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M. Greco: Υ PRODUCTION FROM DUALITY AND THE CHARGE OF THE NEW QUARK.

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ABSTRACT.

Duality ideas are applied to estimate the upsilon production in e^+e^- annihilation, hadronic collisions and photo-production. Simple scaling rules for the cross sections are obtained and compared with experiments. Our results suggest the charge of the new constituent quark is likely to be -1/3.

The recent discovery(1) of at least two narrow states with masses of ~10 GeV, produced in photon-nucleus collisions and decaying into muon pairs, is very suggestive of the existence of bound states of at least a new quark and its an antiquark. There is a fast growing literature(2-5) based on this quite natural hypothesis, which relates the properties of the new Υ states to heavy t(Q=2/3) or b(Q=-1/3) quarks. The various estimates based on gluon cascade models and/or direct production, analogous to the Drell-Yan mechanism(6) of leptonic pair production, seem to prefer Q=-1/3 to Q=2/3. However, no definite conclusion has been reached so far.

In the present letter we discuss the same problem from a different point of view, namely we apply duality ideas in e^+e^- annihilation and dilepton production in hadronic collisions, along the lines of previous works[7,8] of some years ago. In that approach to scaling phenomena, the central idea was that the current induced processes were mediated by hadronic states with increasing mass. An appealing features which emerged in this simple scheme was that the scaling properties of the cross sections in deep inelastic phenomena would be shared by the strong interactions of the high mass states.

It is by now clear that a strict correspondence (duality) exists between the above phenomenological approach and the scaling predictions of the quark parton model. It is then natural to insert the new hadronic mass scale introduced with the observation of the Υ states within the model in order to estimate the production cross sections of the new particles.

In the following we will first test our ideas for J/ψ and ψ' production in e^+e^- and hadronic collisions. We will then consider the case of the new Υ states and estimate the corresponding cross sections. Our results favor the charge Q=-1/3 of the new constituent quark.

Let us consider first e^+e^- annihilation into hadrons. The average contribution to $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^-e^+ \longrightarrow \mu^+\mu^-)$ from a single vector meson is

$$\langle R_i \rangle = \frac{9\pi}{\alpha^2} \frac{m_i \Gamma_i^{e\bar{e}}}{\Delta m_i^2} , \qquad (1)$$

where Δm_i^2 is the spacing between two near resonances of the type -i. Duality in e^+e^- annihilation[8,9] gives

$$\left(\frac{m\Gamma^{e\bar{e}}}{\Delta m^2}\right)_{\varrho} : \left(\frac{m\Gamma^{e\bar{e}}}{\Delta m^2}\right)_{\omega} : \left(\frac{m\Gamma^{e\bar{e}}}{\Delta m^2}\right)_{\varphi} : \left(\frac{m\Gamma^{e\bar{e}}}{\Delta m^2}\right)_{J/\psi} \approx 9:1:2:8, \qquad (2)$$

where the r. h. s. reflects the charges of the constituent quarks, and

$$R = \Sigma_i \langle R_i \rangle \quad . \qquad (3)$$

Both eqs. (2) and (3) are satisfied at the level of (10 ÷ 20)% obtaining $\Gamma_{\psi}^{e\bar{e}} \simeq 4.6$ keV and $R \simeq 2.5 + 1.7 = 4.2$ ($\Delta m_{\varrho}^2 \simeq \Delta m_{\omega}^2 \simeq \Delta m_{\varphi}^2 \simeq 2 m_{\varrho}^2$ and $\Delta m_{\psi}^2 \simeq 4\ \mathrm{GeV}^2$). Furthermore local duality works rather well for the higher members of the ψ-family. In fact, from the equality

$$\left(\frac{m\Gamma^{e\bar{e}}}{\Delta m^2}\right)_{\psi(3.1)} = \left(\frac{m\Gamma^{e\bar{e}}}{\Delta m^2}\right)_{\psi(3.7)} = \left(\frac{m\Gamma^{e\bar{e}}}{\Delta m^2}\right)_{\psi(3.77)}, \qquad (4)$$

one gets $\Gamma_{\psi'}^{e\bar{e}} \simeq .5\,\Gamma_{\psi}^{e\bar{e}}$ and $\Gamma_{\psi''}^{e\bar{e}} \simeq .3\,\Gamma_{\psi'}^{e\bar{e}}$, in good agreement with experiments(10). We have used $\Delta m_{\psi'}^2 = (m_{\psi''}^2 + m_{\psi}^2)/2 \simeq 2.32\ \mathrm{GeV}^2$ and $\Delta m_{\psi''}^2 \simeq .8\ \mathrm{GeV}^2$.

