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Enhanced CP violations in Hadronic Charm Decays

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ABSTRACT

The observation of CP violation in the decay of D mesons will not necessarily be a signal of new physics. If certain strong interaction matrix elements are enhanced, in analogy to the $\Delta I = 1/2$ rule of K decays, then CP violation will be observable in strangeness conserving decays.

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CP violation in the standard model is a subject of continuing interest. At present CP violations have been observed only in kaon physics. The Ks have the property that most of the CP asymmetry comes from the mixing of the K^0 and $\bar{K}^0$, rather than their decay. In this letter we discuss the decay of the D meson.

CP violation in the decay of a particle manifests itself when the partial decay rate of an initial to some final state is different from the CP conjugate decay $\Gamma(\imath \to f) \neq \Gamma(\bar{\imath} \to \bar{f})$. CPT invariance guarantees only the equality of the total decay rates $\Gamma(\imath) = \Gamma(\bar{\imath})$

In this note we will argue that it is possible that such CP violations may be observable in the decays of D mesons if effects occur which are similar to those responsible for the $\Delta I = 1/2$ rule in kaons. The $\Delta I = 1/2$ rule comes about because the matrix elements of certain weak operators are enhanced relative to naive expectations. The exact causes of this phenomenon are not well understood. As has been noted [1], a similar effect in D mesons is unlikely to have large effects on their branching ratios. We point out, however, that the enhancement of hadronic matrix elements is likely to increase the CP violation.

In the standard model, the source of CP violation is the phases in V_{ij}, the KM matrix [2]. In a world with three generations there is one phase which cannot be removed by making phase rotations on the various quark fields. In a two generation world, one can easily see that there is enough freedom to remove all the phases from the KM matrix, and therefore the standard model predicts no CP violation. Since the decay of the D meson involves at tree level only the first two generations, one might be tempted to conclude that CP violation occurs only at loop level. This is not the case. It is easy to show that in a three generation model it is possible to make a most three of V_{cd}, V_{cs}, V_{ud}, and V_{us} real simultaneously. This is because the 2×2 submatrix need not be unitary by itself. Therefore, there is CP violation at tree level in the standard model in processes like D decay, which do not involve third generation quarks directly.

As an example, the two diagrams shown in figure 1 both connect the initial D meson to the same final state. The first involves a factor of $V_{cs}^* V_{us}$, while the second has $V_{cd}^* V_{ud}$. Thus, these two diagrams have different phases, and their interference can manifest itself as a CP violation. As we shall see, it is possible that CP violations occur in any strangeness conserving decay.

We will use the approximate $SU(3)$ flavor symmetry as a bookkeeping device in the discussion of D decay. Following reference [3], we resolve the weak interaction effective hamiltonian responsible for the $\Delta Charm = -1$ process into parts which transform as irreducible representations under flavor $SU(3)$. The hamiltonian is of the form

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} T_{ij}^k (\bar{q}^{i\alpha} \Gamma c_\alpha)(\bar{q}^{j\beta} \Gamma q_{k\beta}) \tag{1}$$

where q are light quark fields, having flavor index i, j and color index α, β; Γ is a gamma matrix structure which will be discussed below; and T^k_{ij} are coefficients given below. This hamiltonian transforms under flavor $SU(3)$ as $3 \otimes 3 \otimes \bar{3} = 15_M \oplus \bar{6} \oplus 3 \oplus 3$. The 15_M is symmetric in i, k and traceless when i or k is contracted with j, the $\bar{6}$ is antisymmetric and traceless, while the traces of the symmetric and antisymmetric parts are the two 3's.

