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THE LOFTY Υ AS BOUND STATES OF NEW HEAVY QUARKS*

C. E. Carlson†

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

R. Suaya††

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

and

Physics Department
McGill University, Montreal, Quebec H3C 3G1

ABSTRACT

The cascade-gluon model is used to show that the observed enhancement at 9.5 GeV can be interpreted as due to the production, and subsequent cascade decay into $^3S_1$ states, of at least two and most likely three sets of C=+ bound states of quarks Q of mass $m_Q \simeq 5$ GeV and charge $-\frac{1}{3}$ e.

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The recent controversy concerning the "high-y anomaly"[1] has cast doubt upon what had been the best evidence for the existence of a heavy quark.[2] Indeed, if the newest neutrino data[1] is taken in isolation, it would be natural to accept the most economical $SU(2) \times U(1)$ Weinberg model[3] for the weak interactions, with only four quark flavors. However, the small upper limits on parity violations in atomic physics[4] and the apparent existence of a heavy lepton[5] obviate the simplest scheme. Both of the preceding experimental observations, taken in conjunction with available theoretical models, suggest that further quarks must exist. Therefore, it is a good time for observations directly indicative of new quark flavors. This we believe is the case for the recent Columbia-Fermilab-Stony Brook experiment.[6]

They report a resonance with a mass of about 9-1/2 GeV produced by proton-nucleus collisions and observed via its $\mu^+\mu^-$ decay. Their experimental resolution is 500 MeV, and if the enhancement seen in the $\mu^+\mu^-$ mass spectrum is fit by a single resonance, its width is about 1.2 GeV. However, the enhancement is asymmetrical, suggesting that more than one state contributes to the observed bump.

In this letter, we shall interpret the observations of the Columbia-Fermilab-Stony Brook group as due to the production of two, and more likely three, $^3S_1$ bound states of $Q\bar{Q}$ (to be dubbed Υ, Υ', Υ'' or perhaps "onium"), where Q is a quark carrying a new flavor quantum number. The lowest several members of the Υ family individually have very narrow widths, but show as a broad enhancement in the data because their spacing is less than the experimental resolution. After making some further remarks about the $Q\bar{Q}$ parameters and mass spectrum, we will try to strengthen the $Q\bar{Q}$ bound state interpretation of the data by calculating the hadronic production cross section in the "gluon cascade" model. There are no overall normalization parameters, so we can make an absolute comparison to the data and we shall find reasonable agreement for λ_Q = electric charge in units of $e = -1/3$. The case $\lambda_Q = 2/3$ is excluded.

The spectrum expected for bound states of a heavy quark has been elucidated by Eichten and Gottfried[7] using the potential

$$V(r) = -\frac{4}{3}\,\frac{\alpha_g}{r} + \frac{r}{a^2} + \text{const} \tag{1}$$

We shall simplify our calculation by using only the linear term. Comparisons to Ref. 7 show that the linear term dominates in the sense that the overall mass splittings and widths are not greatly affected by the inclusion of the Coulomb term. Having a purely linear potential allows us to determine how the various masses, splittings and widths scales as the parameters m_Q and λ_Q change. For the psions, $m_c = 1.84$ GeV and $\underline{a} = 1.94$ GeV^{-1}. The parameter $\underline{a}$ is chosen to be the same as for psions, on the grounds that it is a parameter of the force that binds the quarks and not of the quarks themselves. This can be understood in models. In the string model $a^2 = 2\pi\alpha'$, with α' the universal Regge slope;[8] in the MIT bag model, the linear potential arises for large quark separation from the interplay of the bag pressure and color electrostatic energy and both terms are quark mass independent.[9] For the mass m_Q we use 5.1 GeV, which will put the third P state (the 3P) just below the threshold for strong decay into $Q\bar{q} + q\bar{Q}$, where q is a u, d, or s quark.[10] Finally, when needed, we will use $\alpha_g = 0.17$ as predicted for the present mass range by the renormalization group equation.[11]

Having stated our parameters, we put the lowest S-state at 9.44 GeV as suggested by the experiment, and then find S-states at 9.44, 9.86, and 10.20 GeV, and P-states at 9.69, 10.05, and 10.37 GeV.

