Interpretation of the Υ(9.5) as Evidence for Another Quark

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We interpret the broad dimuon resonance at 9.5 GeV as two or three unresolved narrow states of a b quark and antiquark. We calculate the energy spectrum of $b\bar{b}$ states using a linear plus one-gluon-exchange potential.

Herb *et al.*[1] have recently observed a dimuon resonance Υ with a mass of 9.5 GeV and a width of 1.2 GeV. We interpret this resonance as evidence for a fifth quark of mass $m_b = 4.7$ GeV. We assume that the peak in the dimuon spectrum seen by Herb *et al.* is, in fact, several narrow resonances of the $b\bar{b}$ system, analogous to the ψ and ψ' states which in the quark model are narrow states of $c\bar{c}$.

Many authors have postulated that the quark model should contain more than four quarks.[2] Previous to the discovery of the Υ, the mass of the b has been estimated[3] to be around 4 to 6 GeV. This estimate was based on the so-called high-y anomaly in antineutrino interactions. However, a recent experiment by Holder *et al.*[4] shows no evidence for a high-y anomaly. It therefore seems as if the prediction of a quark with mass near that of the quark in the Υ was a coincidence. In the absence of a high-y anomaly, the new b quark is expected to be left-handed. The handedness of the quark will not be relevant in our considerations.

Our model is very similar to that used by several authors[5-7] to calculate the mass spectrum of charmonium. In particular, we assume that the interaction between the b and $\bar{b}$ quarks can be described by a one-gluon-exchange potential plus a linear confining term. In the nonrelativistic approximation (which should be better for $b\bar{b}$ bound states than for $c\bar{c}$ states) the potential between a b quark and antiquark separated by a distance r is

$$V = -\tfrac{4}{3}\alpha_s/r + \beta(r - r_0) + \tfrac{4}{3}\alpha_s(3\vec{L}\cdot\vec{S} + L^2 + \tfrac{1}{2}S_{12})/(2m_b^2 r^3) + \tfrac{4}{3}\pi\,\alpha_s\,\delta(\vec{r})(1 + \tfrac{2}{3}\vec{\sigma}_1\cdot\vec{\sigma}_2)/m_b^2. \quad (1)$$

Here α_s is the strong-interaction coupling constant, β and r_0 are associated with the slope and intercept of the confining potential, $\vec{L}$ is the orbital angular momentum, $\vec{\sigma}_1$ and $\vec{\sigma}_2$ are Pauli matrices, $\vec{S}$ is the sum of the quark spins, and S_{12} is the tensor operator. The factor $\frac{4}{3}$ arises from the non-Abelian nature of the theory.[6] We have omitted certain terms involving momentum, which, if included, would prevent the wave equation from being of the Schrödinger form. These terms contribute very little to the energy in the present case.

In writing Eq. (1), we have assumed that the spin-orbit, tensor, and other spin-dependent terms derive solely from the Coulomb-like term in the potential. In making this assumption, we are following other authors such as De Rújula, Georgi, and Glashow.[6] Another possibility, which we have considered in a previous paper,[7] is to take, for example, the spin-orbit term to be of the form $(1/r)dV/dr$, where V includes the confining term. We plan to consider this alternative in more extensive future investigations of the Υ spectrum.

Because of asymptotic freedom,[8] α_s should be quite small for the heavy b quark. Various authors[5,6] have estimated $\frac{4}{3}\alpha_s$ to be in the range 0.2 to 0.4 for the $c\bar{c}$ system. In the case of $b\bar{b}$, we take $\frac{4}{3}\alpha_s = 0.2$. A value of this order, a little smaller than the value for $c\bar{c}$, comes from the logarithmic behavior of α_s, expected on the basis of asymptotic freedom. We assume that the slope β of the confining potential is $\beta = 5.8\ \text{fm}^{-2}$, the same as we obtained earlier[7] in fitting the ψ spectrum. The intercept r_0 then is fixed by the requirement that the mass of the lowest Υ state be ~ 9.4 GeV. We obtain $r_0 = 0.27$ fm, a value somewhat different from the value $r_0 = 0.41$ fm which we found in calculating the ψ spectrum with the same model. We do not view this difference as important, because r_0 depends sensitively on the choice of mass for the b quark. By changing m_b a small amount, we can make r_0 be the same for the $c\bar{c}$ and $b\bar{b}$ potentials.

