Suppression of $D_s^+ \to \pi^+ \rho^0$ decay and possible existence of $0^{-(+)}$ hybrid mesons

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If isotriplet hybrid mesons (π_H's) with $J^{PC}=0^{-+}$ exist and their masses are close to that of the D_s^+, they may play a particular role in suppressing efficiently the amplitude for the $D_s^+ \to \pi^+ \rho^0$ decay in consistency with experiment, while corresponding contributions of other members of the same multiplet are also compatible with other charm-meson decays.

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The $D_s^+ \to \pi^+ \rho^0$ decay seems to be strongly suppressed [1], $B(D_s^+ \to \pi^+ \rho^0)_{\rm expt} < 0.21\%$, as was expected from the perspective of short-distance physics since it proceeds through the annihilation-type quark-line diagram [2] [Fig. 1(a)]. However, the $D^0 \to \bar{K}^0 \phi$ decay has a sizable rate [1], $B(D^0 \to \bar{K}^0 \phi)_{\rm expt} = (0.80 \pm 0.16)\%$, although it proceeds through the same annihilation-type diagram in the weak-boson mass $m_W \to \infty$ limit. Thus long-distance effects are important in nonleptonic weak decays of charm mesons.

There have been some extensive studies of charm-meson decays which include long-distance effects. Bauer, Stech, and Wirbel [3] studied exclusive decays of charm mesons from a perspective of the factorization plus annihilation supplemented by final-state interactions. However, the predicted value of $B(D_s^+ \to \pi^+ \rho^0)$ was comparable with that of $B(D^0 \to \bar{K}^0 \phi)$. Blok and Shifman [4] studied them by using the QCD sum rule and predicted the strong suppression of the $D_s^+ \to \pi^+ \rho^0$ decay and the much milder suppression of the $D_s^+ \to \pi^+ \omega$ decay, which is also described by the same annihilation diagrams. The suppression of the $D_s^+ \to \pi^+ \rho^0$ decay was due to a cancellation between the two possible annihilation diagrams, while the corresponding amplitudes for the $D_s^+ \to \pi^+ \omega$ decay interfere constructively with each other. Chau *et al.* [5] also studied them phenomenologically by using quark-line diagrams and mentioned a suppression of the amplitudes due to a possible large $SU_f(3)$-symmetry breaking to explain the observed suppression of also the $D_s^+ \to \pi^+ \omega$ decay [1], $B(D_s^+ \to \pi^+ \omega)_{\rm expt} < 1.3\%$. In these analyses, however, dynamical contributions of hadrons to these processes were not necessarily explicitly taken into account.

The observed simultaneous suppression of the amplitudes for the $D_s^+ \to \pi^+ \rho^0$ and $D_s^+ \to \pi^+ \omega$ decays could well be due to interesting dynamics of hadrons. Indeed, from the formalism [6,7] which directly deals with hadrons but nevertheless takes into account the dynamics of underlying weak interactions, we have already shown that the approximate $|\Delta \mathbf{I}| = \frac{1}{2}$ rule in the $K \to \pi\pi$ decays and also the typical two-body decays of charm mesons can be explained in such a perspective.

In this paper, we study the quasi-two-body decays of charm mesons of the type $P_1(\mathbf{p}_1) \to V(\mathbf{p}_2) + P_2(\mathbf{q})$ from our above-mentioned formalism in some details, where V and P denote a vector and a pseudoscalar (PS) meson, respectively. We start from the amplitude $M(P_1 \to VP_2)$ which is antisymmetrized with respect to the exchange of the two PS mesons P_1 and $\bar{P}_2$ in the crossed amplitude [8]. Under this antisymmetrization the amplitude can be continued smoothly to the one in the relevant flavor-symmetry limit. We then apply a hard PS meson approximation which is realized by extrapolating the three-momentum $\mathbf{q}$ to zero ($\mathbf{q} \to 0$) in the light-cone frame (LCF) (or the infinite-momentum frame, i.e., $\mathbf{p}_1 \to \infty$). Then the amplitude for the decay, $P_1 \to VP_2$, is cast into the form [8] in which the dynamical contribution of various hadrons is manifest, $M(P_1 \to VP_2) \simeq M_{\rm ETC}(P_1 \to VP_2) + M_S(P_1 \to VP_2)$, where $M_{\rm ETC}$ and M_S are given explicitly by Eqs. (1) and (2) below:

$$M_{\rm ETC}(P_1 \to VP_2) = -i(\sqrt{2} f_{P_2})^{-1} \langle V | [V_{\bar{P}_2}, H_w] | P_1 \rangle - (P_1 \leftrightarrow \bar{P}_2) , \tag{1}$$

