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The Newly Found Resonance Υ(9.5) and the Charge of the Heavy Quark

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ABSTRACT

The newly discovered resonance Υ(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 -1/3.

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A striking enhancement named Υ with the mass of around 9.5 GeV was discovered[1] in the $\mu^+\mu^-$ production in proton-nucleus collision at FNAL. This enhancement seems to consist of at least two resonances. With a two-gaussian fit the masses are determined to be 9.44 ± 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

$$\left.\frac{d\sigma}{dy}\right|_{y=0} \cdot \mathrm{BR} = 2.3 \pm 0.2 \text{ and } 0.9 \pm 0.1 \times 10^{-37}\mathrm{cm}^2/\mathrm{nucleon} \quad , \qquad (1)$$

where the first and the second figures correspond to $m = 9.44$ GeV and 10.17 GeV respectively, BR 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 charmonium-like 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[5,6,7] 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 these processes do not exhaust all possible production mechanisms, they are likely to be present within the framework of the quark-parton model and QCD 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

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

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

$$\left.\frac{d\sigma^{III}}{dy}\right|_{y=0} = \sum_{J=0,2}\frac{(2J+1)\Gamma(^3P_J\to 2\ \text{gluons})\Gamma(^3P_J\to\Upsilon(9.44)+\gamma)}{\Gamma_{tot}(^3P_J)}$$

$$\times\frac{16\pi^2}{m_P S}\frac{m_P^2+m^2}{m_P^2-m^2}\int_{m/\sqrt{s}}^{m_P^2/(m\sqrt{s})}dx\ \frac{\tau/x}{(x+\tau/x)^2}\ f_g(x)f_g(\tau/x) \tag{4}$$

$$\times\,\theta(1-x)\theta(1-\tau/x) \quad ,$$

where

$$F^I(x,\ x') = \frac{1}{3}\frac{1}{2}\sum_{N=p,n}\sum_q Q_q^2(f_q^P(x)f_{\bar{q}}^N(x') + q\leftrightarrow\bar{q}) \quad , \tag{5}$$

$$F^{II}(x, x') = \frac{1}{3}\frac{1}{2} \sum_{N=p,n} \sum_{q} (f_q^{\,p}(x) f_{\bar{q}}^{\,N}(x') + q \leftrightarrow \bar{q}) \quad , \qquad (6)$$

and

$$\tau = m_P^{\,2}/S \quad .$$

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 total c.m. energy squared, respectively. In Eqs. (5) and (6), a factor 1/3 is due to color and p and n denote proton and neutron. $f_q^{\,p}(x)\left(f_{\bar{q}}^{\,p}(x)\right)$ 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] $f_g(x) = \frac{1}{16x}(N+1)(1-x)^N$. 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, 5, and 10. We use a static $b\bar{b}$ interaction of the form[2]

$$V(r) = -\frac{4}{3}\alpha_s(m_b^{\,2})\frac{1}{r} + \frac{r}{a^2} \quad , \qquad (5)$$

with $a = 2.22\ \mathrm{GeV}^{-1}$. 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 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 1. 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 1 is the branching ratio BR for the $\mu^+\mu^-$ decay mode, which is independent of the potential chosen. Using the result of Ref. 10, we obtain

$$BR(Q_b^2) = \frac{Q_b^2}{\dfrac{10(\pi^2 - 9)\alpha_s^3}{81\pi\alpha^2} + (R+2)Q_b^2} , \qquad (7)$$

