events near the mass of the D^0 with mean value of 1.861 GeV/c^2. (This is consistent with the measured value[6] of 1.8633 ± 0.0009 GeV/c^2.) The observed rms width of about 4 MeV/c^2 is consistent with the expected experimental resolution. The background estimate is 1.7 events in a 20-MeV/c^2 mass interval centered on the D^0 mass based on Monte Carlo studies and the event distribution in the region 1.70–1.85 GeV/c^2. (The probability of observing 9 events as a result of this background is $\sim 7\times 10^{-5}$.) This leaves an excess of 7.3 ± 3.0 events above background.

Using the $K^-\pi^+\pi^0$ acceptance calculated by Monte Carlo and the measured luminosity of the data sample (1.3 pb^{-1}), the product of the cross section and branching fraction is calculated to be $\sigma B = 1.4 \pm 0.6$ nb. As in Ref. 6, we can calculate the absolute branching fraction of this decay mode by assuming that the $\psi(3.772)$ is a state of definite isospin (either 0 or 1) and that its only substantial decay mode is $D\bar{D}$. The absolute branching fraction is $(12 \pm 6)\%$, where a $\pm 20\%$ systematic error is included.

It is also possible to set an upper limit on the $D^0 \rightarrow \bar{K}^0\pi^0$ decay since no events are observed near the D^0 mass and the acceptance is fairly good. A 90%-confidence-level upper limit of 6% is obtained for the absolute branching fraction. Branching-fraction upper limits (90% confidence level.) for other Cabibbo-favored decay modes involving π^0's are all greater than 25% because of either poor acceptance or background. The ratio of the $K^-\pi^+\pi^0$ branching fraction to other previously measured branching fractions[6] is larger than would be expected from the statistical model.[7]

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Newly Found Resonance $\Upsilon(9.5)$ and the Charge of the Heavy Quark

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The newly discovered resonance $\Upsilon(9.5)$ is studied as a bound state of a heavy quark and its antiquark. From the estimate of the production cross section, it is argued that the charge of the constituent quark is likely to be $-\frac{1}{3}$.

A striking enhancement named Υ with the mass of around 9.5 GeV was discovered[1] in the $\mu^+\mu^-$ production in proton-nucleus collisions at Fermi National Accelerator Laboratory. This enhancement seems to consist of at least two resonances. With a two-Gaussian fit the masses are determined to be 9.44 $\pm$ 0.3 GeV and 10.17 ± 0.05 GeV, and their decay widths are consistent with zero. The reported $\mu^+\mu^-$

production cross sections through these resonances are

$$d\sigma/dy|_{y=0}B=(2.3\pm 0.2 \text{ and } 0.9\pm 0.1)\times 10^{-37}\ \text{cm}^2/\text{nucleon}. \tag{1}$$

where the first and the second figures correspond to $m=9.44$ and 10.17 GeV, respectively, B is the branching ratio for the $\mu^+\mu^-$ decay of the respective resonances, and y is the rapidity in the c.m. frame of a proton and a nucleon. The above mass spectrum is highly suggestive of charmoniumlike bound states of a new quark and its antiquark (we shall hereafter call them b and $\bar{b}$, respectively, for convenience). If one adopts this point of view, an immediate and important question arises as to the charge Q_b of the b quark, a key quantity in studying, above all, the role of this new quark in gauge theories of weak and electromagnetic interactions. This Letter is addressed to this question.

In this Letter, we shall assume the peak at 9.44 GeV, $\Upsilon(9.44)$, to be the 1^3S_1 state of the $b\bar{b}$ system[2] and consider the following three mechanisms for its production (see Fig. 1): (I) the Drell-Yan mechanism[3]; (II) a modified Drell-Yan mechanism,[4] where a quark and an antiquark annihilate into three gluons, which subsequently produce $\Upsilon(9.44)$; and (III) a mechanism[5-7] in which two gluons from the projectile and the target annihilate to produce the 1^3P_J states ($J=0,2$), which subsequently decay into $\Upsilon(9.44)$ and a photon. We emphasize that despite the fact that these processes do not exhaust all possible production mechanisms, they are likely to be present within the framework of the quark-parton model and quantum chromodynamics and give *a lower bound* for the production cross section.

