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How to elucidate the mechanism of *CP* violation

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Several *CP*-violating observables, particularly in semileptonic decays of *K*'s, have the property that they are expected to vanish in the standard model, but are nonzero in alternative models. Thus, they provide very clean ways to test whether the standard model is the (sole) source of *CP* violation and to determine the properties of any other source that may enter. We mainly consider the transverse muon polarization from $K_{\mu 3}$ (which isolates *S* and *P* effective Lagrangians), and the K_{e4} spectrum (which contains a term that isolates *V* and *A* effective Lagrangians). We briefly comment on $W^{\pm}$ production, and heavy-quark and -lepton decays.

I. INTRODUCTION

Even after 25 years of heroic efforts on the part of many experimenters, our knowledge of the basic mechanism of *CP* violation is fundamentally incomplete. All present data can be described by the standard model, but can equally be described other ways. Possible mechanisms include left-right-symmetric theories, theories with phases coming from the scalar sector, supersymmetric theories, mixing of light and extra heavy quarks, and others. There are essentially no experimental probes of *CP* violation in the leptonic sector, and none in *W* or *Z* production or decays. Although most physicists hope that *CP* violation is a profound effect and one that may provide important clues to new physics, nothing prevents it from being essentially an accidental mismatch of phases in mass-matrix diagonalization in the quark or the scalar or the gaugino sector, or in all of these.

In principle, only one phase parameter in the Kobayashi-Makawa (KM) matrix[1] governs *CP* violation in the six-flavor standard model. It is a success of the standard model that this parameter can be fitted to account for the value of ϵ, the *CP*-violating parameter associated with K^0-$\bar{K}^0$ mixing. The recent report of ϵ'/ϵ, the parameter associated with *CP* violation for $\Delta S=1$ channels,[2]

$$\mathrm{Re}(\epsilon'/\epsilon)=(3.3\pm 1.1)\times 10^{-3} , \tag{1}$$

should thus be seen as a crucial test of the model (see also Ref. 3). Unfortunately, for two reasons this test is inconclusive. (i) There is insufficient knowledge of several quantities needed for the theoretical prediction, particularly the top-quark mass, and the precise value of some mixing angles. (ii) There is considerable uncertainty in the evaluation of hadronic matrix elements in the *K* system. While the first question will eventually be resolved by the observation of the top quark, the evaluation of the *K* matrix element is very uncertain. It may not be settled for some time. Experimental evidence probing alternate sources of *CP* violation is thus very much needed. Even if ϵ and ϵ'/ϵ were well measured and calculable with good precision, it is already clear that several approaches can describe them. If a non-standard-model source of *CP* violation exists, it will offer a unique window on "new physics" at TeV energies.

Here we emphasize that semileptonic decays provide an underexploited tool for working out the structure of *CP* violation. For example, the standard model predicts that no *CP* violation can be observed in K_{l3} or K_{l4} decays—observation of a *CP*-violating signal would immediately prove that a source of electroweak *CP* violation in addition to the standard model is present. We will give additional examples in the following.

II. SEMILEPTONIC *K* DECAYS

Semileptonic decays of *K* mesons have long been known to offer tests of $CP(T)$ violation.[4] The charge asymmetry in $K_L \to \pi^{\mp} l^{\pm} \nu$ decay is directly related to the value of ϵ, which describes the departure from a pure (K^0-$\bar{K}^0$) state. The predictions are thus identical in all models. If we consider, however, the momentum and spin distributions of any particular decay, or the charged *K* decays, the various approaches differ widely, and no observable contribution is expected[5] from the standard model [i.e., SU(2)⊗U(1) with minimal scalar structure and *CP* violation originating in the three-family KM mixing matrix]. That is because the dominant contribution [Fig. 1(a)] involves only two families, while three are required for the KM mechanism to operate (in other terms, the mixing matrix element describing the s-u transition can always be chosen real by a unitary transformation of the KM matrix). When this physics situation is combined with the remarkable progress of the past decade in obtaining intense kaon beams and in detectors, the semileptonic kaon decays can be seen to offer an ideal window to look for alternative *CP*-violating mechanisms.

