Scott (Plenum, New York, 1977), p. 489.

[5] See, for example, Matsuda *et al.*, Ref. 4.

[6] M. Peshkin and J. L. Rosner, Nucl. Phys. B122, 144 (1977).

[7] A. Pais and S. B. Treiman, Phys. Rev. D 15, 2529 (1977).

[8] Dynamical models discussing resonances in D decays have been discussed by S. R. Borchardt, T. Goto, and V. S. Mathur, Phys. Rev. D 15, 2022 (1977); N. Cabibbo and L. Maiani, Phys. Lett. 73B, 418 (1978); D. Fakirov and B. Stech, Nucl. Phys. B133, 315 (1978); I. Montvay, to be published.

[9] See, for example, Rosner, Ref. 4, and Pais and Treiman, Ref. 7.

Is the Υ a Bound State of Exotic Quarks?

Yee Jack Ng
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

S.-H. H. Tye
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

(Received 20 March 1978)

To explain the Υ-Υ' mass splitting of the recently discovered Υ 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(3). A quark in the $\underline{8}$ or $\underline{6}$ representation is consistent with the data. We discuss some of its properties and the phenomenological consequences that follow from our suggestion.

It is widely accepted that the newly discovered upsilon resonance[1] $\Upsilon(9.4)$ is a bound state ($b\bar{b}$) of a fifth quark b and its antiquark. However, the experimentally observed splitting[2] of the Υ and Υ' is too big to be explained by the same (essentially) linear potential that has been applied so successfully to the phenomenology of the ψ spectroscopy[3] (at least in the nonrelativistic approximation). To be specific, the potential used by Eichten *et al.*[4] gives a splitting of 0.4 GeV instead of the observed $M_{\Upsilon'} - M_{\Upsilon} \simeq 0.6$ GeV.

To explain the observed splitting, other nonrelativistic potential models have been suggested.[5,6] For example, a logarithmic potential[5] seems to be consistent with both the ψ and Υ spectroscopies in the nonrelativistic 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, ψ spectroscopy, and other hadronic properties strongly indicate a stringlike (or vortexlike) picture for hadrons. A linear potential arises nonrelativistically in any stringlike model. Hence, before abandoning such an intuitively simple picture, it is important to find an explanation for the large Υ-Υ' mass splitting within a simple string model.

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

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 discuss the likelihood of such an exotic quark. We elaborate on the dynamical reasoning behind this possibility and discuss some of its fascinating phenomenological consequences.

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 carry out our discussion 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 are very similar to those 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 α':

$$\alpha'^{-1} = 2\pi(g^2/2)c_3 \equiv 2\pi k, \qquad (1)$$

where c_3 is the square of the color charge operator. For quarks in the fundamental representation of color SU(N), $c_3 = (N^2-1)/2N$. Gauge invariance requires g to be universal for all quarks.

In Table I, α' 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 $m_\pi^2 = (\alpha')^{-1/2} \times (m_u + m_d)$. Using the current quark mass ratios obtained from current algebra,[16] we arrive at the masses of the light quarks shown in Table I. 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 ψ spectroscopy.[17] Naively, the Regge slope obtained by interpolating the ψ and χ states is roughly 0.4 GeV^{-2}, instead of 0.8 GeV^{-2} as shown in Table I. However, the difference is entirely due to the effects of massive quarks.[18] The Regge slope will approach its asymptotic value α' as $m_c/M \to 0$, 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 Υ spectroscopy, it is found[8] that α' acquires a much smaller value $\alpha' \simeq 0.4$ GeV^{-2} or $k \sim 0.41$ 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): $k(\underline{8}) \simeq \frac{9}{4} \times 0.2$ GeV^2. Because of the uncertainties inherent in our estimates (and the experimental errors), the $\underline{6}$ (a nonzero-triality) representation is also consistent with the data: $k(\underline{6}) \simeq \frac{5}{2} \times 0.2$ GeV^2. The strength of the linear potential is too strong for higher representations; for instance $k(\underline{10}) \simeq \frac{9}{2} \times 0.2$ GeV^2. Properties of both the octet and sextet quarks are included in Table II. We should mention that the shifts of the energy levels of the Υ spectroscopy due to the inclusions of a small Coulomb term in the potential are negligible.

Let us first 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 formed 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)$\otimes$U(1) model of Weinberg and Salam[20]]. The Q quark will thus play no role in the present weak-interaction phenomenology involving $(Qq\bar{q})$ or $(Qqqq)$. However, it is likely that Q can decay into color gluons, standard quarks, and/or leptons in a unified theory of strong, weak, and electromagnetic interac-

TABLE I. For all the old ($\underline{3}$) quarks which have masses ranging from 7 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 α' for the new quark Q has only half that value.