where $R = \Gamma(e^+e^- \to \gamma \to \mathrm{had})/\Gamma(e^+e^- \to \ell^+\ell^-)$. 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 the processes I and II, the only quantity that depends on Q_b is the branching ratio exhibited in Eq. (7). For the process III, an additional charge dependence resides in $\Gamma(^3P_J \to \Upsilon(9.44) + \gamma) \propto Q_b^2$. $\Gamma(^3P_J \to 2$ gluons) is independent of Q_b. Numerically, the process III is found to dominate over the processes I and II in pN collision at all energies. In the following, we shall consider the 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 $d\sigma^{III}/dy|_{y=0} \cdot$ BR 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, $Q_b = -1/3$ is favored. For N = 7, both $Q_b = -1/3$ and 2/3 are allowed. However, if the Υ production is similar to that of ψ,[5] our estimate through the process III would account for only 1/3 ~ 1/4 of the total production rate, and $Q_b = 2/3$ sould be unfavored. Exotic charge assignments, such as $Q_b = -4/3$, 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 $\Gamma(1^3P_J \to 2$ 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 $d\sigma^{I, II, III}/dy|_{y=0} \cdot BR$ for $Q_b = -1/3$, the most likely charge assignment, is **examined**. As we mentioned, the process III dominates over the processes I and II for all energies. At ISR energies, we expect the cross section to be enhanced by a factor of about 10 compared with that at Fermilab energies. (ii) For the production of $\Upsilon(9.44)$ in $p\bar{p}$ collision, in contrast to the pN case, contribution from the process II exceeds that from the process III up to $E_{lab} \sim 700$ 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 $\sigma(e^+e^- \to \Upsilon \to e^+e^-)$ V.S. $\sqrt{s}$ 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 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 $Q_{quark} = -1/3$, N = 7, and the quark mass above ~4 GeV, (signal/noise)ΔM(GeV), where ΔM is an invariant mass interval, is found to be invariably greater than 0.5 for all charges (-1/3, 2/3, ...) 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 QCD. Under these assumptions, we conclude that, if the heavy quark is fractionally charged, (i) exotic charge assignments such as -4/3, 5/3, etc., are excluded, (ii) a charge assignment of 2/3 is unlikely unless (a) the 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 -1/3 is consistent with the present data.

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[12]In ψ production, the same feature obtains below $E_{lab} \sim 60$ GeV for N = 7. For N = 5, the sum of the contributions from processes I and II exceeds that from process III up to about 50 GeV. This may have relevance to the experiment of M. J. Corden, et al., Phys. Lett. 68B, 96 (1977).

Q_b (charge)	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{4}{3}$	$\frac{5}{3}$
$\Gamma(\Upsilon(9.44) \to \mu^+\mu^-)$	0.74 KeV	3.0 KeV	12 KeV	19 KeV
$\Gamma(\Upsilon(9.94) \to \gamma \to \text{hadrons})$	3.9 KeV	16 KeV	63 KeV	97 KeV
$\Gamma(\Upsilon(9.44) \to \text{gluons} \to \text{hadrons})$	14 KeV	14 KeV	14 KeV	14 KeV
$BR(\Upsilon(9.44) \to \mu^+\mu^-)$	0.037	0.082	0.12	0.12
$\Gamma(1^3P_0 \to \text{hadrons})$	79 KeV	79 KeV	79 KeV	79 KeV
$\Gamma(1^3P_2 \to \text{hadrons})$	21 KeV	21 KeV	21 KeV	21 KeV
$\Gamma(1^3P_J \to \Upsilon(9.94) + \gamma)$	16 KeV	64 KeV	260 KeV	400 KeV

Table 1. List of the various decay widths for four different values of the charge of the heavy quark. The branching ratio for the $\mu^+\mu^-$ decay mode is also listed.

FIGURE CAPTIONS

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

Fig. 2: Plot of $d\sigma/dy|_{y=0}$ BR for the process II v.s $Q_b^{\,2}$ for N = 3, 5, and 7. The horizontal line represents the experimental value of Ref. 1.

