Interference between doubly-Cabibbo-suppressed and Cabibbo-favored amplitudes in $D^0 \to K_S(\pi^0, \eta, \eta')$ decays

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A definite relative phase and amplitude exists between the doubly-Cabibbo-suppressed amplitude for $D^0 \to K^0 M^0$ and the Cabibbo-favored amplitude for $D^0 \to \bar{K}^0 M^0$, where $M^0 = (\pi^0, \eta, \eta')$: $A(D^0 \to K^0 M^0) = -\tan^2\theta_C A(D^0 \to \bar{K}^0 M^0)$. Here θ_C is the Cabibbo angle. This relation, although previously recognized (for $M^0 = \pi^0$) as a consequence of the U-spin subgroup of SU(3), is argued to be less sensitive to corrections involving SU(3) breaking than related U-spin relations involving charged kaons or strange D mesons. A corresponding relation between $D^+ \to K^0\pi^+$ and $D^+ \to \bar{K}^0\pi^+$ is not predicted by U-spin. As a consequence, one expects the asymmetry parameters $R(D^0, M^0) \equiv [\Gamma(D^0 \to K_S M^0) - \Gamma(D^0 \to K_L M^0)/[\Gamma(D^0 \to K_S M^0) + \Gamma(D^0 \to K_L M^0)]$ each to be equal to $2\tan^2\theta_C = 0.106$, in accord with a recent CLEO measurement $R(D^0) \equiv R(D^0, \pi^0) = 0.122 \pm 0.024 \pm 0.030$. No prediction for the corresponding ratio $R(D^+)$ is possible on the basis of U-spin.

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The large number of flavor-tagged neutral D mesons collected by the CLEO Collaboration has permitted unprecedented studies of branching fractions, shedding light on details of the Cabibbo-Kobayashi-Maskawa matrix, flavor mixing, and signatures for new physics. Recently these data have been analyzed for the decays $D \to K_S\pi$ and $D \to K_L\pi$ [1]. Whereas the rate asymmetry

$$R(D^0) \equiv \frac{\Gamma(D^0 \to K_S\pi^0) - \Gamma(D^0 \to K_L\pi^0)}{\Gamma(D^0 \to K_S\pi^0) + \Gamma(D^0 \to K_L\pi^0)} \quad (1)$$

is found to be nonzero, $R(D^0) = 0.122 \pm 0.024 \pm 0.030$, the corresponding asymmetry for D^+ decays,

$$R(D^+) \equiv \frac{\Gamma(D^+ \to K_S\pi^+) - \Gamma(D^+ \to K_L\pi^+)}{\Gamma(D^+ \to K_S\pi^+) + \Gamma(D^+ \to K_L\pi^+)} \quad (2)$$

is consistent with zero: $R(D^+) = 0.030 \pm 0.023 \pm 0.025$. In this paper I shall show that one expects on general grounds a definite value $R(D^0) = 2\tan^2\theta_C \simeq 0.106$, where θ_C is the Cabibbo angle: $\tan\theta_C \simeq 0.230$, while in general no such prediction is possible for $R(D^+)$. Moreover, $R(D^0, \eta) = R(D^0, \eta') = 2\tan^2\theta_C$ is predicted independently of the flavor-octet/flavor-singlet makeup of η and η'. This picture remains valid for a more general representation of η and η' involving flavor-symmetry breaking [2].

The possibility of interference between Cabibbo-favored (CF) decays of charmed mesons to $\bar{K}^0 + X$ and doubly-Cabibbo-suppressed (DCS) decays to $K^0 + X$ was noted in Refs. [3,4]. For the decays $D \to K_{S,L}\pi$ asymmetries $R(D^{0,+}) \simeq 2\tan^2\theta_C$ were anticipated [4], with the relation expected to be more exact for D^0. We shall show that $R(D^0) = 2\tan^2\theta_C$ is predicted by the U-spin [5] subgroup of SU(3) [6–8] without identifiable SU(3)-violating corrections, whereas a corresponding relation for $R(D^+)$ is not predicted by U-spin.

The U-spin argument [8] proceeds as follows. The initial $D^0 = c\bar{u}$ state is a U-spin singlet because it contains no d or s quarks. The Cabibbo-favored transition $c \to su\bar{d}$ has $\Delta U = -\Delta U_3 = 1$ while the doubly-Cabibbo-suppressed $c \to du\bar{s}$ transition, with amplitude $-\tan^2\theta_C$ relative to the first, has $\Delta U = \Delta U_3 = 1$. Thus, the two transitions lead to $U = 1$ final states which are U-spin reflections of one another.

