Hydronic molecules and the charmonium atom

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We consider the possible existence of levels in a system consisting of a charmed particle and a charmed antiparticle; these levels result from exchange of ordinary mesons (ω,ρ,ϵ,ϕ, etc.). An interpretation of the resonances in e^+e^- annihilation in the region 3.9–4.8 GeV is proposed.

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A large aggregate of data indicates that ψ, ψ', and other "psions" (χ, P_C, X) are different states of charmonium, a bound state of c and $\bar{c}$ quarks.[1] One cannot speak as yet, however, of a quantitative agreement between the charmonium model and the experimental data with on the level positions and widths. We wish to note here that it is necessary to superimpose on the simple quark-gluon "atomic" structure of charmonium a much more complicated and in a certain sense fundamental structure of levels of "molecular" type, which represent bound states of a charmed hadron and a charmed antihadron, for example bound and (or) resonant dimension states $D\bar{D}$ ($D^+ = c\bar{n}$, $D^0 = c\bar{p}$) as well as states of the type $C\bar{C}$, where C is a charmed baryon.

For a rough estimate we assume, following[3], that just as for the levels of the nucleon-antinucleon system, the potential acting between the particle and antiparticle is due to the exchange of ω, ρ, ϕ, ϵ, and other more massive mesons. We write the potential between D and $\bar{D}$ in the form

$$U^T = U_0 + \vec{\tau}_1\vec{\tau}_2 U_1 = U_0 + [2T(T+1) - 3]U_1 ,$$

where T is the isospin of the system $D\bar{D}$ ($T = 1$ or 0). If $U_0(U_1)$ is due to $\omega(\rho)$ meson exchange, then in the static limit we have $U_0 = -\alpha_\omega \exp(-\mu r)/r$ and $U_1 = \alpha_\rho \exp(-\mu r)/r$, where $\alpha_\omega = g^2_{\omega D\bar{D}}$, $\alpha_\rho = g^2_{\rho D\bar{D}}$, and $\mu \approx 780$ MeV. Consequently, $U^{0,1} = -\alpha^{0,1}\exp(-r)/r$, where $\alpha^0 = \alpha_\omega + 3\alpha_\rho$ and $\alpha^1 = \alpha_\omega - \alpha_\rho$. According to the simplest quark diagrams, $\alpha \approx \alpha_\rho$; the same requirement is imposed by vector dominance and exchange degeneracy (duality). Therefore $|U^1| \ll |U^0|$. Estimates yield $2.8 \lesssim \alpha^0 \lesssim 4.4$ and $0 \lesssim \alpha^1 \lesssim 1.7$. This scatter corresponds to three variants:

a) $\alpha_{\rho N\bar{N}} \approx 0.7, \quad \alpha_{\omega N\bar{N}} \approx 21 \quad \Rightarrow \quad \alpha^0 \approx 4.4, \quad \alpha^1 \approx 1.7$,

b) $\alpha_{\rho N\bar{N}} \approx 0.7, \quad \alpha_{\omega N\bar{N}} \approx 9 \quad \Rightarrow \quad \alpha^0 \approx 3, \quad \alpha^1 \approx 0.3$,

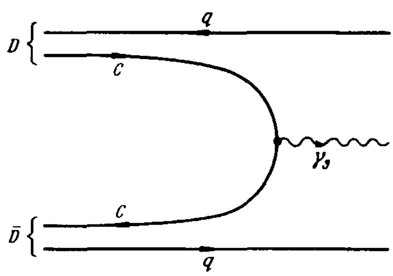
c) $\alpha_{\rho N\bar{N}} \approx 0.7, \quad \alpha_{\omega N\bar{N}} \approx 6.3 \quad \Rightarrow \quad \alpha^0 \approx 2.8, \quad \alpha^1 \approx 0$.

For variants (a) and (b) see[3] and[4] respectively; variant (c) corresponds to the vector-dominance model using a width $\rho \to 2\pi$ ($\alpha_{\rho\pi\pi} = 2.8$). In the recalculation, in accordance with the quark model, it was assumed that $\alpha_\rho \equiv g^2_{\rho D\bar{D}} \approx \alpha_{\rho\pi\pi}/4 \approx \alpha_{\rho N\bar{N}}$ and $\alpha_\omega \equiv g^2_{\omega D\bar{D}} \approx \alpha_{\omega N\bar{N}}/9 \approx \alpha_{\rho N\bar{N}}$.

The Regge trajectory for the Yukawa potential is characterized by the parameter $G=\alpha m_D/\mu$. According to[5], the 1S level appears at $G \gtrsim 1.7$, and 1P has a resonant character (it is metastable with respect to decay into DD) at $7.3 \lesssim G \lesssim 9.0$ and is stable at $G \gtrsim 9.0$. Recognizing that $m_D/\mu \approx 2.5$, we can assume that isosinglet P levels almost certainly exist in the DD system, and their mass apparently differs from threshold $2m_D$ by not more than 100 MeV. It is not excluded that there exist also isotriplet S levels. An enticing interpretation of at least some of the resonances in the region 3.9—4.5 GeV, recently observed at Stanford,[6] is that they are P states of the dimensions $D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}$, and $D^*\bar{D}^*$ (D^* is the vector analog of the D meson). There should be altogether four such states in e^+e^- annihilation.