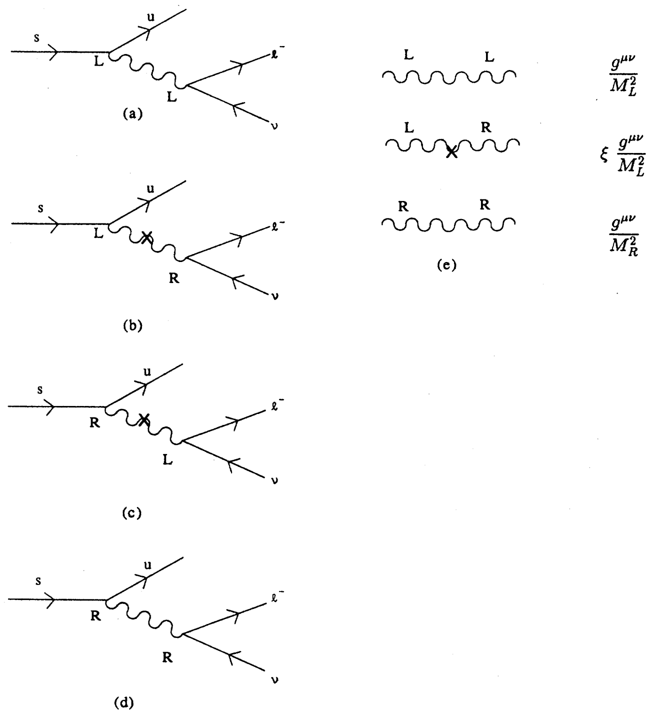

FIG. 1. Vector contributions to semileptonic decays [only (a) appears in the standard model].

A. K_{l3} decays

The simplest case, and the most celebrated such parameter[4,6] is observed in K_{l3} decays of the type

$$K^+(K) \to \pi^0(k) l^+(p) \nu(q) \ , \tag{2}$$

where the absence of final-state strong interactions makes the transverse polarization of the lepton:

$$\mathbf{s}_l \cdot (\mathbf{p} \times \mathbf{k})$$

a signal of *CP* violation, up to higher-order electromagnetic corrections.[7] As described above, the standard model predicts zero polarization of a muon transverse to the decay plane,[8] except for the Coulomb corrections at the level of about 10^{-6}.

We consider successively the alternative *CP*-violating examples of models based on $SU(2)_L \otimes SU(2)_R \otimes U(1)$, and on an extended set of scalars.

1. Left-right-symmetrical models (Ref. 9)

As shown in Ref. 10 the contribution of "right" bosons to the $\Delta S = 2$ channel (the box "diagram" of K^0-$\bar{K}^0$) is strongly enhanced with respect to their contribution in $\Delta S = 1$ channels. This mechanism was exploited in Ref. 11 to suggest a model of *CP* violation where ϵ'/ϵ is dynamically suppressed. Developments of this model (Ref. 12) confirm that the principal contribution to ϵ' is then due to the mixing ξ between "left" and "right" bosons. From data alone $|\xi| \leq 0.1$ in general,[13,14] and $|\xi| \leq 0.05$ if *RH* neutrinos are light enough to occur in μ decay.[15] Indirect limits typically require $|\xi| \leq 0.005$; see Ref. 14.

Because the mixing parameter ξ is small we adopt the representation of Fig. 1; we also neglect the momentum transfer L^μ in the denominators, as well as the longitudinal $L^\mu L^\nu / M^2$. For the processes considered, this procedure is equivalent to, but more intuitive than, the use of the mixed bosons mass eigenstates W_1 and W_2. In addition to these graphs, contributions from flavor-changing scalar bosons are also expected; we will neglect these here. The graph in Fig. 1(a) is the usual $SU(2) \times U(1)$ contribution; no *CP* violation on the hadronic side arises until all three families are involved, and we choose this amplitude to be real. On the hadronic side, we have to consider the matrix elements of the chiral currents $V^\mu - A^\mu$ and $V^\mu + A^\mu$.

