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Brief Reports

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Breakdown of nonet symmetry in Cabibbo-allowed decays of charmed mesons into two pseudoscalars

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We assume the flavor-symmetry properties predicted by the standard model for the decays of charmed mesons into two pseudoscalar mesons and test the additional hypothesis of nonet symmetry. From the measured branching ratios for D^+ and D^0, we show that nonet symmetry must be badly broken for the pseudoscalar nonet. Because the branching ratios for the D_s meson are not well known at present, we cannot determine whether one of the SU(3) representations **6*** and **15** dominates the effective interaction. There are some indications that both are equally important.

In the standard model, the Cabibbo-allowed decays of charmed mesons have well-defined flavor-symmetry properties.[1] The interaction transforms as an admixture of the **6*** and **15** representations under flavor SU(3) and behaves as a vector in isospace. These transformation properties enable us to express the amplitudes for individual decay modes in terms of a limited number of SU(3)-invariant amplitudes; for example, the nine decay modes of D mesons into a pair of pseudoscalars can be expressed in terms of at most five SU(3) invariants.[2] Obviously this fact leads to constraints on the properties of the decay modes, and in this paper we shall study the constraints in light of present data.

The two questions we shall examine are whether one of the two SU(3) representations, **6*** or **15**, dominates the effective interaction, and whether nonet symmetry is valid for the pseudoscalar mesons. Nonet[3] symmetry is based on the ideal mixing of vector mesons, but it has been extended to pseudoscalar mesons in many of the original discussions of charm decay.[1,4] It has the effect of relating the coupling constants associated with SU(3)-singlet mesons to those of their octet partners and it thereby reduces the number of SU(3)-invariant amplitudes; in the case of decays into two pseudoscalars, it reduces the number of invariants from five to three.[2]

Using the existing data on the decays[5] of D^+ and D^0, we shall show that nonet symmetry for pseudoscalar mesons is badly broken. Without precise knowledge of the decays of D_s, however, we cannot determine whether one of the two SU(3) representations actually dominates the interaction; indications from the data presently available are that both representations make comparable contributions to it.

One by-product of this analysis concerns the relative phases associated with final-state interactions (FSI). Although the effects of CP noninvariance are expected to be small and the SU(3) amplitudes are expected to be real, final-state interactions can introduce nonvanishing phases. It has already been shown that in the context of the $\Delta T=1$ rule for two-body D decays, large phases are needed to fit the isospin constraints.[6] We shall therefore treat the effective SU(3) invariants as complex, rather than real, numbers and determine some of the relative phases from the data.

Another by-product is the mixing angle for the η-η' system. We shall show that the choice[7] of $(-20°)$ gives much more satisfactory results for various branching ratios than does the choice of $(-10°)$.

The two pseudoscalar mesons are in an S wave in the final state of the decay, and so the flavor-SU(3) quantum numbers of the final state must correspond to the symmetric product of two nonets, that is a symmetric octet $\mathbf{8}_S$ and a 27-plet (Refs. 1 and 4). When we combine the triplet $\bar{D}_i^4$ $(i=1,2,3)$ representing the charmed mesons with the octet, we can form one **6*** representation and one **15**, but when we combine it with the **27** we can only form a **15**. There are therefore only three independent amplitudes[2,4] when nonet symmetry holds. When nonet symmetry is broken, there will be an additional octet $\mathbf{8}_B$ formed from the product of the singlet member of one nonet and the octet of the other. This additional final state gives rise to two more terms in the effective interaction, a **6*** and a **15**. The expressions for each decay mode in terms of these invariants are shown in Table I.

We begin with the well-known $\Delta T=1$ sum rule for $D\to K\pi$:

$$A(D^0\to\pi^+K^-)+\sqrt{2}A(D^0\to\pi^0\bar{K}^0)=A(D^+\to\pi^+\bar{K}^0)\ , \quad (1)$$

TABLE I. Amplitudes and phase-space factors for specific decay modes of charmed mesons into two pseudoscalar mesons. The symbols S, T, and B denote the $\mathbf{8}_S$, $\mathbf{27}$, and $\mathbf{8}_B$ final states, respectively, and the subscripts refer to the overall SU(3) transformation properties of the particular term in the effective Hamiltonian. The phase-space factor is proportional to the center-of-mass momentum.