$$M_S(P_1 \to VP_2) = -\frac{i}{\sqrt{2} f_{P_2}} \left[\sum_n \left[\frac{m_V^2 - m_1^2}{m_n^2 - m_1^2} \right] \langle V | A_{\bar{P}_2} | n \rangle \langle n | H_w | P_1 \rangle + \sum_l \left[\frac{m_V^2 - m_1^2}{m_l^2 - m_V^2} \right] \langle V | H_w | l \rangle \langle l | A_{\bar{P}_2} | P_1 \rangle \right] - (P_1 \leftrightarrow \bar{P}_2) , \tag{2}$$

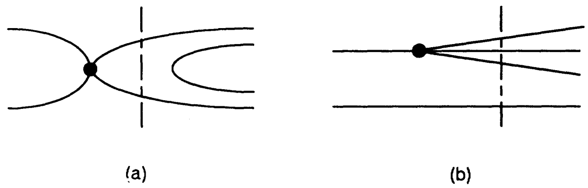

FIG. 1. Quark-line diagrams describing (the s-channel contributions to) nonleptonic weak decays into two-meson final states. (a) The annihilation diagram and (b) the spectator diagram in the infinite-weak-boson-mass limit. The solid circle denotes the weak vertex.

and must now be evaluated in the LCF. Here, f_{P_i} is the decay constant of P_i, and V_i and A_i with the flavor index i are the vector and axial-vector charges. $\sum$ denotes the sum over all the possible *on-shell* one-particle states with infinite momentum. Unlike in the case of $M_{\rm ETC}$, various kinds of hadrons, i.e., not only the ordinary $\{Q\bar{Q}\}$ but also the (still not completely established) glueball, hybrid, and multiquark mesons, can contribute to the intermediate states of M_S. Thus the exotic hadrons can play an important role if their masses happened to be close to those of the external hadrons, provided that their matrix elements have reasonable strengths. However, in the quasi-two-body decays of charm mesons under consideration, the term proportional to $(\sqrt{2}f_{P_1})^{-1}$ in M_S [the last term in Eq. (2)] is small because of $m_n^2, m_l^2 \gg m_V^2, m_2^2$ and can safely be neglected.

It is important to appreciate the fact that the amplitude is thus governed solely by the single-hadron *asymptotic* matrix elements of H_w. Therefore, the main task is to obtain constraints on the *asymptotic* matrix elements of H_w. To this, we have used two alternative (and complementary) methods. One of them is algebraic [9] and is based on the asymptotic realization of the commutation relations among V_i, A_i, and H_w. The other is based on a more intuitive quark-line argument [6,7] in LCF. The results which we will use in this paper are

$$\langle \pi^+|H_w|D_s^+\rangle + \langle \bar{K}^0|H_w|D^0\rangle = 0 \ , \tag{3a}$$

$$\langle \rho^+(\lambda=0)|H_w|D_s^+\rangle + \langle \bar{K}^{*0}(\lambda=0)|H|D^0\rangle = 0 \ , \tag{3b}$$

in LCF. We also have obtained

$$\langle \bar{K}^{*0}|H_w|D^0\rangle = \pm\langle \bar{K}^0|H_w|D^0\rangle \tag{3c}$$

in LCF from our algebraic approach [9].

The hybrid mesons π_H, K_H, ... with $J^{P(C)}=0^{-(+)}$ which we are concerned with will be the states [10] with total orbital angular momentum $L=1$ and S wave $\{Q\bar{Q}\}$. Then, applying to $\langle\{Q\bar{Q}g\}|H_w|\{Q\bar{Q}\}_0\rangle$ the same quark-line arguments as those used to obtain Eqs. (3a) and (3b), we also obtain

$$\langle \pi_H^+|H_w|D_s^+\rangle + \langle \bar{K}_H^0|H_w|D^0\rangle = 0 \ . \tag{4a}$$

Here we parametrize the *asymptotic* matrix elements of H_w in Eq. (4a) as

$$\langle \bar{K}_H^0|H_w|D^0\rangle = (\tilde{k}/\tilde{h})\langle \bar{K}^{*0}|H_w|D^0\rangle \tag{4b}$$

by using the *asymptotic* ground-state meson matrix element $\langle \bar{K}^{*0}|H_w|D^0\rangle$ and a parameter $\tilde{k}$ introduced, where $\tilde{h} = -\langle\rho^0|A_{\pi^-}|\pi_H^+\rangle = -\sqrt{2}\langle\phi|A_{K^0}|\bar{K}_H^0\rangle$.