We may use a renormalization group analysis [4] to compute the coefficients of the various operators described above. The bare operators in the $\Delta Charm = -1$, strangeness conserving decay are

$$\begin{aligned}\mathcal{H}_{bare} = \frac{4G_F}{\sqrt{2}} \big(& V^*_{cd} V_{ud} (\bar{d}^\alpha L^\mu c_\alpha)(\bar{u}^\beta L_\mu d_\beta) \\ & + V^*_{cs} V_{us} (\bar{s}^\alpha L^\mu c_\alpha)(\bar{u}^\beta L_\mu s_\beta) + V^*_{cb} V_{ub} (\bar{b}^\alpha L^\mu c_\alpha)(\bar{u}^\beta L_\mu b_\beta)\big)\end{aligned} \tag{2}$$

where $L^\mu = \gamma^\mu (1 - \gamma_5)/2$. The renormalized effective hamiltonian is a function of the scale μ. We assume that at $\mu = M_W$, the W boson mass, the effective hamiltonian is the same as equation (2). Assuming the top quark mass is bigger than 60 GeV or so, we may compute the effective operator at $\mu = m_c$, the charm quark mass, via a two step process. The effective hamiltonian is run from $\mu = M_W$ to $\mu = m_b$, the b quark mass, at which scale the b quark is frozen out, and then the hamiltonian is run down to $\mu = m_c$.

Equation (2) may be written in the form

$$\mathcal{H}_{bare} = \frac{G_F}{\sqrt{2}} \left((2\mathcal{O}^{(15_M)} + 2\mathcal{O}^{(\bar{6})})\Sigma + \left(3\mathcal{O}_2 - \mathcal{O}_1 + \mathcal{O}^{(15_M)\prime}\right)\Delta + 4V^*_{cb}V_{ub}\mathcal{O}_8 \right) \tag{3}$$

where

$$\begin{aligned}\Sigma &= \frac{1}{2}(V^*_{cs}V_{us} - V^*_{cd}V_{ud}) \\ \Delta &= \frac{1}{2}(V^*_{cs}V_{us} + V^*_{cd}V_{ud})\end{aligned}$$

and

$$\begin{aligned}\mathcal{O}^{(15_M)} =& (\bar{s}^\alpha L^\mu c_\alpha)(\bar{u}^\beta L_\mu s_\beta) + (\bar{u}^\alpha L^\mu c_\alpha)(\bar{s}^\beta L_\mu s_\beta) - (\bar{d}^\alpha L^\mu c_\alpha)(\bar{u}^\beta L_\mu d_\beta) - (\bar{u}^\alpha L^\mu c_\alpha)(\bar{d}^\beta L_\mu d_\beta) \\ \mathcal{O}^{(15_M)\prime} =& (\bar{d}^\alpha L^\mu c_\alpha)(\bar{u}^\beta L_\mu d_\beta) + (\bar{u}^\alpha L^\mu c_\alpha)(\bar{d}^\beta L_\mu d_\beta) + (\bar{s}^\alpha L^\mu c_\alpha)(\bar{u}^\beta L_\mu s_\beta) + (\bar{u}^\alpha L^\mu c_\alpha)(\bar{s}^\beta L_\mu s_\beta) \\ & - 2(\bar{u}^\alpha L^\mu c_\alpha)(\bar{u}^\beta L_\mu u_\beta) \\ \mathcal{O}^{(\bar{6})} =& (\bar{s}^\alpha L^\mu c_\alpha)(\bar{u}^\beta L_\mu s_\beta) - (\bar{u}^\alpha L^\mu c_\alpha)(\bar{s}^\beta L_\mu s_\beta) - (\bar{d}^\alpha L^\mu c_\alpha)(\bar{u}^\beta L_\mu d_\beta) + (\bar{u}^\alpha L^\mu c_\alpha)(\bar{d}^\beta L_\mu d_\beta) \\ \mathcal{O}_1 =& (\bar{u}^\alpha L^\mu c_\alpha)((\bar{u}^\beta L_\mu u_\beta) + (\bar{d}^\beta L_\mu d_\beta) + (\bar{s}^\beta L_\mu s_\beta)) \\ \mathcal{O}_2 =& (\bar{u}^\alpha L^\mu c_\beta)((\bar{u}^\beta L_\mu u_\alpha) + (\bar{d}^\beta L_\mu d_\alpha) + (\bar{s}^\beta L_\mu s_\alpha)) \\ \mathcal{O}_8 =& (\bar{u}^\alpha L^\mu c_\beta)(\bar{b}^\beta L_\mu b_\alpha)\end{aligned}$$

Here we have used a Fierz rearrangement to write $\mathcal{O}_2$ and $\mathcal{O}_8$ in this form. The operators $\mathcal{O}^{(15_M)}$ and $\mathcal{O}^{(15_M)\prime}$ are two different members of the same $SU(3)$ 15-plet. The operators $\mathcal{O}_1$, $\mathcal{O}_2$, and $\mathcal{O}_8$ transform as members of triplets.