Clearly,

$$\langle \pi^0 | A^\mu | K^+ \rangle = 0$$

since we cannot form an axial vector out of K^ρ and k^σ alone. Thus,

$$\begin{aligned} \langle \pi^0 | V^\mu - A^\mu | K^+ \rangle &= \langle \pi^0 | V^\mu + A^\mu | K^+ \rangle \\ &= \langle \pi^0 | V^\mu | K \rangle \\ &= f_+ (K^\mu + k^\mu) + f_- (K^\mu - k^\mu) \ , \end{aligned} \tag{3}$$

where $V^\mu = \bar{s} \gamma^\mu u$. Thus our arguments obviously apply to any combination of V, A. Observe that f_+ and f_- are necessarily relatively real, whatever the phases later associated with the right-handed couplings, because of the *CP* invariance of the strong interactions.

The full amplitude then reads $[P_L \equiv (1-\gamma_5)/2;\ P_R \equiv (1+\gamma_5)/2;\ M_L \simeq M_W]$

$$\begin{aligned} M = \left[\frac{g}{\sqrt{2}} \right]^2 & \sin\theta_C \tfrac{1}{2} [f_+ (K^\mu + k^\mu) + f_- (K^\mu - k^\mu)] \frac{g^{\mu\nu}}{M_L^2} \\ & \times [\bar{\nu} \gamma^\nu P_L l (1 + \alpha \xi) + \bar{\nu} \gamma^\nu P_R l (\alpha' \xi + \alpha'' \rho)] \end{aligned} \tag{4}$$

with $\rho = M_L^2 / M_R^2$, and $\alpha, \alpha', \alpha''$ are phase factors associated with the right-handed couplings.

In general, the right-handed couplings are complex, even for two families of fermions. If the leptonic couplings can be taken to be real (e.g., if the neutrino masses vanish) we have $\alpha' = \alpha''$; $\alpha = 1$. In order to observe some *CP*-violating effect we must get an interference between the two pieces of the lepton current in Eq. (4); namely, we look for the contribution proportional to Im A, with

$$A = (1 + \alpha \xi)(\alpha'^* \xi + \alpha''^* \rho) \ . \tag{5}$$

The relevant part of the square of the leptonic amplitude is thus

$$X^{\mu\rho} = \bar{\nu} \gamma^\mu P_L l \bar{l} \gamma^\rho P_R \nu A + \bar{\nu} \gamma^\mu P_R l \bar{l} \gamma^\rho P_L \nu A^* \ . \tag{6}$$

It is clear from Eq. (6) that a chirality flip is needed for the neutrino; the result will vanish for massless neutrinos, and this is already sufficient to make this channel hopeless to observe an effect in the muon transverse polarization $P_\mu^\perp$ in left-right-symmetric theories, or any theory with V, A currents.

This argument has since independently been extended by Leurer,[16] who showed that the transverse lepton polarization in $K_{\mu 3}$ is zero for any type of neutrinos for any vector currents. She has also given a general expression[16] for the muon polarization in terms of couplings from a general (S, V, T, A, P) effective Lagrangian.

2. *Other contributions*

Conversely, as is well known, scalar (and/or pseudoscalar) currents can lead to nonzero $P_\mu^\perp$. Such scalar currents can arise directly from scalar or pseudoscalar exchanges, e.g., Higgs scalars with complex couplings,[6,7,17] or from effective Lagrangians coming from leptoquark exchanges as in Fig. 2, or from supersymmetric loops. In the leptoquark case the helicity structure requires the nonstrange quark to be right handed, so Fig. 2 is not related by an SU(2) rotation to $K_L \to \mu e$ and is not limited in size by limits on $B(K_L \to \mu e)$.