The hadronic production of Υ's proceeds[12-13] as diagrammed in Fig. 1. Only those C=+ intermediate states with appreciable branching ratios into $^3S_1$ states need be included. This eliminates all states above the threshold for strong decay as well as the $^1S_0$ states, which can decay into $^3S_1$ states only by forbidden magnetic transitions. This leaves the ^3P_j states. The cross sections for producing a n $^3S_1$ Υ state from a given set of m ^3P_j states is

$$\left.\frac{d\sigma}{dy}\right|_{y=0} = \frac{8\pi^2 M_{nS}}{M^4_{mP}} \times \Gamma_{eff}(n,m) \times \tau f_g^2(\sqrt{\tau}) \tag{2}$$

where y is the rapidity, $\tau = M^2_{mP}/s$, f_g is the gluon (g) distribution function,

$$f_g = \frac{N+1}{16x}(1-x)^N \quad , \tag{3}$$

and

$$\Gamma_{eff}(n,m) = \sum_{J=0,2} (2J+1) \frac{\Gamma\left(m\,^3P_j \to gg\right) \Gamma\left(m\,^3P_j \to n\,^3S_1 + \gamma\right)}{\Gamma_{total}\left(m\,^3P_j\right)} \tag{4}$$

The widths and also some branching ratios that we use are given in Table I. The widths may be obtained by direct calculation, or by scaling from charmonium according to the rules $\Gamma(P \to gg) \propto \alpha_g^2\ m_Q^{-7/3}\ a^{-10/3}$, $\Gamma(P \to \Upsilon\gamma) \propto \lambda_Q^2\ m_Q^{-5/3}\ a^{-8/3}$, and $\Gamma(\Upsilon \to \mu\bar{\mu}) \propto \lambda_Q^2\ m_Q^{-1}\ a^{-2}$, assuming a linear potential.

The leptonic branching ratios are straightforwardly obtained. The branching ratios of higher Υ's into lower Υ's deserve some comment. First and importantly, we should note that the summed $\mu\bar{\mu}$ cross section, i.e., the sum over Υ states of $B(\Upsilon^i \to \mu\bar{\mu}) \cdot d\sigma(\Upsilon^i)/dy$, does not depend on these branching ratios if the potential is linear. This can be shown because the width for decay into $\mu\bar{\mu}$ is the same for all Υ states. Next, one expects the branching ratio $B(\Upsilon' \to \Upsilon X)$ to be less than the corresponding one for psions because the mass splitting is smaller. The decays $\Upsilon' \to \Upsilon X$ will be dominantly $\Upsilon' \to \Upsilon + 2\pi$, and if we use phase space to scale down the width from the ψ' decay, we get $B(\Upsilon' \to \Upsilon X) = 36\%$. However, we favor a smaller estimate, 10-20%, because the 2π mass spectrum in ψ' decays shows a peaking at high dipion mass. Finally, the ratios $B(\Upsilon'' \to \Upsilon$ or $\Upsilon' + X)$ are chosen reasonably: phase space suggests that $B(\Upsilon'' \to \Upsilon' X)$ is small, and $B(\Upsilon'' \to \Upsilon X)$ is large.

We may now calculate the Υ production. For N=3, 4, 5 [14] (see Eq. (3)), we obtain $\sum B(\Upsilon^i \to \mu\bar{\mu}) \cdot d\sigma/dy|_{y=0} = 0.82,\ 0.51,\ 0.30$ pb, respectively, to be compared to the experimental value of 0.34 pb. For N=4, Fig. 2 shows the three bumps smeared by the 500 MeV experimental resolution, using the calculated heights of the Υ, Υ', and Υ'' bumps, which are 0.36, 0.12, and 0.03 pb. The agreement is good, and does indicate we are on the right track to think that we have $Q\bar{Q}$ bound states produced in this way.

The charge of the quark enters our calculation in both $B(\Upsilon \to \mu\bar{\mu})$ and $B(P \to \Upsilon + \gamma)$. The numerator of each of these is proportional to λ_Q^2. Although the denominator of each also increases somewhat with λ_Q^2, nonetheless changing to a quark of charge 2/3 increases our calculated cross section by about a factor of 8.

In conclusion, gluons seem to us to be the most natural mediators between the old SU(3) hadrons and the new bound states $Q\bar{Q}$.[15] Both theory (QCD) and experiment (deep inelastic electroproduction) have indicated the need for gluons in the hadronic wave function. In the present calculation, the fact that agreement with experiment came out directly, without forcing or fitting parameters,[16] gives us confidence that photons can be discovered in conjunction with Υ or J/ψ in hadronic experiments.