The coefficient Δ would be 0 if the 2×2 submatrix of the KM matrix were unitary. If the world has only three generations (as we assume throughout), then unitarity of the KM matrix requires that $V_{cb}^* V_{ub} = -2\Delta$.

Since the strong interactions conserve flavor $SU(3)$, one sees that it is not possible to mix different $SU(3)$ multiplets and that all members of an $SU(3)$ multiplet must renormalize the same way. It is, however, possible to mix operators with different gamma matrix structures. The tracelessness of the 15_M and $\bar{6}$ representations of $SU(3)$ guarantees that there are no gluon "penguin" diagrams for these operators, only gluon corrections to the four-fermi vertex. Therefore the 15_M and $\bar{6}$ operators do not mix with any other operators; they are multiplicatively renormalized.

For the triplet operators the situation is more complicated. In this case the operators $\mathcal{O}_1$, $\mathcal{O}_2$, and $\mathcal{O}_8$ mix not only with each other, but, through "penguin" diagrams, with other operators as well. $\mathcal{O}_1$, $\mathcal{O}_2$, and $\mathcal{O}_8$ plus the operators listed below is a set which is closed under renormalization.

$$
\begin{aligned}
\mathcal{O}_3 &= (\bar{u}^\alpha L^\mu c_\alpha)((\bar{u}^\beta L_\mu u_\beta) + (\bar{d}^\beta L_\mu d_\beta) + (\bar{s}^\beta L_\mu s_\beta) + \ldots + (\bar{q}^\beta L_\mu q_\beta)) \\
\mathcal{O}_4 &= (\bar{u}^\alpha L^\mu c_\beta)((\bar{u}^\beta L_\mu u_\alpha) + (\bar{d}^\beta L_\mu d_\alpha) + (\bar{s}^\beta L_\mu s_\alpha) + \ldots + (\bar{q}^\beta L_\mu q_\alpha)) \\
\mathcal{O}_5 &= (\bar{u}^\alpha L^\mu c_\alpha)((\bar{u}^\beta R_\mu u_\beta) + (\bar{d}^\beta R_\mu d_\beta) + (\bar{s}^\beta R_\mu s_\beta) + \ldots + (\bar{q}^\beta R_\mu q_\beta)) \\
\mathcal{O}_6 &= (\bar{u}^\alpha L^\mu c_\beta)((\bar{u}^\beta R_\mu u_\alpha) + (\bar{d}^\beta R_\mu d_\alpha) + (\bar{s}^\beta R_\mu s_\alpha) + \ldots + (\bar{q}^\beta R_\mu q_\alpha)) \\
\mathcal{O}_7 &= (\bar{u}^\alpha L^\mu c_\alpha)(\bar{b}^\beta L_\mu b_\beta)
\end{aligned}
$$

where $R^\mu = \gamma^\mu(1+\gamma_5)/2$. Here "$+ \ldots + (\bar{q}q)$" is meant to indicate a sum over all other active quarks. That is, when running from M_W to M_b, we add c and b quarks, and below the m_b we add only the c quark.

The anomalous dimension matrix for this set of operators is

$$
\gamma_{ij} = \frac{g^2}{8\pi^2} \begin{pmatrix}
-1 & 3 & -1/9 & 1/3 & -1/9 & 1/3 & 0 & 0 \\
3 & -1 & -1/3 & 1 & -1/3 & 1 & 0 & 0 \\
0 & 0 & -11/9 & 11/3 & -2/9 & 2/3 & 0 & 0 \\
0 & 0 & 3-n/9 & -1+n/3 & -n/9 & n/3 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -3 & 0 & 0 \\
0 & 0 & -n/9 & n/3 & -n/9 & -8+n/3 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 3 \\
0 & 0 & -1/9 & 1/3 & -1/9 & 1/3 & 3 & -1
\end{pmatrix} + O(g^4) \quad (4)
$$

