We are grateful to L. Clavelli, G. Feldman, O. W. Greenberg, P. T. Matthews, S. Oneda, G. A. Snow, J. Sucher, C. H. Woo, and T. C. Yang for several helpful discussions and B. Barnett and G. Zorn for clarification of the data.

*Work supported in part by the National Science Foundation under Grant No. GP-4366 2X.

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[6]G. S. Abrams, private communication.

[7]See footnotes 23 and 30 of Ref. 5.

[8]Maintenance of SU(3′) color as a global symmetry is discussed in a forthcoming preprint by R. N. Mohapatra, J. C. Pati, and A. Salam.

[9]This is by using isospin and charge-conjugation selection rules.

[10]This is similar to the approach of M. Gell-Mann, D. Sharp, and W. G. Wagner [Phys. Rev. Lett. 8, 261 (1962)], but we would advocate using subtracted dispersion relations for the diagonal transitions (leading to *charge* form factors) and unsubtracted ones for nondiagonal transitions ($U\to\eta'+\gamma$, $\rho\to\pi+\gamma$, etc.). This does not alter much the applications of vector-meson dominance to $\rho\to\pi+\gamma$, $\omega\to\pi+\gamma$, etc., since $m_{\rho,\omega}\sim 1$ BeV [thus $(1\ \mathrm{BeV})^2/m_\rho^2\sim O(1)$]; but for color-octet transitions, we do not expect the dispersion denominator damping to be compensated by the numerator; thus $(1\ \mathrm{BeV})^2/m_U^2\sim 10^{-1}$.

[11]U being heavy, $(S^0+\gamma)$, $(\epsilon^0+\gamma)$, and (many pions $+\gamma$) modes may also be *relatively* significant.

[12]Note that $\Gamma_e(U)+\Gamma_e(V)$ is independent of ξ.

[13]The corresponding matrix element $\langle \text{hadrons}\,|T(J_\mu^{\text{em}}\times J_\mu^{U^0})|\,U\rangle$ can be dominated by low-mass states and hence should not suffer any suppression.

[14]With φ_c, one expects $\Gamma(\varphi_c\to\text{hadrons}+\gamma)/\Gamma(\varphi_c\to\text{hadrons})\approx\alpha$.

[15]Allowing for heavy mass damping of order-e amplitudes we still find $R\lesssim\alpha$.

[16]We have examined whether the large enhancement of a somewhat similiar decay $\rho'\to\rho+\pi+\pi$ ($h_{\rho'}^2/4\pi\gtrsim 400$) may be relevant to enhance $\psi'\to\psi+\pi+\pi$ decay to the extent needed (if it were a forbidden decay) and find that this is unlikely.

[17]The familiar Zweig-rule suppression of φ_c and $\varphi_c'\to$ hadrons by about 10^{-3} in the amplitude also applies to $\varphi_c'\to\varphi_c+\pi+\pi$. With the ρ'-decay enhancement factor (Ref. 16), we may then expect $h^2/4\pi\approx 10^{-6}\times 400=4\times 10^{-4}$. The situation will, of course, alter if exceptions to the Zweig rule for $\varphi_c'\to\varphi_c+\pi+\pi$-type decays may be understood consistently.

[18]The gluons $V_{\rho^\pm}$, V_{K^*} (carrying I_3' or $Y'\neq 0$) will be produced primarily in an associated manner in hadronic collisions and in e^-e^+ annihilation and singly in charged-current neutrino interactions (see Refs. 4 and 5). They would decay solely via their small components into lepton pairs and known hadrons, if there are no lighter mass color-octet states with similar quantum numbers.

Are There Narrow *D*-Wave Baryon-Antibaryon Resonances?

H. P. Dürr
Max-Planck-Institut für Physik und Astrophysik, München, Germany
(Received 23 December 1974)

The conjecture of a possible narrow *D*-wave resonance of the $\Omega\bar{\Omega}$ system is extended to general baryon-antibaryon systems. On the basis of the well-known *NN* forces one finds that $B\bar{B}$ systems bound by pion forces are more likely to produce narrow resonances. In particular one may expect narrow resonances below the $N\bar{N}$, $\Lambda\bar{\Lambda}$, and perhaps even the $\Xi\bar{\Xi}$ thresholds. A narrow $B\bar{B}$ resonance may serve in a second step (similar to the α particle) to explain the narrow ψ and ψ'.