The cross sections for the production of $\Upsilon(9.44)$ through the processes I, II, and III (indicated, below, by superscripts) may be expressed as

$$\left.\frac{d\sigma^{\mathrm{I}}}{dy}\right|_{y=0}=\frac{12\pi^2\Gamma(\Upsilon(9.44)\to\mu^+\mu^-)}{ms}F^{\mathrm{I}}(x,x)\Big|_{x=m/\sqrt{s}}, \tag{2}$$

$$\left.\frac{d\sigma^{\mathrm{II}}}{dy}\right|_{y=0}=\frac{\pi^2\Gamma(\Upsilon(9.44)\to 3\ \text{gluons})}{ms}F^{\mathrm{II}}(x,x)\Big|_{x=m/\sqrt{s}}, \tag{3}$$

$$\left.\frac{d\sigma^{\mathrm{III}}}{dy}\right|_{y=0}=\sum_{J=0,2}\frac{(2J+1)\Gamma(^3P_J\to 2\ \text{gluons})\Gamma(^3P_J\to\Upsilon(9.44)+\gamma)}{\Gamma_{\text{tot}}(^3P_J)}\frac{16\pi^2}{m_P s}\frac{m_P^2+m^2}{m_P^2-m^2}\times\int_{m/\sqrt{s}}^{m_P^2/m\sqrt{s}}dx\,\frac{\tau/x}{(x+\tau/x)^2}f_g(x)f_g(\tau/x)\theta(1-x)\theta(1-\tau/x), \tag{4}$$

where

$$F^{\mathrm{I}}(x,x')=\tfrac{1}{3}\times\tfrac{1}{2}\sum_{N=p,n}\sum_q Q_q^2[f_q^p(x)f_{\bar{q}}^N(x')+q\to\bar{q}], \tag{5}$$

$$F^{\mathrm{II}}(x,x')=\tfrac{1}{3}\times\tfrac{1}{2}\sum_{N=p,n}\sum_q[f_q^p(x)f_{\bar{q}}^N(x')+q\to\bar{q}], \tag{6}$$

and $\tau=m_P^2/s$.

m, m_P, Q_q, and s denote the mass of $\Upsilon(9.44)$, the mass of 1^3P_J states, the charge of the q quark, and the square of the total c.m. energy, respectively. In Eqs. (5) and (6), a factor $\frac{1}{3}$ is due to color and p and n denote proton and neutron. $f_q^p(x)$ $[f_{\bar{q}}^p(x)]$ is the q-quark (antiquark) distribution in the longitudinal momentum fraction x inside a proton. For these we use the modified McElhaney-Tuan distributions.[8] As for the gluon distribution $f_g(x)$, assumed to be the same for proton and neutron, we take the form[4] $f_g(x)=\frac{1}{16}x^{-1}(N+1)(1-x)^N$. The three cases of interests are (i) $N=7$, for which the distribution resembles that of the quark sea; (ii) $N=5$, which is obtained from a naive extension of the quark counting rule[9]; and (iii) $N=3$, for which gluons are like valence quarks.

To estimate the various decay widths appearing in Eqs. (2), (3), and (4), we follow the work of Refs. 2 and 5 and of Appelquist and Politzer.[10] We use a static $b\bar{b}$ interaction of the form[2]

$$V(r)=-\tfrac{4}{3}\alpha_s(m_b^2)r^{-1}+r/a^2, \tag{7}$$

with $a=2.22\ \text{GeV}^{-1}$. The mass m_b of the b quark is determined through the analysis of Ref. 2 to be 4.6 GeV. The value of the strong "fine structure constant" α_s at the b-quark mass is related