It is possible to write models[7,17] with $P_\mu^\perp > 10^{-3}$. Since any such model depends necessarily on hypothetical physics and parameters beyond the standard model, we do not want to associate our general observations with any particular model, and we content ourselves with emphasizing that (1) a nonzero value of $P_\mu^\perp$ can be achieved with a scalar effective Lagrangian and cannot arise from the standard model or left-right-symmetric theories, (2) showing $P_\mu^\perp$ is zero at the 10^{-3}–10^{-4} level will help constrain alternative ideas about *CP* violation. Obtaining numbers in this range in Higgs theories requires either ratios of vacuum expectation values significantly different from unity, or horizontal mixing so that masses larger than m_μ / m_s occur at the vertices.[18]

The most sensitive $P_\mu^\perp$ measurement can be done for $K^+ \to \pi^0 \mu^+ \nu$, because the Coulomb final-state interaction is negligible. Our arguments hold equally well for $K_L \to \pi^\mp \mu^\pm \nu$, even though K_L is a mixture of K^0 and $\bar{K}^0$ because K^0 and $\bar{K}^0$ produce μ^+ and μ^-, respectively, and do not interfere in $K_L \to \pi^- \mu^+ \nu$ or $K_L \to \pi^+ \mu^- \nu$; in $K_L \to \pi^\mp \mu^\pm \nu$ the Coulomb effects can be calculated[19] and give $P_\mu^\perp \le 10^{-3}$. Final-state interactions (strong or electromagnetic) do not flip sign under C, and can therefore be distinguished with certainty by comparing charge-conjugate processes.[4] In this short paper we have ignored possible contributions of tensor interactions; they often reduce to the other currents for K decays because of the limited number of independent vectors available.

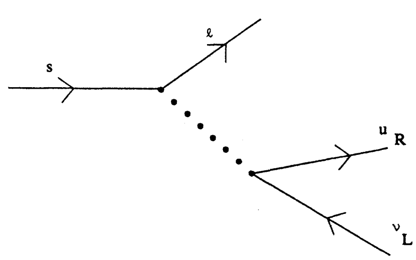

FIG. 2. Leptoquark contribution to semileptonic decays.

B. K_{l4} decays

The K_{l4} decays offer the possibility, at least in principle, to test for *CP* violation induced by *LR* models and other V, A models. The reason is the presence of nonvanishing matrix elements for both the vector and axial-vector hadronic currents.

An exhaustive study of the process $K^+(K) \to \pi^+(k_+)\pi^-(k_-)l^+(p)\nu(q)$ for vector and axial-vector currents is presented in Ref. 20. We follow their presentation closely, with minimal differences due to the choice of metric conventions; we also retain higher partial waves in the $\pi\pi$ system and $\Delta I = \frac{3}{2}$ contributions to see to what extent they could mimic the *CP*-violating contributions of interest. Let

$$\begin{aligned} a^\mu &= \langle \pi^+\pi^- | \bar{s}\gamma^\mu\gamma_5 u | K^+ \rangle \\ &= -[fP^\mu + gQ^\mu + r(K-P)^\mu]\frac{1}{M} , \\ v^\mu &= \langle \pi^+\pi^- | \bar{s}\gamma^\mu u | K^+ \rangle = \frac{(-i)}{M^3} h \epsilon^{\mu\nu\rho\sigma} K_\nu P_\rho Q_\sigma , \end{aligned} \tag{7}$$

and

$$\begin{aligned} &P = k_+ + k_- , \quad Q = k_+ - k_- , \quad L = p + q , \quad N = p - q , \\ &s_\pi = P^2 , \quad s_l = L^2 . \end{aligned} \tag{8}$$

