Two-particle nonleptonic decays of D and F mesons, and structure of weak interactions

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(Submitted February 11, 1975)
ZhETF Pis. Red. **21**, No. 6, 403–407 (March 20, 1975)

We consider nonleptonic decays of the hypercharged (charmed) D and F mesons. Relations are obtained between the amplitudes of different decays, which follow from unitary symmetry and from the assumption that the Hamiltonian of the weak interactions takes the form of the product of a current by a current. We consider the consequences of the T-, U-, and V-spin selection rules.

In this article we consider nonleptonic decays of the charmed mesons D^+, D^0, $\tilde{D}^0$, and F^+. In the quark model, the D and F mesons consist of one charmed quark p and one of the usual antiquarks $\tilde{p}$, $\tilde{n}$, and $\tilde{\lambda}$ ($D^+ \sim p'\tilde{n}$, $D^0 \sim p'\tilde{p}$, $F^+ \sim p'\tilde{\lambda}$). The D and F mesons have not yet been observed in experiment, but should be discovered in the nearest future if the interpretation of the narrow resonances $\Psi(3.1)$ [1,2] and $\Psi(3.7)$ [3] as particles with latent charm is correct, i.e., if they can be interpreted as bound states of $p'\tilde{p}'$ quarks. The spin of D and F mesons is equal to zero, and the mass is close to 2 GeV.

Nonleptonic decays of charmed mesons have already been discussed in the literature.[4-6] In particular, the estimates of the complete ($\Gamma_{D,F} \sim 10^{12}$—$10^{13}$ sec^{-1}) and partial widths are contained in[5]. A V-spin selection rule $\Delta V = 0$ was proposed in[6], and is a generalization, to the case of decay of charmed particles, of the well known selection rule $\Delta T = 1/2$ for nonleptonic decays with change of strangeness.

The purpose of the present paper is to analyze more completely two-particle nonleptonic decays of D and F mesons within the framework of unitary symmetry. We write down the weak-interaction Hamiltonian in the form

$$H^W = \frac{G}{\sqrt{2}} j_\mu j_\mu^+ ,$$

$$j_\mu = \bar{p} 0_\mu n_\theta + \bar{p}' 0_\mu \lambda_\theta, \qquad 0_\mu = \gamma_\mu (1 + \gamma_5). \tag{1}$$

where $n_\theta = n\cos\theta + \lambda\sin\theta$, $\lambda_\theta = \lambda\cos\theta - n\sin\theta$, and θ is the Cabibbo angle. It follows from (1) that the Hamiltonian responsible for the decay of the charmed particles can belong to the representations $\bar{6}$ and 15 of the $SU(3)$ group, $H^W = H_{\bar{6}} \otimes H_{15}$. It is important to note that there is no triplet representation, owing to the orthogonality of the states n_θ and λ_θ.

Let us determine the number of independent amplitudes describing the decays of the D and F mesons. The mesons form the representation $\bar{3}$. The expansion of the product $\bar{3}$ into the sum $\bar{6} + 15$ contains the following representations

$$\bar{3} \otimes (\bar{6} + 15) = 8 + 8' + \bar{10} + \bar{10}' + 27 . \tag{2}$$

The expansion of the final state of two mesons in terms of irreducible representations, as is well known, takes the form

$$8 \otimes 8 = 1 + 8_d + 8_f + 10 + \bar{10} + 27 . \tag{3}$$

Since we are considering two-particle decays in an s wave, then it is necessary to stipulate in addition the symmetry of the wave functions to permutation of the mesons. This requirement is satisfied only by the representations 1, 8_d, and 27. From a comparison with (2) follows that the number of independent amplitudes is equal to three, 8_d, $8'_d$, and 27. In explicit form, the complete amplitude is given by

