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Semileptonic D-meson decays and the mechanism of CP violation

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Semileptonic D-meson decays can be used to distinguish between various descriptions of CP violation. A nonvanishing effect would rule out the Kobayashi-Maskawa scheme. An effect below 0.4% could be explained on the basis of Higgs-boson exchange. A large effect (up to 10%) would speak in favor of left-right-symmetric theories, with a relative phase between the V,A currents. Strong CP violation cannot contribute.

Sixteen years after the discovery of CP violation in K-meson decays,[1] we still do not have an accepted theory or even a unique description. Even if we accept the current dogma of gauge theories, we do not know whether CP nonconservation originates in Higgs- or gauge-boson interactions. Many models have been suggested and so it is very important to devise new tests which would distinguish among them. In this paper we suggest that semileptonic D-meson decays, such as $D \to K\pi l\nu$, might serve such a purpose. At the tree level, the process is governed by the exchange of a charged gauge boson and/or a Higgs boson, as shown in Fig. 1. We will analyze the predictions of various models and show that they may be substantially different. *Any* observation of CP nonconservation would be inconsistent with the Kobayashi-Maskawa extension of the standard model, while a large (up to 10%) effect could only be explained in the basis of left-right-symmetric gauge theories. Higgs-boson exchange gives at most a 0.4% effect, and different behavior for $l = \mu, e$. Further, $D \to Kl\nu$ only allows scalar and vector currents so a nonvanishing effect here would require both of these to interfere.

I. KOBAYASHI-MASKAWA (KM) SCHEME[2]

Since $D \to K\pi l\nu$ does not know about the existence of heavier quarks (at least at the tree level), then clearly we have an effective four-quark theory and so there can be no physical phase for gauge-boson interactions.[3] Therefore, the *KM scheme predicts no CP violation in* $D \to K\pi l\nu$. (By the KM scheme we mean interactions mediated by gauge bosons, not by Higgs bosons).

II. $SU(2)_L \times U(1)$ MODELS WITH CP-VIOLATING HIGGS-BOSON INTERATIONS

Once we go beyond the single Higgs doublet, we should expect the interactions of the Higgs bosons with quarks to violate CP. For example, in the minimal soft CP model with two Higgs doublets, one vacuum expectation value may be complex,[4] leading to both complex quark mass matrices and to complex physical Yukawa interactions. In this case CP violation resides both in the gauge-boson and in the Higgs-boson sector. On the other hand, there are models where one forbids $\Delta S = 2$ neutral-Higgs-boson exchange and where CP violation occurs only through the exchange of fairly light charged Higgs bosons.[5] In any case, we are to expect the CP-violating exchange of a charge Higgs boson in Fig. 1.

Let us denote the ratio of CP-violating to CP-conserving amplitudes by η_D. It is easy then to ar-

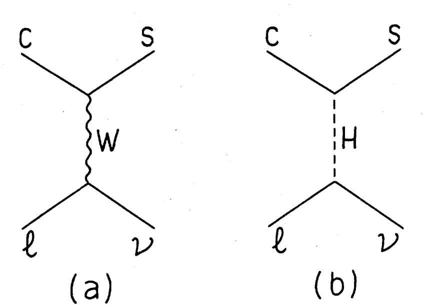

FIG. 1. Semileptonic decays $D \to K\pi l\nu$ at the quark level. The process is governed by the exchange of a charged gauge meson as in (a) or by the exchange of a charged Higgs scalar as in (b).

rive at

$$\eta_D^{\text{Higgs}} \simeq \frac{m_l m_c}{m_H{}^2} \sin\delta \;, \tag{1}$$

where δ is a CP-violating phase, m_l is the lepton mass, m_H is a charged-Higgs-boson mass, and m_c is the charmed-quark mass. From (1) we can put bonds on η_D^{Higgs}, since $m_H \gtrsim m_b$ in order not to be in conflict with B-meson decays. Therefore,

$$\eta_D^{\text{Higgs}}(\text{muon}) \leq m_\mu m_c/(5\ \text{GeV})^2 \simeq 4\times 10^{-3} \;, \tag{2}$$

whereas η_D^{Higgs} (electron) $\leq 2\times 10^{-5}$. Obviously, the effects are practically vanishing in the case when l=electron, and they are still quite small for l=muon. Most important, if the effect is observed at all, it can be done separately for $D\rightarrow K\pi\mu\nu$ and $D\rightarrow K\pi e\nu$ to look for the expected difference due to the different Higgs-boson—lepton couplings.

