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Are There Charmed-Strange Exotic Mesons?

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ABSTRACT

Theoretical arguments more general than original MIT bag calculation predict exotic charmed-strange scalar mesons with striking signatures in same mass range as F and F^*, on the same basis as the prediction of the low-lying nonexotic $qq\bar{q}\bar{q}$ scalar nonet. Identification of $\delta(970)$ as $qq\bar{q}\bar{q}$ state enables rough mass prediction for charmed-strange exotics via charmed-strange analogy. Dominant signatures and decay modes of exotics are discussed.

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Exotic charmed-strange mesons with either the wrong sign of isospin or the wrong sign of strangeness can be expected in the same mass range as the nonexotic $F^{\pm}$ mesons. This prediction follows from very general theoretical arguments[1] in any quark model which introduces a spin-dependent force to explain the ρ-π, K^*-K and Δ-N mass differences of 300-600 MeV. This same force can provide additional binding in $qq\overline{qq}$ configurations, if the spins and isospins of the multi-quark system are coupled to optimize the binding. These theoretical arguments are now supported by the presently accepted classification as four quark exotics of the lowest 0^+ mesons in the conventional hadron spectrum.[2] Since these are in the same mass range as the vector mesons, charmed-strange four-quark states may also be in the mass range[3] of the F and F^*.

In contrast with the conventional hadron spectrum, where the lowest four quark states do not have exotic quantum numbers and are not easily recognized,[1] the lowest charmed-strange four quark states are predicted to include exotics with striking signatures. We denote the two types of exotics by $\tilde{F}_I$ ($u\bar{d}c\bar{s}$, etc. - wrong isospin) and $\tilde{F}_S$ ($ud\bar{c}\bar{s}$, etc. - wrong sign of strangeness). Also predicted is a "crypto-exotic" four quark state ($u\bar{u}c\bar{s}$) denoted by F_x, with the same quantum numbers as the F. The $\tilde{F}_I$ can be considered as an $F\pi$ or DK resonance or bound state, the $\tilde{F}_S$ as a $\overline{D}K$ resonance or bound state and the F_x as an excited F coupled to the DK channel. Rough estimates of their masses are near the DK threshold. If the F_s and F_x are below the DK threshold, as appears likely, they would be stable against strong decays and decay only weakly or electromagnetically.

Table I lists these states with their quark structure, quantum numbers, dominant strongly coupled channels, possible weak and EM decay modes and their "charm-strange analog" states in the light-quark hadron spectrum, obtained by changing the charmed quark to a strange quark.

The essential physical input for Jaffe's prediction of exotics is that the N-Δ mass difference is much larger than the binding energy of the deuteron:

$$M_{\Delta} - M_{N} >> M_{n} + M_{p} - M_{d} . \quad (1)$$

The physics of Eq. (1) is that the dominant spin-independent (color charge) forces which bind quarks into color singlet hadrons saturate[4] at the $q\bar{q}$ and 3q states and the residual forces between hadrons is only of order 2 MeV like the deuteron binding energy. However, the spin dependent (color magnetic) force, responsible for the N-Δ mass difference is very much larger, of order 300 MeV. Thus bringing two hadrons close enough to make the quarks in one feel the interactions of the quarks in the other produces only a very weak force if the functions of the individual hadrons are not changed. However, if the spins of the quarks are recoupled to optimize the spin-dependent interactions between the quarks in different hadrons, binding energies of the order of 300 MeV are available and could give rise to bound exotics. In the quark-antiquark system, the ρ-π mass splitting shows that 600 MeV is gained by changing the spins from S = 1 to S = 0.

Consider the D^+K^- system, for example, where the spins of the $\bar{d}$ antiquark in the D^+ and the s quark in the K^- are uncorrelated and in a statistical mixture which is 75% S = 1 and 25% S = 0. Recoupling these spins to a mixture which is 75% S = 0 and 25% S = 1 would gain a binding energy of half the K^*-K mass difference; i.e. 200 MeV, and might produce a bound charmed-strange exotic. A full calculation of the binding includes spin recoupling effects for all six two-body interactions in the four-body system.