The width of the $D\bar{D}$ dimesons can be estimated from the nonrelativistic formula $\Gamma_{e^+e^-}=8\alpha^2|F|^2|R'_p(0)|^2M^{-4}$. Here M is the dimeson mass, $R'_p(0)$ is the derivative of the radial part of the wave function of the P level $r=0$, and F is the form factor of the vertex $D\bar{D}_\gamma$. The $SU(3)$-octet part of the form factor should be negligibly small at $q_2 \approx (4\text{ GeV})^2$, and the $SU(3)$-singlet part, which is connected with the charge of the c-quark, should be close to $F=Q_c=2/3$. If we put $|R'_p(0)|^2 \approx \mu^5$ (inasmuch as the radius of the system is $\approx \mu^{-1}$), we obtain $\Gamma_{e^+e^-} \approx 0.2$ keV, which is in fair agreement with the experimental data.

The width of the decay of the dimeson resonances of the levels into $D\bar{D}$ (or $F\bar{F}$) is very sensitive to the extent to which the mass of the level exceeds the threshold. This is confirmed by calculations of the imaginary and real parts of the Regge trajectory[5] ($\Gamma_{D\bar{D}}=2\,\mathrm{Im}l/d\,\mathrm{Re}l/dE$). Decay into ordinary hadrons (mainly into π^-, η^-, and K mesons) can proceed for such dimesons not via three-gluon annihilation (as in the case of ψ), but via the state $q\bar{q}\gamma_S$, where q are ordinary quarks (p,n,λ), and γ_S is a gluon (see Fig. 1). One might therefore as-



sume that the width of such decays can reach about 10 MeV. Finally, an essential role can be played by decays of dimeson levels into $\psi+n\pi$ or $\eta_c+n\pi$. The latter decay can play an important role in the "charm burning". The discussed mechanisms can explain in part the negative results of searches for charmed particles in e^+e^- annihilation.

As to the S levels, the nonrelativistic formulas give for them a binding energy ~ 2 GeV. It is obvious that in this case the nonrelativistic analysis is not valid and it is necessary to discuss the properties of the exotic four-quark molecule $qqcc$ (see[7–9]).[1)] The same pertains to the $C\bar{C}$ levels, where C is a charmed baryon.

The lightest of the charmed baryons, the isosinglet C_0^+ and the isotriplet C_1^{++},

C_1^+, and C_1^0, should have a mass ~2.5 GeV (see[12,13]). In the $C_0^+C_1$ system, tem, we have $\alpha_{\omega C\bar{C}} \approx (4/9)\,\alpha_{\omega N\bar{N}} \approx 4-9$, and therefore the binding energy of the S level is very large. One can speculate that the neutral C-odd level in such a system can appear in experiment in the form of an isotriplet state with $M \approx 2.4$ GeV. $(3.4 \to 2.4 + \rho)$. (We note that $C(G)$-parity doublets should appear in a system of the type $C_0\bar{C}_1$ and $\bar{C}_0C_1$. The interpretation whereby the particle X with $M \approx 2.8$ GeV is regarded as a $C\bar{C}$ level makes likely a larger probability of the decay of this particle to $P\bar{P}$ or $\Lambda\bar{\Lambda}$, which also are made up of six quarks. Great interest attaches to exotic systems of the type $C\bar{N}$, $D\bar{K}$, etc. and also to multi-hadron molecules of the type $DD\bar{D}\bar{D}$, $C_0C_0\bar{C}_0\bar{C}_0$, etc.

We note that if our estimates of α^0 for $D\bar{D}$ are too high and no P state of $D\bar{D}$ is produced, then it is possible that the e^+e^- annihilation resonances in the region 3.9—4.5 GeV are $^3S_1$ states of the baryon pairs $C\bar{C}$, $A\bar{A}$, or $S\bar{S}$. In this case a noticeable fraction should constitute decays of these resonances into nucleon or hyperon pairs.

The complicated resonant structure of the "molecular levels" casts doubts on the possibility of employing this region of such relations as $R = \sum Q_i^2$ and of the conclusion, based on this relation, that additional quarks (fifth, sixth, etc.) or heavy leptons must contribute at $\sqrt{S} \sim 5$ GeV.

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1)After the completion of this paper, preprints appear[10,11] in which, in contrast to our work, the 3.9—4.5 GeV levels in e^+e^- annihilation are regarded not as hadronic molecules, but as exotic four-quark states (molecules) $q\bar{q}c\bar{c}$. The difference between the quark and hadronic molecules is that in the former the attraction is due to gluons, and in the latter to composite mesons. It is obvious that we are dealing with two idealized limiting cases, between which there is a continuous transition.

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