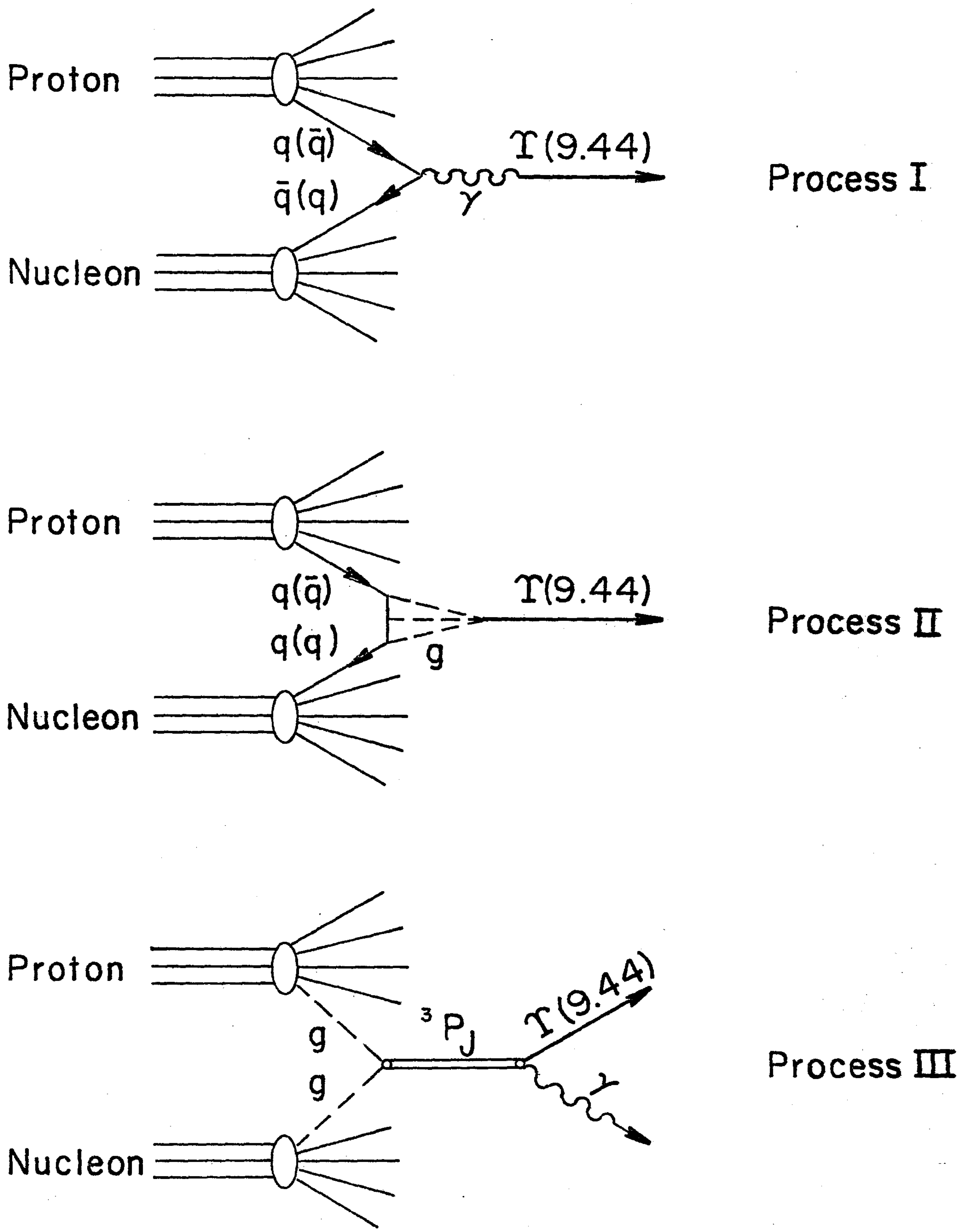
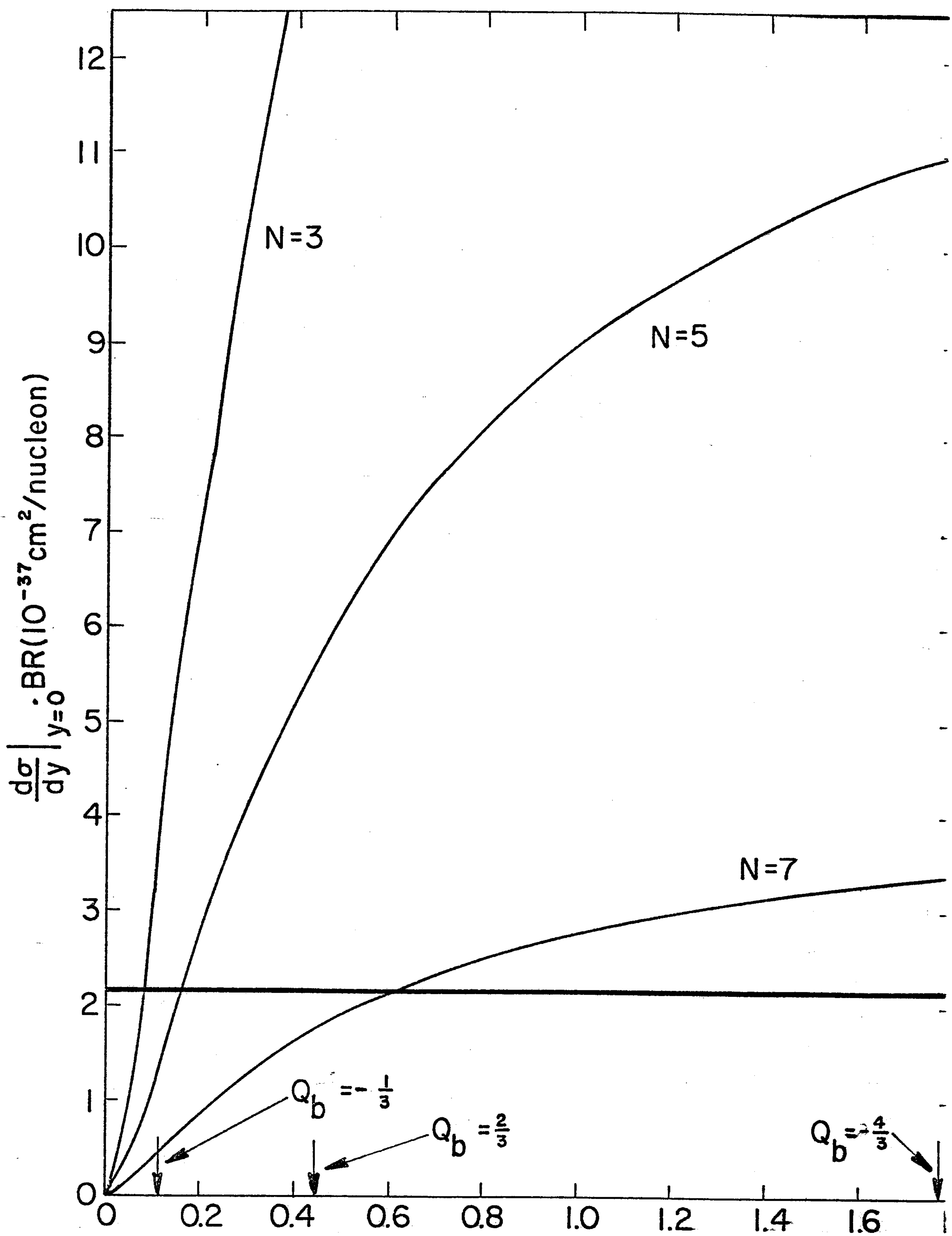

Proton
q(q̄)
q̄(q)
Υ(9.44)
γ
Process I
Nucleon
Proton
q(q̄)
q(q)
Υ(9.44)
g
Process II
Nucleon
Proton
g
g
³P_J
Υ(9.44)
γ
Process III
Nucleon

Fig. 1



N=3
N=5
N=7
$Q_b = -\frac{1}{3}$
$Q_b = \frac{2}{3}$
$Q_b = -\frac{4}{3}$
$\frac{d\sigma}{dy}\Big|_{y=0} \cdot BR(10^{-37} cm^2/\text{nucleon})$
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6
0 1 2 3 4 5 6 7 8 9 10 11 12