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Resonant structure in charmed-meson decays

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It is suggested that the multihadronic states observed recently at SLAC from the decay of new particles have a resonant structure. The composition of such a structure is discussed on the basis of a phenomenological model for the nonleptonic decays of charmed mesons.

Recently narrow peaks have been reported[1,2] from SLAC in the invariant-mass spectra of the hadronic state $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ at about 1865 $\pm$ 15 MeV and in $K^{\pm}\pi^{\mp}\pi^{\mp}$ at about 1876 $\pm$ 15 MeV. It is natural to try to identify these peaks with charmed-particle states. More peaks in other multihadronic distributions are clearly expected on the basis of this interpretation, so that a detailed investigation of the nonleptonic decays of charmed particles acquires considerable importance. Recently such an attempt was made[3] on the basis of a simple phenomenological model and in the present note we comment specifically on possible resonant structure one might expect on the basis of this model in the hadronic states observed at SLAC.

The charm-changing ($\Delta C = \pm 1$) weak nonleptonic Hamiltonian can be written effectively in the current-current form, and following the arguments in the literature,[4] we shall assume that it transforms under SU(3) as a member of the $\underline{6} \oplus \underline{6}^*$ representation. We confine ourselves to the standard Glashow-Iliopoulos-Maiani model[5] of charm, with the weak currents taken to be in the usual $V-A$ form. Furthermore, we consider only the Cabibbo-dominated piece ($\propto \cos^2\theta_C$) of the weak Hamiltonian, so that

$$H_w(|\Delta C|=1) = \frac{xG_F}{4\sqrt{2}} \cos^2\theta_C (\{J^2_{\mu 1}, J^4_{\mu 3}\} - \{J^2_{\mu 3}, J^4_{\mu 1}\}) + \text{H.c.} \tag{1}$$

In Eq. (1) $J^{\alpha}_{\mu\beta} = V^{\alpha}_{\mu\beta} + A^{\alpha}_{\mu\beta}$ is the $V-A$ hadronic current and $\alpha, \beta = 1, \ldots, 4$ denote the quark flavors. Also x is an enhancement factor that boosts the particular SU(3) representation we are considering over others. The model we use is implemented by the following phenomenological relations between currents and fields:

$$V^{\alpha}_{\mu\beta} = \sqrt{2}\, \frac{m_V{}^2}{f_V} \phi^{\alpha}_{\mu\beta} \ ,$$
$$A^{\alpha}_{\mu\beta} = \sqrt{2}\, f_P \partial_\mu P^{\alpha}_{\beta} \ , \tag{2}$$

where $\phi^{\alpha}_{\mu\beta}$ and P^{α}_{β} are the physical vector- and pseudoscalar-meson fields and f_V and f_P represent the vector and axial-vector couplings of the appropriate mesons to vacuum. Equations (2) represent a generalization of the meson-dominance model used by Sakurai[6] some time ago, which reproduces the current-algebra constraints in $K \rightarrow 2\pi$ and describes the parity-violating hyperon decays reasonably well. The nonleptonic interaction is then effectively a two-meson vertex involving vector and/or pseudoscalar mesons.

The multihadronic states can be produced directly or through states involving resonances like $\overline{K}^*$ and ρ. Thus in addition to the direct four-body decay, the $K^-\pi^+\pi^+\pi^-$ state can also arise from quasi-two-body decays like $D^0 \rightarrow \overline{K}^{0*}\rho^0$ or quasi-three-body decays like $D^0 \rightarrow \overline{K}^{0*}\pi^+\pi^-$ and $K^-\pi^+\rho^0$. Similarly, the $K^-\pi^+\pi^+$ state can also result from the quasi-two-body mode $D^+ \rightarrow \overline{K}^{0*}\pi^+$. The calculations of the various decay rates are performed as follows. For the two-body or the quasi-two-body decays, we use the phenomenological model outlined above. The three- or four-body decays are hard to calculate reliably in this model or by any other known methods, so we estimate them by current-algebra techniques. Treating pions as soft, the three- or four-body-decay matrix elements may be reduced to two-body or quasi-two-body decay amplitudes, which in turn can be calculated using the phenomenological model. Taking pions to be soft may be questionable here, but we do not expect these estimates to be too unreliable.[7] For the calculation of two-body or quasi-two-body decays in the model, we also need to know the strong coupling constants at the three-meson vertex involving various vector and/or pseudoscalar mesons. For simplicity, we shall assume generalized universality of vector couplings (all strong vertices involve at least one vector meson) and adopt an SU(4) generalization of the Sakita-Wali[8] interaction Hamiltonian

$$H_{\rm str} = ig\,{\rm Tr}(\phi_\mu P \overleftrightarrow{\partial}_\mu P) + \frac{2g}{m}\epsilon_{\mu\nu\lambda\rho}\,{\rm Tr}(P\partial_\mu\phi_\nu\partial_\lambda\phi_\rho) - \tfrac{2}{3}ig\,{\rm Tr}(F_{\mu\nu}\phi_\mu\phi_\nu) - \frac{2ig}{9m^2}{\rm Tr}(F_{\mu\nu}F_{\nu\lambda}F_{\lambda\mu}) \;, \qquad (3)$$

where g is the universal coupling constant and m is the invariant mass. Considering our present meager knowledge and understanding of charmed particle decays, it is neither feasible nor perhaps desirable at this stage to complicate the analysis by introducing symmetry-breaking effects in Eq. (3) through unknown parameters. However, it should be noted that experience based on SU(3) indicates that coupling constants, unlike masses, are better described by group symmetry. Furthermore, one might expect that the principle of universality of vector couplings may provide a reasonable approximation in some special sense.[9] We shall be interested in calculating the ratios of the rates for various decay modes which would be independent of the coupling constant g. Note also that these ratios are also independent of the enhancement factor x in the Hamiltonian (1).

