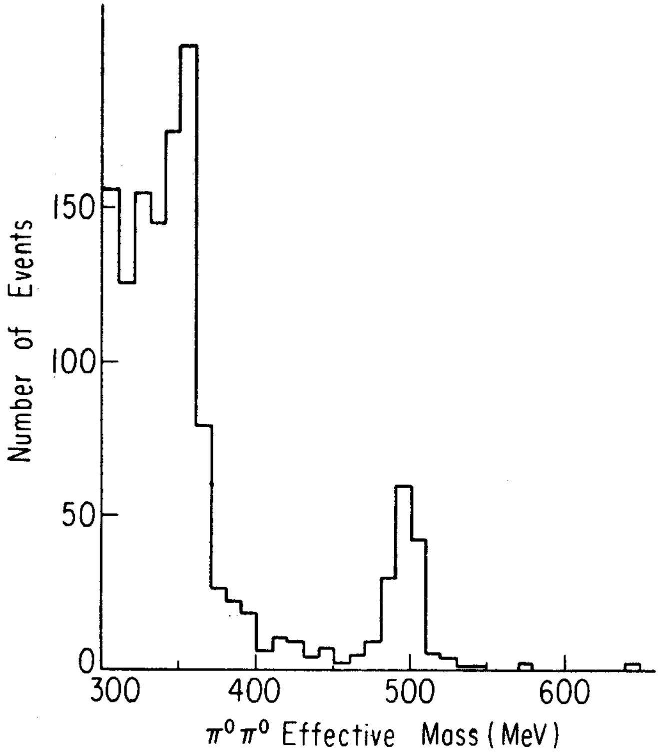

Fig. 3. Mass plot of a small sample of $K_L \to \pi^0\pi^0$ events from the Fermilab experiment

one expects a larger value for $|\varepsilon'/\varepsilon|$. More generally one can conclude that a positive result will double our knowledge about CP violation, since at present all data can be understood in terms of a single parameter, namely that in the mass matrix,

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

We regard the precise measurement of $|\eta_{00}/\eta_{+-}|$ as the most promising one to extend our knowledge concerning the nature of CP violation. Let us now describe some other efforts which are planned to investigate the nature of CP violation.

A more accurate measurement of η_{+-0} is planned by Experiment 621 at Fermilab. Running for this experiment will begin in 1984. In early runs it is expected that an error of ± 0.003 will be obtained for η_{+-0}, and ultimately an error of $\sim \pm 0.0005$ may be obtained. If there is no direct CP violation in the mode $\pi^+\pi^-\pi^0$, one expects $\eta_{+-0} = \varepsilon$. This experiment will represent a factor 100 improvement over the present knowledge, but it will not significantly tighten the limits on a CPT violation because that is limited by η_{000}, as well as by the difference $(\delta/2 - \mathrm{Re}\, \varepsilon_0)$. It will, however, be a very important experiment if it can in fact demonstrate that $\eta_{+-0} \neq \varepsilon$. The sensitivity goal is essential if the experiment is to add significantly to our knowledge of CP violation.

We have shown by the unitarity argument that time reversal violation must also be present in nature and it is natural to search for such violation in various physical systems.

Many experiments have been carried out in nuclear physics and particle physics searching for observables that are odd under time reversal. So far no positive results have been found [27]. We will mention some progress in sensitivity that has been made since the review of reference [27].

The polarization of the muon transverse to the decay plane in $K_L \to \pi^-\mu^+\nu$ and $K^+ \to \pi^0\mu^+\nu$ is an observable which is odd under time reversal. Measurements of the observable $\vec{\sigma}_\mu \times (\vec{p}_\mu \cdot \vec{p}_\pi)$ have been carried out for both decay modes [28]. A combination of both experiments leads to the conclusion that Im $\zeta = -0.01 \pm 0.02$. This result comes from the measurement of a transverse muon polarization $P = (-1.8 \pm 3.6) \times 10^{-3}$. It is difficult to assess the significance of a null result. The detection of a positive effect would most likely be interpreted as a CP violation residing in a Higgs sector more complex than the simple single Higgs required in the standard model [29]. The level of sensitivity of the experiment is in the range of what might be expected, but the Higgs sector as a source of CP violation cannot be ruled out by these experiments.

