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Molecular charmonium and C-exotic mesons?*

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Recently De Rújula *et al.* and Okun and Voloshin suggested that several peaks in e^-e^+ annihilation cross section into hadrons are due to resonances between two charmed mesons in a relative P wave. Such a picture raises at once the question whether C-exotic mesons formed also from two charmed mesons (or four-quark molecules) in a relative P wave may not coexist at comparable mass. We examine briefly here the spectroscopy for C-exotic mesons with $J^P=0^-$, $I^G=0^-$, 1^+, and $J^P=1^-$, $I^G=0^+$, 1^-.

An experimentally unresolved question to date is whether nature takes advantage of C-abnormal (or C-exotic) mesonic states as a part of the hadron spectroscopy. These C-exotic mesons (called C-abnormal mesons by Gell-Mann[1] some years back) are not coupled to $N\overline{N}, q\overline{q}$ and hence have *low production rates* in many processes. This can be attributed, at least partially, to the absence or smallness of many pole terms (one-particle exchange) that are fully allowed in the case of normal particles. Several theoretical attempts have been made[2,3] to motivate the existence of these new species of hadronic matter, for instance through the clashing of broken internal symmetries[2] SU(3) and nonchiral SU(2)×SU(2) or via the field-current identity[3] for a possible $C=+1$ electromagnetic current. However, the data have not given unambiguous support to these approaches.

Recent work by Jaffe[4] about the possible importance of states of four light quarks in normal hadron spectroscopy, and especially the work of De Rújula *et al.*[5] and Okun and Voloshin[6] on molecular charmonium, have given a new impetus to the search for C-exotic mesons. Jaffe pointed out that such low-lying states as $S^*(993)$ and $\delta(970)$ belonging to a $J^P=0^+$ nonet are essentially S-wave $\overline{K}K$ molecules; De Rújula *et al.*[5] claimed that since the D's are much heavier than K's it is even more likely that there should exist molecules made up of two oppositely charmed mesons. In particular, they suggested that the 4.028-GeV structure in e^+-e^- annihilation be associated with a P-wave $D^*\overline{D}^*$ resonance just above elastic threshold with $J^P=1^-$, $I^G=0^-$, 1^+. This is especially interesting in that they suggest that the *P-wave four-quark system can lie close to threshold in the charm system* reached by e^+-e^- annihilation.[7] It has long been recognized that though C-exotic mesons cannot be formed from the $(q\overline{q})$ system with L excitations, nor with the S-wave states formed out of the $(q\overline{q}q\overline{q})$ configuration,[3] *the low-spin ones can be formed as P-wave states out of a four-quark configuration.* Hence they should lie at mass comparable to that of the 4.028-GeV state. We proceed here to examine briefly the spectroscopy of such C-exotic mesons and the feasibility for their experimental search from e^+-e^- annihilation in the mass region of the $D\overline{D}$ to $D^*\overline{D}^*$ threshold.

It is straightforward to establish that the prominent C-exotic states not coupled to $q\overline{q}$ or $N\overline{N}$ are:

$$\begin{aligned} &J^{PC}=0^{--};\, I^G=0^-,1^+,\\ &J^{PC}=0^{+-};\, I^G=0^-,1^+,\\ &J^{PC}=1^{-+};\, I^G=0^+,1^-,\\ &J^{PC}=2^{+-};\, I^G=0^-,1^+. \end{aligned} \tag{1}$$

These can be of course accompanied by $I=\frac{1}{2}$ members to form a nonet, and we have tacitly accepted Jaffe's argument[4] in Eq. (1) that the low-lying multiquark states may be nonets rather than (I,Y) exotics, e.g., mesonic states with $I=2$ or $\frac{3}{2}$. With our concentration on $D\overline{D}$, $D\overline{D}^*$, $D^*\overline{D}^*$ systems for molecular charmonium, $I=0$ and $I=1$ channels are in any case the appropriate ones to emphasize.

