Troubles with Nonleptonic Charm Decays

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Conclusions about weak interactions from nonleptonic D^0 decays are completely changed by strong final-state interactions. The suppression of $D^0 \to \bar{K}^0\pi^0$ found in some models is completely reversed to $\Gamma(D^0 \to \bar{K}^0\pi^0) = 8\Gamma(D^0 \to K^-\pi^+)$ by introduction of experimentally measured $K\pi$ scattering phase shifts in the exotic $I=\frac{3}{2}$ and nonexotic $I=\frac{1}{2}$ amplitudes. The $K^+K^-/\pi^+\pi^-$ ratio is very sensitive to meson resonances expected at the D mass. Predictions less sensitive to final-state interactions are discussed.

Recent treatments of nonleptonic decays of charmed mesons[1] consider very specific and detailed properties of the weak interactions but completely ignore strong-interaction effects that can completely swamp the effects under consideration.[2,3] A simple example is given by the $K\pi$ decays of the D^0. Some treatments suggest that the $\bar{K}^0\pi^0$ decay mode is strongly suppressed[3,4] relative to $K^-\pi^+$. However, both states are linear combinations of isospin eigenstates with $I=\frac{1}{2}$ and $I=\frac{3}{2}$. Suppression of the $\bar{K}^0\pi^0$ mode implies that the two isospin amplitudes nearly cancel in the $\bar{K}^0\pi^0$ mode. This cancellation is changed by final-state interactions which shift the relative phases.

Consider a simple model with all final-state interactions parametrized by phase-shift factors $\exp(i\delta_1)$ and $\exp(i\delta_3)$. The D^0 decay amplitudes are

$$A(D^0 \to K^-\pi^+) = (\sqrt{\tfrac{1}{3}})A_3 \exp(i\delta_3) - (\sqrt{\tfrac{2}{3}})A_1 \exp(i\delta_1)\,, \qquad (1a)$$

$$A(D^0 \to \bar{K}^0\pi^0) = (\sqrt{\tfrac{2}{3}})A_3 \exp(i\delta_3) + (\sqrt{\tfrac{1}{3}})A_1 \exp(i\delta_1)\,, \qquad (1b)$$

where A_1 and A_3 denote the $I=\frac{1}{2}$ and $I=\frac{3}{2}$ amplitudes without final-state interactions. If the neutral state (1b) is completely suppressed in the absence of final-state interactions, then

$$A_1 = -\sqrt{2}\,A_3 \qquad (2a)$$

and

$$\Gamma(D^0 \to \bar{K}^0\pi^0) = \frac{8\,\Gamma(D^0 \to K^-\pi^+)}{9\cot^2[\frac{1}{2}(\delta_3 - \delta_1)] + 1}\,. \qquad (2b)$$

In the presence of final-state interactions the neutral decay is suppressed only if $\delta_3 \approx \delta_1$. But the $I=\frac{3}{2}$ channel is exotic and has no resonances; the $I=\frac{1}{2}$ channel is not exotic and has many K^* resonances. In a recent partial-wave analysis of elastic $K\pi$ scattering[5] the $I=\frac{1}{2}$ s wave shows a resonance with a mass of 1.4 to 1.45 GeV and a width of 200–300 MeV, giving an s-wave phase at 1.85 GeV varying between 110° and 160° for different solutions. The $I=\frac{3}{2}$ s wave shows no resonances and a smooth phase variation well described by an effective-range fit with a value around −25° to −30° at 1.85 GeV. For $\delta_3 - \delta_1 = -180°$ the suppression is completely reversed, $\Gamma(D^0 \to \bar{K}^0\pi^0) = 8\,\Gamma(D^0 \to K^-\pi^+)$, and other predictions[3,4] are drastically modified.

Complete descriptions of nonleptonic decay must include such final-state interactions in full dynamical calculations not possible at present. Approximate estimates of final-state interactions are obtainable from phenomenological models using hadron scattering data and constraints from analyticity and unitarity.[6] Alternatively, flavor-symmetry predictions using approximate symmetry groups[1,7-9] automatically include all effects of those final-state interactions invariant under this symmetry. We list here several examples.

