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Weak Decay Modes of Charmed Mesons*

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A simple dynamical model is used to calculate the partial rates for various decay modes of charmed pseudoscalar and vector mesons. Our results together with the presently available data lend support to the hypothesis that the lowest-lying charmed particles are vector mesons. It is suggested that the multiparticle state $K^-\pi^+\pi^-\pi^+$ should be produced fairly copiously in charmed-vector-meson decays, which could offer a fruitful way of identifying charm.

If charmed hadrons exist, the analysis of various experimental results and the eventual identification of such particles would be greatly facilitated if estimates can be made for the relative importance of various decay modes of the lowest lying of these particles. Detailed information of this nature cannot be obtained from free-quark models, which provide[1] estimates for the inclusive decay rates, or by using symmetry or current-algebra arguments which essentially give sum rules.

In this paper we undertake a detailed study of the weak decays of the lowest-lying charmed mesons on the basis of a simple dynamical model. The model we use is a generalization of the vector-meson-dominance model suggested by Sakurai[2] to describe the nonleptonic decay of ordinary hadrons. The weak Hamiltonian responsible for charmed-particle decays can be written as

$$H_w = (G_F/\sqrt{2})[(\cos\theta_c J_{\mu 3}{}^4 - \sin\theta_c J_{\mu 2}{}^4) l_\mu + \text{H.c.}] + H_w{}^{\text{N.L.}}, \tag{1}$$

where l_μ is the usual weak leptonic current and $J_{\mu\beta}{}^\alpha = V_{\mu\beta}{}^\alpha + A_{\mu\beta}{}^\alpha$ is the hadronic $V-A$ current which in the usual four-flavor,[3] three-color quark model is given by

$$J_{\mu\beta}{}^{\alpha} = i \sum_{\text{colors}} \bar{q}_{\beta} \gamma_{\mu} (1+\gamma_5) q^{\alpha},$$

$(\alpha, \beta = 1, \ldots, 4)$. For the nonleptonic piece of the Hamiltonian, we assume 20-plet dominance,[4] so that the Cabibbo-angle favored $|\Delta C| = 1$ decay is described by

$$H_w{}^{\text{N.L.}}(|\Delta C| = 1) = (xG_{\text{F}}/4\sqrt{2}) \cos^2\theta_c \left[\{J_{\mu 1}{}^2, J_{\mu 3}{}^4\} - \{J_{\mu 3}{}^2, J_{\mu 1}{}^4\} \right] + \text{H.c.}, \tag{2}$$

where x is an enhancement factor which we will take to be the same as the corresponding factor for the nonleptonic decays of ordinary hadrons, induced by the piece $H_w{}^{\text{N.L.}}$ $(\Delta C = 0)$, also contained in the 20-plet. We shall not need an estimate of x, since the charmed-meson decays would be normalized to the decay of the kaon.

Generalizing Sakurai's model, we adopt the phenomenological relations

$$V_{\mu\beta}{}^{\alpha} = \tfrac{1}{2}\sqrt{2}(m_v{}^2/f_v)\varphi_{\mu\beta}{}^{\alpha}, \quad A_{\mu\beta}{}^{\alpha} = \tfrac{1}{2}\sqrt{2} f_p \partial_{\mu} P_{\beta}{}^{\alpha}, \tag{3}$$

where $\varphi_{\mu\beta}{}^{\alpha}$ and $P_{\beta}{}^{\alpha}$ are the physical vector-meson and pseudoscalar-meson fields, and $m_v{}^2/f_v$ and f_p are the corresponding couplings.[2] For the three-meson strong vertex which would involve at least one vector meson, we assume generalized universality of vector couplings. Following Sakita and Wali,[5] the generalized vector couplings would be described by the interaction Hamiltonian

$$H_{\text{str}} = ig\, \text{Tr}(\varphi_{\mu} P \overleftrightarrow{\partial}_{\mu} P) - (2g/m)\epsilon_{\mu\nu\lambda\rho}\, \text{Tr}(P \partial_{\mu}\varphi_{\nu}\partial_{\lambda}\varphi_{\rho}) - \tfrac{2}{3} ig\, \text{Tr}(F_{\mu\nu}\varphi_{\mu}\varphi_{\nu}) - (2ig/9m^2)\, \text{Tr}(F_{\mu\nu}F_{\nu\lambda}F_{\lambda\mu}). \tag{4}$$

The constant g can be estimated from $\rho \to 2\pi$; however, since we normalize all decays to the kaon decay, we would not need the value of this coupling. Somewhat arbitrarily, but in conformity with the usual practice, m will be taken to be the mass of the decaying particle.