The strong-decay pattern of C-exotic ψ particles of Eq. (1) into $(D\overline{D}, D\overline{D}^*, D^*\overline{D}^*)$ can be summarized as follows. All combinations of J^{PC} in (1) do not decay into $D\overline{D}$ because of C conservation for $J^{PC}=0^{--}$, 1^{-+}, 2^{+-}, and P conservation for $J^{PC}=0^{+-}$. The $J^{PC}=0^{--}$, 1^{-+} members have strong decays via the P wave into $(D\overline{D}^*\pm\overline{D}D^*)$, while those of $J^{PC}=0^{+-},2^{+-}$ have strong decays via the D wave into $(D\overline{D}^*\pm\overline{D}D^*)$. Finally, the $D^*\overline{D}^*$ mode is forbidden for $J^{PC}=0^{--},0^{+-}$ because of C invariance while allowed for $J^{PC}=1^{-+},2^{+-}$ as P- and D-wave molecules, respectively. Clearly, the low-lying C-abnormal molecular charmonium states are likely to be the P-wave molecules

$$\begin{aligned} &\psi(J^{PC}=0^{--};\, I^G=0^-,1^+),\\ &\psi(J^{PC}=1^{-+};\, I^G=0^+,1^-), \end{aligned} \tag{2}$$

which may be located at a mass comparable to the P-wave ($J^{PC}=1^{--}$; $I^G=0^-,1^+$) $D^*\bar{D}^*$ resonance interpretation[5] for the 4.028-GeV structure in e^+-e^- annihilation.

The strong decays of C-exotic molecular charmonium states into normal hadrons will be inhibited by the Zweig rule, and hence the decay widths will be correspondingly narrow; in some cases order-e electromagnetic transitions may be competitive. We summarize below purely phenomenologically some decay transitions of $\psi(J^{PC};I^G)$:

$$\begin{aligned}
&\psi(0^{--};0^-)\to\rho\pi,\,3\pi,\,\rho'(1600)\pi,\ \text{etc.},\\
&\psi(0^{--};1^+)\to\omega\pi,\,\omega'\pi,\ \text{etc.}\\
&(\omega':\ \text{radial excitation of }\omega),\\
&\psi(0^{+-};0^-)\to5\pi,\,2\pi\gamma,\ \text{etc.},\\
&\psi(0^{+-};1^+)\to4\pi,\,2\pi\gamma,\ \text{etc.},\\
&\psi(1^{-+};0^+)\to2\rho,\,2\omega,\,2\phi,\,\omega\phi,\,K^*\bar{K}^*,\,K^*\bar{K}+\bar{K}^*K,\\
&\pi\pi\rho,\,\pi\pi\eta,\,\bar{K}K\pi,\ \text{etc.},\\
&\psi(1^{-+};1^-)\to3\pi,\,\rho\omega,\,\rho\phi,\,K^*\bar{K}^*,\,K^*\bar{K}+\bar{K}^*K,\ \text{etc.},\\
&\psi(2^{+-};0^-)\to\pi\rho,\,3\pi,\,\pi\rho'(1600),\ \text{etc.},\\
&\psi(2^{+-};1^+)\to\omega\pi,\,\omega'\pi,\,\rho^\pm\rho^0,\ \text{etc.}\\
&(\omega':\ \text{radial excitation of }\omega).
\end{aligned}\tag{3}$$

A distinctive signature for these C-exotic states is the *absence* of many prominent modes because of conservation of the usual strong (G, isospin, P, C, and Bose statistics) and electromagnetic (C,P) quantum numbers. To take a sample, the $\psi(0^{+-};0^-)$ is strictly forbidden to decay into 2π, 3π, $\pi+\gamma$, 2γ, $\pi+2\gamma$, while the $\psi(1^{-+};0^+)$ and $\psi(1^{-+};1^-)$ states have respectively no strong decays into 2π, 3π, $2\eta^0$, $K\bar{K}$, and 2π, $K\bar{K}$, $2\eta^0$, $2\rho^0$. Of course, regarded as composites of D^* ($=c\bar{d}$ or $c\bar{u}$) and $\bar{D}^*$ ($=\bar{c}d$ or $\bar{c}u$), decay modes into $\rho\phi$, $\omega\phi$, 2ϕ, $K\bar{K}$, $K^*\bar{K}^*$, etc., are further suppressed by the absence of $s\bar{s}$ content in the initial state.