Further search for a time reversal violation in $K^+ \to \pi^0\mu^+\nu$ is still worthwhile. Since there is only one charged particle in the final state, there is no correction for Coulomb interaction in the final state. In contrast for the $K_L \to \pi^-\mu^+\nu$ decay one expects Im $\zeta = 0.008$ even with no time reversal violation.

The existence of an electric dipole moment for a fundamental particle with spin is a violation of both parity and time reversal. One looks for an energy shift in an electric field of the form,

$$\Delta\varepsilon = \vec{d} \cdot \vec{E},$$

where $\vec{d}$ is the electric dipole moment and $\vec{E}$ is the electric field. The only direction associated with the particle is its spin, so $\vec{d} = k\vec{\sigma}$. The observable $\vec{\sigma} \cdot \vec{E}$ is odd under both parity and time reversal. The search for an electric dipole moment of the neutron began more than thirty years ago [30]. From the earliest time the authors were testing the assumptions on which an electric dipole moment was expected to be zero. While no positive effect has been seen, the upper limit on the electric dipole moment has been reduced by six orders of magnitude.

Evidence for an electric dipole moment is a shift in the magnetic resonance frequency of the neutron when an electric field is added parallel to the magnetic field. It is of interest to consider the parameters of a typical modern experiment. The shift in resonant frequency between electric and magnetic field parallel and antiparallel is given by,

$$\Delta\nu = \frac{4dE}{h}.$$

For $d \approx 10^{-24}\, e \cdot \mathrm{cm}$, $E = 10^4$ volts/cm, this shift is 10^{-5} Hz, which is a shift in energy of 10^{-20} ev. For such a shift to be observable, a narrow line width must be achieved for the magnetic resonance. This line width will be affected by magnetic inhomogeneities, and by the uncertainty principle. The first effect is reduced by a low fixed magnetic field with a corresponding low resonant frequency. The second effect is reduced by observing the neutrons for a long time.

Ultra cold neutrons, which can be stored from 5–100 sec, have been used. With 100 sec

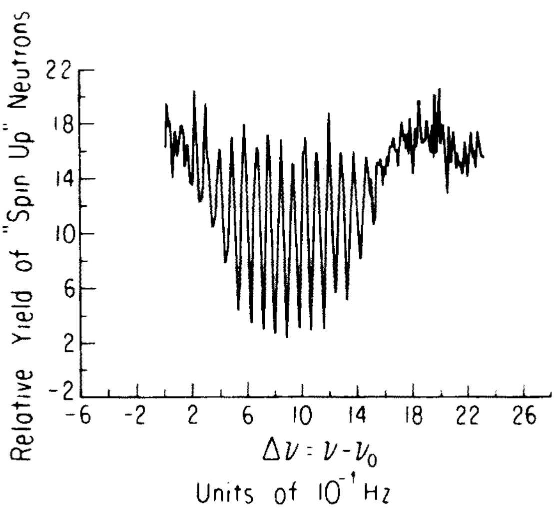

Fig. 4. Magnetic resonance curve for ultra-cold neutrons stored for 40 sec. The Ramsey double resonance technique is used. The width of each RF pulse is 4 sec. The pattern is equivalent to a double slit diffraction pattern where the width of the slits is 1/10 of the slit separation. The line width is 1.25×10^{-2} Hz

of storage a line width of $\sim 10^{-2}$ Hz can be obtained. Typical fixed magnetic fields of 10^{-2} gauss give a resonant frequency of 30 Hz. Figure 4 shows a magnetic resonance curve for neutrons stored for 40 sec [31]. To detect an electric dipole moment, the RF frequency is set on a steep part of the curve. One observes a change in rate correlated with the reversal of the electric field, if an electric dipole moment is observed.

At present one experiment has been completed of this type at Leningrad [32] giving a result,

$$d = (2.4 \pm 2.3) \times 10^{-25}\ e \cdot \mathrm{cm}, \qquad \text{or} \qquad |d| < 6 \times 10^{-25}\ (90\%\ \text{conf}).$$

This experiment has evolved over a number of years; the authors continue to improve it. However, systematic errors with the particular apparatus will make it difficult to progress much below $10^{-25}\ e \cdot$ cm.

A second experiment is being carried out at Grenoble [33] which was the source of the data shown in figure 4. This experiment expects to reach a sensitivity comparable to the Leningrad experiment. The data are taken and the result will be available in the very near future. In a few years one can expect sensitivities which will give upper limits less than $10^{-25}\ e \cdot$ cm. Progress beyond this level will be difficult. One can expect sensitivities down to 10^{-26} only by the end of the decade.