where g is the strong coupling constant, n is the number of active quarks, either 4 or 5. Let the coefficient functions of the operators be $C_i(\mu)$. By assumption, cf. equation (3),

$$
C(M_W) = \frac{G_F}{\sqrt{2}} \Delta(3, -1, 0, 0, 0, 0, 0, -8) \quad (5)
$$

The evolution equation for C is

$$\left(\mu\frac{\partial}{\partial\mu}+\beta(g)\frac{\partial}{\partial g}-\gamma^T\right)C(\mu)=0 \tag{6}$$

where $\beta(g) = (11-2/3n)/(16\pi^2)g^3 + O(g^5)$. The solution is, in the leading logarithm approximation

$$C(\mu')_i = M_{ij}\left(\frac{\alpha(\mu)}{\alpha(\mu')}\right)^{(3e_j)/(33-2n)} M^{-1}_{jk}C(\mu)_k \tag{7}$$

where e_j are the eigenvalues of $(-8\pi^2/g^2)\gamma$ and M is such that $M^{-1}\gamma^T M$ is diagonal. The ratios of α's are given by the standard one loop formula, where we have used [5] $\Lambda_{QCD} = 230$ MeV in the 4 quark theory, which is equivalent to $\Lambda_{QCD} = 153$ MeV in the 5 quark theory.

We find that the effective hamiltonian renormalized at a scale m_c is*

$$\begin{aligned}\mathcal{H} = \frac{G_F}{\sqrt{2}}\Bigg(&\Big[(1.52)\mathcal{O}^{(15_M)} + (3.46)\mathcal{O}^{(\bar{6})}\Big]\Sigma + \\ &\Big[(-2.70)\mathcal{O}_1 + (4.22)\mathcal{O}_2 + (.074)\mathcal{O}_3 + (-.182)\mathcal{O}_4 + \\ &(.055)\mathcal{O}_5 + (-.212)\mathcal{O}_6 + \left(\frac{1.52}{2}\right)\mathcal{O}^{(15_M)'}\Big]\Delta\Bigg)\end{aligned} \tag{8}$$

Of course, $\mathcal{O}_7$ and $\mathcal{O}_8$ do not appear below the b quark scale. It is, however, important to include the effects of $\mathcal{O}_8$ in the low energy physics. Leaving out this operator at the high scale would have resulted in coefficients of $\mathcal{O}_3$, $\mathcal{O}_4$, $\mathcal{O}_5$, $\mathcal{O}_6$ of about twice the magnitude of those given above.

The interesting thing about equation (8) is the enhancement of $\mathcal{O}_1$ and $\mathcal{O}_2$, and the relatively large coefficient of $\mathcal{O}_6$. $\mathcal{O}_6$ is an operator with different lorentz structure, involving both left- and right-handed quarks. Matrix elements of operators like this are frequently considerably larger than a naive estimate would indicate.

In reference [1] it is argued that the enhancement to this operator is likely to be smaller than for the comparable operator K decay. Essentially, this follows from the fact that the charm quark mass is about the same as the chiral symmetry breaking scale Λ_C. Where before we found enhancements like $\Lambda_C^2/m_s^2 > 10$, we will now find only $\Lambda_C^2/m_c^2 < 1$. On the other hand, we know that there are large final state interactions in charm quark decays [6], and yet this argument would have persuaded us that these phase shifts should be small. We prefer to let this issue be resolved by experiment.

*A similar expression to this was given in reference [1]. Unfortunately only numerical values were given; the procedure was not described in detail.

The reason that an enhancement of the triplet causes enhancement of CP violation can be seen by examining the form of Σ and Δ. Using the parameterization of the KM matrix given in reference [7],

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \tag{9}$$

we find

$$\begin{aligned} \Delta &= -\frac{1}{2}e^{-i\delta}s_{23}s_{13}c_{13} \\ \Sigma &= s_{12}c_{12}c_{23}c_{13} + \frac{1}{2}c_{13}s_{23}s_{13}e^{-i\delta} - s_{12}^2c_{13}s_{23}s_{13}e^{-i\delta} \end{aligned} \tag{10}$$

That is, Δ is small in magnitude, but has a large phase, while Σ is essentially real. Since the triplet operator multiplies Δ, its enhancement increases the CP violation.