We shall henceforth concentrate on the P-wave molecules given by Eq. (2) as the more likely candidates to be found in the region immediately above $D\bar{D}$ threshold. The D-wave molecules are likely to be higher in mass, and may not be relevant to the resonance region in e^+-e^- annihilation between 4.1 to 4.4 GeV c.m. energy under current experimental search. The P-wave C-exotic molecules cannot be directly seen in e^+-e^- annihilation, since even the $J^{PC}=1^{-+}$ state cannot be reached by one-photon exchange because of C invariance in electromagnetism. They can be explored as the end product of a *molecular transition*[5] from a normal molecular charmonium vector state $\psi(1^{--};I^G=0^-$ or $1^+)$ reached in e^+-e^- annihilation, e.g.,

$$\begin{aligned}
&\psi(1^{--};0^-)\to\psi(1^{-+};0^+)+\omega_P(\phi_P),\\
&\psi(1^{--};1^+)\to\psi(1^{-+};1^-)+\omega_P(\phi_P),\\
&\psi(1^{--};0^-\text{ or }1^+)\to\psi(1^{-+};0^+\text{ or }1^-)+\gamma,\\
&\psi(1^{--};0^-)\to\psi(0^{--};0^-)+\eta_P,\\
&\psi(1^{--};1^+)\to\psi(0^{--};1^+)+\eta_P.
\end{aligned}\tag{4}$$

Here subscript P refers to $l=1$ transition. Some of these intermediate states (e.g., the $J^{PC}=1^{-+}$ states) could be detected by the observation of peaks in the momentum distribution of low energy "ϕ^0" $=K^+K^-$ (off-mass-shell) or photons. Again, the ϕ modes may be suppressed because of the quark composition of the charmonium molecules.

So far as our C-abnormal states $\psi(1^{-+})$ and $\psi(0^{--})$ are concerned, *quark rearrangement*[5] might give us the following pattern of final decays into standard charminium states $J/\psi(3.1)$, $X^0(2.85)$, and $P_c(3.5)$ plus normal hadrons:

$$\begin{aligned}
&\psi(1^{-+};0^+)\to\begin{cases}J/\psi(1^{--};0^-)+\omega_P(\phi_P)\\ X^0(0^{-+};0^+)+\eta_P\\ P_c(1^{++};0^+)+\eta_S,\end{cases}\\
&\psi(1^{-+};1^-)\to\begin{cases}J/\psi(1^{--};0^-)+\rho_P\\ X^0(0^{-+};0^+)+\pi_P\\ P_c(1^{++};0^+)+\pi_S,\end{cases}\\
&\psi(0^{--};0^-)\to\begin{cases}J/\psi(1^{--};0^-)+\eta_P\\ X^0(0^{-+};0^+)+\omega_P(\phi_P)\\ P_c(1^{++};0^+)+\omega_S(\phi_S),\end{cases}\\
&\psi(0^{--};1^+)\to\begin{cases}J/\psi(1^{--};0^-)+\pi_P\\ X^0(0^{-+};0^+)+\rho_P\\ P_c(1^{++};0^+)+\rho_S.\end{cases}
\end{aligned}\tag{5}$$

Here subscripts S and P, respectively, refer to $l=0$ and $l=1$ transitions.

For orientation, we have illustrated in Fig. 1 the transitions from the isoscalar and isovector 4.4 GeV resonant state, assuming like De Rújula *et al.*[5] that this structure is a $J^{PC}=1^{--}$ molecular charmonium state. Here we have taken the viewpoint that since De Rújula *et al.*[5] have assigned the 4.028-GeV resonance as a P-wave molecule, it seems likely that the other P-wave molecular states (including C-exotic ones) will lie close to this level. Hence we would be in a more favorable position to exploit the discovery of the C exotics as an end product of cascade chains from a *higher-mass* $J^{PC}=1^{--}$ *molecule.*