The well-known selection rule

$$\Gamma(F^+ \to \pi^+\pi^0) = 0 \qquad (3)$$

follows only from the isospin transformation properties of H_{weak} and isospin invariance of strong interactions and is unaffected by SU(3) symmetry breaking, strong final-state interactions, or an increase in the number of quark flavors. It is therefore no surprise that it holds in an SU(3) treatment even when the number of flavors are increased from four to six.[2]

The U-spin symmetry predictions[9] for D^0 decays in the four-quark model,

$$\Gamma(D^0 \to K^0\bar{K}^0) = 0\,, \qquad (4a)$$

$$\Gamma(D^0 \to K^+K^-) = \Gamma(D^0 \to \pi^+\pi^-)\,, \qquad (4b)$$

are not as solid as the isospin selection rule (3) because of U-spin symmetry-breaking effects already discussed[10] for the analogous electromagnetic U-spin predictions,

$$\sigma(e^+e^- \to \gamma \to K^0\bar{K}^0) = 0, \tag{5a}$$

$$\sigma(e^+e^- \to K^+K^-) = \sigma(e^+e^- \to \pi^+\pi^-). \tag{5b}$$

Whether such U-spin breaking is significant at this mass is still an open question, with arguments presented on both sides.[7,11-13] However, serious SU(3) breaking would be introduced by an ideally mixed nonet of scalar resonances in this mass range. A scalar nonet nearly degenerate with the tensor nonet is suggested by the $\epsilon(1300)$ under the f with a width of 200–400 MeV and the $K^*(1420)$ mentioned above. An isoscalar state under the $f'(1516)$ with a width of 200–400 MeV, a tail appreciable at the D mass, and a coupling to $K\bar{K}$ but not to $\pi\pi$ could explain the experimental discrepancies reported for the relation (4b) by introducing a relatively small resonant amplitude interfering constructively with nonresonant background.

Corrections to the selection rule (4a) for SU(3) breaking in final-state interactions are obtainable with the approach used in Eqs. (1):

$$\Gamma(D^0 \to K^0\bar{K}^0) = \Gamma(D^0 \to K^+K^-)\tan^2[\tfrac{1}{2}(\delta_0 - \delta_1)], \tag{6}$$

where δ_0 and δ_1 are the $I=0$ and $I=1$ phase shifts, respectively.

U-spin predictions less sensitive to symmetry breaking may be obtained by relating charge-conjugate final states which have the same resonance structure and strong interactions. The U-spin Weyl reflection[9] which interchanges s and d flavors induces the transformations

$$K^0 \leftrightarrow \bar{K}^0, \tag{7a}$$

$$K^+\pi^- \leftrightarrow K^-\pi^+, \tag{7b}$$

$$D^0 \leftrightarrow D^0. \tag{7c}$$

Using (7) we obtain for the four-quark model

$$\Gamma(D^0 \to K^0K^-\pi^+) = \Gamma(D^0 \to \bar{K}^0K^+\pi^-). \tag{8}$$

The kind of symmetry breaking discussed in connection with Eq. (6) should not affect the relation (8). Thus a comparison of the experimental tests of the two predictions (6) and (8) should indicate whether the violation of (6) presently observed comes from an additional $U=0$ component in $H_{\rm weak}$ or from U-spin-nonconserving final-state interactions. However, subtle U-spin-symmetry breaking effects can still be present. The contribution of the $K^{*+}K^-$ state to $K^0K^-\pi^+$ is not balanced by the U-spin-reflection contribution of $\rho^+\pi^-$ to $\bar{K}^0K^+\pi^-$ because the $\bar{K}^0K^+$ channel is closed for ρ^+ decay.