Now consider the final states consisting of $\bar{K}^0 M^0$ or $K^0 M^0$, where $M^0 = (\pi^0, \eta, \eta')$, with

$$\eta = \eta_8 \cos\theta + \eta_1 \sin\theta, \qquad \eta' = -\eta_8 \sin\theta + \eta_1 \cos\theta; \quad (3)$$

$$\eta_8 \equiv \tfrac{1}{\sqrt{6}}(2s\bar{s} - u\bar{u} - d\bar{d}), \qquad \eta_1 \equiv \tfrac{1}{\sqrt{3}}(s\bar{s} + u\bar{u} + d\bar{d}). \quad (4)$$

A reasonable representation of octet-singlet mixing in η and η' is obtained for $\sin\theta \simeq -1/3$ [9–12] but our results will be not only independent of θ but valid even for a more general picture of η and η' than Eq. (3) [2].

The π^0 and η_8 are admixtures of U-spin singlets and triplets with $U_3 = 0$. Because of Bose symmetry, the U-spin triplets, when combined with final-state neutral kaons which necessarily have $U = 1$ and $U_3 = \pm 1$, can only form states of total $U = 2$, which are not produced in the $c \to su\bar{d}$ or $c \to du\bar{s}$ transitions. Consequently, only the U-spin singlet projections of π^0 and η_8 contribute to the decays $D^0 \to \bar{K}^0 M^0$ and $D^0 \to K^0 M^0$.

The flavor-singlet component η_1, when combined with the neutral kaon, necessarily gives a state with $U = 1$. Thus any state $K^0 M^0$ or $\bar{K}^0 M^0$ produced in D^0 decay, with $M^0 = (\pi^0, \eta, \eta')$, is a state with $U = 1$ and $U_3 = \pm 1$. As a result, symmetry under U-spin reflection implies

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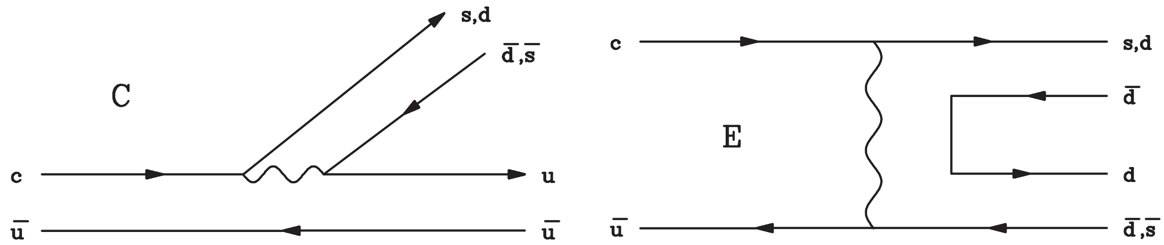

FIG. 1. Diagrams contributing to $D^0 \to \bar{K}^0 M^0$ and $D^0 \to K^0 M^0$. Left: color-suppressed (C); right: exchange (E).

$$\frac{A(D^0 \to K^0 M^0)}{A(D^0 \to \bar{K}^0 M^0)} = -\tan^2\theta_C. \quad (5)$$

This result does not depend upon any specific picture of $\eta - \eta'$ mixing but only on U-spin. It remains valid even when Eq. (3) is replaced by a more general representation of η and η' based on two mixing angles rather than one, required in a consistent treatment of flavor-symmetry breaking [2].

Equation (5) does not appear to receive any corrections associated with flavor-SU(3) breaking. In the language of flavor diagrams [13–15], the amplitudes for $D^0 \to \bar{K}^0 M^0$ and $D^0 \to K^0 M^0$ are both linear combinations of the reduced amplitudes C and E, differing by an overall factor of $-\tan^2\theta_C$. C is a color-suppressed amplitude in which the subprocess $c \to su\bar{d}$ or $c \to du\bar{s}$ is followed by the incorporation of the $s\bar{d}$ into a $\bar{K}^0$ or the $d\bar{s}$ into a K^0. These processes are expected to occur with equal amplitude and phase. E is an exchange amplitude involving the spectator $\bar{u}$ quark in the D^0 in the subprocess $c\bar{u} \to s\bar{d}$ (Cabibbo-favored) or $c\bar{u} \to d\bar{s}$ (doubly-Cabibbo-suppressed). These diagrams are illustrated in Fig. 1. Assuming that the four-fermion interaction mediated by the W (depicted by a wiggly line) is local, the evolution of the $s\bar{d}$ system into $\bar{K}^0 M^0$ should be characterized by the same amplitude and strong phase as that of $d\bar{s}$ into $K^0 M^0$. There may be short-distance flavor-dependent QCD corrections to the four-fermion interactions, but we cannot identify any important long-distance sources of SU(3) breaking in the U-spin relation (5).