Consider the decay of a D meson to a two pseudoscalar final state. Bose symmetry allows only five invariant amplitudes:

$$\begin{aligned} \langle[8]^i_j|[\bar{6}]_{kl}|D_r\rangle &= S\mathcal{T}^i_{jklr} \\ \langle[8]^i_j|[15_M]^{kl}_m|D_r\rangle &= E\mathcal{T}^{ikl}_{jmr} \\ \langle[27]^{ij}_{kl}|[15_M]^{mn}_p|D_r\rangle &= T\mathcal{T}^{ijmn}_{klpr} \\ \langle[8]^i_j|[3]^k|D_r\rangle &= F\mathcal{T}^{ik}_{jr} \\ \langle[1]|[3]^i|D_r\rangle &= G\mathcal{T}^i_r \end{aligned} \tag{11}$$

where by $[3]^i$ we mean the sum of the triplet operators given in equation (8), and $[\bar{6}]_{kl}$ and $[15_M]^{mn}_p$ include the numerical coefficients. The tensor structures $\mathcal{T}$ are made out the of $SU(3)$ invariant objects δ^i_j and ϵ_{ijk} and have the symmetry and tracelessness properties appropriate for the terms on the left hand sides. The normalizations of the $\mathcal{T}$ tensors are chosen to meke the amplitudes given below simple.

We may now see why an enhancement of F and G could produce observable CP violating effects. Table 1 of reference [3] gives the amplitudes for all the two meson final states. They are of the form

$$a(D \to \mathcal{PP}) = a\Sigma + b\Delta \tag{12}$$

where a and b are different combinations of S, E, T, F, and G, depending on the two pseudoscalar final state $\mathcal{PP}$. For example,

$$a(D^+ \to K^+\bar{K}^0) = (3T - E - S)\Sigma + \left(T + \frac{E}{2} + \frac{3F}{2}\right)\Delta \tag{13}$$

The asymmetry A between this decay and its CP conjugate is

$$A \equiv \frac{\Gamma(D^+ \to \mathcal{P}\mathcal{P}) - \Gamma(D^- \to \bar{\mathcal{P}}\bar{\mathcal{P}})}{\Gamma(D^+ \to \mathcal{P}\mathcal{P}) + \Gamma(D^- \to \bar{\mathcal{P}}\bar{\mathcal{P}})} = \frac{2\mathrm{Im}(a^*b)\mathrm{Im}(\Sigma^*\Delta)}{|a|^2|\Sigma|^2 + |b|^2|\Delta|^2 + 2\mathrm{Re}(a^*b)\mathrm{Re}(\Sigma^*\Delta)} \approx s_\delta \frac{s_{23}s_{13}}{s_{12}} \mathrm{Im}\left(\frac{b}{a}\right) \tag{14}$$

where the approximation holds if $|b|$ is not much larger than $|a|$. If $s_\delta \mathrm{Im}(b/a) \approx 1/2$, $s_{12} = .220$, $s_{23} = .05$, and $s_{13} = .007$, then $A \approx 8 \times 10^{-4}$. To observe an asymmetry A as an m standard deviation effect in a decay mode with a branching ratio B requires $N > m^2/(A^2B)$ mesons. For example† $BR(D^+ \to K^+\bar{K}^0) = (8 \pm 2) \times 10^{-3}$, so for a 3σ effect in this decay mode 2×10^9 D mesons are required, a number which is a bit larger than can be obtained in present experiments.

On the other hand, as we have seen, an enhancement of the triplet operator increases only $|b|$. Therefore, it will have the effect of increasing the asymmetry. An enhancement of $|b|$ by a factor of 20, as occurs in the $\Delta I = 1/2$ rule of K decays, would reduce the number of D mesons needed by a factor of 400, so only 5×10^6 would be required.