Quark	Mass m	α'
u (up)	7 MeV	0.9
d (down)	12 MeV	0.9
s (strange)	0.22 GeV	0.8–0.9
c (charmed)	1.15 GeV	0.8
Q	4.3 GeV	0.4

TABLE II. Table showing the color-charge-squared Casimir operator c_3, the continuum threshold (ct), the S states and the vibrational (vib) states in GeV below ct in the e^+e^- channel (relativistic corrections < 100 MeV to the energy levels have not been included), the increase in the hadronic to μ-pair ratio R in e^+e^- annihilation, the contribution to c_2 of the β function (see Ref. 19 for notations) and the decay coefficients G corresponding to the three color representations (rep) for the new quark. $\Gamma_{e^+e^-}$ is the leptonic width in keV.

Representation	$\underline{3}$	$\underline{6}$	$\underline{8}$
c_3	4/3	10/3	9/3
ct	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	
ΔR	$3e_Q^2$	$6e_Q^2$	$8e_Q^2$
Δc_2	1/2	5/2	6/2
G_γ	3	6	8
G_{3g}	5/18	(5/18) × (49/2)	0
$G_{2g+\gamma}$	2	25	27
$\Gamma_{e^+e^-}$	$6.3e_Q^2$	$12.6e_Q^2$	$16.8e_Q^2$

tions.[21] In case it is stable or metastable, hadrons formed out of it will exhibit many remarkable features discussed by Cahn.[22] In the QCS the ground-state meson $(Qqqq)$ cannot decay into $(Qq\bar{q})$ and (qqq) because of lack of phase space. Hence we expect the lowest-mass bosonic states as well as the lowest-mass fermionic states to be stable in strong interaction. 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 of Q is determined by the $(Qu\bar{u})$ $(\bar{Q}u\bar{u})$ pair. A rough estimate gives $m(Qu\bar{u}) \sim 5.8 \pm 0.5$ 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.

In QCD it is straightforward to calculate the decay modes of $\Upsilon(Q\bar{Q})$. Denoting the energy of the system by M and the wave function 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,

$$\Gamma(3g) = G_{3g}\Gamma(3\gamma)$$

$$= G_{3g}\tfrac{16}{9}(\pi^2 - 9)(4\alpha_c^{\,3}/M^2)|\psi(0)|^2, \tag{2a}$$

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

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

where α is the fine-structure constant and α_c is the color coupling constant. The coefficients G are given in Table II which also summarizes some interesting properties of Q. We note the remarkable feature that the $\Upsilon(Q\bar{Q})$ 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.

For the $\underline{6}$ representation, Q also does not decay in the present weak-interaction phenomenology; but it may decay in a unified theory of strong, weak and electromagnetic interactions. 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 quarks are summarized in Table II. For $e_Q = \pm\frac{1}{3}$, the leptonic width of $\Upsilon(9.4)$ is estimated to be 1.36 keV. Within the framework of QCD, we note that the leptonic branching ratio B_l for a $\underline{6}$ quark bound state is much smaller than that for a $\underline{3}$ quark bound state (with same $|e_Q|$ and same quark mass): $B_l(\underline{6})/B_l(\underline{3}) \sim 0.1$; and since $\Upsilon(Q\bar{Q})$ can decay into three gluons the mean sphericity of events should show a marked deviation as one tunes through the resonance peak.[13]

For both the $\underline{8}$ and the $\underline{6}$ quarks, the $\Gamma(2g+\gamma)$ is enhanced due to group factors. It is helpful to recall that the angular distribution for this decay[23] goes as $(3 - \cos^2\theta^*)$ where θ^* is the center-of-mass angle for the normal of the decay plane relative to the e^+e^- (which produces the Υ) beam direction. The distribution of hard photons[22] $(2E_\gamma/M_\Upsilon - 1)$ behaves like $(1 + \cos^2\theta_\gamma)$ with θ_γ 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.

In conclusion we have explored the possibility that the upsilon resonances are bound states of color-octet or -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. Many of the phenomenological properties discussed here can readily be extended to other heavy exotic quarks as well.

Thanks are due to W. A. Bardeen, J. Bjorken, S. Brodsky, R. Cahn, T. A. DeGrand, C. Quigg, and P. Sikivie for helpful discussions, and to F. Gilman for reading the manuscript. This work was supported by the U. S. Department of Energy.

---

[1] S. W. Herb *et al.*, Phys. Rev. Lett. 39, 252 (1977).

[2] W. R. Innes *et al.*, Phys. Rev. Lett. 39, 1240, 1640(E) (1977).

[3] For a lucid review, see e.g., K. Gottfried, Cornell University Report No. CLNS-376, 1977 (to be published).

[4] E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, and T.-M. Yan, Phys. Rev. Lett. 34, 369 (1975).

[5] C. Quigg and J. L. Rosner, Phys. Lett. 71B, 153 (1977), and 72B, 462 (1978); see also M. Machacek and Y. Tomozawa, to be published.

[6] W. Celmaster, H. Georgi, and M. Machacek, Harvard University Report No. HUTP-77/A060, 1977 (to be published); H. B. Thacker, C. Quigg, and J. L. Rosner, Fermilab Report No. FERMILAB-PUB-77/109-THY (unpublished); see also K. Johnson, unpublished; E. Eichten and K. Gottfried, Phys. Lett. 66B, 286 (1977); J. Ellis, M. K. Gaillard, D. V. Nanopoulos, and S. Rudaz, Nucl. Phys. B131, 285 (1977).