We can conclude that within $SU(2)_L \times U(1)$ models, the D decays are either CP conserving as in the KM scheme or $\eta_D \leq 4\times 10^{-3}$ as in the extended Higgs-boson case and μ/e universality is violated.

III. LEFT-RIGHT-SYMMETRIC GAUGE THEORIES

In these models, introduced by Mohapatra, Pati, Salam, and Senjanović,[6] the basic weak Lagrangian is invariant under space reflections, due to the presence of both $V-A$ and $V+A$ charged currents. The noninvariance of the vacuum results in the heavier right-handed gauge boson, and as a result, the low-energy weak processes appear as in $SU(2)_L \times U(1)$ theory, with corrections of order $(M_{W_L}/M_{W_R})^2$. As we shall see, these corrections will be responsible for CP violation in D decays.

A few words about the model are in order. The gauge group is $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$ with electric charge given by

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2} \;. \tag{3}$$

The fermions are placed in doublets, in a left-right-symmetric manner. To set the notation, we will write

$$\psi_{iL} = \begin{bmatrix} \mathcal{P}_i \\ \mathcal{N}_i \end{bmatrix}_L \;, \quad \psi_{iR} = \begin{bmatrix} \mathcal{P}_i \\ \mathcal{N}_i \end{bmatrix}_R \;, \tag{4}$$

where $\mathcal{P}_i$ and $\mathcal{N}_i$ are up and down unphysical fields (weak eigenstates). Introducing the Higgs multiplet needed to give masses to the quarks

$$\phi \equiv (\tfrac{1}{2}, \tfrac{1}{2}, 0), \quad \tilde{\phi} \equiv \tau_2 \phi^* \tau_2 \;, \tag{5}$$

we can write the most general Yukawa couplings

$$\begin{aligned} \mathcal{L}_Y = {} & \bar{\psi}_{iL}(h_{ij}\phi + \tilde{h}_{ij}\tilde{\phi})\psi_{jR} \\ & + \bar{\psi}_{jR}(h_{ij}\phi^\dagger + \tilde{h}_{ij}\tilde{\phi}^\dagger)\psi_{iL} \;. \end{aligned} \tag{6}$$

In (6) we have assumed that the Yukawa couplings are real. The theory conserves CP prior to symmetry breaking. Under parity conjugation

$$\psi_{iL} \leftrightarrow \psi_{iR} \;,$$

$$\phi \leftrightarrow \phi^\dagger, \quad \tilde{\phi} \leftrightarrow \tilde{\phi}^\dagger$$

which implies

$$h_{ij} = h_{ji}, \quad \tilde{h}_{ij} = \tilde{h}_{ji} \;. \tag{7}$$

Now, consistent with the minimization of the potential, ϕ gets complex vacuum expectation values for a range of parameters of the Lagrangian[7]

$$\langle \phi \rangle = \begin{bmatrix} Z' & 0 \\ 0 & Z \end{bmatrix} . \tag{8}$$

That in turn implies complex quark mass matrices

$$\begin{aligned} (M_{\mathcal{P}})_{ij} &= h_{ij} Z' + \tilde{h}_{ij} Z^* \;, \\ (M_{\mathcal{N}})_{ij} &= h_{ij} Z + \tilde{h}_{ij} Z'^* \;, \end{aligned} \tag{9}$$

so that (7) makes $M_{\mathcal{P}}$ and $M_{\mathcal{N}}$ symmetric:

$$M_{\mathcal{P}}^T = M_{\mathcal{P}}, \quad M_{\mathcal{N}}^T = M_{\mathcal{N}} \;. \tag{10}$$

The above matrices are diagonalized by biunitary transformations

$$U_L^\dagger M U_R = D \;. \tag{11}$$

Equation (10) leads then to[8]

$$U_R = U_L^* K \tag{12}$$

with

$$K = \begin{bmatrix} e^{i\phi_1} & 0 \\ 0 & e^{i\phi_2} \end{bmatrix}$$

for both up and down quarks. This is a useful result: The Cabbibo-type angles are the same in both left- and right-handed currents, but the phases are not.