Mode	Phase-space factor	S_6	S_{15}	T_{15}	B_6	B_{15}
$D^+\to\pi^+K^0$	0.92	0	0	2	0	0
$D^0\to\pi^+K^-$	0.92	1	1	4/5	0	0
$D^0\to\pi^0\bar{K}^0$	0.92	$-1/\sqrt{2}$	$-1/\sqrt{2}$	$3\sqrt{2}/5$	0	0
$D^0\to\eta_8\bar{K}^0$	0.83	$-1/\sqrt{6}$	$-1/\sqrt{6}$	$\sqrt{6}/5$	0	0
$D^0\to\eta_1\bar{K}^0$	0.61	$2/\sqrt{3}$	$2/\sqrt{3}$	0	1	1
$D_s\to\pi^+\pi^0$		0	0	0	0	0
$D_s\to K^+\bar{K}^0$	0.86	-1	$+1$	4/5	0	0
$D_s\to\pi^+\eta_S$	0.92	$-\sqrt{(2/3)}$	$+\sqrt{(2/3)}$	$-2\sqrt{6}/5$	0	0
$D_s\to\pi^+\eta_1$	0.76	$-2/\sqrt{3}$	$2/\sqrt{3}$	0	-1	1

where $A(D\to XY)$ denotes the amplitude for decay into pseudoscalar mesons $X+Y$. We choose units for the amplitude by expressing the branching ratio for the decay mode in the form

$$B(D\to XY)=|A(D\to XY)|^2F(XY)\div\Gamma(D)\ , \tag{2}$$

where $F(XY)$ is a phase-space factor proportional to the center-of-mass momentum and $\Gamma(D)$ is the total width of the parent D meson. In view of the empirical relation[3]

$$\Gamma(D^0)=\Gamma(D_s)=2.5\Gamma(D^+)\ , \tag{3}$$

we can express all amplitudes as multiples of G_0, the square root of the D^0 width:

$$G_0=\sqrt{\Gamma}(D^0)\ . \tag{4}$$

Measured branching ratios and phase-space factors are shown in Table II. For our purposes, it will be sufficient to use the central values of the branching ratios.

The amplitudes for the three $D\to K\pi$ decay modes can be expressed in terms of two isospin amplitudes, A_3 and A_1, for the isospin $\frac{3}{2}$ and $\frac{1}{2}$ final states, respectively.[9] When we try to fit the branching ratios in Table II to these two amplitudes, we need to introduce a phase between them. Taking A_3 to be real, we find, from Table I,

$$A_3=2T_{15}=0.12G_0\ ,$$
$$A_1=\frac{3}{\sqrt{2}}(S_6+S_{15})+\frac{\sqrt{2}}{5}T_{15}=0.43e^{i76^\circ}G_0\ . \tag{5}$$

The next piece of information we use is the 1.6% branching ratio for $D^0\to\bar{K}^0\eta$, which determines the magnitude but not the phase of the corresponding amplitude:

$$A(D^0\to\bar{K}^0\eta)=0.14e^{i\chi}\ . \tag{6}$$

From Table I and the standard mixing formulas[7] for η and η', we can relate the amplitude for $D^0\to\bar{K}^0\eta'$ to known amplitudes:

$$A(D^0\to\bar{K}^0\eta')=-\cot\theta_m\,A(D^0\to\bar{K}^0\eta)+\frac{\csc\theta_m}{\sqrt{3}}A(D^0\to\bar{K}^0\pi^0)\ . \tag{7}$$

The η' decay mode has not yet been seen and the present upper limit on its branching ratio is 2.7%; we therefore look for the phase angle χ which leads to the smallest branching ratio through Eq. (7). For the mixing angle θ_m of (-10°) the smallest value is 6%, whereas for $\theta_m=-20^\circ$ the smallest value is 1.3%. Thus we choose

$$\theta_m=-20^\circ,\quad \chi=-81^\circ \tag{8}$$

and predict

$$B(D^0\to\bar{K}^0\eta')=1.3\%\ . \tag{9}$$

We are now able to determine those combinations of SU(3)-invariant amplitudes that control the decays of nonstrange charmed mesons. They are

$$T_{15}=0.06G_0\ ,$$
$$(S_6+S_{15})=0.2e^{i78^\circ}G_0\ , \tag{10}$$
$$(B_6+B_{15})=0.41e^{i268^\circ}G_0\ .$$

It is clear from this result that there is a large breaking of

TABLE II. Branching ratios for specific decay modes of charmed mesons into two pseudoscalar mesons. We quote only the central values of the measurements.