For definiteness we consider *LR* models. Any interference between left- and right-handed currents in the leptonic sector gives terms proportional to the light neutrino mass; we thus consider only the left-handed leptonic current. In this case the amplitude is found to be proportional to

$$\begin{aligned} &\left[\frac{g}{\sqrt{2}}\right]^2 \sin\theta_C \frac{1}{M_L^2} \bar{\nu}^\mu \frac{1-\gamma_5}{2} \\ &\quad \times l \tfrac{1}{2} [\langle \pi^+\pi^- | \bar{s}\gamma^\mu u | K^+ \rangle (1+\alpha\xi) \\ &\quad - \langle \pi^+\pi^- | \bar{s}\gamma^\mu\gamma_5 u | K^+ \rangle (1-\alpha\xi)] . \end{aligned} \tag{9}$$

Note the coefficient of α changes sign between the two terms, from $(1-\gamma_5)+\xi\alpha(1+\gamma_5)$. Reference 20 stresses the redundancy between polarization measurements and angular distribution in this case; we will thus only consider the latter, and sum over lepton spins.

The difficulty in isolating the *CP*-violating terms (without resorting to an explicit comparison with the K^- decay) stems from the presence of strong interactions in the final state between pion pairs. We need thus to expand f, g, r, h in terms of the strong-interaction eigenstates (angular momentum and isospin channels). This is most easily done in the center of mass of the two pions. Taking the z axis in the direction of $\mathbf{L}$, and x in the direction defined by $\mathbf{L} \times \mathbf{Q}$, we have ($\theta_\pi$ is the angle between z and $\mathbf{k}_+$)

$$\begin{aligned} a_y &= -2g |\mathbf{k}_+| \sin\theta_\pi / M , \\ v_x &= -i4hE_\pi |\mathbf{K}| |\mathbf{k}_+| \sin\theta_\pi / M^3 , \end{aligned} \tag{10}$$

while a_0 and a_z do not involve $\sin\theta_\pi$. For further reference, it is useful to express the c.m. momenta in terms of invariant quantities. One has

$$E_\pi = \sqrt{s_\pi}/2, \quad |\mathbf{k}_+| = \sqrt{-Q^2/2}\ ,$$
$$|\mathbf{K}| = \left[\frac{(P\cdot L)^2 - s_\pi s_l}{s_\pi}\right]^{1/2} \equiv \frac{X}{\sqrt{s_\pi}}\ . \tag{11}$$

Linear combinations of a_0 and a_z can be directly expanded in terms of $P_l(\cos\theta)$. Their relative phase is determined by $e^{i\delta_l^I}$, where $I=0,1,2$ refers to the isospin channel considered. For the components x and y one uses $Y_l^{\mp 1}$, which can be expressed in terms of $(d/d\theta)P_l(\cos\theta) = -\sin\theta P_l'(\cos\theta)$ and l fixes the total angular momentum (h and g therefore start automatically with a p wave). Thus we define, following Ref. 20,

$$\frac{h}{M^2}\sqrt{-Q^2}X = F_3/\sqrt{s_l}, \quad g\sqrt{-Q^2} = F_2/\sqrt{s_l}\ , \tag{12}$$

and

$$F_{2,3} = \sum_{l,I} f_{l2,3}^I e^{i\delta_l^I(s_\pi)} P_l'(\cos\theta_\pi)\ . \tag{13}$$

F_1 and F_4 are introduced in a similar way for linear combinations of a_z and a_0 (see Ref. 20); $F_{1,4} = \sum f_{l1,4}^I e^{i\delta_l^I(s_\pi)} P_l(\cos\theta_\pi)$. The first contribution to (11) comes from the p wave. Bose statistics impose an odd isospin; since the transition considered is $\Delta I = \frac{1}{2}$, we need only consider $I=1$. For the even terms, $I=0$. A small contribution of $I=2$ could be due to $\Delta I = \frac{3}{2}$ (suppressed) transitions, but for semileptonic decays that occur at the quark level no such contributions are expected.