For detailed quantitative calculations Jaffe used the N-Δ and ρ-π mass splittings as input for the strength of the spin dependent interaction. Only one further ingredient was needed to calculate its effect in binding exotic configurations, the color dependence of the interaction. In color singlet $q\bar{q}$ and 3q systems, every $q\bar{q}$ pair is in a color singlet state and every qq pair is in the antisymmetric color triplet state. Exotic configurations, even if they are overall color singlets, can have some color octet $q\bar{q}$ pairs and some symmetric sextet qq pairs. These interactions are not obtainable from observed masses, but are computed by assuming the color dependence of the interaction to be that of the spin-dependent part of the one-gluon exchange potential in QCD. This assumption is supported by the agreement with qualitative features of the low-lying hadron spectrum not obtained in any other way, in particular the signs of the N-Δ and Λ-Σ mass splittings.[5]

The contribution of this interaction to the binding of exotic hadron states is easily calculated by the use of algebraic techniques.[1] One result is simply expressed as the "flavor-antisymmetry principle." The binding force between two quarks of different flavors in the optimum color and spin state is stronger than the binding force between two quarks of the same flavor. The color and spin dependences appear as a flavor dependence as a result of the generalized Pauli principle. Strongest binding occurs in a state which is overall symmetric in color and spin together. Thus if the quarks are in the same orbit and therefore symmetric in space, they must be flavor antisymmetric. This is seen in the N-Δ example where the $I = 1/2$ state is lower than the $I = 3/2$ state even with isospin independent forces, because the Pauli principle requires the correlation between spin and isospin of (1/2, 1/2) and (3/2, 3/2) for a color singlet state.

The flavor antisymmetry principle requires the most strongly bound state of a system of quarks and antiquarks to have quarks and antiquarks separately in the most antisymmetric flavor state allowed by the quantum numbers. Thus for example the lowest state of the six quark system has the configuration (uuddss) with no more than two quarks of any one flavor. This state has been proposed as a resonance or bound state of the ΛΛ system.[6]

For the $qq\bar{q}\bar{q}$ system flavor antisymmetry gives two very interesting qualitative predictions.

1. The lowest states do not have exotic quantum numbers.
2. The lowest states which have both charm and strangeness include exotics.

These predictions follow from the requirement that the two quarks have different flavors and the two antiquarks have different flavors. When there are four flavors, the charmed-strange states in which all of the four particles have different flavors and have exotic quantum numbers can satisfy flavor antisymmetry. But with only three flavors and four bodies, flavor antisymmetry requires one quark-antiquark pair to have the same flavor. Their flavor quantum numbers then cancel out, leaving the hadron with the non-exotic quantum numbers of the remaining pair. A similar argument applies to the $4q\bar{q}$ baryon configuration. Thus flavor antisymmetry provides a natural explanation for the absence of low-lying exotics.

Exact mass predictions for charmed-strange exotics are difficult because of uncertainties in the model. Rough estimates are obtained by use of the charm-strange analogy, in which mass relations for systems involving strange quarks are assumed to hold when one strange quark is replaced by a charmed quark in each state. Examples of the success of this analogy are the SU(6) quark model relations for mass differences between strange and nonstrange particles

$$M(K^*)^2 - M(\rho)^2 = M(K)^2 - M(\pi)^2 \tag{2a}$$

$$M(K^*) - M(\rho) = M(\Sigma^*) - M(\Delta) \tag{2b}$$

and the Federman-Rubinstein-Talmi relation for baryon spin splittings[7]

$$(1/2)[M(\Sigma) + 2M(\Sigma^*) - 3M(\Lambda)] = M(\Delta) - M(N). \tag{2c}$$

The charm analogs of these relations are found to be in good agreement with experiment:[8]

$$M(D^*)^2 - M(\rho)^2 = M(D)^2 - M(\pi)^2 \tag{3a}$$

$$M(D^*) - M(\rho) = M(C_1^*) - M(\Delta) \tag{3b}$$

$$(1/2)[M(C_1^*) + 2M(C_1) - 3M(C_0)] = M(\Delta) - M(N). \tag{3c}$$

While the theoretical basis of these mass relations is still not understood, the observation that whatever works for strange quarks also works for charmed quarks suggests that the anology may be used to extrapolate mass relations valid for systems with two strange quarks to systems with one strange quark and one charmed quark. We assume that the $\delta(970)$ is a four-quark exotic 0^+ state with the configuration $(q\bar{q}s\bar{s})$, where q denotes u or d light quarks, and note the inequalities