$$\begin{aligned}
& a_1 \{ \cos^2\theta [F^+ (2/\sqrt{6}\pi^+\eta + \bar{K}^\circ K^+) + D^\circ (1/\sqrt{2}\, \bar{K}^\circ \pi^\circ \\
& + 1/\sqrt{6}\, \bar{K}^\circ \eta - K^-\pi^+) + \cos\theta \sin\theta [F^+ (1/\sqrt{2}\, K^+\pi^\circ - 1/\sqrt{6}\, K^+\eta \\
& + K^\circ \pi^+) + D^+ (2/\sqrt{6}\, \pi^+\eta + \bar{K}^\circ K^+) + D^\circ (\pi^+\pi^- - K^+K^- \\
& + \pi^\circ\pi^\circ - 1/\sqrt{3}\, \pi^\circ \eta - \eta\eta) + \sin^2\theta [D^+ (1/\sqrt{2}\, K^+\pi^\circ \\
& - 1/\sqrt{6}\, K^+\eta + K^\circ \pi^+) + D^\circ (K^+\pi^- + 1/\sqrt{2}\, K^\circ \pi^\circ - 1/\sqrt{6}\, K^\circ \eta)] \} \\
& + a_2 \{ \dots \} + a_3 \{ \cos^2\theta [F^+ (- 2/\sqrt{6}\, \pi^+\eta + \bar{K}^\circ K^+) + D^+ (2\bar{K}^\circ \pi^+) \\
& + D^\circ (K^-\pi^+ + 1/\sqrt{2}\, \bar{K}^\circ \pi^\circ + 1/\sqrt{6}\, \bar{K}^\circ \eta)] + \cos\theta \sin\theta [F^+ (1/\sqrt{2}\, K^+\pi^\circ \\
& - 3/\sqrt{6}\, K^+\eta - K^\circ \pi^+) + D^+ (\sqrt{2}\, \pi^+\pi^\circ - 4/\sqrt{6}\, \pi^+\eta + K^+\bar{K}^\circ) \\
& + D^\circ (K^+K^- - \pi^+\pi^- + \pi^\circ\pi^\circ - \sqrt{6}\, \eta\eta - 2/\sqrt{6}\, \pi^\circ \eta] \\
& + \sin^2\theta [D^+ (1/\sqrt{2}\, K^+\pi^\circ - 1/\sqrt{6}\, K^+\eta + K^\circ \pi^+) \\
& + D^\circ (- \pi^- K^+ + 1/\sqrt{2}\, K^\circ \pi^\circ + 1/\sqrt{6}\, K^\circ \eta)] \} .
\end{aligned} \tag{4}$$

The explicit form of $a_2\{\cdots\}$ is obtained from the expression for a_1 by reversing the signs of the amplitudes of the D^0-meson decays.

It is obvious that the total number of relations between the decay amplitudes is large. We write down only the predictions for the amplitudes proportional to $\cos^2\theta$:

$$\begin{aligned}
& A(D^\circ \to K^-\pi^+) + \sqrt{2} A(D^\circ \to \bar{K}^\circ \pi^\circ) = A(D^+ \to \bar{K}^\circ \pi^+), \\
& A(D^\circ \to K^-\pi^+) + \sqrt{6} A(D^\circ \to \bar{K}^\circ \eta) = A(D^+ \to \bar{K}^\circ \pi^+), \\
& \sqrt{6} A(F^+ \to \pi^+\eta) - 2A(F^+ \to \bar{K}^\circ K^+) = -2A(D^+ \to \bar{K}^\circ \pi^+).
\end{aligned} \tag{5}$$

We note also that the decay

$$F^+ \to \pi^+\pi^\circ \tag{6}$$

is forbidden, owing to the isotopic selections rule

$$\Delta T = 1, \quad \text{if } \Delta C = \Delta S = \pm 1,$$

which is contained in the Hamiltonian (1). The decay (6) is possible only as the result of electromagnetic corrections, and its experimental observation with a noticeable probability would call for a change in the form of the Hamiltonian.