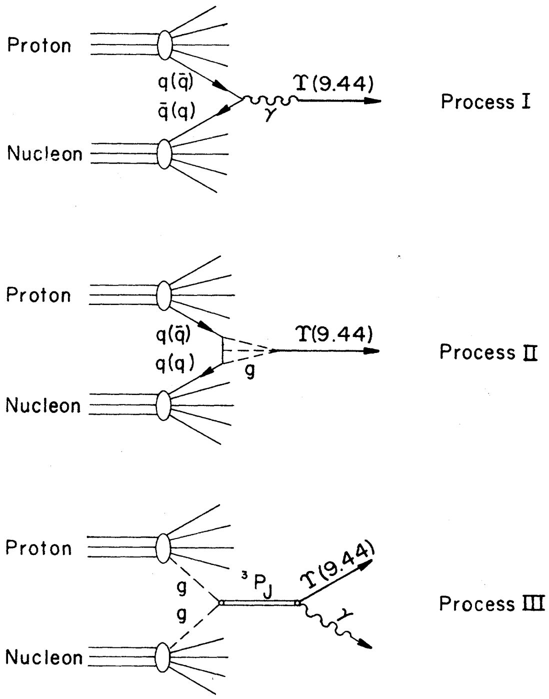

FIG. 1. Three mechanisms for the production of $\Upsilon(9.44)$ considered in the text.

through the renormalization-group analysis[11] to that at the c-quark mass and found to be $\alpha_s(m_b^2) = 0.15$ with the choice $\alpha_s(m_c^2) = 0.19$. The various decay widths of $\Upsilon(9.44)$ and 1^3P_J states are estimated in this static potential model for four different values of Q_b and are listed in Table I. Some comments are in order. (a) The hadronic and the $\mu^+\mu^-$ decay widths of the 1^3S_1 state are estimated following Refs. 2 and 10. (b) The cascade photon decay down to the 1^3S_1 state and the hadronic decay widths of the 1^3P_J ($J = 0, 2$) states are estimated using $1S$ and $1P$ radial wave functions obtained by a variational calculation similar to that of Ref. 5. The mass spectrum as well as the radial overlap integral between 1^3S_1 and 1^3P_J states are compared with the results of Ref. 2 and found to be in good agreement. We find the mass of the $1P$ states to be 9.72 GeV.

Also listed in Table I is the branching ratio B for the $\mu^+\mu^-$ decay mode, which is independent of the potential chosen. Using the result of Ref. 10, we obtain

$$B(Q_b^2) = Q_b^2\left(\frac{10(\pi^2-9)\alpha_s^3}{81\pi\alpha^2} + (R+2)Q_b^2\right)^{-1} \qquad (8)$$

where $R = \Gamma(e^+e^- \to \gamma \to \text{had})/\Gamma(e^+e^- \to l^+l^-)$. This expression gives an excellent agreement in the case of ψ with $R \simeq 2.3$, the value in the vicinity of the ψ mass. Accordingly, we have chosen $R \simeq 5.3$ for the present case.

We are now in a position to examine the charge Q_b in the picture adopted here. For processes I and II, the only quantity that depends on Q_b is the branching ratio exhibited in Eq. (8). For process III, an additional charge dependence resides in $\Gamma(^3P_J \to \Upsilon(9.44) + \gamma) \propto Q_b^2$. $\Gamma(^3P_J \to 2 \text{ gluons})$ is independent of Q_b. Numerically, process III is found to dominate over processes I and II in pN collisions at all energies. In the following, we shall consider process III only, which gives an underestimate for the cross section. In other words, *our estimate will be bounded from above by the experimental value.* In Fig. 2 we plot $[d\sigma^{\text{III}}/dy]_{y=0}B$ against Q_b^2 for $N = 3$, 5, and 7, together with the present experimental data. If the heavy quark is fractionally charged, Fig. 2 indicates that for $N = 3$ and 5, $Q_b = -\frac{1}{3}$ is favored. For $N = 7$, both $Q_b = -\frac{1}{3}$ and $\frac{2}{3}$ are allowed. However, if the Υ production is similar to that of ψ,[5] our estimate through process III would account for only $\frac{1}{3}$–$\frac{1}{4}$ of the total production rate, and Q_b

TABLE I. List of the various decay widths, in keV, for four different values of the charge of the heavy quark. The branching ratio for the $\mu^+\mu^-$ decay mode is also listed.