Additional U-spin predictions relate Cabibbo-allowed transitions to doubly unfavored transitions. The terms in $H_{\rm weak}$ which generate these transitions go into one another under U-spin reflection. Using the notation of Quigg[1] for the $C=1$ part of $H_{\rm weak}$,

$$H_{\rm weak}(\Delta C=1) = \{\bar{c}s, \bar{d}u\}V_{11}V_{22} + \{\bar{c}s, \bar{s}u\}V_{12}V_{22} + \{\bar{c}d, \bar{d}u\}V_{11}V_{21} + \{\bar{c}d, \bar{s}u\}V_{12}V_{21}, \tag{9}$$

we obtain

$$\frac{\Gamma(D^0\to\tilde{f})}{\Gamma(D^0\to f)} = \frac{\Gamma(D^+\to\tilde{f}')}{\Gamma(F^+\to f')} = \frac{\Gamma(F^+\to\tilde{f}'')}{\Gamma(D^+\to f'')} = \left(\frac{V_{12}V_{21}}{V_{11}V_{22}}\right)^2, \tag{10}$$

where f, f', or f'' denotes any Cabibbo-favored final state for the decay considered, and $\tilde{f}$ denotes the doubly unfavored state obtained from f by a U-spin reflection. Thus

$$\frac{\Gamma(D^0\to K^+\pi^-)}{\Gamma(D^0\to K^-\pi^+)} = \frac{\Gamma(D^0\to K^0\pi^0)}{\Gamma(D^0\to\bar{K}^0\pi^0)} = \frac{\Gamma(D^0\to K^0\eta)}{\Gamma(D^0\to\bar{K}^0\eta)} = \left(\frac{V_{12}V_{21}}{V_{11}V_{22}}\right)^2. \tag{11}$$

These predictions are unaffected by a treatment of final-state interactions like Eq. (1a) if the phase shifts are invariant under charge conjugation.

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[13]After the original version of this paper was submitted for publication a paper by J. F. Donoghue and Barry R. Holstein [Massachusetts Institute of Technology Report No. CTP-779 (to be published)] was received including a discussion of final-state interactions with a point of view similar to ours, but a very different analysis of the scalar meson resonances and very different conclusions.

Decay $J/\psi \to 3\gamma$ and a Search for the η_c

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The decay J/ψ into 3γ final states has been studied. No evidence is found for the existence of the $X(2.83)$ or any heavy narrow state (e.g., the η_c) decaying into two photons. Upper limits are given on the branching ratio $J/\psi \to \eta_c$, $\eta_c \to 2\gamma$ for η_c masses in the 2.7–3.0-GeV region. In addition, the branching ratios $J/\psi \to \gamma\eta, \gamma\eta'$ are measured. It is found that the η' branching ratio is higher than previously reported.

Using a nonmagnetic neutral-particle detector, the "Crystal Ball," we are studying the e^+e^- annihilation process with the SPEAR storage ring at various energies. We report here our results for the decay of the J/ψ into 3γ final states with the J/ψ produced directly via $e^+e^- \to J/\psi$, and indirectly via $e^+e^- \to \psi' \to \pi^+\pi^- J/\psi$.

The three-photon final states of the J/ψ can be reached through either $J/\psi \to \gamma X$, where X is any state which decays into two γ's (e.g., π^0, η, η'), or $J/\psi \to 3\gamma$ (direct). When the J/ψ is produced directly, the quantum electrodynamics (QED) reaction $e^+e^- \to 3\gamma$ also contributes. There is no such contribution when the J/ψ originates from ψ' decays.

The η_c, which is the $^1S_0$ state of charmonium predicted by charmonium models,[1] is a further possibility for the X. Evidence for a state at a mass of 2.83 GeV has been reported by another experiment[2] in a study of the reaction $e^+e^- \to J/\psi \to 3\gamma$. However, the strength of the signal at the reported mass is inconsistent with the prediction of these models and has posed serious difficulty to their advocates.

The Crystal Ball is shown schematically in Fig. 1. The main components are the following: (1) The ball, consisting of two hemispherical shells of NaI(Tl) 16 radiation lengths thick, cen-

