Is there a four-quark state near the $B\bar{B}$ threshold?

Ernest Ma, James Pantaleone, and S. Uma Sankar
Physics Department, University of California, Riverside, California 92521
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Recent e^+e^- experiments have found evidence for an unexpectedly large rate of high-momentum J/Ψ production on the $\Upsilon(4S)$ and at a nearby energy. This may be explained as being due to a four-quark state which mixes with the $\Upsilon(4S)$. The four-quark state is described as a diquark-antidiquark bound state where the diquarks are in a color-sextet representation.

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CLEO [1] and ARGUS [2] have reported observing high-momentum ψ's while running on the $\Upsilon(4S)$. Recently, there has been a preliminary report of similar high-momentum ψ's also having been observed at 50 MeV below the $\Upsilon(4S)$ [3]. At other energies "in the continuum," the high-momentum ψ's have failed to be observed [1,2], but there is less data available here and so definite conclusions are not yet possible. While these observations may be explained in terms of continuum production [3], that is not the only possibility. As we shall demonstrate, it is also possible to explain consistently the observations as a new resonance which lies below the $\Upsilon(4S)$, but has a small admixture with the $\Upsilon(4S)$ state. Previous explanations [4] of the data have also invoked new resonances [6], but have had difficulty with the bounds on hard photons from CUSB-II [5]. Here we propose a specific, detailed model which can accommodate all of the present experimental data.

Similarly to Khodjamirian, Rudaz, and Voloshin [6], we postulate a mixing:

$$|\text{observed } \Upsilon(4S)\rangle = \cos\alpha|\text{bare } \Upsilon(4S)\rangle + \sin\alpha|\text{four-quark state}\rangle \ . \tag{1}$$

However, here the four-quark state is taken to have the b quark and a light u or d quark in a tightly bound spin-0 diquark. The diquark-antidiquark bound state has a parity of $(-1)^L$ and a charge conjugation of $(-1)^L$. Hence the $L=1$ states will have the same quantum numbers as the $\Upsilon(4S)$, and so mixing between the two is possible. The diquarks are taken here to be in a color-sextet state—which is different than many discussions of diquarks. Often, only color-antitriplet diquarks are considered because tree-level perturbation theory gives the result that the force between two color triplets is repulsive when they form a sextet. However, when one of the quarks is light, perturbation theory is not valid. Calculations using the strong-coupling expansion indicate that such states should exist [7]. More importantly, similar states may already have been observed. The narrow resonances U^+, U^0, U^- seen at the CERN Super Proton Synchrotron (SPS) [8] and the U^{--} seen at Serphukov [9] are commonly interpreted [10] as a diquark-antidiquark bound state with the diquarks in the color-sextet representation. These states have been called mock or M baryonia in the literature; in this new application we shall simply denote them as M states.

The decay of an M state into gluons can be calculated in QCD perturbation theory for fundamental diquarks. In a radiation gauge, only the diagram shown in Fig. 1 contributes to the decay of $L=1$ states [11,12]. This decay is logarithmically divergent in the momentum of the singe-gluon emission—similar to the decay of the $b\bar{b}$ $^3P_1$ states [13]. In fact, the three-gluon width of an M state can be related to that of the $b\bar{b}$ $^3P_1$ state:

$$\frac{\Gamma(M\ 1P\to ggg)}{\Gamma(1\ ^3P_1\to ggg)} = \frac{5}{12}\,\frac{49}{2}\left|\frac{5}{2}\right|^{5/(2+n)} ,$$
$$\Gamma(M\ 1P\to ggg)\approx 10\ \text{MeV} , \tag{2}$$

where the factor of $\frac{49}{2}$ is the color factor enhancement of sextet over triplet annihilation and the last factor is just the ratio of the derivatives of the P state wave functions at the origin. To evaluate this latter ratio, we use a scaling factor from the static potentials [14]. Here $\frac{5}{2}$ is the ratio of the potentials $V_{[6]}/V_{[3]}$ at tree level (and also one loop [12]) and $5/(2+n)$ is the scaling exponent assuming $V_{[m]}=C_{[m]}r^n$. For the numerical estimate, we used the conservative value of $n\approx 0$ because the diquarks are not fundamental and their coherence in the two-gluon annihilation coupling is at best only approximate. This width is much larger than typical three-gluon annihilation widths of the Υ states because of the three-gluon–sextet color combinatorics, the log singularity, and the somewhat smaller size of the sextet bound state.