We have calculated partial rates for various decay modes of the charmed mesons using Eqs. (1) to (4). For the decays involving hadrons in the final state, this involves calculating the vector- and pseudoscalar-meson pole diagrams. The calculations have been done both for the charmed-pseudoscalar-meson decays (D^0, D^+, F^+) as well as the charmed-vector-meson decays (D^{0*}, D^{+*}, F^{+*}). As observed by Altarelli, Cabibbo, and Maiani,[4] broken SU(4) mass formulas[1,6] give nearly identical masses for the charmed pseudoscalar and vector mesons and so cannot be relied upon in the prediction of level ordering.

For the nonleptonic decay we have calculated the two-body and quasi-two-body modes containing the ordinary pseudoscalar mesons, vector mesons, or both. The two-vector-meson final state VV would manifest itself as four or more pseudoscalar mesons, and the vector- and pseudoscalar-meson final states VP as three or more pseudoscalar mesons. Direct three- or more-particle decays into PPP, $PPPP$, VPP, VVP, etc. can be estimated[1] from the two-body decays using current-algebra techniques, but are not expected to be dominant. In our calculations, we have used the SU(4) values for the pseudoscalar coupling constants[7] appearing in Eq. (3), i.e., $f_D = f_F = f_K = f_{\pi}$ ($\simeq$ 93 MeV). For the vector couplings in Eq. (3) we use the (first) Weinberg spectral function sum rule,[8] generalized to SU(4), which, when saturated with vector mesons, leads to identical values of $m_v{}^2/f_v{}^2$ for ρ, K^*, D^*, and F^*. The masses of various charmed mesons are presumably around 2 GeV, and for calculational purposes have been taken from the results[6] of the quadratic SU(4) mass formulas. All calculated results are normalized to the $K_S \to 2\pi$ decay rate.

For the semileptonic decays, calculations have been made for the three- or quasi-three-body final states of the type $Pl^+\nu_l$ and $Vl^+\nu_l$ and the results are normalized to the K_{l3} decay rate. Finally, the pure leptonic decay rates have also been computed and, as expected from the helicity argument, these are negligibly small for pseudoscalar mesons. For the vector mesons, only $F^{+*} \to l^+\nu_l$ is Cabibbo-angle favored.

A partial list of our results is exhibited in Tables I and II for the decay of charmed pseudoscalar and vector mesons, respectively. We have tabulated the two most prominent nonleptonic decay modes out of all two- or quasi-two-body channels, and have also listed the dominant leptonic or semileptonic decay mode. The partial rate for each decay mode, as well as the total sum of all the calculated nonleptonic, semileptonic, and leptonic rates is also quoted. The third columns in the tables list the calculated "branching ratio."

TABLE I. Prominent charmed pseudoscalar meson decays. The total calculated decay rates are $\Gamma_T(D^0) = 2.32\times 10^{13}$ sec^{-1}, $\Gamma_T(D^+) = 3.47\times 10^{12}$ sec^{-1}, $\Gamma_T(F^+) = 2.84\times 10^{13}$ sec^{-1}. "K^{ch} fraction" represents the fraction of events containing one charged kaon.

Process	$\Gamma(\mathrm{sec}^{-1})\times 10^{-12}$	Branching ratio	Multiplicities
$D^0 \to \rho^+ K^-$	8.92	0.38	$\langle n^{\mathrm{ch}}\rangle = 1.81$
$\to \bar{K}^0{}^*\eta$	4.42	0.19	$\langle \pi^{\mathrm{ch}}\rangle = 1.16$, $\langle K^{\mathrm{ch}}\rangle = 0.65$
$\to K^- l^+ \nu_l$	0.11	0.005	K^{ch} fraction $= 0.63$
$D^+ \to \bar{K}^0{}^*\pi^+$	1.90	0.55	$\langle n^{\mathrm{ch}}\rangle = 1.72$
$\to \rho^+ \bar{K}^0$	1.31	0.38	$\langle \pi^{\mathrm{ch}}\rangle = 1.29$
$\to \bar{K}^0 l^+ \nu_l$	0.11	0.03	$\langle K^{\mathrm{ch}}\rangle \simeq K^{\mathrm{ch}}$ fraction $= 0.37$
$F^+ \to \rho^+\pi^0$ or $\rho^0\pi^+$	7.59	0.27	$\langle n^{\mathrm{ch}}\rangle = 1.96$
$\to \bar{K}^0{}^* K^+$	7.13	0.25	$\langle \pi^{\mathrm{ch}}\rangle = 1.49$, $\langle K^{\mathrm{ch}}\rangle = 0.47$
$\to \eta l^+ \nu_l$	0.08	0.003	K^{ch} fraction $= 0.31$

As mentioned before, the neglect of direct three- or more-particle decay modes is not expected to cause significant changes to the branching ratios.[9] At any rate, we believe that the dominant decay modes have been properly identified. Finally, also displayed in the tables are the various calculated charge multiplicities, and the fraction of decays with a charged kaon.

