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# IS THE UPSILON A BOUND STATE OF EXOTIC QUARKS?*

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## ABSTRACT

To explain the $\Upsilon$-$\Upsilon'$ mass splitting of the recently discovered $\Upsilon$ resonances, we interpret them as bound states of a quark and an antiquark which are not members of the fundamental ($\underline{3}$) representation of color SU($\underline{3}$). A quark in the $\underline{8}$ (or maybe $\underline{6}$) representation is consistent with the data. We discuss some of its properties and the phenomenological consequences that follow from our suggestion.

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It is widely accepted that the newly discovered upsilon resonance[1] T (9.4) is a bound state ($b\bar{b}$) of a fifth quark b and its antiquark. However, the experimentally observed splitting[2] of the T and T' is too big to be explained by the same (essentially) linear potential that has been applied so successfully to the phenomenology of the $\psi$ spectroscopy[3] (at least in the non-relativistic approximation). To be specific, the potential used by Eichten et al.[4] gives a splitting of 0.4 GeV instead of the observed $M_{T'}-M_{T} \simeq 0.6$ GeV.

To explain the observed splitting, other non-relativistic potential models have been suggested.[5,6] For example, a logarithmic potential[5] seems to be consistent with both the $\psi$ and T spectroscopies in the non-relativistic limit. However, such potential models provide little connection to other aspects of hadronic phenomena.

On the other hand, recent theoretical investigations on quark confinement, linear Regge trajectories for light hadrons, $\psi$ spectroscopy and other hadronic properties strongly indicate a string-(or vortex-) like picture for hadrons. A linear potential arises non-relativistically in any string-like model. Hence, before abandoning such an intuitively simple picture, it is important to find an explanation for the large T-T´ mass splitting within a simple string model.

One obvious possibility is that T and T´ are bound states of two different types of quarks. In particular, using either a simple linear potential[7] or the modified one of Ref. 4, the first radially excited state of the ground state T(10.0) occurs at roughly 10.4 GeV, precisely where some structure[2], namely T´´(10.4), has been observed. The real T´ is then presumably buried between the T(9.4) and T (10.0).

Another possible explanation within the string picture, suggested by Giles and Tye[8], is that the Υ (and Υ′) is a bound state of an exotic quark-antiquark pair, i.e. quarks which are not in the fundamental representation $\underline{3}$ of color SU(3).[9,10] In this Letter we would like to emphasize the likelihood of such an exotic quark. We elaborate on the dynamical reasoning behind this possibility and discuss some of its fascinating phenomenological consequences. Experimentalists studying "upsilon" physics should bear in mind this intriguing possibility.

Since hadron physics is still poorly understood, our dynamical reasoning must necessarily be model dependent. We shall assume exact color confinement; for the sake of clarity and definiteness we shall discuss within the framework of the quark-confining string (QCS) model[11], which is assumed here to be a phenomenological model[12,13] of quantum chromodynamics (QCD). Our attitude and philosophy is very similar to that of Eichten et al.[4] Hence it should be obvious that the validity of our argument is more general; for example, we believe it is equally applicable to lattice gauge theories[14].

In the QCS quark confinement arises from the confinement of the color electric flux along a string. The quark-gluon coupling g (with dimension of mass) is related to the asymptotic Regge slope $\alpha'$

$$\alpha'^{-1} = 2\pi C \frac{g^2}{2} \equiv 2\pi k \qquad (1)$$

where C is the color charge-squared Casimir operator. For quarks in the fundamental representation of color SU(N), $C = (N^2-1)/2N$. Gauge invariance requires g to be universal for all quarks.

In Table 1, $\alpha'$ for the quarks are given. Some explanations are needed. Since the QCS has proper chiral symmetry properties[15], the pion mass can be related to the quark masses by $m_\pi^2 = \frac{1}{\sqrt{\alpha'}}(m_u + m_d)$. Using the current quark mass ratios obtained from current algebra[16], we arrive at the masses of the light quarks shown in Table 1. We note that the quark masses obtained here are very close to those expected of the current quark masses[16]. The Regge slope and the mass for the charmed quark are extracted from $\psi$ spectroscopy[17]. Naively, the Regge slope obtained by interpolating the $\psi$ and $\chi$ states is roughly 0.4 $\text{GeV}^{-2}$, instead of 0.8 $\text{GeV}^{-2}$ as shown in Table 1. However, the difference is entirely due to the effects of massive quarks[18]. The Regge slope will approach its asymptotic value $\alpha'$ as $\frac{m_c}{M} \to 0$, where M is the mass of a pure rotationally excited state (i.e. no radial or vibrational modes).