From now on we specifically consider the case of four quarks relevent for the processes under consideration. We can write, for the gauge currents,[9]

$$\mathscr{L}_{WH} = g/\sqrt{2}(\bar{P}_L \gamma_\mu U_{CL} N_L W_L^{+\mu} + \bar{P}_R \gamma_\mu U_{CR} N_R W_R^{+\mu}) + \text{H.c.} \tag{13}$$

with

$$P_L = \begin{bmatrix} u_L \\ c_L \end{bmatrix}, \quad N_L = \begin{bmatrix} d_L \\ s_L \end{bmatrix}, \qquad P_R = \begin{bmatrix} u_R \\ c_R \end{bmatrix}, \quad N_R = \begin{bmatrix} d_R \\ s_R \end{bmatrix} \tag{14}$$

and

$$U_{CL} = U^{\dagger}_{\mathscr{P}R} U_{NL}, \qquad U_{CR} = U^{\dagger}_{\mathscr{P}R} U_{\mathscr{N}R}. \tag{15}$$

If we write

$$U_{CL,R} = \begin{bmatrix} e^{i\alpha}\cos\theta & e^{i\delta}\sin\theta \\ -e^{-i\delta}\sin\theta & e^{-i\alpha}\cos\theta \end{bmatrix}_{L,R} \tag{16}$$

and perform phase transformations

$$P_{L,R} \rightarrow \begin{bmatrix} e^{i\alpha_L} & 0 \\ 0 & e^{-i\delta_L} \end{bmatrix}_{P_{L,R}}, \qquad N_{L,R} \rightarrow \begin{bmatrix} 1 & 0 \\ 0 & e^{-i(\delta_L-\alpha_L)} \end{bmatrix}_{N_{L,R}}, \tag{17}$$

then we arrive at the useful form for the left-handed and right-handed Cabbibo rotations

$$U_{CL} = \begin{bmatrix} \cos\theta & \cos\theta \\ -\sin\theta & \cos\theta \end{bmatrix}, \qquad U_{CR} = \begin{bmatrix} e^{i\alpha}\cos\theta & e^{i\delta}\sin\theta \\ -e^{-i\delta}\sin\theta & e^{-i\alpha}\cos\theta \end{bmatrix}, \tag{18}$$

where $\alpha = -2\alpha_L$ and $\delta = \phi_2 - \phi_1 - 2\delta_L$. Equation (18) is our basic result and it reflects the well-known fact that the left-handed interactions are *CP* conserving in the case of four quarks. The same is not true, obviously, for right-handed interactions. Owing to spontaneous symmetry breaking, the theory has become *CP* violating. We would like to mention that spontaneous breaking of *CP* invariance is not only philosophically appealing, but also can account for the natural suppression[10] of strong *CP* nonconservation, which results from nonperturbative phenomena.[11]

What about the actual predictions of the model? We will distinguish between the two basically different cases.

(a) *Neutrino is a Dirac particle.*[6] In this case ν couples to W_R and from Fig. 2(a) we easily arrive at the expression

$$\eta_D^{\text{Dirac}}(LR) \simeq \left[\frac{m_L}{m_R}\right]^2 \sin\alpha , \tag{19}$$

where m_L and m_R are the masses of $W_L^{\pm}$ and $W_R^{\pm}$. From β and μ decays, we have[10] $(m_L/m_R)^2 < \frac{1}{10}$ while the angle α is unconstrained so

$$\eta_D^{\text{Dirac}}(LR) \lesssim 10^{-1} . \tag{20}$$

(b) *Neutrino is a Majorana particle.* In this case ν_R is a heavy Majorana neutral lepton[12] $(m_{\nu_R} \simeq M_{W_R})$ and so it does not participate in low-energy weak interactions. The interesting aspect of this model is that the left-handed neutrino has a naturally small Majorana mass.[3] The point here is that the *CP* violation in *D*-meson decays will arise from W_L-W_R mixing, as is seen from Fig. 2(b):