We note that the vector interaction starts with a p wave; we must thus look for a p-wave term in the axial-vector interaction if we want to observe the CP-violating phase difference not masked by strong-interaction effects. We concentrate thus on the interference of F_2 and F_3, i.e., on the term (which we label Z_{23}) proportional to h times the y projection (in the 2π c.m.) of the term proportional to g: gQ_y^ρ. (In principle, a $\cos\theta_\pi$ analysis and/or a comparison between K^+ and K^- decays might allow the extraction of a signal in other channels. The F_2-F_3 interference seems, however to be the most promising contribution.) From Eq. (10), the CP violation is then contained in

$$Z_{23} \equiv -\left[\frac{g^2}{2}\right]^2 \sin^2\theta_C \frac{1}{M_W^4}\frac{1}{2}$$
$$\times\left[(1+\alpha\xi)(1-\alpha^*\xi)i\frac{g^*h}{M^4}\epsilon^{\mu\nu\lambda\sigma}k_\nu P_\lambda Q_\sigma Q_y^\rho + (1-\alpha\xi)(1+\alpha^*\xi)(-i)\frac{gh^*}{M^4}\epsilon^{\rho\nu\lambda\sigma}k_\nu P_\lambda Q_\sigma Q_y^\mu\right]$$
$$\times(q^\mu p^\rho - g^{\mu\rho}pq + p^\mu q^\rho - i\epsilon^{\alpha\mu\beta\rho}q_\alpha p_\beta)\ . \tag{14}$$

For simplicity we have written this in terms of Q_y^ρ, where $\mathbf{Q}_y = (\mathbf{Q}\cdot\hat{\mathbf{y}})\hat{\mathbf{y}}$ and $\hat{\mathbf{y}}$ is a unit vector in the y direction [see text above Eq. (10)].

In order again to discriminate against strong-interaction phases, we keep only the term symmetrical in $p^\mu q^\rho, Z_{23}'$:

$$Z_{23}' \equiv -\left[\frac{g^2}{2M_W^2}\right]^2 \sin^2\theta_C \frac{\mathrm{Im}[(1+\alpha\xi)h(1-\alpha^*\xi)g^*]}{M^4}$$
$$\times(Q_y\cdot N)\epsilon^{\mu\nu\lambda\sigma}N_\mu k_\nu P_\lambda Q_\sigma\ , \tag{15}$$

or, finally,

$$Z_{23}' = \left[\frac{g^2}{2M_W^2}\right]^2 \frac{1}{M^4}\sin^2\theta_C \frac{1}{4}\left[1-\frac{m^2}{s_l}\right]^2$$
$$\times \mathrm{Im}[F_2^* F_3(1+\alpha\xi)(1-\alpha^*\xi)]\sin^2\theta_\pi \sin^2\theta_l \sin 2\phi\ , \tag{16}$$

where θ_l describes the lepton orientation with respect to the z axis, in the lepton center of mass (this axis is chosen parallel to the z axis in the 2π c.m.), and ϕ is the azimuthal angle between the lepton and $\pi\pi$ planes, seen from the pion c.m. Note the factor $(1-m_l^2/s_l)$ which suppresses $K_{\mu 4}$ relative to K_{e4}. A similar factor comes from the overall phase space, namely,

$$\text{phase space} = \frac{1}{M}\frac{1}{(2\pi)^6}\left[\frac{1}{4}\right]^4\left[\frac{-Q^2}{s_\pi}\right]^{1/2}\left[1-\frac{m^2}{s_l}\right]$$
$$\times X\, d\phi\, d\cos\theta_l\, d\cos\theta_\pi\, ds_\pi\, ds_l\ , \tag{17}$$

so for kinematical reasons K_{e4} is easier to observe. The contribution of Eq. (16) is of course the I_9 contribution of Ref. 20. One can check from their formula (4) that its $\sin 2\phi$ dependence makes it unique. Note that it is important to be able to measure distributions in θ_π and ϕ independently, and if possible θ_l as well.