In a recent Letter[1] an interpretation of the $\psi(3100)$ as a ${}^7D_1$ compound (in the notation ${}^{2S+1}l_j$) of the $\Omega\bar{\Omega}$ system was suggested. It was argued that an angular momentum $l=2$ may keep the constituents sufficiently apart to substantially reduce their annihilation probability and therefore improve their stability. This mechanism only works if there is no strong leakage into S waves. To suppress this leakage it was assumed that the spin-changing forces are weak. In the present

Letter I intend to look more closely into the question of whether the forces expected for such a system can be strong enough to effect binding in a D state without strongly admixing S states. The investigation will be immediately extended to include also particle-antiparticle systems of the stable spin-$\frac{1}{2}$ baryons in order to probe a possible existence of narrow resonances below the thresholds of the other $B\overline{B}$ systems. I will limit myself in this Letter to stating some of the relevant results. Details of the investigation will be published elsewhere.

The baryon-antibaryon interaction may be deduced from the baryon-baryon interaction. There are a number of attempts to analyze the NN forces in terms of potentials connected with the exchange of bosons.[2] They all indicate a long-range part, essentially given by π exchange, a medium region where the exchange of the heavier mesons ($\eta, \rho, \omega, \varphi, A_1, E, D, \epsilon$) are important, and a short-range part $r \leq 0.4$ fm which is strongly repulsive (hard or soft core) where no theoretical description is possible or necessary. The baryon-antibaryon forces may be obtained in this parametrization by inverting all forces arising from the exchange of bosons with negative G parity. One expects, therefore, the $B\overline{B}$ forces to be considerably different from the BB forces; e.g., the ω force which is repulsive for BB will be attractive for $B\overline{B}$. To prevent a complete collapse of the $B\overline{B}$ system in certain configurations it will, however, be necessary to retain the repulsive core at small distances to some extent, or at least to assume a sufficiently "weak hole." If one limits the consideration to $l=2$ states (or at least $l\neq 0$) it then may be legitimate to assume that the centrifugal potential will substantially suppress the wave function in the small-distance region. As a consequence, a description of the interaction in terms of effective Yukawa potentials mediated by the lightest mesons can be physically meaningful as in the case for the deuteron.

Because of the very small mass of the π meson there exists an important quantitative difference between systems which have strong π forces (i.e., $N\overline{N}$ and $\Sigma\overline{\Sigma}$, but also $\Lambda\overline{\Lambda}$ via Σ transmutation) and systems which have only weak π forces or none (i.e., $\Xi\overline{\Xi}$, because of the presumably small coupling, and $\Omega\overline{\Omega}$). If π exchange is possible one may expect rather "loose" compounds. The second most important contribution arises from the "magnetic" forces of the ρ which (if the F/D ratio for the vector mesons is assumed to be similar to the F/D ratio of the pseudoscalar mesons) occur in all systems with strong π forces. Only in third place do the "charge" forces of the ω and φ come into play. The SU(3) scalar combination of these mesons should produce equal attraction in all $B\overline{B}$ pairs. As a consequence the $\Xi\overline{\Xi}$ and the $\Omega\overline{\Omega}$ (because of the smaller ω mass) should be more tightly bound than the other $B\overline{B}$ systems.

In contrast to the predominantly S-wave compound of NN (deuteron), the tensor force associated with pseudoscalar and vector-meson exchange will be of decisive importance in a predominantly D-wave system of $B\overline{B}$. In contrast to the BB system, the tensor forces of π and ρ will add for the $B\overline{B}$ system. For the expectation value of the tensor-force operator S_{12} of baryons with spin $\frac{1}{2}$, one finds for the various $l=2$ configurations

$$\begin{aligned} \langle {}^1D_2|S_{12}|{}^1D_2\rangle &= 0, \\ \langle {}^3D_1|S_{12}|{}^3D_1\rangle &= -2, \\ \langle {}^3D_2|S_{12}|{}^3D_2\rangle &= +2, \\ \langle {}^3D_3|S_{12}|{}^3D_3\rangle &= -\tfrac{4}{7}. \end{aligned} \tag{1}$$

As a consequence the $I^G=0^-$ configuration of ${}^3D_1$ and ${}^3D_3$ and the $I^G=1^+$ configuration of ${}^3D_2$ will lead to a long-range attraction with relative strengths

$${}^3D_1{}^{(0)}:{}^3D_2{}^{(1)}:{}^3D_3{}^{(0)} = 6:2:\tfrac{12}{7}. \tag{2}$$

At the distance m_π^{-1} the attraction in the ${}^3D_1$ will be about 14 times stronger than the π force in the deuteron. A numerical estimate indicates that at m_π^{-1} the forces are about 75 MeV attractive (75% coming from the π-tensor force), at about $0.75m_\pi^{-1}$ they win over the centrifugal repulsion, and at $0.5m_\pi^{-1}$ they are about twice the centrifugal forces, leading to a net attraction of ≈ 500 MeV. To squeeze the particle into the region $r<0.4$ fm (where the repulsion again takes over) leads to a kinetic energy of about 100 to 200 MeV. Hence there is no doubt that binding can be effected at least for the ${}^3D_1$ state. This all presupposes that the additional forces which set in at intermediate range (and which are particularly attractive for the ${}^3D_1$) do not prevent an effective take-over of the repulsion for $r<0.4$ fm.