The value of a negative result requires its comparison with some predictions. The model which places the CP violation in the Higgs sector [29] also predicts that the electric dipole moment of the neutron is in the range of $10^{-25}\ e \cdot$ cm [34]. This limit is nearly reached by the experiments. The prediction for the electric dipole moment of the neutron using the K–M model is $\sim 10^{-30}\ e \cdot$ cm which is far beyond any sensitivity that can be imagined.

Throughout these talks I have not mentioned that there are a whole new set of particles which are similar to the K^0–$\bar{K}^0$ system. These are the charm and beauty particles D^0 B^0 B^0_s

ld have similar properties and hence CP violating phenomena. There are ons to believe that in the next several years the hope for experiments sensitive ion is not too great. The principal reason being that the production of charm particles is not very large because of small cross sections and low luminosities colliders. There is an ample literature on this subject, and there is an excellent hich the reader is referred [35].

3. Conclusions

s a renewed experimental effort to learn more about CP violation. Within years there is hope that CP violation can be characterized by more than a single The most promising experiment is the measurement of $|\eta_{00}|/|\eta_{+-}|$. A positive give heavy weight to the fact that a phase in the K–M matrix is responsible violation. An important question then will be to understand the origin and of this phase. Experimentalists have experienced many changes in theoretical I doubt that a negative result for $|\eta_{00}/\eta_{+-}|$ (i.e., $|\eta_{00}/\eta_{+-}|$ consistent with unity n of 0.001) will lead to any clarification of our understanding of CP violation. ek is more information of a positive nature. Such information will automatite the superweak hypotheses [36]. A new positive result will represent a break- a doubling of our knowledge. Then experimentalists will attempt more difficult ts because there will be a better prospect for positive results.

we must realize that at present we know very little about CP violation, we ne number. It is not beyond possibility that the effect may be energy dependent endent, although there is not even a hint of such dependence at present. At sity machine which can run continuously, such as the Brookhaven A.G.S., gine measuring $|\eta_{+-}|^2$ to a precision of 0.25 %/day and 0.1 % per week. Reputable ve considered such a possibility.

. This article was proofread by the editors only, not by the author.

REFERENCES

kopf, E. P. Wigner, *Z. Phys.* **63**, 54 (1930); the explicit application of this approximation utral K meson system was given by Lee, Oehme and Yang, *Phys. Rev.* **106**, 340 (1957). oximation is valid for times which are large compared to $\hbar/M_K = 10^{-24}$ sec. The time scale nce here is $\tau_S \approx 10^{-10}$ sec.

eral discussion of the Hermiticity question, see B. G. Kenny, R. G. Sachs, *Phys. Rev.* **D8**, 3).

lar-Benetez et al., *Phys. Lett.* **111B**, (1982).

ı, C. N. Yang, *Phys. Rev. Lett.* **13**, 380 (1964).

l, J. Steinberger, Proceedings of the Oxford International Conference on Elementary 1965, edited by R. G. Moorhouse, A. E. Taylor, T. R. Walsh, Rutherford Laboratory, England 1966, p. 195.

lues represent the author's own evaluation of the original work and differ slightly from the Data Group, see Ref. [3]. The references for the original work are given in Ref. [3]. The δ is a weighted average for Ke3 and Kμ3 decays.

ı all these parameters, the treatment is not quite exact. We have neglected the parameter ω

(which has a value 0.045) when compared to unity. Also $\delta/2$ should be replaced by $\delta/2[|1-x|^2/(1-|x|)^2]$ where x is the parameter which measures the violation of the $\Delta Q/\Delta S$ rule. We have neglected Γ_L compared to Γ_S. These approximations are satisfactory given the errors in the experimental measurements.

[8] L. Rosselet et al., *Phys. Rev.* **D15**, 574 (1977).

[9] J. Baton et al., *Phys. Lett.* **B33**, 528 (1970); P. Estabrooks, A. D. Martin, *Nucl. Phys.* **B79**, 301 (1974); C. Bricman et al., *Phys. Lett.* **75B**, 115 (1978); W. Hoogland et al., *Nucl. Phys.* **B69**, 266 (1974); N. N. Biswas et al., *Phys. Rev. Lett.* **47**, 1380 (1981).