We obtain

$$\eta_D^{\text{Maj}}(LR) \simeq \tan\xi_{LR} \sin\alpha , \tag{21}$$

where ξ_{LR} is a mixing between W_L and W_R. Phenomenological analysis implies[13] $\tan\xi_{LR} \leq 6\%$, while α is unconstrained, so that

$$\eta_D^{\text{Maj}}(LR) \leq 6\% . \tag{22}$$

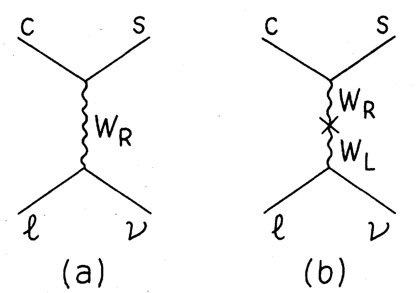

FIG. 2. Graphs which lead to *CP*-violating pieces of the amplitude for *D* decays (there is always a W_L exchange, which is *CP* conserving). When the neutrino is a Dirac particle, it couples to W_R and so there is a direct W_R-exchange graph, as in (a). In the Majorana case, ν does not couple to W_R, but there is a nonvanishing contribution through W_L-W_R mixing [see diagram (b)].

IV. DISCUSSION

As is evident from our analysis, we have no way of predicting the value of η_D, except in the case of the KM scheme: $\eta_D(KM)=0$ to the lowest order. However, the various models that we have analyzed are in principle distinguishable. A large effect of order of a few percent could only be explained through the exchange of right-handed gauge bosons. Consequently, these decays could tell us not only about the origin of *CP* nonconservation, but also help us understand the origin of parity violation in low-energy weak interactions. An effect $\lesssim \frac{1}{2}\%$ could also be due to direct Higgs-boson exchange; the behavior in μ and e modes should distinguish.

Before we conclude, we would like to emphasize why *D*-meson decays may be important in deciding between the competing models of *CP* nonconservation. Namely, all these theories were suggested in order to agree with the observed *CP* violation in *K*-meson decays (they of course predict different values for ϵ'/ϵ which may also help decide). Another important observable for which they give different predictions is the electric dipole moment of the neutron (d_n). Unfortunately, the situation there is completely obscured by the strong *CP* violation: as is known, the KM scheme predicts[14] practically vanishing d_n, whereas the Higgs-boson models (fundamental or dynamical) and left-right-symmetric theories tend to lead to $d_n \simeq 10^{-25} - 10^{-28}$ e cm.[15] However, in the KM scheme we have no control over strong *CP*, so that a large dipole moment of the neutron in the range $10^{-24}-10^{-27}$ e cm could arise from strong *CP* violation and unfortunately tell us nothing about the nature of weak *CP* nonconservation.

Experimentally, since $D \rightarrow K\pi l \nu$ is a large branching ratio for *D* decay, it may be possible in pratice to search for *CP* violation there. Probably, future experiments at SPEAR can have sufficient statistics, and perhaps also at the Femilab fixed-target Tevatron where over 10^8 *D*'s per year should be produced and good vertex detectors should be available. The techniques to find effects are the same as those for K_{l4} and are described in detail in Ref. 16; a treatment for D_{l4} is given in Ref. 17.

We would like to add, before closing, that recently a BNL-Yale collaboration[18] presented their experimental results on *CP* violation in the $K_{\mu 3}$ process. The effect was found to be less than about 0.1% and consistent with a vanishing result. That, unfortunately, does not put a limit on relevant parameters for *D*-meson decay in the left-right-symmetric theory, since it is phase δ (and *not* α) which is relevant for this process. On the other hand, from $K \rightarrow 2\pi$, one gets[19] $\sin\delta\, m_L{}^2/m_R{}^2 \approx 10^{-3}$, so that the findings are consistent with the theoretical predictions. This experiment may be relevant for Weinberg-type[5] models, but the experimental result would have to be improved somewhat before one could rule out the theoretical predictions.[20]

In summary, we have shown that the semileptonic *D*-meson decays may play in important role in determining the origin of *CP* nonconservation, observed up to now only in *K*-meson decays. In particular they have the potentials, if *CP* violation is observed, to unambiguously decide whether the KM scheme, Higgs-boson schemes, or the competing left-right-symmetric theories are correct.

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