The calculations are elementary and the details will be left out. The parameters of the model f_V, f_P, and m may be better determined when sufficient experimental information on charmed-meson decays is available. For present purposes we choose them as follows. If we use Weinberg's first sum rule[10] for asymptotic SU(4) saturated by vector mesons alone, we obtain that m_V^2/f_V^2 would be the same for $V=\rho$, K^*, D^*, and F^*. This determines all the f_V's we need if we use the value $f_\rho^2/4\pi \simeq 2.1$ obtained from the experimental rate[11] for $\rho\to e\bar{e}$. For the pseudoscalar coupling constants, we may use the SU(4) result $f_\pi = f_K = f_D = f_F$ together with the determination $f_\pi \simeq 93$ MeV from the leptonic decay of pions.[11] The mass m will be chosen, somewhat arbitrarily, to be the mass of the decaying particle. Now, our calculations show that the contributions to the rate for $D^0\to K^-\pi^+\pi^+\pi^-$ decay arising from various decay modes are given in the ratio[12]

$$\bar{K}^{0*}\rho^0 : \bar{K}^{0*}\pi^+\pi^- : \rho^0K^-\pi^+ : K^-\pi^+\pi^+\pi^- \text{ (direct)} = 2.0\times10^{-2} : 2.4\times10^{-2} : 1 : 9.1\times10^{-2} \;. \qquad (4)$$

Similarly, the contributions to $D^+\to K^-\pi^+\pi^+$ arising from the decay modes $D^+\to \bar{K}^{0*}\pi^+$ and $D^+\to K^-\pi^+\pi^+$ (direct) are obtained to be

$$\bar{K}^{0*}\pi^+ : K^-\pi^+\pi^+ \text{ (direct)} = 1:0.18 \qquad (5)$$

The results (4) and (5) show that the dominant contribution to the decay $D^0\to K^-\pi^+\pi^+\pi^-$ arises from the hadronic state $\rho^0K^-\pi^+$, whereas the final state $K^-\pi^+\pi^+$ in the decay of D^+ arises mostly from $\bar{K}^{0*}\pi^+$. The quantitative estimates in (4) and (5) may suffer from some uncertainty inherent in our model and the current-algebra techniques employed, and may also be subject to some change with the variation in the input parameters (within reason). However, we believe the qualitative features of these results are sufficiently reliable to be of interest. We urge the experimentalists to look for any resonant structures in the multihadronic states resulting from the decays of the new particles. Confirmation (or contradiction) of our results would be of great value in providing clues towards an eventual understanding of the nonleptonic decays of charmed mesons.

The spin-parity assignment of the new particles observed at SLAC has not yet been determined experimentally. It is conceivable that these particles are charmed vector[3,13] rather than charmed pseudoscalar mesons. If this were the case, the analog of the results (4) and (5) for the relative importance of the various modes contributing to the decays $D^{0*}\to K^-\pi^+\pi^+\pi^-$ and $D^{+*}\to K^-\pi^+\pi^+$ are, respectively, given by[14]

$$\bar{K}^{0*}\rho^0 : \bar{K}^{0*}\pi^+\pi^- : \rho^0K^-\pi^+ : K^-\pi^+\pi^+\pi^- \text{ (direct)} = 1 : 9.0\times10^{-2} : 0.14 : 1.1\times10^{-2} \qquad (6)$$

and

$$\bar{K}^{0*}\pi^+ : K^-\pi^+\pi^+ \text{ (direct)} = 1:0.10 \;. \qquad (7)$$

In contrast to the result (4), in the present case one would expect to observe roughly equal numbers of $\bar{K}^{0*}$ and ρ^0 in the final hadronic state $K^-\pi^+\pi^+\pi^-$.

In conclusion we would like to mention that in our analysis we have not considered decay modes involving resonances other than $\bar{K}^*$ and ρ. If the phase-space restrictions are not too severe, some of these modes may be important. Thus, even if we ignore the uncertainties in our calculations, the quantitative dominance of ρ and $\bar{K}^*$ in the hadronic states may not be as large as one might infer from the results (4) and (5), or from (6) and (7). The relative importance of the various decay modes considered would of course remain unchanged.

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[7]In the soft-pion approach here one is presumably neglecting the pion four-momentum components compared to the mass of the charmed particle. We do not expect the estimates of the rates to be uncertain by more than a factor of about two.

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[12]The masses of charmed mesons D and D^* are taken to be 1.86 GeV and 2.02 GeV, respectively. The masses of F and F^* are then obtained from the SU(4) mass formula; see S. Okubo, V. S. Mathur, and S. R. Borchardt, Phys. Rev. Lett. 34, 236 (1975).

[13]The recoil-spectrum fit of A. De Rújula *et al.*, Phys. Rev. Lett. 37, 398 (1976), however, is based on the assumption that the pseudoscalar charmed mesons are lower lying than the corresponding vector mesons.

[14]The masses of D and D^* in this calculation have been chosen to be the reverse of those in Ref. 12.