As this report of our work was being written, a preprint was received from J. Ellis, M. Gaillard, D. Nanopoulos, and S. Rudaz, who discuss the interpretation of the Υ as a $Q\bar{Q}$ resonance and production via a Drell-Yan type mechanism.

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FOOTNOTES AND REFERENCES

1. F. Eisele, in Proceedings of the 1977 SLAC Summer Institute in Particle Physics; B. C. Barish et al., preprints CALT 68-604 to 68-607 (1977).
2. A. Benvenuti et al., Phys. Rev. Lett. 36, 1478 (1976); ibid. 37, 189 (1976).
3. S. Weinberg, Phys. Rev. Lett. 19, 1264 (1974).
4. P.E.G. Baird et al., Nature 264, 528 (1976).
5. M. L. Perl et al., Phys. Lett. 63B, 466 (1976).
6. S. W. Herb et al., Fermilab preprint 77/58.
7. E. Eichten and K. Gottfried, Phys. Lett. 66B, 286 (1977).
8. Some weak mass dependence may be present when, for example, vibrational modes are excited as in R. C. Giles and S.-H. Tye, Phys. Rev. Lett. 37, 1175 (1976).
9. See J. Kuti in Charm-Color and ψ, Compte Rendu X^{eme} Rencontre de Moriond, Vol. II, J. Tran Thanh Van, editor (1975), p. 209.
10. That the 3P state is bound follows from Ref. 7 (E. Eichten, private communication). If the 3P state were unbound, our summed cross sections would be 70-75% of the values we quote.
11. H. D. Politzer, Phys. Rev. Lett. 30, 1346 (1973); D. Gross and F. Wilczek, ibid. 30, 1343 (1973).
12. C. E. Carlson and R. Suaya, Phys. Rev. D 14, 3115 (1976); Phys. Rev. D 15, 1416 (1977).
13. S. Ellis, M. Einhorn, and C. Quigg, Phys. Rev. Lett. 36, 1263 (1976).

14. Justifications can be found for each of these. N=5 results from counting rules; N=4 is perhaps the best and results when the gluon arises from bremsstrahlung off a valence quark; N=3 was the value that fit $d\sigma/dx$ best in Ref. 10.

15. But see also J. Gunion, Phys. Rev. D 12, 1345 (1975); M. B. Green, M. Jacob, and P. Landshoff, Nuovo Cimento 29A, 123 (1975); D. Sivers, Nucl. Phys. B106, 95 (1976); A. Donnachie and P. Landshoff, Nucl. Phys. B112, 233 (1976).

16. It is proper that we point out that the recent experiment of M. J. Corben et al. [Phys. Lett. 68B, 96 (1977)] might be embarrassing to the gluon model because of their quoted ratio $\sigma(p)/\sigma(\bar{p}) = 0.15 \pm 0.08$ [where $\sigma(\bar{p}) \equiv \sigma(\bar{p}+p \to \psi + X)$], in contrast to the asymptotic prediction of unity. We feel it is too early to reach conclusions, because simple kinematics due to threshold effects can already account for a factor of two in this ratio. This topic is under investigation.

Table I. Relevant widths (in keV) and branching ratios, for the process shown in Fig. 1.

Initial State	E1 Widths 1S	2S	3S	gg Width for $^3P_0$
1P	12.8	--	--	90
2P	2.5	12.8	--	140
3P	0.18	0.76	13.5	193

$B(\Upsilon \to \mu\bar{\mu}) = 3.7\%$	$B(\Upsilon' \to \Upsilon X) = 15\%$
$B(\Upsilon' \to \mu\bar{\mu}) = 3.0\%$	$B(\Upsilon'' \to \Upsilon X) = 80\%$
$B(\Upsilon'' \to \mu\bar{\mu}) = .73\%$	$B(\Upsilon'' \to \Upsilon' X) \simeq 0$

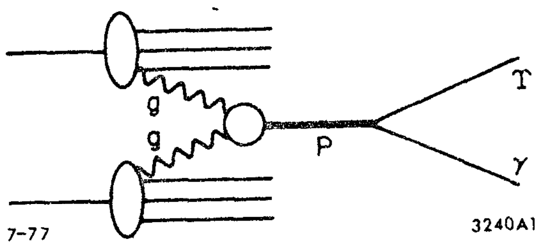

Fig. 1. Process of producing the Υ states in hadronic collisions.