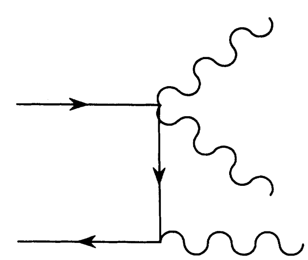

FIG. 1. The one diagram (plus permutations) that contributes to ggg decay of the $L=1$ state in the radiation gauge.

Thus similar size enhancements are *not* expected for other hadronic decays (however, see our later discussion of Υ hadronic transitions). Because the three gluon width is comparable to the observed 24-MeV decay width of the $\Upsilon(4S)$, a moderate amount of mixing, α in Eq. (1), would yield observable non-$B\overline{B}$ decays of the $\Upsilon(4S)$.

The three-gluon phase space is dominated by emission of one soft gluon and two hard gluons because of the logarithmic singularity. The high-momentum ψ's are assumed to come from one of the hard gluons (as is the case for previous models [4,6]). Here the hard gluons are found to be uniformly distributed with respect to the beam axis, while the soft gluon has an angular distribution of $[1+\cos^2\theta]$, with θ the angle between the soft gluon and beam axis.

Photons will also be produced in the decay of $L=1$ M states. Referring to Fig. 1, the only place that a photon can replace a gluon is at the single gauge boson vertex—where the width is log singular. Thus the decay is dominantly into soft photons with a photon spectrum given approximately by

$$\frac{1}{\Gamma}\frac{d\Gamma}{dk}\approx\frac{1}{k+\Delta/2}\,\frac{1}{\ln(M/\Delta)}\ , \qquad (3)$$

where Δ is of order the binding energy and M is the mass of the M state. The angular distribution of the soft photon is $[1+\cos^2\theta]$. To calculate the width for this decay, we must specify the light-quark content of our diquark. Since the Υ states have isospin 0, the mixing will be with the $I=0$ M state, which has a diquark electric charge squared of $Q^2=[\frac{1}{3}+-\frac{2}{3}]^2/2=1/18$. Then

$$\frac{\Gamma(MP\to\gamma gg)}{\Gamma(MP\to ggg)}=0.2\%\ . \qquad (4)$$

Such a photon is below the present bounds set by CUSB-II.

Another source of photons is from radiative transitions [12] of the $L=1$ M state to a $L=0$ M state. The ratio of widths for the $n=1$ states is

$$\frac{\Gamma(M\ 1P\to M\ 1S+\gamma)}{\Gamma(M\ 1P\to ggg)}=2\%\ (k/1.1\ \text{GeV})^3\ , \qquad (5)$$

where 1.1 GeV is a naive calculation of $1P$-$1S$ splitting using sextets with no structure. However, diquarks will have structure, and its effects will be much more pronounced for S than for P states; so we expect the splitting to actually be considerably smaller than 1.1 GeV. Also, the width of the $1S$ is expected to be quite large, $\Gamma(M\ 1S\to gg)\approx200$ MeV, and so the photon will be smeared out. Thus this rate also appears to be consistent with the CUSB-II limits. The angular distribution of the photon is again $[1+\cos^2\theta]$.

The leptonic width of the $L=1$ M state can be calculated as done above. Including the one-loop QCD correction between the diquarks [12] and using the same ratio of wave functions as for ggg decay,

$$\Gamma(M\ 1P\to e^+e^-)<0.1keV\ . \qquad (6)$$

The inequality is used because this decay proceeds through a single, virtual 10-GeV photon for which the diquark coupling is much less likely to be coherent than for the two 5 GeV gluon couplings of Fig. 1. Thus 0.1 keV may be a substantial overestimate. Because the observed leptonic width of the $\Upsilon(4S)$ is 0.24 keV, mixing with an M state [Eq. (1)] implies that the leptonic width of the bare $\Upsilon(4S)$ is larger. This is in much better agreement with the predictions of potential models [15] and could explain why the leptonic width of the observed $\Upsilon(4S)$ is smaller than that of the $\Upsilon(5S)$ state.