We now consider the following decays which proceed only through the annihilation-type quark-line diagrams in the $m_W\to\infty$ limit:

$$D^0\to\bar{K}^0\phi, \quad D_s^+\to\pi^+\rho^0(\pi^0\rho^+), \quad \text{and } D_s^+\to\pi^+\omega \ .$$

Since then the intermediate state in the s channel contains only one pair of valence quark Q and antiquark $\bar{Q}$ [and possibly gluon(s)], if the connectedness of the quark lines describing the matrix elements of H_w is insisted upon, only the ordinary $\{Q\bar{Q}\}_L$ (labeled by the level L) and hybrid $\{Q\bar{Q}g\}$ mesons can contribute to the one-particle intermediate state $|n\rangle$ in the first term of [ ] on the right-hand side (RHS) of Eq. (2). However, the matrix elements of H_w taken between the $\{Q\bar{Q}\}_L$ meson states will be small [8] if, at least, one of them is of $L\neq 0$. The second term of [ ] on the RHS of Eq. (2) has no $\{Q\bar{Q}\}$ but four-quark $\{QQ\bar{Q}\bar{Q}\}$ meson contributions, if they exist, in this type of decay. However, taking account of the fact that $m_l^2 \gtrsim m_1^2 = m_{D_s}^2$, $m_D^2 \gg m_V^2 = m_\phi^2, m_\rho^2, m_\omega^2$ for $l=\{QQ\bar{Q}\bar{Q}\}$ and also of the small overlapping of the wave functions between the ground state $\{Q\bar{Q}\}_0$ and the $\{QQ\bar{Q}\bar{Q}\}$ mesons, we find that the four-quark meson contributions will be reasonably small and we therefore neglect the second line in Eq. (2) for these decays. Therefore, in the annihilation-type decays, only the ground-state $\{Q\bar{Q}\}_0$ and the hybrid $\{Q\bar{Q}g\}$ mesons can give a substantial contribution to M_S.

Using Eqs. (3) and (4) and choosing the positive sign in Eq. (3c), we end up with the simple approximate amplitudes

$$M(D^0\to\bar{K}^0\phi) \simeq i(\sqrt{2}f_K)^{-1}\langle \bar{K}^{*0}|H_w|D^0\rangle \left[1+\left[\frac{m_D^2-m_\phi^2}{m_D^2-m_K^2}\right](\tfrac{1}{2})^{1/2}h - \left[\frac{m_D^2-m_\phi^2}{m_{K_H}^2-m_D^2}\right]\tilde{k}\right] , \tag{5a}$$

$$M(D_s^+\to\pi^+\rho^0) \simeq -M(D_s^+\to\pi^0\rho^+)$$
$$\simeq -\frac{i}{f_\pi}\langle \bar{K}^{*0}|H_w|D^0\rangle \left[1+\left[\frac{m_{D_s}^2-m_\rho^2}{m_{D_s}^2-m_\pi^2}\right](\tfrac{1}{2})^{1/2}h - \left[\frac{m_{D_s}^2-m_\rho^2}{m_{\pi_H}^2-m_{D_s}^2}\right]\tilde{k}\right] , \tag{5b}$$

$$M(D_s^+\to\pi^+\omega) \simeq 0 \ . \tag{5c}$$

Here $M_{\rm ETC}(D_s^+\to\pi^+\omega)=0$ since $V_{\pi^-}|D_s^+\rangle = V_{\pi^-}|\omega\rangle =0$ and $V_{D_s^+}|\pi^-\rangle = V_{D_s^+}|\omega\rangle=0$ in the ideal ω-ϕ mixing. $M_S(D_s^+\to\pi^+\omega)\simeq 0$ since the appropriate quantum numbers of the intermediate state in the s channel cannot be realized by the $\{Q\bar{Q}\}_0$ and a hybrid meson with $J^{PC}=0^{-+}$. The above reflects the fact that, in the quark-line approach in Ref. [5], the amplitudes described by two different quark-line diagrams cancel each other when the full amplitude for the $D_s^+\to\pi^+\omega$ decay is properly antisymmetrized. However, in contrast the corresponding two amplitudes describing the $D_s^+\to\pi^+\rho^0$ interfere constructively with each other. Therefore, to reproduce the observed suppression of the latter decay, something new has to happen. We discuss this below. The first terms on the RHS of Eqs. (5a) and (5b) arise from $M_{\rm ETC}$, while the second and the third terms are the ground-state and the hybrid meson pole contributions [11] [$M_S^{(L=0)}$ and $M_S^{(\rm hybrid)}$], respectively, to M_S. Here we have applied the following (asymptotic) SU$_f$(3) parametrization [9] of the matrix elements of A_{π^-} and A_{K^0}: $h=-\langle\rho^0|A_{\pi^-}|\pi^+\rangle=-\sqrt{2}\langle\phi|A_{K^0}|\bar{K}^0\rangle$. The size of h can be estimated [9] to be $|h|\simeq 1.0$ from $\Gamma(\rho\to\pi\pi)_{\rm expt}\simeq 160$ MeV [1].