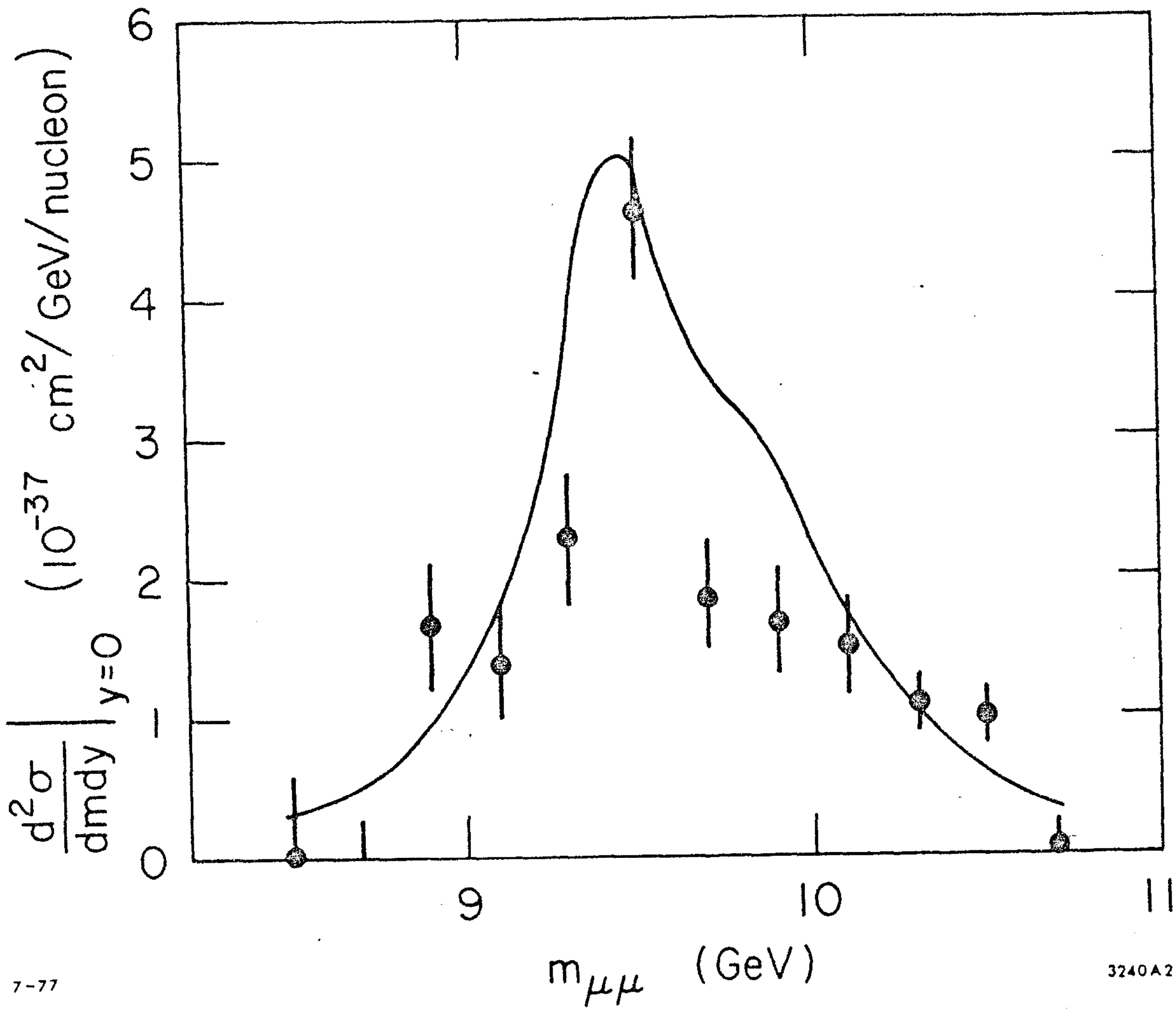

Fig. 2. Our calculation of Υ, Υ', and Υ'' production smeared by the experimental resolution and compared to the data of Ref. 6.