When the QCS is applied to the T spectroscopy, it is found[8] that $\alpha'$ acquires a much smaller value $\alpha' \simeq 0.4\ \text{GeV}^{-2}$ or $k \sim 0.41\ \text{GeV}^2$. Such a large value of k can be accounted for by putting the new quark Q in the $\underline{8}$ (a zero-triality) representation of color SU(3): $k(\underline{8}) \simeq \frac{9}{4}\ (0.2)\ \text{GeV}^2$. Due to the uncertainties inherent in our estimates, we cannot rule out the $\underline{6}$ (a non-zero triality) representation: $k(\underline{6}) \simeq \frac{5}{2}\ (0.2)\ \text{GeV}^2$. The strength of the linear potential is too strong for higher representations; for instance $k(10) \simeq \frac{9}{2}\ (0.2)\ \text{GeV}^2$. Properties of both the octet and sextet quarks are included in Table 2. We should mention that the shifts of the energy levels of the T spectroscopy due to the inclusions of a small coulomb term in the potential is negligible.

Let us now concentrate on the octet quark Q. The lightest color singlet hadrons containing Q are fermions $(Qq_1\bar{q}_2)$ and antifermions $(\bar{Q}q_2\bar{q}_1)$ where $q_i$ is an old quark (u,d,s,c). The lightest boson is

(Qqqq). In fact, for every (old) meson and baryon state observed, there is a corresponding new state by attaching a Q or $\bar{Q}$ to it. The existence of Q obviously presents a very rich spectroscopy. In passing we should also mention the possible existence of hadrons composed of Q and gluon.

As long as the strong gauge group and the weak gauge group commute, the bare Q quark is stable under color SU(3) and the weak and electromagnetic interactions (e.g. the SU(2) × U(1) model of Weinberg and Salam[19]). The Q quark will thus play no role in the weak interaction phenomenology involving $(Qq\bar{q})$ or (Qqqq). However, it is likely that Q can decay (albeit slowly) into color gluons, standard quarks, and/or leptons in an unified theory of strong, weak and electromagnetic interactions[20]. In case it is stable or metastable, hadrons formed out of it will exhibit many remarkable features discussed by Cahn.[21] In the QCS the ground state meson (Qqqq) cannot decay into $(Qq\bar{q})$ and (qqq) due to lack of phase space. Hence we expect the lowest-mass bosonic states as well as the lowest-mass fermionic states to be stable or metastable. If the electric charge $(e_Q)$ of Q is fractional (integral) then all hadrons consisting of one Q quark also have fractional (integral) charges. For fractional $e_Q$ it will be difficult to distinguish the signal for such hadrons from free quarks. Since the present weak interaction phenomenology does not require a new quark flavor at this mass, Q can have any of the known flavors or any combination of them. It may also have a new flavor. Its baryon number is not determined.

In the $e^+e^-$ annihilation channel, the continuum threshold (c.t) of Q is determined by the $(Qu\bar{u})$ $(\bar{Q}u\bar{u})$ pair. A rough estimate gives $m(Qu\bar{u})\sim$

5.8 ± 0.5 GeV. With the continuum threshold at around 11.6 GeV, there are many radially excited and vibrational states below the threshold in the $e^+e^-$ channel. A very rich array of radiative transitions is expected. This is particularly prominent in the QCD framework, since the three gluon decay mode is completely suppressed. Let us elaborate on this point.

Assuming QCD it is straightforward to calculate the decay modes of $\Upsilon(Q\bar{Q})$. Denoting the energy of the system by M, the wavefunction at the origin by $\psi(0)$, we have, at resonance $(M^2 \sim 4m_Q^2)$ the three-gluon, one-photon-plus-two-gluon and the muon-pair decay widths respectively

$$\Gamma(3g) = G_{3g}\Gamma(3\gamma) = G_{3g}\,\frac{16}{9}\,(\pi^2-9)\,\frac{4\alpha_c^2}{M^2}\,|\psi(0)|^2 \qquad (2a)$$

$$\Gamma(2g+\gamma) = G_{2g+\gamma}\,\frac{\alpha}{\alpha_c}\,e_Q^2\,\Gamma(3\gamma) \qquad (2b)$$

$$\Gamma(\mu^+\mu^-) = G_\gamma e_Q^2\,\frac{16\pi}{3}\,\frac{\alpha^2}{M^2}\,|\psi(0)|^2 \qquad (2c)$$

where $\alpha$ is the fine structure constant and $\alpha_c$ is the color coupling constant. The coefficients G are given in Table 2 which also summarizes some interesting properties of Q. We note the remarkable feature that the $\underline{\Upsilon}(Q\bar{Q})$ cannot decay into three gluons if Q is in the $\underline{8}$ representation. However it can still decay into hadrons via the intermediary of a photon and two gluons whose momenta are coplanar. In this respect it is helpful to recall that the angular distribution for this decay[22] goes as $(3-\cos^2\Theta^*)$ where $\Theta^*$ is the center-of-mass angle for the normal of the decay plane relative to the $e^+e^-$ (which produces the $\Upsilon$) beam direction. The distribution of hard photons[22] $(\frac{2E_\gamma}{M_\Upsilon} \to 1)$ behaves like $(1+\cos^2\Theta_\gamma)$ with $\Theta_\gamma$ being the angle between the photon and the $e^+e^-$ direction. The angular distribution on the decay plane of the photon and the two hadronic jets resulting from the two gluon fragmentation is still the same as that given for the three gluon case.[13] These distributions would provide a very clean test for QCD.