The fact that the observed decay rate [1] for the $D_s^+\to\pi^+\rho^0$ is suppressed implies, in the present approach, that an efficient cancellation among the amplitudes, $M_{\rm ETC}$, $M_S^{(L=0)}$, and $M_s^{(\rm hybrid)}$, takes place, i.e.,

$$1+\left[\frac{m_{D_s}^2-m_\rho^2}{m_{D_s}^2-m_\pi^2}\right](\tfrac{1}{2})^{1/2}h\simeq\left[\frac{m_{D_s}^2-m_\rho^2}{m_{\pi_H}^2-m_{D_s}^2}\right]\tilde{k}\ . \quad (6)$$

Although the LHS is known, the RHS contains two unknown parameters: m_{π_H} and $\tilde{k}$. Using the known mass values involved and also $h\simeq 1.0$ estimated above, we obtain $m_{\pi_H}\simeq\sqrt{2.048\tilde{k}+3.877}$ GeV from Eq. (6). For a small value of $\tilde{k}$, which is expected from the small overlapping of wave functions between the $\{Q\bar{Q}\}_0$ and $\{Q\bar{Q}g\}$ mesons, m_{π_H} is thus estimated around 2 GeV. If we choose tentatively [12] $\tilde{k}\simeq 0.1$, we obtain $m_{\pi_H}\simeq 2.02$ GeV. Although the theoretical prediction of the hybrid meson mass is still in controversy, there are indeed arguments [10] which indicate that the mass of the π_H is around $\simeq 2$ GeV.

We now check the contribution of $\bar{K}_H^0$ to $D^0\to\bar{K}^0\phi$. m_{K_H} is estimated to be $m_{K_H}\simeq 2.12$ GeV by using the quark counting $m_{K_H}-m_{\pi_H}\simeq m_{D_s}-m_D$ and the above value of m_{π_H}. However, the effect estimated with $\tilde{k}\simeq 0.1$ is negligibly small ($\simeq\frac{1}{10}$ of the main contribution). Therefore, the contribution of the $\bar{K}_H^0$ in Eq. (5a) does not disturb the sizable branching ratio $B(D^0\to\bar{K}^0\phi)\simeq 0.8\%$, estimated from $M_{\rm ETC}$ and $M_S^{(L=0)}$ by comparing with the amplitude [7] for $D^0\to\pi^+K^-$, which contains contributions from the ground-state $\{Q\bar{Q}\}_0$ and possible $\{QQ\bar{Q}\bar{Q}\}$ mesons, and by using the observed [1] $B(D^0\to\pi^+K^-)_{\rm expt}=(3.71\pm 0.25)\%$ as input. A similar result has also already been obtained in Ref. [8] in which the algebraic approach was instead used.

The decay $D_s^+\to\pi^+\phi$ proceeds only through the spectator diagram, Fig. 1(b), which implies that only the $\{us\bar{d}\bar{s}\}$ mesons (because of the connectedness of quark lines at the weak vertex under consideration) can contribute to the s-channel intermediate states of M_S. Among $\{QQ\bar{Q}\bar{Q}\}$ mesons, $C_\pi^s(18^*)$ is expected to give the most important contribution in M_S since its calculated mass [13] is very close to m_{D_s}, i.e., $m_{C_\pi^s}\simeq 1.95$ GeV. By taking account of the $C_\pi^s(18^*)$ contribution, the amplitude for the $D_s^+\to\pi^+\phi$ is given by

$$M(D_s^+\to\pi^+\phi)\simeq -i(\sqrt{2}f_\pi)^{-1}\langle\bar{K}^{*0}|H_w|D^0\rangle\left[\frac{f_\pi}{f_{D_s}}+\left[\frac{f_\pi}{f_{D_s}}\right]\left[\frac{m_\phi^2-m_\pi^2}{m_{D_s}^2-m_\pi^2}\right](\tfrac{1}{2})^{1/2}h-\left[\frac{m_{D_s}^2-m_\phi^2}{m_{D_s}^2-m_{C_\pi^s}^2}\right]k^*\right]\ . \quad (7)$$