[7] E.g., B. J. Harrington, S. Y. Park, and A. Yildiz, Phys. Rev. Lett. 34, 168 (1975).

[8] R. C. Giles and S.-H. H. Tye, Phys. Lett. 73B, 30 (1978).

[9] The possible existence of quarks in representations other than the 3 has been suggested by many theorists [see E. Ma, Phys. Lett. 58B, 442 (1975), and Phys. Rev. Lett. 36, 1573 (1976); G. Karl, Phys. Rev. D 14, 2374 (1976); F. Wilczek and A. Zee, Phys. Rev. D 16, 860 (1977); S. L. Glashow, in Proceedings of the Irvine Conference on Leptons and Quarks, 1977 (unpublished)]. Inevitably, the argument for the existence of such exotic quarks ranges from a "why not?" to pure theoretical speculations. We believe ours is the first argument, albeit model dependent, based on Υ phenomenology.

[10] Ma, Ref. 9; Karl, Ref. 9; Wilczek and Zee, Ref. 9; Glashow, Ref. 9.

[11] S.-H. H. Tye, Phys. Rev. D 13, 3416 (1976); see also Y. J. Ng and S.-H. H. Tye, Phys. Rev. D 16, 2468 (1977).

[12] For more discussion on this point of view, see Sect. 5 of Ng and Tye, Ref. 11. For another point of view see T. A. DeGrand, Y. J. Ng, and S.-H. H. Tye, Phys. Rev. D 16, 3261 (1977). We note that the argument to be given below for the evidence of Υ as a bound state of exotic quarks does not depend on QCD.

[13] DeGrand, Ng, and Tye, Ref. 12.

[14] K. Wilson, Phys. Rev. D 10, 2445 (1974); J. Kogut and L. Susskind, Phys. Rev. D 11, 395 (1975); W. A. Bardeen and R. Pearson, Phys. Rev. D 14, 547 (1976).

[15] W. A. Bardeen and S.-H. H. Tye, unpublished.

[16] See, e.g., S. Weinberg, Harvard University Report No. HUTP-77/A057 (to be published).

[17] R. C. Giles and S.-H. H. Tye, Phys. Rev. Lett. 37, 1175 (1976), and Phys. Rev. D 16, 1079 (1977).

[18] See A. Chodos and C. B. Thorn, Nucl. Phys. 72B, 509 (1974), in particular Eqs. (2.7)-(2.9).

[19] H. D. Politzer, Phys. Rep. 14C, 130 (1974).

[20] S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Elementary Particle Physics*, edited by M. Svartholm (Almquist and Wiksells, Stockholm, 1968), p. 367.

[21] It is beyond the scope of this Letter to discuss such unified theories. We note that exotic quarks can occur in such theories, e.g., models of supersymmetry.

[22] R. N. Cahn, Phys. Rev. Lett. 40, 80 (1978). We know of no convincing evidence ruling out stable (or metastable) particles with a mass bigger than 5 GeV. See, for example, J. A. Appel *et al.*, Phys. Rev. Lett. 32, 428 (1974); H. R. Gustafson *et al.*, Phys. Rev. Lett. 37, 474 (1976); L. W. Jones, Rev. Mod. Phys. 49, 717 (1977), and University of Michigan Report No. UM-HE-78-5, 1978 (to be published).

[23] M. Krammer and H. Krasemann, Phys. Lett. 73B, 58 (1978); S. J. Brodsky, D. G. Coyne, T. A. DeGrand, and R. R. Horgan, to be published.

Comparison of High-p_T Events Produced by Pions and Protons

M. D. Corcoran, L. Cormell, C. Cortez, M. Dris, A. R. Erwin, P. J. Gollon,
E. H. Harvey, A. Kanofsky, W. Kononenko, G. Lazo,[a] R. J. Loveless,
E. M. O'Neill,[b] B. Robinson, W. Selove, M. Thompson, and B. Yost
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, and Lehigh University, Bethlehem, Pennsylvania 18015, and University of Pennsylvania, Philadelphia, Pennsylvania 19104, and University of Wisconsin, Madison, Wisconsin 53706
(Received 3 April 1978)

We have measured high-p_T π^0's and jets with a two-arm calorimeter detector. Pions produce large-x_T jets more readily than do protons. We report the first direct measurement of two-arm jets. We find that the jet pairs have roughly balanced p_T and that pions produce jet pairs at more forward angles than do protons. These results give evidence for a constituent-scattering model, with constituents of higher average momentum in the pion.

We present results from an experiment performed at Fermilab comparing the production of high-p_T π^0's and jets by pion and proton beams. In a quark-scattering model one would expect more abundant production of particles of high x (both $x_T = 2p_T/\sqrt{s}$ and $x_L = 2p_{\parallel}/\sqrt{s}$) from pions than from protons.[1] Naively, this expectation is simply a reflection of the fact that pions have fewer constituents (only two valence quarks) than do protons (three valence quarks); and therefore