This effect is unlike the situation in K decays, in which enhancement of the $\Delta I = 1/2$ operator makes the observation of ϵ'/ϵ more difficult. In that case, the denominator of the expression comparable to equation (14) contains two operators with coefficients of the same size, so when one operator is enhanced the asymmetry gets suppressed.

It is important to understand the role that the $SU(3)$ flavor symmetry has played in this analyis. In the derivation of equation (8) the $SU(3)$ was merely a bookkeeping device; it was used to organize the operators in a simple way, but any other grouping would have yielded the same result. $SU(3)$ symmetry really should be used to relate different decay modes to each other, but, in arguing that the matrix elements of the triplet operators may be enhanced, we do not really need to do this. We may take all the different hadronic matrix elements of $[3], [\bar{6}]$, and $[15_M]$ to be different, not related by equation (11). In that case we simply note that the matrix elements of [3] are the ones which are likely to be large, and they are multiplied by the coefficient Δ.

In reference [10] it was noted that it is possible to obtain tree level CP violation in $D_s^+ \to K^+\pi^0$ decays from the interference of the "spectator" diagram with the "annihilation" diagram. Because the annihilation diagram is suppressed by f_D^2/m_D^2, where f_D is the D meson decay constant, the CP violation in the D_s^+ decays from this mechanism is small, requiring about 4×10^{10} D mesons to manifest itself as a 3σ effect. In D^0 and D^+ decays the effect was too small to be observed. It was also pointed out that the anomalously short

†This branching ratio is from the Review of Particle Properties, reference [5], based on references [8] and [9].

lifetime of the D_s^+ relative to the D^+ might have been an indication that the annihilation diagram was larger than naively expected, in which case the CP violation would be easier to observe. Today it is believed that the short lifetime of the D_s^+ is not due to an enhancement of the annihilation diagram, rather it is caused by large phase shifts in the final state [6]. As we have seen, these phase shifts are crucial to the observation of CP violation.

It is worth noting that the three and four body strangeness conserving decays of the D to are also good places to look for asymmetries; there may be an enhancement of the triplet operator in a decay to a multibody final state. For example‡, $BR(D^+ \to K^+K^-\pi^+ \text{ (nonresonant)}) = (4 \pm 1) \times 10^{-3}$, just a factor of 2 smaller than the two body decay above. Since the two diagrams shown in figure 1 have different phases, it is very easy to see how CP violations occur in the decay to this final state.

An outstanding puzzle in D decays is the ratio $\Gamma(D^0 \to K^+K^-)/\Gamma(D^0 \to \pi^+\pi^-)$. Experimentally§, this ratio is about 7/2. $SU(3)$ predicts that the decay rates should be nearly identical, because the amplitudes are [3]

$$\begin{aligned} a(D^0 \to K^+K^-) &= \ (2T + E - S)\Sigma + \frac{1}{2}(3T + 2G + F - E)\Delta \\ a(D^0 \to \pi^+\pi^-) &= -(2T + E - S)\Sigma + \frac{1}{2}(3T + 2G + F - E)\Delta \end{aligned} \tag{15}$$

If we wish to explain this ratio by the enhancement of the triplet operators, we need $(2G+F)\Delta$ of the same order of magnitude as $(2T+E-S)\Sigma$, or an enhancement of nearly three orders of magnitude. This would lead to gigantic CP violations, an asymmetry of order 1. This is of course very unlikely; the preferred explanation for the larger rate into kaons is that $SU(3)$ violating effects are large in this decay.

While the violations of $SU(3)$ flavor symmetry cannot be ignored in discussing the decays of the D, it is likely that the qualitative features of the analysis described here are valid. Observation of CP violation in D meson decays may not be a signal of new physics, just of more low energy effects that we don't understand.

We are grateful to E. Eichten for a discussion.

‡From reference [5], based on references [8] and [11].

§From reference [5], based on references [8] and [12].

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Figure 1

Two diagrams for charm decay into the same final state. The first diagram has a coefficient $V_{cs}^* V_{us}$, while the second has $V_{cd}^* V_{ud}$.