The signal we are looking for results from the interference of the p waves. For the term in the square brackets in Eq. (16) we get a CP-violating contribution proportional to

$$A_{CP} \equiv 2\xi(\mathrm{Im}\alpha) f_{2,1}^1 f_{3,1}^1\ . \tag{18}$$

Recall $f_{2,1}^1$ and $f_{3,1}^1$ are the hadronic matrix elements from the quark-model contribution of Fig. 1(a), with the $\pi\pi$ system in the $I=l=1$ state, and α is the phase factor arising from Fig. 1(c). The strong-interaction corrections that could mimic CP violation come from higher waves:

$$F_2 = f_{1,2}^1 e^{i\delta_1^1} + (f_{2,2}^0 e^{i\delta_2^0} + f_{2,2}^2 e^{i\delta_2^2})3\cos\theta_\pi$$
$$+ f_{3,2}^1 e^{i\delta_3^1}(\tfrac{15}{2}\cos^2\theta_\pi - \tfrac{3}{2}) + \cdots \tag{19}$$

and similarly for F_3. The first term that could cause trouble is very small if one averages θ_π, keeping the weighting factor $\sin^2\theta_\pi$ already present in Eq. (16), over any interval where $\sin^2\theta_\pi$ is orthogonal to both $\cos\theta_\pi$ and to $5\cos^2\theta_\pi - 1$ (in particular, upon integration over $0 \le \theta_\pi \le \pi$, all nondiagonal contributions vanish due to the orthogonality of the spherical harmonics). The correction is then

$$\sin(\delta_2^0 - \delta_2^2)(f_{2,2}^2 f_{3,2}^0 - f_{2,2}^0 f_{3,2}^2) , \quad (20)$$

which is proportional to the square of the d wave and to the nonquark model $\Delta I = \frac{3}{2}$ contribution. Thus compared to Eq. (18) it should be very small if a source of CP violation is present, so the final-state interactions do not prevent one from using K_{l4} decays to look for CP violation.

Although we have found a term in the K_{e4} angular distribution that isolates vector effective Lagrangians, there does not seem to be any simple way to separate scalar effects from strong-interaction final-state effects in K_{e4}. The muon polarization in $K_{\mu 4}$ also receives contributions from both scalar and vector exchanges. [For example, scalar CP violation would mimic an A_7 term in Eq. (9′) of Ref. 20.] If nonzero CP-violating effects are observed in $K_{\mu 3}$ and K_{e4}, full measurements of the angular distribution and polarizations will be valuable.

By a Fierz transformation, leptoquark interactions and loop contributions can simulate both scalar and vector interactions, so ultimately it will be essential to untangle the full structure if any CP-violating effects are observed in any semileptonic decay.

In K_{l4} we showed above that the effect of strong-interaction phases can be separated from CP-violating phases by appropriate angular projection. The Coulomb phases, however, will still be present. Calculating their effect is possible, though the ultimate accuracy is limited by knowledge of the hadronic form factors, which enter in integrations. The Coulomb effects can be eliminated by studying $K^+ \to \pi^0\pi^0 l^+ \nu$, but the $\pi^0\pi^0$ system cannot be in a p wave so the coefficient of the CP-violating contribution to the $\sin 2\phi$ term is suppressed. These problems can be circumvented by comparing results from CP-conjugate processes, from $K^\pm$ decays and K_L decays.

How big can A_{CP} be? An experimental measurement in K_{e4} (Ref. 21) gives an upper bound on the relative phase of the f and g factors appearing in Eq. (12),

$$\omega_2 = 0.14 \pm 0.22 , \quad (21)$$

which can be related to the LR parameters through

$$\sin\omega_2 \simeq -2\xi \,\mathrm{Im}\alpha . \quad (22)$$

From a theoretical point of view, the only real limit comes from the bounds on LR mixing as discussed above; typically $|\xi| <$ few 10^{-3} if the right-handed Cabibbo angles are similar to the left ones.[14]

Compared to the dominant term, the coefficient of $\sin^2\theta_\pi \sin^2\theta_l \sin 2\phi$ could be suppressed for three reasons: (a) $2|\xi| \le 0.01$, (b) the phase factor $\mathrm{Im}\alpha$ could be of order unity, or smaller, and (c) from Eq. (7), when h enters there are an extra two or three powers of momenta (depending on the region of phase space); each power of momenta is presumably of order $\frac{1}{4}$. (h is of the same order as f,g,r.) For other approaches than the LR theory, (a) and (b) will be replaced by the appropriate statement.