[10] Average of world data given by M. Baldo-Ceolin et al., *Nuovo Cimento* **25A**, 688 (1975).

[11] V. V. Barmin et al., preprint, Institute for Theoretical and Experimental Physics, Moscow, and Institute of Physics, Padua 1983.

[12] J. Graham et al., *Nuovo Cimento* **9A**, 166 (1972).

[13] F. Niebergall et al., *Phys. Lett.* **49B**, 103 (1974). The figure quoted is the world average as quoted by the authors.

[14] P. Schwinberg, 1979 Doctoral Thesis, University of Washington; result is quoted in *Atomic Physics* **7**, 337 (1981), edited by D. Kleppner and F. Pipkin, Plenum Publishing Co.

[15] D. Ayres et al., *Phys. Rev.* **3D**, 1051 (1971).

[16] W. Ford et al., *Phys. Lett.* **38B**, 335 (1972).

[17] These data are taken from the Particle Data Group. Ref. [3]; the proton mass comes from a review by Cohen, Journal of Physical Chemistry, Ref. Data 2, 663 (1973); the anti-proton mass from Hu et al., *Nucl. Phys.* **A254**, 403 (1975); and Robertson et al., *Phys. Rev.* **C16**, 1945 (1977).

[18] E. Zavattini et al., Proceedings of TRIUMF Muon Workshop, P. 62, 1980; see also Ref. [3].

[19] F. Lobkowicz et al., *Phys. Rev.* **185**, 1676 (1969).

[20] L. Okun, Private communication 1983.

[21] M. Banner et al., *Phys. Rev. Lett.* **28**, 1597 (1972).

[22] M. Holder et al., *Phys. Lett.* **B40**, 141 (1972).

[23] J. Christenson et al., *Phys. Rev. Lett.* **43**, 1209 (1979).

[24] M. Kobayashi, K. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).

[25] F. Gilman, M. Wise, *Phys. Rev.* **D21**, 3150 (1980); B. Guberina, R. Peccei, *Nucl. Phys.* **B163**, 289 (1980); recently the estimates from the K–M model have changed, because of an unexpectedly long lifetime for the B meson; F. Gilman, J. Hagelin, Private communication September 1983.

[26] The proposals for these experiments can be found in many libraries or can be obtained from the relevant laboratory.

[27] There is no recent comprehensive review of these negative results. A table of some of the more sensitive tests as of January 1, 1981 is given by J. Cronin, *Rev. Mod. Phys.* **53**, 373 (1981).

[28] W. Morse et al., *Phys. Rev.* **21D**, 1750 (1980), for $K_L \to \pi^-\mu^+\nu$; M. K. Campbell et al., *Phys. Rev. Lett.* **47**, 1032 (1981) for $K^+ \to \pi^0\mu^+\nu$.

[29] S. Weinberg, *Phys. Rev. Lett.* **37**, 657 (1976); A. R. Zhitnitskii, *Yad. Fiz.* **31**, 1024 (1980) [*Sov. J. Nucl. Phys.* **31**, 529 (1981)]; A. I. Sanda, *Phys. Rev.* **D23**, 2647 (1981); N. G. Deshpande, *Phys. Rev.* **D23**, 2654 (1981). The latter two papers have shown that this explanation of CP violation leads to contradictions with the experimental value of ε'/ε.

[30] E. M. Purcell, N. F. Ramsey, *Phys. Rev.* **78**, 807 (1950).

[31] Permission to use this figure was kindly given to the author by B. Heckel and N. F. Ramsey. This experiment is being performed at the Institute Laue-Langevin, Grenoble, France.

[32] I. Alterev et al., *Phys. Lett.* **102B**, 13 (1981).

[33] N. F. Ramsey, B. Heckel, Private communication; the experiment is being carried out by a collaboration of Institute Laue-Langevin, Sussex, and Harvard.

[34] There are many calculations; an example is I. Kriplovich, A. Zhitnitsky, *Yad. Fiz.* **34**, 167 (1981) [*Sov. J. Nucl. Phys.* **34**, 95 (1981)].

[35] Ling-Lie Chau, *Phys. Rep.* **95**, 1 (1983).

[36] L. Wolfenstein, *Phys. Rev. Lett.* **13**, 569 (1964).

[37] N. Cabbibo, G. Conforto, *Phys. Rev.* **D25**, 3075 (1982).