Q_b(charge)	$-1/3$	$2/3$	$-4/3$	$5/3$
$\Gamma(\Upsilon(9.44) \to \mu^+\mu^-)$	0.74	3.0	12	19
$\Gamma(\Upsilon(9.44) \to \gamma \to \text{hadrons})$	3.9	16	63	97
$\Gamma(\Upsilon(9.44) \to \text{gluons} \to \text{hadrons})$	14	14	14	14
$B(\Upsilon(9.44) \to \mu^+\mu^-)$	0.037	0.082	0.12	0.12
$\Gamma(1^3P_0 \to \text{hadrons})$	79	79	79	79
$\Gamma(1^3P_2 \to \text{hadrons})$	21	21	21	21
$\Gamma(1^3P_J \to \Upsilon(9.44) + \gamma)$	16	64	260	400

$=\frac{2}{3}$ should be unfavored. Exotic charge assignments, such as $Q_b = -\frac{4}{3}$, $\frac{5}{3}$, etc., seem to be strongly excluded for any N. We have checked that these conclusions are insensitive to the variations (say ~50%) of α_s, R, $\Gamma(1^3P_J \to \Upsilon + \gamma)$, and $\Gamma(1^3P_J \to 2 \text{ gluons})$. The inclusion of the hyperfine splittings of 1^3P_J of the same order of magnitude as in the ψ case affects the estimated cross section by only about 20%.

Before summarizing, we shall make several comments. (i) The energy dependence of $[d\sigma^{\mathrm{I,II,III}}/dy]_{y=0}B$ for $Q_b = -\frac{1}{3}$, the most likely charge assignment, is examined. As we mentioned, process III dominates over processes I and II for all energies. At about 2500 GeV, we expect the cross section to be enhanced by a factor of about 10 compared with that at around 400 GeV (lab). (ii) For the production of $\Upsilon(9.44)$ in $p\bar{p}$ collisions, in contrast to the pN case, the contribution from process II exceeds that from process III up to $E_{\mathrm{lab}} \sim 700$ GeV.[12] The production cross section $[d\sigma/dy]_{y=0}$ is estimated to be $\sim 2\times 10^{-34}$ cm^2 at 400 GeV and $\sim 8\times 10^{-34}$ cm^2 at 2400 GeV. (iii) In e^+e^- annihilation, the area under the resonance $\Upsilon(9.44)$ in the plot of $\sigma(e^+e^- \to \Upsilon \to e^+e^-)$ vs $\sqrt{s}$ is estimated to be 7.1 nb MeV. (iv) We have examined the signal-to-noise ratio for $\mu^+\mu^-$ production through a resonance consisting of an as yet new quark-antiquark pair in the quark mass range 2–5 GeV (corresponding to 5–11 GeV for the mass of the resonance). Except for the case with $Q_{\mathrm{quark}} = -\frac{1}{3}$, $N = 7$, and the quark mass above ~4 GeV, (signal/noise)ΔM, where ΔM is an invariant-mass interval, is found to be invariably greater than 0.5 GeV for all charges $(-\frac{1}{3}, \frac{2}{3}, \ldots)$ and all N values (3, 5, and 7) considered. This indicates that existence of a new quark flavor with the mass of 2–5 GeV is unlikely.

We summarize our analysis of the newly discovered resonance $\Upsilon(9.44)$ as follows. $\Upsilon(9.44)$ is assumed to be the 1^3S_1 state of a new heavy-quark-antiquark bound system. Three processes (I, II, and III of Fig. 1) are considered as possible mechanisms for the production of $\Upsilon(9.44)$. The various decay widths involved are estimated using a static potential and asymptotically free quantum chromodynamics. Under these assumptions, we conclude that, if the heavy quark is fractionally charged, (i) exotic charge assignments such as $-\frac{4}{3}$, $\frac{5}{3}$, etc., are excluded, (ii) a charge assignment of $\frac{2}{3}$ is unlikely unless (a) process III accounts for nearly all the production cross section and (b) the power N of the gluon distribution is $\gtrsim 7$, and (iii) a charge assignment of $-\frac{1}{3}$ is consistent with the present data.