Finally, molecular states of $F\bar{F}$ [where $F=(c\bar{s})$

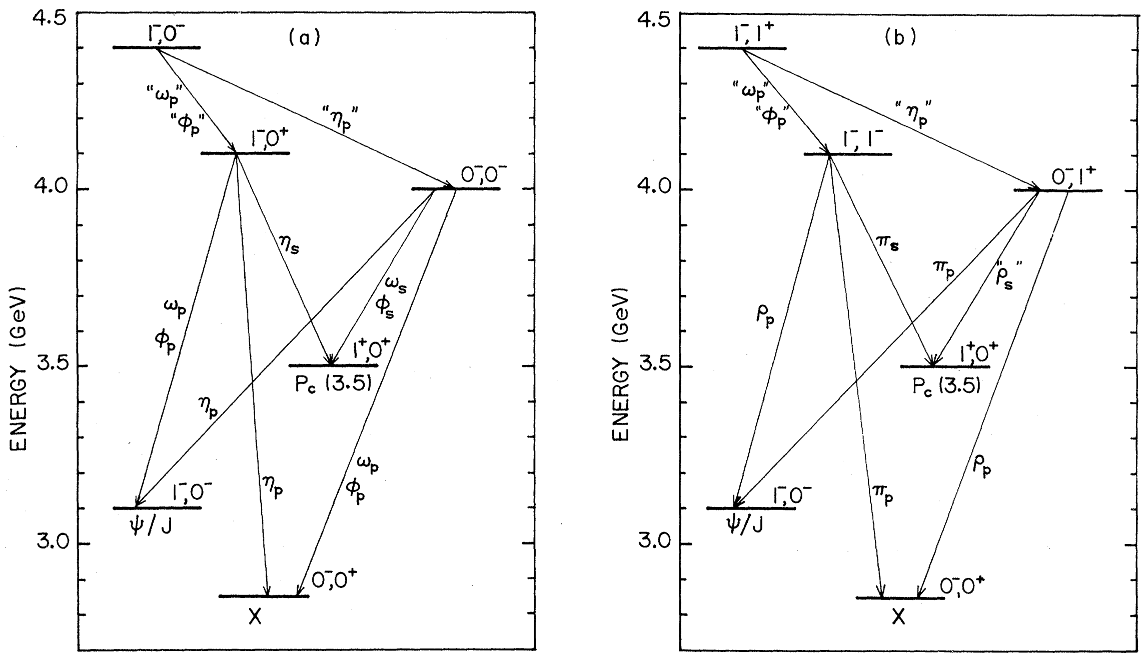

FIG. 1. Transitions from the (a) isoscalar and (b) isovector $\psi(4.4)$. Subscripts S and P respectively refer to $l=0$ and $l=1$ transitions. The X, ψ/J, P_c decays constitute the "atomic" charmonium picture while the ($1^-,0^+$; 1^-, 1^-; 0^-, 0^-; 0^-, 1^+) decays constitute the P-wave "molecules" picture, which for definiteness we have placed in the 4.0-to-4.1-GeV region appropriate to the thresholds for $D\bar{D}^*$ and $D^*\bar{D}^*$.

and $\bar{F}=(\bar{c}s)$], $F\bar{F}^*$, $F^*\bar{F}^*$, may also exist with $J^{PC}=1^{--}$, $I^G=0^-$ and be produced directly in e^+e^- annihilation. They can also form C-abnormal states

$$\psi(1^{-+};0^+),\qquad\qquad (6)$$
$$\psi(0^{--};0^-).$$

The transition chain here would schematically be represented by Fig. 1(a), where we pick out just those transitions with emissions of (ϕ,η) in the S and P waves and interpret the $\psi(1^{--};0^-)$ state as well as the C exotics $\psi(1^{-+};0^+)$ and $\psi(0^{--};0^-)$ of (6) as molecular states made up of $F\bar{F}$, $F\bar{F}^*$, and $F^*\bar{F}^*$, rather than as $D\bar{D}$, $D\bar{D}^*$, etc.

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[1]See, for instance, M. Gell-Mann and Y. Ne'eman, *The Eightfold Way* (Benjamin, New York, 1964), p. 98.

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[4]R. L. Jaffe, Phys. Rev. D 15, 267 (1977); 15, 281 (1977).

[5]A. De Rújula *et al.*, Phys. Rev. Lett. 38, 317 (1977); references to past literature are given here.

[6]Lev B. Okun and M. Voloshin, Zh. Eksp. Teor. Fiz. 23, 369 (1976) [JETP Lett. 23, 333 (1976)]. These authors were the first to consider molecular charmonium states resulting from exchange of ordinary mesons (π, ρ, ω, ϵ, ϕ, etc.).

[7]For the normal hadrons, such a P-wave four-quark system may lie sufficiently higher than the S-wave $K\bar{K}$ molecules as to be less tractable experimentally.