Our procedure is to solve a nonrelativistic Schrödinger equation with the potential of Eq. (1), except for the contact term, which we evaluate in lowest-order perturbation theory. We include a cutoff in the r^{-3} term in the potential, as otherwise this term is too singular to allow us to obtain a solution. Our cutoff procedure is to replace r^{-3} by $r^{-1}(r^2+a^2)^{-2}$, where a is a parameter chosen to give results fairly close to the results we would obtain by evaluating the r^{-3} term in perturbation theory without a cutoff.

Several of the lowest-mass levels calculated with this model are given in Table I. Because, in the case of $c\bar{c}$, the model gives somewhat too small a spin-orbit splitting and too small a splitting between singlet and triplet spin states, we guess that the same will be true for these $b\bar{b}$ levels. However, the separation between the $^3S_1$ states comes out about right for the $c\bar{c}$, and we conjecture that this will be the same here.

We see from Table I that three $L=0$ states with $J^{PC}=1^{--}$, having masses of 9.43, 9.88, and 10.22 GeV, are in the mass region of the Υ. There is also an $L=2$ state with $J^{PC}=1^{--}$ of mass 9.95 GeV in this region. All of these states are expected to be considerably narrower than the 0.5-GeV energy resolution of the experiment.

An interesting question for the model is how many of these states contribute to the broad Υ peak. Before we attempt to answer this question, we consider the related question of what is the threshold energy for the production of meson pairs containing the new quantum number.

To a first approximation, the mass of each vector meson belonging to the ground state of the quark-antiquark system is simply the sum of the quark masses the meson contains. According to this simple model, the ρ and ω mesons, both of which contain u and d quarks, should be approximately degenerate in mass in agreement with experiment. Thus, the u and d quarks can be considered to have masses

$$m_u \simeq m_d \simeq \tfrac{1}{2}m_\rho \simeq \tfrac{1}{2}m_\omega \simeq 0.39 \text{ GeV}. \quad (2)$$

Likewise the masses of the s, c, and b quarks are about half the masses of the φ, ψ, and Υ, respectively:

$$m \simeq \tfrac{1}{2}m_\varphi \simeq 0.51 \text{ GeV}, \quad m_c \simeq \tfrac{1}{2}m_\psi \simeq 1.55 \text{ GeV},$$
$$m_b \simeq \tfrac{1}{2}m \simeq 4.72 \text{ GeV}. \quad (3)$$

These quark masses are in approximate agreement with masses estimated by others,[4-6,9] using more sophisticated arguments. According to this simple model, the masses of the K^*, D^*, and K_b^* (the meson carrying the b quantum number) are predicted to be

$$m_{K^*} \simeq m_s + m_u \simeq 0.90 \text{ GeV},$$
$$m_{D^*} \simeq m_c + m_u \simeq 1.94 \text{ GeV}, \quad (4)$$
$$m_{K_b^*} \simeq m_b + m_u \simeq 5.11 \text{ GeV}.$$

The observed masses of the K^* and D^* are

$$m_{K^*}(\text{observed}) = 0.89 \text{ GeV},$$
$$m_{D^*}(\text{observed}) = 2.01 \text{ GeV}. \quad (5)$$