We can also make an educated guess at the decay widths of $\Upsilon$ and $\Upsilon'$. These widths have large uncertainties and are given only for illustrative purposes. Following Eichten and Gottfried[23] we obtain for the octet quark $\Gamma(\Upsilon\to \text{all}) \simeq 179e_Q^2$ keV, $\Gamma(\Upsilon'\to\text{all}) \simeq 176e_Q^2$ keV $+ \Gamma'$, and the muon-pair branching ratios $B(\Upsilon\to\mu^+\mu^-) \simeq \frac{16.3}{179}$ and $B(\Upsilon'\to\mu^+\mu^-) \simeq 10e_Q^2/(176e_Q^2+\Gamma')$ where we have used $\alpha_c(m_\Upsilon) \simeq 0.15$ and have denoted the $\Upsilon'\to\Upsilon\pi\pi$ decay width by $\Gamma'$. Let $R_p$ be the primordial hadronic production of $\Upsilon'$ to $\Upsilon$ ratio. The ratio of the observed $\mu^+\mu^-$ signals at Fermilab is then given by[1,2]

$$R_\mu = \frac{R_p}{1+R_p B(\Upsilon'\to \Upsilon+X)} \frac{B(\Upsilon'\to\mu^+\mu^-)}{B(\Upsilon\to\mu^+\mu^-)} \simeq 0.4 \quad . \tag{3}$$

Assuming $R_p \leq 1$ such that $R_p/[1+R_p B(\Upsilon'\to\Upsilon+X)] < 1$ gives $B(\Upsilon'\to\mu^+\mu^-)/B(\Upsilon\to\mu^+\mu^-) > 0.4$. Following Ref. 23 and 24 we estimate that $\Gamma' \sim 48$ keV. The inequality then becomes

$$64e_Q^2 > 31 \quad . \tag{4}$$

Hence it is possible that $e_Q^2 = 1$,[25] a value we prefer since all new hadrons would then have integral charges. This would result in a dramatic rise in R in $e^+e^-$ annihilation.

So far we have discussed the octet representation. For the $\underline{6}$ quark, the lightest hadron formed out of it is $(Q\bar{q}\bar{q})$, again a fermion.[10] For all new hadrons to have integral charges we must assign $e_Q = \frac{1}{3} \pm$ integer. Some of the properties of the sextet quark are summarized in Table 2.

In conclusion we have suggested that the upsilon resonances are bound states of color octet (or perhaps sextet) quarks. The phenomenological consequences we have outlined in this paper can be cleanly tested in the $e^+e^-$ annihilation machines in the near future.

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## TABLE CAPTIONS

1. For all the old ($\underline{3}$) quarks which have masses ranging from 7 MeV to 1.15 GeV the asymptotic Regge slope $\alpha' \simeq 0.8$-$0.9$ GeV$^{-2}$ (corresponding to $k \simeq 0.2$ GeV$^2$). But $\alpha'$ for the new quark Q has only half that value.

2. Table showing the color charge-squared Casimir operator C, the continuum threshold (c.t.), the S states and the vibrational states in GeV below c.t. in the $e^+e^-$ channel (relativistic corrections < 100 MeV to the energy levels have not been included), the increase in the hadronic to $\mu$-pair ratio R in $e^+e^-$ annihilation, the contribution to $C_2$ of the $\beta$-function (see Ref. 26 for notations) and the decay coefficients G corresponding to the three color representations for the new quark.

TABLE 1

| quark | mass m | $\alpha'$ |
|---|---|---|
| u (up) | 7 MeV | 0.9 |
| d (down) | 12 MeV | 0.9 |
| s (strange) | 0.22 GeV | 0.8-0.9 |
| c (charm) | 1.15 GeV | 0.8 |
| Q | 4.3 GeV | 0.4 |

TABLE 2

| Representation | $\underline{3}$ | $\underline{6}$ | $\underline{8}$ |
|---|---|---|---|
| C | $\frac{4}{3}$ | $\frac{10}{3}$ | $\frac{9}{3}$ |
| c.t. (in GeV) | 10.8 | 11.6 | |
| S states | 9.4,10.0,10.5 | 9.4,10.0,10.5,10.9,11.3 | |
| Vibrational states | 10.6 | 10.6,11.0,11.2,11.3,11.5 | |
| $\Delta R$ | $3e_Q^2$ | $6e_Q^2$ | $8e_Q^2$ |
| $\Delta C_2$ | 1/2 | 5/2 | 6/2 |
| $G_\gamma$ | 3 | 6 | 8 |
| $G_{3g}$ | 5/18 | $\frac{5}{18} \times \frac{49}{2}$ | 0 |
| $G_{2g+\gamma}$ | 2 | 25 | 27 |