There are a number of striking features of our results, which we would comment on briefly. (1) Our results, coupled with the search by Boyarski *et al.*[10] for simple two- and three-body hadronic final states, strongly suggest that the pseudoscalar charmed mesons cannot all be the lowest-lying charmed states. Note in particular that our calculations show a pronounced $D^+ \to \bar{K}^0{}^*\pi^+$ decay mode which should produce a clear $K^-\pi^+\pi^+$ signal for which Boyarski *et al.*[10] set a rather stringent upper limit, too small by a factor of 5 or so. Even with the theoretical and experimental uncertainties, this discrepancy seems to be rather large. The calculated nonleptonic decays of charmed vector mesons, on the other hand, are quite consistent with the present bounds given in Ref. 10. (2) The calculated small semileptonic and leptonic branching ratios for the charmed pseudoscalar mesons also seem to be incapable of accounting for the rather copious production of dimuons[11] in neutrino-induced reactions, particularly if the presumed charm production is suppressed by the factor $\sin^2\theta_c$ and by the relative rarity of the sea quarks.[12] By contrast, the F^* has a large pure leptonic branching ratio, and could provide a possible explanation of the dimuon events. (3) If charmed vector mesons are lower lying, Table II shows that the dominant decays involve two vector mesons. We would like to draw special attention to the decay mode $D^0{}^* \to \bar{K}^0{}^*\rho^0$ which has a large branching ratio and would lead to an observable final state of $K^-\pi^+\pi^-\pi^+$ with the invariant masses of the $K^-\pi^+$ and $\pi^+\pi^-$ pairs peaked around the K^* and ρ masses, re-

TABLE II. Prominent charmed vector meson decays. The total calculated rates are $\Gamma_T(D^0{}^*) = 7.17\times 10^{12}$ sec^{-1}, $\Gamma_T(D^+{}^*) = 5.97\times 10^{12}$ sec^{-1}, $\Gamma_T(F^+{}^*)$ 9.63 $\times 10^{12}$ sec^{-1}. "K^{ch} fraction" has the same meaning as in Table I.

Process	$\Gamma(\mathrm{sec}^{-1})\times 10^{-12}$	Branching ratio	Multiplicities
$D^0{}^* \to \bar{K}^0{}^*\rho^0$	3.28	0.46	$\langle n^{\mathrm{ch}}\rangle = 2.47$
$\to \bar{K}^0{}^*\varphi$	0.64	0.09	$\langle \pi^{\mathrm{ch}}\rangle = 1.82$, $\langle K^{\mathrm{ch}}\rangle = 0.65$
$\to K^-{}^* l^+ \nu_l$	0.02	0.003	K^{ch} fraction $= 0.57$
$D^+{}^* \to \bar{K}^0{}^*\rho^+$	4.39	0.74	$\langle n^{\mathrm{ch}}\rangle = 2.12$
$\to \rho^+ \bar{K}^0$	0.66	0.11	$\langle \pi^{\mathrm{ch}}\rangle = 1.52$, $\langle K^{\mathrm{ch}}\rangle = 0.56$
$\to l^+ \nu_l$	0.11	0.018	K^{ch} fraction $= 0.56$
$F^+{}^* \to \rho^+\rho^0$	2.99	0.31	$\langle n^{\mathrm{ch}}\rangle = 1.88$
$\to \rho^+ \varphi$	0.64	0.07	$\langle \pi^{\mathrm{ch}}\rangle = 1.26$, $\langle K^{\mathrm{ch}}\rangle = 0.23$
$\to l^+ \nu_l$	1.88	0.20	K^{ch} fraction $= 0.14$

spectively. We believe this may be the most fruitful way to search for the charmed D^{0*}. (4) Finally, we present some rough estimates of how the multiplicities would change as we cross the threshold for charm production in the $e\bar{e}$ experiments. If we assume that roughly half of the post-threshold physics is due to pair production of charmed vector mesons, all three species being produced with equal probability, we find as we cross the charm threshold that the charged-particle multiplicity should rise from the experimental value[13] of about 3.5 to about 3.9, and the fraction of events with a K^- should rise from about[13] 0.2 to about 0.26. In calculating these numbers, we have assumed that the charmed pair production is not accompanied by other ordinary particles (presumably pions); if present, they would tend to raise the average charge multiplicity.[14] However, if the new physics involves, besides charmed particles, the production of a pair of heavy leptons,[15] one would expect[16] that at energies above the various thresholds, the calculated values for the two numbers would be somewhat smaller than the ones quoted above. Details of this work would be published elsewhere.

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