For the ${}^3D_3$ ($I=0^-$) the potential may still be deep enough to effect binding. For ${}^3D_2$ ($I=1^+$) the "charge" part of the ω will be repulsive which may make binding more difficult but also may have a stabilizing influence with regard to collapse. For the opposite isospin assignment the tensor force will be repulsive and therefore the $S=0$ configurations will be energetically favored. For ${}^1D_2$ ($I=1^-$), the ρ force is attractive (A_3?!). The ${}^3D_1$ ($I=1^+$) and ${}^3D_3$ ($I=1^+$) may be tight ω-bound systems (ρ',g?!) with high annihilation rates.

With the tensor force being the prime force for holding the loosely bound $B\overline{B}$ systems together, one has to expect considerable configuration mixing with the S states for the ${}^3D_1$ state but none for ${}^3D_2$ and ${}^3D_3$. Because of

$$\langle {}^3D_1|S_{12}|{}^3S_1\rangle = 2\sqrt{2}, \quad (3)$$

the S-wave admixture will be roughly

$$P_S \approx 8|\langle S|U_T|D\rangle/(E_D - E_S)|^2, \quad (4)$$

with $\langle U_T\rangle$ the expectation value of the tensor force in the S- and D-wave radial overlap region. The difference $E_D - E_S$ of the binding energies in the D and S states may be assumed to be of the order of 1 GeV or more (if one associates the S states with the vector mesons, etc.), and $U_T \approx 250$ MeV at m_π^{-1}. The radial overlap of the S- and D-wave functions may be very poor because of a strong confinement of the S waves near the origin. This is in apparent contrast to the deuteron where the S wave is pushed far out because of the very small binding and hence overlaps rather well with the D wave. With these factors taken into proper account a $P_S \approx 0.1\%$ seems not unreasonable. Because of the assumed small extension of the S wave one would expect about 100% annihilation in this state. Assuming an "unobstructed width"[1] of about $2m_\pi = 280$ MeV, a partial annihilation width via configuration mixing,

$$\Gamma_{D\to S} \approx 300 \text{ keV}, \quad (5)$$

would be expected. In the ${}^3D_2$ and ${}^3D_3$ no configuration leakage is possible and hence one would expect the corresponding resonances to be considerably sharper.

As a consequence we would expect a moderately broad ${}^3D_1$ (0^-) resonance about 200 MeV below the $N\overline{N}$ threshold, and rather narrow ${}^3D_2$ (1^+) and ${}^3D_3$ (0^-) resonances slightly below the threshold. A similar situation should occur below the $\Lambda\overline{\Lambda}$ threshold (but not below the $\Sigma\overline{\Sigma}$ threshold because of the linkage to $\Lambda\overline{\Lambda}$). Since for $\Xi\overline{\Xi}$ the π forces are presumably a factor 10 less than for nucleons, there may be barely enough attraction to bind the ${}^3D_1$, but there still might be a chance because of the smaller kinetic term. Because the wave function will be considerably outside the potential range, configuration mixing could be small and the width accordingly narrow.

For the $\Omega\overline{\Omega}$ system the situation is quite different because of the absence of π forces. The binding forces should be essentially established by ω exchange with much shorter range. They lead again to strong tensor forces at the distance where binding can be effected. For spin-$\frac{3}{2}$ particles one derives for the tensor-force operator

$$\begin{aligned}
&\langle {}^1D_2|S_{12}|{}^1D_2\rangle = 0,\\
&\langle {}^3D_3|S_{12}|{}^3D_3\rangle = -\tfrac{68}{35},\\
&\langle {}^3D_2|S_{12}|{}^3D_2\rangle = +\tfrac{34}{5},\\
&\langle {}^3D_1|S_{12}|{}^3D_1\rangle = -\tfrac{34}{5},\\
&\langle {}^5D_1|S_{12}|{}^5D_1\rangle = -6,\\
&\langle {}^7D_1|S_{12}|{}^7D_1\rangle = -\tfrac{432}{35}.
\end{aligned} \quad (6)$$