$$M(\eta) + M(\pi) < M(\delta) < 2M(K). \tag{4}$$

Changing one strange quark to a charmed quark everywhere gives

$$M(\tilde{F}) + M(\pi) \overset{?}{<} M(\tilde{F};q\bar{q}c\bar{s}) < M(K) + M(D), \tag{5}$$

where the question mark expresses the uncertainty due to mixing in the η, which is not a pure $s\bar{s}$ state and therefore not strictly the charm-strange analog of the F. Thus the statement that the δ is below the $K\bar{K}$ threshold and decays to $\eta\pi$ leads to the analog that the $\tilde{F}$ should be below the DK threshold and might decay to $F\pi$, but it might also be below this threshold.

We now consider the most interesting possibilities for decay modes and signatures for the different mass ranges. Note that the $F\pi$ decay is forbidden by isospin for strong decays of the F_x, the $F2\pi$ decay is forbidden by angular momentum and parity for all strong and electromagnetic decays and the $F3\pi$ channel is probably well above DK threshold.

1. <u>All States Above the DK Threshold</u>: Strong decays would be recognized as resonances in mass plots of the DK, $D\bar{K}$, $\bar{D}K$, and $\overline{DK}$ systems. Decays in the $F\pi$ and $F3\pi$ mode would also be allowed for the $\tilde{F}_I$. Particularly striking signatures would be the double-strangeness decay modes

$$\tilde{F}_S \to D^+K^- \to K^-K^-\pi^+\pi^+ \tag{6a}$$

$$\bar{\tilde{F}}_S \to D^-K^+ \to K^+K^+\pi^-\pi^- . \tag{6b}$$

2. <u>States Below the DK Threshold but Above $F\pi$</u>: The $\tilde{F}_I$ can still decay strongly to final states containing an F, but the F_x must decay electromagnetically and the $\tilde{F}_S$ weakly. The $F_x \to F$ decay is a second order $0^+ \to 0^-$ transition with the emission of either two photons or no photon,

$$F_x^{\pm} \rightarrow F^{\pm} + 2\gamma. \tag{7a}$$

$$F_x^{\pm} \rightarrow F^{\pm} + \pi^{o}. \tag{7b}$$

There is also the first order radiative decay

$$F_x^{\pm} \rightarrow F^{\pm}\pi^{o}\gamma. \tag{7c}$$

An intermediate $F^{*}\gamma$ state could be present in the decay (7a).

Another possible decay for the F_x is into the $\tilde{F}_I$, if it is above the $\tilde{F}_I$. There would then be the cascade decay,

$$F_x^{\pm} \rightarrow \tilde{F}_I^{\pm} + (2\gamma \text{ or } e^+e^-) \rightarrow F^{\pm} + \pi^{o} + (2\gamma \text{ or } e^+e^-). \tag{7d}$$

The e^+e^- decay mode is included because it is also second order in α in this $0^+ \rightarrow 0^+$ transition.

The Cabibbo favored weak decays of the $\tilde{F}_S$ are to state of strangeness -2. States with two charged kaons would provide the best signature for identifying these states, since neutral kaons lose the memory of their strangeness by decaying in the K_L and K_S modes,

$$\tilde{F}_S \rightarrow K^-K^-\pi^+ + (\text{leptons and/or pions})^+ \tag{8a}$$

$$\bar{\tilde{F}}_S \rightarrow K^+K^+\pi^- + (\text{leptons and/or pions})^-. \tag{8b}$$

Strong K^* signals might be expected in the $K^{\pm}\pi^{\mp}$ combinations, and there should be no D present in the final state. Decays to the four-body final states $KK\pi\pi$ might be the best signature, analogous to the decays (6) but without the intermediate DK state and with the possibility of one or two K^*'s. Another possible signature is in the two-body neutral decays,

$$\tilde{F}_S \to \overline{K^o K^o} \to K_S K_S \tag{9a}$$

$$\bar{\tilde{F}}_S \to K^o K^o \to K_S K_S. \tag{9b}$$

Although the final states have lost the memory of the double strangeness, the dominant CP-conserving decay remembers that the initial state is even under CP. If this decay mode of the F_S is important, it can lead to $\tilde{F}_S$ - $\bar{\tilde{F}}_S$ mixing, as in the neutral kaon system.