Other U-spin relations noted in Ref. [8], namely

$$\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)} = \frac{A(D^+ \to K^0\pi^+)}{A(D_s^+ \to \bar{K}^0 K^+)} = \frac{A(D_s^+ \to K^0 K^+)}{A(D^+ \to \bar{K}^0\pi^+)} = -\tan^2\theta_C \quad (6)$$

do not appear immune to SU(3) breaking. The second and third involve spectator quarks with different masses and thus one expects them to be characterized by different form factors. The first involves amplitudes of the form $T + E$, where E is an exchange amplitude as noted above and T is a color-favored "tree" (or factorized) amplitude involving the subprocess $c \to \pi^+ s$ (Cabibbo-favored) or $c \to K^+ d$ (doubly-Cabibbo-suppressed) as depicted in Fig. 2. The ratio in the first term of Eq. (6) thus involves ratios of decay constants f_K/f_π and form factors $F(D \to \pi)/F(D \to K)$ each of which can differ substantially from unity. (See the remarks in Ref. [7].) The observed ratio [1] $r^2_{K\pi} \equiv \mathcal{B}(D^0 \to K^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+)$ is $0.003\,63 \pm 0.000\,38$, about 2.2σ above its value of $\tan^4\theta_C = 0.002\,79$ predicted by U-spin. Rescattering processes $K^-\pi^+ \to \bar{K}^0 M^0$ and $K^+\pi^- \to K^0 M^0$ can lead to contributions topologically equivalent to the E diagram. These processes, if important, could lead to some violation of the U-spin relation between $D^0 \to K^0 M^0$ and $D^0 \to \bar{K}^0 M^0$.

The amplitudes for $D^+ \to K^0\pi^+$ and $D^+ \to \bar{K}^0\pi^+$ are related upon U-spin reflection to amplitudes for $D_s^+ \to \bar{K}^0 K^+$ and $D_s^+ \to K^0 K^+$, respectively, and not to one another. They do not have the same flavor-SU(3) decomposition. One finds instead [14,15] $A(D^+ \to K^0\pi^+) = C + A$ while $A(D^+ \to \bar{K}^0\pi^+) = T + C$ aside from an overall ratio $-\tan^2\theta_C$. Here A is an annihilation amplitude involving the spectator quark. The process $c\bar{d} \to u\bar{s}$ is followed by the evolution of the $u\bar{s}$ pair into $K^0\pi^+$. Thus without further flavor-SU(3) analysis (for example, by updating the results of [14,15]) it is impossible to predict the amplitude ratio $A(D^+ \to K^0\pi^+)/A(D^+ \to \bar{K}^0\pi^+)$.

The phase conventions in which the above amplitudes have been expressed are such that the CP eigenstates of neutral kaons (neglecting CP violation) are [4]

$$K_S = \frac{1}{\sqrt{2}}(\bar{K}^0 - K^0), \qquad K_L = \frac{1}{\sqrt{2}}(\bar{K}^0 + K^0). \quad (7)$$

The $\bar{K}^0$ and K^0 contributions are thus, according to Eq. (5), expected to add constructively for $D^0 \to K_S M^0$ and destructively for $D^0 \to K_L M^0$, leading (in first order of the ratio of DCS to CF amplitudes) to

$$R(D^0, M^0) = 2\tan^2\theta_C \simeq 0.106 \quad (8)$$

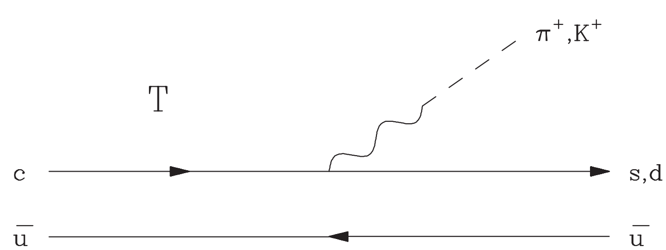

FIG. 2. Color-favored diagram contributing to $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$.

as noted. This relation should hold not only for $M^0 = \pi^0$ but also for $M^0 = (\eta, \eta')$, independently of the makeup of η and η' and of any flavor-symmetry violation in their description.

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