Mode	Branching ratio (%)	Reference
$D^+\to\pi^+K^0$	3.2	(5,8,10)
$D^0\to\pi^+K^-$	4.3	(5,8,10)
$D^0\to\pi^0\bar{K}^0$	1.8	(5,8,10)
$D^0\to\eta_S\bar{K}^0$	$1.6(\eta)$	(10)
$D^0\to\eta_1\bar{K}^0$	$\le 2.7(\eta')$	(10)
$D_s\to\pi^+\pi^0$		0
$D_s\to K^+\bar{K}^0$	$\approx B_\phi$	(5,8)
$D_s\to\pi^+\eta_8$	$\approx nB_\phi(\eta)$	(10,11)
$D_s\to\pi^+\eta_1$	$\approx nB_\phi(\eta')$	(10,11)

nonet symmetry and that the amplitude for the **27** final state in $D \to PP$ is small. However, because of the combinations of **6*** and **15** amplitudes appearing in Eq. (10), we cannot establish whether one of the two SU(3) representations is dominant. To do this, we must look at the decays of the strange charmed meson D_s, which depend on the differences rather than the sums of invariant amplitudes.[2]

Unfortunately the properties of D_s decays are not well known at this time. There have been some determinations of branching ratios relative to the $D_s \to \phi\pi^+$ mode, but the latter has not been measured directly; estimates suggest that it lies between 2 and 4%. The best piece of data is the approximate equality of the branching ratios for $D_s \to K^+\bar{K}^0$ and $D_s \to \phi\pi^+$. Branching ratios for $D_s \to \pi\eta$ and $D_s \to \pi\eta'$ have been measured, but there is no consensus[10] as to their values. We therefore set

$$\begin{aligned} B(D_s \to K^+\bar{K}^0) &= B_\phi(e^{i\alpha}) , \\ B(D_s \to \pi\eta) &= nB_\phi(e^{i\beta}) , \\ B(D_s \to \pi\eta') &= n'B_\phi(e^{i\gamma}) , \end{aligned} \tag{11}$$

where B_ϕ is the branching ratio for $D_s \to \phi\pi^+$, n and n' are as yet not well-known numerical ratios, and the phases in parentheses are the phases of the corresponding amplitudes.

With the aid of Table I, we can express the amplitudes associated with Eq. (11) in terms of the SU(3)-invariant combinations $(S_6 - S_{15})$, $B(S_6 - B_{15})$, and T_{15}. Since we are actually dealing with four decay amplitudes and writing them in terms of three SU(3) invariants, we have a consistency condition among the amplitudes. For an η-η' mixing angle of $(-20°)$, it takes the form

$$n^{1/2}e^{i\beta} - 0.4(\eta')^{1/2}e^{i\gamma} = 0.9e^{i\alpha} - \frac{0.1}{\sqrt{B_\phi}} . \tag{12}$$

This condition ensures that once we have fixed the phase α, we can then determine the phases β and γ.

Not knowning the parameters n and n' too well, we cannot do much with the condition at this time. Nevertheless, it is instructive to look at some examples. If we take the two parameters to be 1.5 and 2.5, respectively, values suggested by recent Mark II results,[11] and choose B_ϕ to be 2.5%, a value indicated by a recent SU(3) analysis of $D \to PV$ decays,[12] we find that

$$\begin{aligned} (B_6 - B_{15}) &= 0.22e^{i287°} , \\ (S_6 - S_{15}) &= -(0.08 + i0.11) \end{aligned} \tag{13}$$

for $\alpha = 41°$. If, on the other hand, we take n' to be 1, a value closer to the Mark III upper bound,[10] we find

$$\begin{aligned} (B_6 - B_{15}) &= 0.43e^{i187°} , \\ (S_6 - S_{15}) &= (0.21 - i0.1) \end{aligned} \tag{14}$$

for $\alpha = 135°$. In both cases we can use Eq. (10) to solve Eqs. (13) and (14) for the individual invariants, and we find no clear pattern of domination by a single representation. It is clear however that the nonet-symmetry-breaking term is significant for both choices of the phase angle α given above; we may reasonably presume that this will be the case for most choices.

Note added. After completion of this work, the attention of the author was drawn to a recent paper by Kamal, Sinha, and Sinha[13] in which a model for nonet-symmetry breaking is discussed. This paper comes to a similar conclusion as we do about the η-η' mixing angle, but it predicts a much larger branching ratio for $(D^0 \to \bar{K}^0\eta')$ than that given in Eq. (9).

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