3. <u>States Below the DK and Fπ Thresholds but Above the F.</u> The $\tilde{F}_I^{\pm}$ would decay electromagnetically by two photon emission

$$\tilde{F}_I^{\pm} \to F^{\pm} + 2\gamma. \tag{10}$$

The other charge states of the $\tilde{F}_I$ would decay weakly. Since the $\tilde{F}_I$ has the quantum numbers of an s-wave $F\pi$ bound state, these decays would resemble the expected decays of the F with an extra pion, and the Cabibbo favored decays would be into states of zero strangeness. In addition there would be the two-body decays

$$\tilde{F}_I^{\pm\pm} \to \pi^{\pm}\pi^{\pm} \tag{11a}$$

$$\tilde{F}_I^o,\ \bar{\tilde{F}}_I^o \to \pi^+\pi^-,\ \pi^o\pi^o,\ K^+K^-,\ K_S K_S. \tag{11b}$$

The exotic double-charge signature for the decay (11a) might be a useful indicator for this state.

The two-pseudoscalar decay modes (11b) are all states of even CP for a J = 0 final state. The two states $\tilde{F}_I^o$ and $\bar{\tilde{F}}_I^o$ can be expected to mix like the neutral kaons. If CP violation is neglected, then the eigenstates will be CP eigenstates and the even state will have the decay modes (11b) while the odd CP state will not decay into the two pseudo-scalars and will decay to three or more in the nonleptonic modes and into semi-leptonic decay modes. Note that this $\tilde{F}_I^o - \bar{\tilde{F}}_I^o$ mixing will be much stronger than $K^o - \bar{K}^o$ mixing in a gauge theory, because it can go via exchange of two intermediate W bosons with all vertices Cabibbo favored and no cancellations of the GIM type.

4. <u>States Below the F</u>. This is highly improbable, but if the $\tilde{F}_I$ is below the F, the F would now decay into the $\tilde{F}_I$ and the roles of the F and $\tilde{F}_I$ would be reversed.

Note that if the $F - \tilde{F}_I$ mass difference is less than the pion mass in either direction there will be a particle whose dominant decay mode is electromagnetic with the emission of a low mass photon pair or electron pair. The mass spectrum of the pair will be continuous, but its maximum must be less than the pion mass.

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Table 1. Properties of Charmed-Strange Four-Quark Mesons

State	Quark Structure	(I, S, C)	Resonance or Bound State of	Possible Weak or EM Decays	CS Analo
$_{S}^{o}$	$cs\bar{u}\bar{d}$	(0, -1, +1)	$D^{+}K^{-}$	$K^{-}K^{-}\pi^{+}\pi^{+}, K_{S}K_{S}$	None
$\bar{}_{S}^{o}$	$\bar{c}\bar{s}ud$	(0, +1, -1)	$D^{-}K^{+}$	$K^{+}K^{+}\pi^{-}\pi^{-}, K_{S}K_{S}$	None
$_{I}^{\pm\pm}$	$cu\bar{s}\bar{d}$ and c. c.	(1, ±1, ±1)	$D^{\pm}K^{\pm}, F^{\pm}\pi^{\pm}$	$\pi^{\pm}\pi^{\pm}$	$\delta^{\pm}$
$_{I}^{o}$	$(cd\bar{s}\bar{u})$	(1, ±1, +1)	$D^{o}K^{o}, F^{+}\pi^{-}$	$\pi^{+}\pi^{-}, K^{+}K^{-}, K_{S}K_{S}$	δ^{-}
$\bar{}_{I}^{o}$	$(\bar{c}\bar{d}su)$	(1, -1, -1)	$\bar{D}^{o}\bar{K}^{o}, F^{-}\pi^{+}$	$\pi^{+}\pi^{-}\pi^{o}, K^{+}K^{-}\pi^{o}$	δ^{+}
$^{\pm}$	$\left[c\bar{s}(q\bar{q})_{I=1}\right]$ and c. c.	(1, ±1, ±1)	$D^{\pm}K_{S}^{o}, F^{\pm}\pi^{o}$	$F^{\pm}\gamma\gamma$	δ^{o}
$_{x}^{\pm}$	$\left[c\bar{s}(q\bar{q})_{I=0}\right]$ and c. c.	(0, ±1, ±1)	$D^{\pm}K_{S}^{o}$	$F^{\pm}\gamma\gamma, F^{\pm}\pi^{o}$	S^{*}