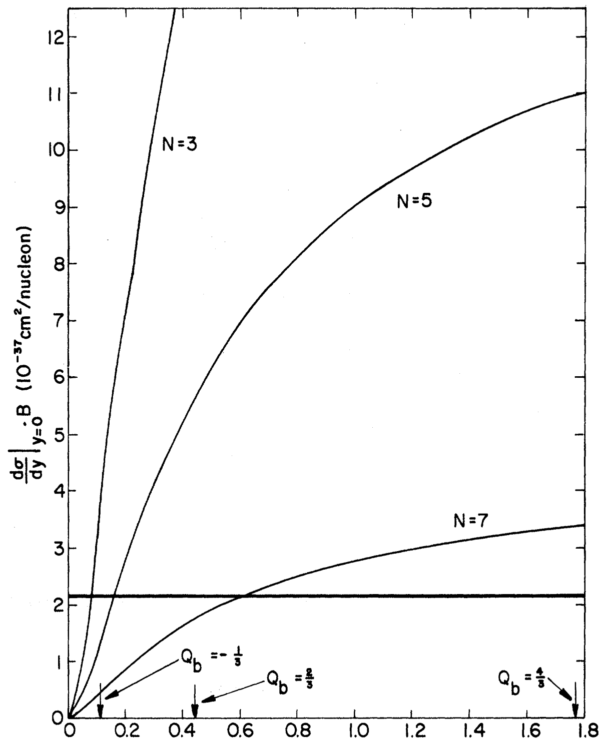

FIG. 2. Plot of $[d\sigma/dy]_{y=0}\,B$ for the process II vs Q_b^2 for $N=3$, 5, and 7. The horizontal line represents the experimental value of Ref. 1.

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Note added.—After this paper had been submitted for publication, several works which discussed similar and related subjects were brought to our attention: C. E. Carlson and R. Suaya, Phys. Rev. Lett. 39, 908 (1977); R. N. Cahn and S. D. Ellis, University of Michigan Report No. UM HE 76-45, 1976 (to be published); J. Ellis, M. K. Gaillard, D. V. Nanopoulos, and S. Ruaz, CERN Report No. CERN TH-2346, 1977 (unpublished).

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New Absolutely Stable Hadrons

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Observed universality among the known quarks and leptons requires that additional quarks be mixed little, or not at all, with the four conventional quarks. Discrete symmetries can result in the latter possibility and give rise to absolutely stable (pseudoscalar) hadrons. These particles would produce remarkable β decays, x-ray spectra, and hypernuclei.

The $\Upsilon(9.4)$[1] is widely presumed to be a 1^{--} state associated with a fifth (and perhaps sixth[2]) quark. In this Letter I wish to emphasize the likelihood that additional quarks—unlike the c quark and τ lepton—may well be radically different from the old quarks and leptons. Specifically, there are general grounds for anticipating that some of the new hadrons or leptons may be absolutely stable, even against weak decay.

The argument for new stable particles is simply that universality observed in weak interactions constrains the mixing of any additional quarks or leptons with the previously known ones to be rather small.[3] That there are such small mixing angles is not precluded: Indeed, it is possible to argue that small mixing angles may well result from large mass differences among quarks and leptons. Nevertheless, an equally attractive proposal is to prevent mixing entirely by the introduction of discrete symmetries which assign different values of some new quantum number to new quarks or leptons and thus forbid their decay into old quarks or leptons. This argument is quite general, though it has been advanced earlier in specific models. An illustrative and interesting example is the $SU(3)\otimes U(1)$ model of Lee and Weinberg,[4] which has been studied extensively by Lee and Shrock.[5] In this model, there is a discrete symmetry, *RU*, under which all known fundamental fermions are even, but for which all new fermions would be odd. The lightest new fermion would be stable. Whether there would be stable leptons or hadrons would depend on the masses of the new fermions.

Throughout the remainder I shall confine myself primarily to stable hadron possibility, although it should be clear that some of the considerations apply equally to the stable lepton option. It is assumed that the stable hadrons would be pseudoscalars, which are denoted by $\mathfrak{D}$ in the following. The new quark is denoted q. Since the d quark appears to be about 4 MeV heavier than the u quark,[6] the stable pseudoscalars would be $u\bar{q}$ and $\bar{u}q$, with charge zero if $e_q=\frac{2}{3}$ and charges ± 1, if $e_q=-\frac{1}{3}$. The unstable pseudoscalar would β decay into the stable one with a rate determined by conserved vector current (CVC) in a fashion entirely analogous to pion β decay, with a factor

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