The first, second, and third terms on the RHS of Eq. (7) arise from $M_{\rm ETC}$, $M_S^{(L=0)}$, and $M_S^{(18^*)}$, respectively. Assuming $f_\pi\simeq f_{D_s}$, choosing again $k^*\simeq 0.1$ which corresponds to the parameter $\tilde{k}$ introduced previously and comparing the resulting amplitude with that for the $D^0\to\pi^+K^-$, we estimate $B(D_s^+\to\pi^+\phi)\simeq 3.7\%$, which is not far from the observed one [1], $B(D_s^+\to\pi^+\phi)_{\rm expt}=(2.7\pm 0.7)\%$.

The decay $D^0\to\bar{K}^0\rho^0$ proceeds not only through the annihilation type of diagram but also through the spectator diagram. Therefore the four-quark mesons in addition to the ground-state $\{Q\bar{Q}\}_0$ and the hybrid mesons can contribute to the intermediate states of M_S. However, the four-quark meson contribution is most important here since $M_{\rm ETC}\simeq 0$ for $f_D\simeq f_K$ and $M_S^{(L=0)}$ and $M_S^{(\rm hybrid)}$ interfere destructively with each other for $h\simeq 1.0$, $\tilde{k}\simeq 0.1$, and $m_{K_H}\simeq 2.12$ GeV estimated above. Among $\{QQ\bar{Q}\bar{Q}\}$ mesons, we pick out $E_{\pi K}(18^*)$ and $C_K(18^*)$, which belong to the same multiplet involving the $C_\pi^s(18^*)$ used in the discussion of the $D_s^+\to\pi^+\phi$ decay. The order of magnitude of the contribution of these exotic mesons is estimated as follows. The ratio of the amplitudes, $M_S^{(18^*)}(D^0\to\bar{K}^0\rho^0)$ to $M_S^{(18^*)}(D_s^+\to\pi^+\phi)$, arising from the **18*** contributions which are described in terms of the same type of spectator diagrams is of the order $\sim(m_{C_\pi^s}^2-m_{D_s}^2)/(m_{C_K}^2-m_D^2)/\sqrt{2}$. Using the values of the masses m_{C_K} and $m_{C_\pi^s}$ estimated in Ref. [13] and the observed [1] $B(D_s^+\to\pi^+\phi)_{\rm expt}=(2.7\pm 0.7)\%$ and $\tau(D_s^+)_{\rm expt}\simeq\tau(D^0)_{\rm expt}$ as input, we obtain $B(D^0\to\bar{K}^0\rho^0)\sim 0.3\%$ which is compatible with the observed one [1] $B(D^0\to\bar{K}^0\rho^0)_{\rm expt}=(0.43^{+0.31}_{-0.19})\%$.

For the $D^0\to K^-\rho^+$ decay, $M_{\rm ETC}$ is nonvanishing even in the symmetry limit ($f_D=f_K$) in sharp contrast to

$D^0 \to \bar{K}^0 \rho^0$. Therefore, the fact that the observed $B(D^0 \to K^- \rho^+)$ is much larger than $B(D^0 \to \bar{K}^0 \rho^0)$ is understood naturally in the present formalism. The other quasi-two-body decays of the type $P_1 \to VP_2$ are a little more complicated (though still controllable in our approach) since the amplitudes will contain contributions of various terms, M_{ETC}, $M_S^{(L=0)}$, $M_S^{(\mathrm{hybrid})}$, $M_S^{(\mathrm{exotic})}$, ...

In summary, we have studied the quasi-two-body decays of charm mesons which proceed through the annihilation diagrams and demonstrated that in the $D_s^+ \to \pi^+ \rho^0$ decay the contribution of the hybrid meson π_H can suppress the rate in consistency with other charm-meson decays. The corresponding contribution of the $\bar{K}_H^0$ will not disturb the sizable decay rate of the $D^0 \to \bar{K}^0 \phi$. The mechanism of the suppression of $D_s^+ \to \pi^+ \rho^0$ is thus different from that of $D_s^+ \to \pi^+ \omega$. The amplitude for the latter decay is always small since exotic mesons play a diminished role. This result is very different from that of Ref. [4], although both of them are consistent with the present data [1]. In the decays which proceed through the so-called spectator diagram, the contributions of the four-quark mesons also become important. It is thus interesting to see that the dynamics of nonleptonic weak interactions are intimately related to hadron spectroscopy.

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