In principle, more stringent limits on the phases could arise from CP violation in the $K \to \pi\pi$ channels, since the presence of LR mixing leads to a contribution to ϵ'. This contribution is enhanced both by matrix elements of pseudoscalar operators and by radiative corrections.[11,12] The parameters involved are however different even if we limit ourselves to a two-family model, and assume no phases is the leptonic sector. The contribution to ϵ' is indeed found to be proportional to

$$\epsilon' \sim \xi \,\mathrm{Im}(e^{-i(\delta_s - \delta_u)} + \epsilon^{i(\delta_d - \delta_u)}) \equiv \xi \,\mathrm{Im}\beta , \quad (23)$$

where $\delta_u, \delta_s, \delta_d$ are the phases parametrizing the right-handed mixing matrix (only three of them are needed). Although the estimates of matrix elements may vary, Eq. (1) strongly constrains β; typically

$$\xi \,\mathrm{Im}\beta < 10^{-6} .$$

The relevant phase factor α appearing in semileptonic decays is however given by (if no phase is assumed for the

TABLE I. This table shows the different ways various mechanisms produce CP-violating effects. The entries "yes" and "no" report whether each mechanism is able to produce an observable effect for the experiment in the left-hand column.

		Mechanism		
Experiment	Standard model	Strong CP violation	Non-standard-model V,A effective Lagrangian	Non-standard-model S,P effective Lagrangian
ϵ, ϵ'	Yes	No	Yes	Yes
d_n (at level $\gtrsim 10^{-27}$ e cm)	No	Yes	Yes	Yes
d_e (at level $\gtrsim 10^{-27}$ e cm)	No	No	Yes	Yes
$K_{\mu 3}$ transverse muon polarization	No	No	No	Yes
$K_{e4}\sin 2\phi$ term	No	No	Yes	No

leptons) $\alpha=\epsilon^{-i(\delta_s-\delta_u)}$ and is not directly constrained by Eq. (1).

A nice feature of V, A theories is that the hadronic matrix elements are all measured, so from the data of Ref. 21 accurate simulations can be made in preparation for future experiments.

The most important result of this section is that the coefficient of $\sin 2\phi$ arises *only* from non-standard-model theories with V, A effective Lagrangians. It is not hard to check that scalar or pseudoscalar effective Lagrangians do not populate the $\sin 2\phi$ term under consideration. Thus one can construct Table I—by studying several processes it is possible to make progress toward untangling the structure of CP violation.

This approach can be extended[5] to semileptonic decays of c,b quarks. The mass dependence of different models is different; in particular any effect from scalar effective Lagrangians may be enhanced for heavier quark systems. Also, as can be seen from Eq. (7), the vector matrix element in K_{l4} is suppressed by three powers of momenta. In D and B decays the larger phase space may allow larger effects for kinematical reasons. The approach can also be extended to other kaon decays and to the lepton sector, where the standard model always predicts zero or unobservably small CP-violating effects in decays. The μ polarization in $K_L \rightarrow \mu^+\mu^-$ and electron dipole moment are also interesting tests of CP in the leptonic sector, but are usually strongly constrained by the small value of the neutrino mass. It is however possible to construct models where large effects are possible, even with $m_\nu=0$ (Ref. 22). The approach can also be extended to $W^\pm$ production, where again the standard model predicts an unobservably small effect; CP violation could be studied in W production and decay by using $W\rightarrow t\bar{b}$ decay if $m_t < M_W$. Table I can be extended to include other K decays, and D, B, τ, and W decays.

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