The decays

$$D^\circ \to K^\circ \bar{K}^\circ, \qquad \pi_u \pi_u, \qquad \eta_u \eta_u, \tag{7}$$

where $\pi_u = \pi^0/2 - \sqrt{3}\eta/2$, $\eta_u = \eta/2 + \sqrt{3}\pi^0/2$ are also forbidden, owing to the u-spin selection rule

$$\Delta u = 1. \tag{8}$$

and are valid with the same accuracy with which $SU(3)$ symmetry holds. The rule (8) in the terms proportional to $\sin\theta$ ($\Delta C = 1$, $\Delta S = 0$) is the consequence of the antisymmetry of these terms of the Hamiltonian under the substitution $\lambda \longleftrightarrow n$. It is precisely this property of the Hamiltonian which is directly connected, according to the usual premises of[7], which the suppression of the decay $K_L^0 \to 2\mu$, and the smallness of the mass difference between the K_L^0 and K_S^0 mesons. Therefore a check of the forbiddennesses of the decays (7) is of great interest.

Additional relations appear if it is assumed that the matrix elements of $H_{\bar{6}}$ are dynamically enhanced in comparison with the matrix elements of H_{15}. This enhancement is the result[8] of the behavior of the amplitudes at small distances in asymptotically free theories, and can be of the same nature as the enhancement of the amplitudes with $\Delta T = 1/2$ and the suppression of the amplitudes with $\Delta T = 3/2$ in the usual nonleptonic decays. However, in the concrete calculations,[8,9] this enhancement turned out to be numerically small (~ 5) and insufficient to explain the selection rule $\Delta T = 1/2$. From the purely phenomenological point of view, the enhancement of $H_{\bar{6}}$ follows from the approximate $SU(4)$

symmetry and the selection rule $\Delta T=1/2$. Indeed, the representations $\bar{6}$ and 15 of the group $SU(3)$ enter in representations 20 and 84 of the group $SU(4)$. The latter, together with the transitions $\Delta T=1/2$ in the decays of ordinary particles, contains the transitions $\Delta T=3/2$ with comparable amplitude, which contradicts the experimental data. Therefore the representations 84 can be considered only if $SU(4)$ is strongly broken.

If we assume enhancement of the matrix elements of $H_{\bar{6}}$, then we need retain only the amplitude a_1 (see (4)). This results in additional relations between the amplitudes of different decays. In particular, the right-hand sides in (5) are equal to zero (this corresponds to the selection rule $\Delta V=0$), and the sum rules (5) go over into the relations obtained in[6].

We note also the relations that follow from the isotopic selection rules of the Hamiltonian with $\Delta C=-1$ ($\Delta T=1/2$ for $\Delta S=0$, $\Delta T=0$ for $\Delta S=+1$):

$$\begin{aligned} &\Gamma(F^+\to K^+\pi^\circ) = \tfrac{1}{2}\Gamma(F^+\to K^\circ\pi^+) \sim \sin^2\theta\,, \\ &\Gamma(D^\circ\to\pi^+\pi^-) = 2\Gamma(D^\circ\to\pi^\circ\pi^\circ) \sim \sin^2\theta\,, \\ &2\Gamma(D^+\to K^+\pi^\circ) = \Gamma(D^+\to K^\circ\pi^+) \sim \sin^4\theta, \\ &\Gamma(D^\circ\to\pi^- K^+) = 2\Gamma(D^\circ\to K^\circ\pi^\circ) \sim \sin^4\theta\,. \end{aligned} \tag{9}$$

Relations (9) are not violated by the semistrong interaction, and a comparison with experiment would be most critical to a check on the hypothesis of the enhancement of $H_{\bar{6}}$. Allowance for the contribution of H_{15} makes it possible to interrelate the possible violations of relations (9).

Thus, owing to the small number of independent unitary amplitudes, there are many relations between the widths of different decays. In this respect, the situation is more favorable than in the decays of the heretofore known particles. In particular, by studying the decays of the D and F mesons it is possible not only to check on the enhancement of $H_{\bar{6}}$, but also to verify that the non-enhanced transitions are connected with corresponding turns in the Hamiltonian, and not with electromagnetic corrections. It appears also that the nature of the $\Delta T=1/2$ rule would be clarified at the same time.

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