This leads to attraction in ${}^3D_3$ and all $J=1^-$ configurations (${}^3D_1$, ${}^5D_1$, ${}^7D_1$) favoring spin-spin alignment. The central ω force is attractive, too. As a consequence, bound states may be energetically possible. But it remains rather doubtful whether annihilation can be sufficiently suppressed in such tightly bound systems. In addition, the transition elements

$$\begin{aligned}
&\langle {}^3D_1|S_{12}|{}^3S_1\rangle = 34\sqrt{2}/5,\\
&\langle {}^7D_1|S_{12}|{}^3S_1\rangle = -12\sqrt{7}/25,\\
&\langle {}^5D_1|S_{12}|{}^3S_1\rangle = 0,
\end{aligned} \quad (7)$$

show that configuration mixing for ${}^5D_1$ with the ${}^3S_1$ is zero but for the ${}^7D_1$ it does not vanish but amounts to $\approx 13\%$ of the mixing of the ${}^3D_1$ state, which is small but by no means negligible. Hence it is not clear whether in the ${}^7D_1$ annihilation can be suppressed strong enough as to account for the small width of the $\psi(3100)$. It appears also likely that the $\Omega\overline{\Omega}$ should be able, via a long-ranged K^0-derivative force, to convert into a $\Xi\overline{\Xi}$ [if the $\Xi K\Omega$ coupling is not very weak, which according to SU(3) cannot be expected] which then could easily disintegrate. In this case the ψ should show a dominant $B\overline{B}$ decay mode. Since $\psi'(3700)$ is above the $\Omega\overline{\Omega}$ threshold it definitely should have a very pronounced $\Omega\overline{\Omega}$ decay if it is related to a $(\Omega\overline{\Omega})$ ${}^5D_1$.

If rather narrow $N\overline{N}$ resonances slightly below the $N\overline{N}$ threshold [e.g., like the ${}^3D_2$ ($I=1^+$) or the ${}^3D_3$ ($I=0^-$) or even the ${}^3D_1$ ($I=0^-$)] can be indeed established, there may be a fair chance to expect narrow $l=1$ compounds of these objects below the α-particle mass (3751 MeV) in various configurations, in particular also in the 1^- configurations which then may be identified with ψ and ψ'. Because the $N\bar{N}$ compounds are rather extended objects, the α-type object should be dynamically treated as a four-body system. Without a detailed investigation of this configuration it will be hard to judge whether such a system can be sufficiently stable against annihilation. With an α structure the baryonic decays should not dominate but emission of mesons formed by the "transition to the ground state" $D \to S$ should be preferred.

It should also be emphasized that the P states of the $N\bar{N}$ system and their "strange" counterparts may be quite appropriate to render a "natural" explanation for the 0^+, 1^+, and 2^+ resonances one observes between the 0^- and 1^- mesons (S waves?) and the $B\bar{B}$ thresholds.

I gratefully acknowledge interesting discussions with Dr. C. C. Chiang.

Note added.—After conclusion of this work the author learned of a similar general proposal by Goldhaber and Goldhaber.[3] In their short note, however, no specific dynamical scheme is suggested. These authors refer to very extensive earlier work on the $N\bar{N}$ bound states by Shapiro *et al.*[4] There exist further interesting papers along this line.[5]

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Electromagnetic Decay of the New Heavy Mesons at 3.1 and 3.7 GeV

Jeffrey Borenstein and R. Shankar*
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 23 December 1975)

We examine some experimental consequences of the "charmonium" picture, in which the boson resonances at 3.1 and 3.7 GeV are interpreted as bound triplet-s states of a charmed quark-antiquark pair. We investigate the radiative decays of the observed resonances into other charmonium states.

We use the term "charmonium picture"[1,2] to refer to the description of the recently discovered[3-6] resonances at 3.105 (orthocharmonium-I or o-Ch I) and 3.7 GeV (o-Ch II) as triplet-s bound states of a charmed quark (c) and its antiquark ($\bar{c}$). Whereas we shall endeavor to adhere to this general picture of charmonium, we shall occasionally deal with the rather specific model that Appelquist and Politzer[1] employed to describe o-Ch I and its singlet counterpart, paracharmonium-I (p-Ch I)—as $c\bar{c}$ systems bound by a Coulomb-like force mediated by gluons.

Let us begin with the electromagnetic transition from o-Ch I and o-Ch II to p-Ch I. While the very existence of such transitions will lend broad support to this picture, more detailed predictions on the decay rates will test the various assumptions that go into these models in corresponding detail.

If we assume that these states are pure $c\bar{c}$ states described by some nonrelativistic wave function, the width for a general reaction o-Ch $\to p$-Ch $+\gamma$ can be calculated, ignoring spin-orbit coupling, to be

$$\Gamma(o\text{-Ch} \to p\text{-Ch} + \gamma) = (\tfrac{4}{3})(\alpha)(\tfrac{2}{3})^2\left(\frac{k}{m_c}\right)^2\left(\frac{k}{1 + k/(M_p{}^2 + k^2)^{1/2}}\right)|I|^2, \quad (1)$$

where the photon momentum $k = (M_o{}^2 - M_p{}^2)/2M_o$; m_c, M_o, and M_p are the masses of c, orthocharmonium, and paracharmonium, respectively, and

$$I = \int \psi_p{}^*(\vec{x}) \cos(\vec{k}\cdot\vec{x}/2)\psi_o(\vec{x})\, d^3x, \quad (2)$$