Thus the model predicts the mass of the K^* to be about as observed, but underestimates the mass of the D^* by about 0.07 GeV. If this same trend holds for the K_b^*, its actual mass will be higher than 5.11 GeV by at least 0.07 GeV, and probably more. Furthermore, the splitting of the pseudoscaler K_b from the vector K_b^* is expected to be considerably less than the 0.14-GeV splitting of the D and D^* mesons. Therefore, it is likely that the threshold for production of $K_b\bar{K}_b$ pairs is a little above 10.22 GeV, or above the mass of the $3\,^3S_1$ state of $b\bar{b}$. If this is so, then there ought to be three distinct $^3S_1$ states of $b\bar{b}$ which do not have enough energy to decay into $K_b\bar{K}_b$ pairs. All of these states are expected to be narrow according to the Okubo-Zweig-Iizuka[10] (OZI) rule, and therefore all of them should have appreciable branching fractions into $\mu^+\mu^-$ pairs.

The $^3D_1$ state of mass 9.95 GeV is also expected to be narrow by the OZI rule. However, according to the Van Royen–Weisskopf[11] model, the partial decay width of a vector meson into lepton pairs is proportional to the square of its wave function at the origin. But the wave func-

TABLE I. Calculated values of bound states of $b\bar{b}$.

J^{PC}	$n\,^{2S+1}L_J$	Meson mass (GeV)
0^{-+}	$1\,^1S_0$	9.41
1^{--}	$1\,^3S_1$	9.43
0^{++}	$1\,^3P_0$	9.72
1^{+-}	$1\,^1P_1$	9.73
1^{++}	$1\,^3P_1$	9.73
2^{++}	$1\,^3P_2$	9.73
0^{-+}	$2\,^1S_0$	9.86
1^{--}	$2\,^3S_1$	9.88
1^{--}	$1\,^3D_1$	9.95
2^{-+}	$1\,^1D_2$	9.95
0^{++}	$2\,^3P_0$	10.08
1^{++}	$2\,^3P_1$	10.09
1^{+-}	$2\,^1P_1$	10.09
0^{-+}	$3\,^1S_0$	10.21
1^{--}	$3\,^3S_1$	10.22
1^{--}	$2\,^3D_1$	10.27
1^{--}	$4\,^3S_1$	10.51

tion of any state with $L>0$ is zero at the origin. The model is not exact, but nevertheless we expect that an $L=2$ state will have a small decay width into lepton pairs. Because of the tensor force, the $^3D_1$ state has a small admixture of $^3S_1$. However, we have verified that in the present case the coupling tensor force is too weak to give substantial decay of the 9.95-GeV state to lepton pairs. We therefore believe that it will take an experiment with considerably more sensitivity than that of Herb *et al.*[1] to detect the presence of this state.

As in the case of the ψ and ψ', the Υ, Υ', and Υ'' should have progressively larger widths. This means that the branching fractions of these particles into $\mu^+\mu^-$ pairs should decrease with increasing mass. Since the production cross sections of these particles will probably also decrease with increasing mass, it follows that $\Upsilon(9.43)$ will contribute most to the broad peak observed by Herb *et al.*, the $\Upsilon(9.88)$ next, and the $\Upsilon(10.22)$, even if it is below the $K_b\overline{K}_b$ threshold, will contribute least. Our qualitative argument is not precise enough to let us state definitely whether the production cross section of the $\Upsilon(10.22)$, multiplied by its branching fraction into $\mu^+\mu^-$ pairs, is sufficiently large to contribute significantly to the observed enhancement. We therfore conclude that at least two, and possibly three, very narrow states contribute to the $\Upsilon(9.5)$ enhancement observed in the experiment of Herb *et al.*

After this work was completed we came upon a prior paper by Eichten and Gottfried,[12] who calculated the spectrum for possible bound states of heavy quarks and antiquarks using a Coulomb-like plus a linear potential. These authors did not include the other terms in the potential of Eq. (1). However, since these terms make a small contribution, our energy spectrum is similar to that of Eichten and Gottfried. In addition, subsequent to completing our work, we learned of a paper by Ellis *et al.*[13] also interpreting the Υ as a $b\bar{b}$ state and discussing the production and decays of low-lying vector states.

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