In addition to the $|\text{observed }\Upsilon(4S)\rangle$ state [Eq. (1)], there should exist the orthogonal state

$$|\text{observed }M\ 1P\rangle = -\sin\alpha|\text{bare }\Upsilon(4S)\rangle+\cos\alpha|M\ 1P\rangle\ . \qquad (7)$$

Because of the small mixing and small leptonic width [Eq. (6)], this state will give rise to only a small increase in the total cross section in an e^+e^- annihilation experiment—it would be difficult to discriminate it from the continuum. However, in the limit that the beam width is larger than the width of the $\Upsilon(4S)$ and M state, and that the largest contribution to the leptonic width of the M state comes from mixing [Eq. (7)], then

$$\frac{R(s=M(4S);\,ggg)}{R(s=M(M\ 1P);\,ggg)}=1\ . \qquad (8)$$

The rate of ggg decays and subsequent ψ production when running at the $\Upsilon(4S)$ will be equal to that observed when running on the M $1P$ state. Thus, to accommodate the recent observation of ψ's at 50 MeV below the $\Upsilon(4S)$ resonance [3], we interpret this as being the energy of the $|\text{observed }M\ 1P\rangle$ state [Eq. (7)].

With a detailed model for gluon production (Fig. 1), we can calculate the rate for ψ production. In the color evaporation model (CEM) [16], one calculates the rate for producing a $c\bar{c}$ pair on the ψ mass shell, but in a color-octet representation. A somewhat arbitrary overall constant is then included which represents the probability of this pair becoming a ψ. Here we shall eliminate this arbitrary constant by relating our result to the measured rate of ψ production at the $\Upsilon(1S)$ using the CEM calculation of this rate by Fritzsch and Streng [17]. We find

$$\frac{B(M1P\to\psi gg)}{B(\Upsilon(1S)\to\psi gg)}\approx1\ . \qquad (9)$$

Using $B(\Upsilon(1S)\to\psi gg)=0.1\%$, this predicts the branching ratio of the observed $\Upsilon(4S)$ to be $0.1\%\times\sin^2\alpha$, much smaller than the reported rate of order 0.2% [1]. Before commenting on this, let us examine another CEM calculation—the rate of continuum production of ψ's. Using [17] and [18], we find

$$\frac{R\,[\sigma(e^+e^-\to\psi g)/\sigma(e^+e^-\to\mu^+\mu^-)]}{B(\Upsilon(1S)\to\psi gg)} =0.4\ (10\ \text{GeV})^2/s\ . \qquad (10)$$

This predicts the rate of continuum production near the $\Upsilon(4S)$ to be $R\approx4\times10^{-4}$, in agreement with previous estimates [19], while the observed rate corresponds to $R=4\times10^{-3}$. Thus both production mechanisms have roughly equal difficulty in accounting for observations;

i.e., both predict rates a factor of 10 below the observed rate. If the experimental observations are confirmed, then the color evaporation model is inadequate.

The existence of four-quark states may also have an effect on decays of the $\Upsilon(3S)$. While the hadronic transitions $\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-$ and $\psi(2S)\to\psi(1S)\pi^+\pi^-$ are well explained by the gluon radiation mechanism, the transitions $\Upsilon(3S)\to\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(3S)\to\Upsilon(2S)\pi^+\pi^-$ are not [20]. One previously proposed explanation of the latter transitions invoked an intermediate state of a pion and an $I=1$ four-quark state [21]. It is probable that $I=1$ M states accompany our $I=0$ state and influence the hadronic transition; however, there is another possibility. If the $I=0$ M $1P$ state has a large width (say about 10% of the gluonic width) for decay into $\Upsilon(1S)\pi^+\pi^-$, then a very small mixing between the $\Upsilon(3S)$ and the M $1P$ state might explain the data. This latter possibility can be tested by looking for the $\Upsilon(4S)\to\Upsilon\pi^+\pi^-$, where the branching fraction is estimated to be of order 0.4%, which is also the present experimental upper bound.

In summary, we have constructed a model which can accommodate non-$B\bar{B}$ decays of the $\Upsilon(4S)$, the CUSB limits on photons, and also the preliminary reports of ψ production "in the continuum." A new four-quark bound state is introduced where the four quarks are bound into color-sextet diquarks, M states, and the properties of these states are calculated in some detail. There are several ways to test this model. One method is an accurate measurement of semileptonic branching ratios of B mesons [5]. Also, the smeared photon from the radiative transition $[M\ 1P\to M\ 1S+\gamma]$ might be observable. In addition, if high-momentum ψ's are found to be produced at several different energies in the continuum, then this model will not be necessary.

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