The success of this analysis gives us good confidence in applying the same ideas to the Υ's production. We note first that the observed spacing $M(\Upsilon') - M(\Upsilon)$, which is remarkably close to $M(\psi') - M(\psi)$, leads to satisfy the relation

$$\frac{m}{\Delta m^2} \sim \text{const}, \qquad (5)$$

indepedent of the sequence. The approximate validity of (5) for ϱ, ω, φ and J/ψ mesons was observed by Close et al.(11). An example of non relativistic potentials describing the interaction of heavy quarks, which leads to $Q\bar{Q}$ level spacings independet of the quark mass is provided by $V(r) \sim c \ln(r/r_o)$, as noticed by Quigg and Rosner(4).

A simple consequence of eq. (5), implemented by duality (eq. (2) is

$$\Gamma_{\varrho}^{e\bar{e}} : \Gamma_{\omega}^{e\bar{e}} : \Gamma_{\varphi}^{e\bar{e}} : \Gamma_{\psi}^{e\bar{e}} : \Gamma_{\Upsilon}^{e\bar{e}} = 9 : 1 : 2 : 8 : 2\ (8), \qquad (6)$$

where the last factor 2(8) in the r. h. s. of (6) refers to the case $Q = -1/3$ ($Q = 2/3$). The approximate validity of (6) for $\varrho, \cdots, \psi$ mesons was noted empirically by Yennie(12). We would therefore predict

$$\Gamma(\Upsilon \longrightarrow e\bar{e}) \simeq 1.2\ \text{keV}, \qquad (7)$$

for the case $\Upsilon \equiv (b\bar{b})$. For comparison the corresponding estimate by Eichten and Gottfried[2], based on the application of the charmonium model to heavier quarks, is $\Gamma(\Upsilon \longrightarrow e\bar{e}) \simeq 0.7$ keV. A similar value is predicted by Quigg and Rosner[4] in the case of the logarithmic potential mentioned above.

From eq. (7) and using QCD to estimate[3] the direct hadronic decay we obtain

$$\Gamma(\Upsilon \longrightarrow \text{dir. had.}) \simeq 24 \text{ keV}$$

$$\Gamma(\Upsilon \longrightarrow \text{all}) = \Gamma_{e\bar{e}} + \Gamma_{\mu\bar{\mu}} + \Gamma_{\tau\bar{\tau}} + \Gamma(\Upsilon \longrightarrow \gamma^{*} \longrightarrow \text{had}) + \qquad (8)$$

$$+ \Gamma(\Upsilon \longrightarrow \text{dir. had}) \simeq 32 \text{ keV}$$

The expected hadronic peak cross section, including radiative corrections, is given by[13] $(\Gamma/\sigma \ll 1)$

$$\tilde{\sigma}(M) \simeq \frac{6\pi^2}{\sqrt{2\pi}\,\sigma}\,\frac{1}{M^2}\,\frac{\Gamma_{ee}\;\Gamma_{had}}{\Gamma}\left(\frac{\Gamma}{M}\right)^{\beta}\left[1 + \beta \ln\frac{2\sqrt{2}\,\sigma}{\Gamma} - \frac{1}{2}\gamma\right] \times$$

$$\left\{1 + \frac{13}{12}\beta + \frac{\alpha}{\pi}\left(\frac{\pi^2}{3} - \frac{17}{18}\right)\right\}, \qquad (9)$$

where $\gamma = 0.5772$ is Euler's constant, $\beta = \frac{4\alpha}{\pi}\left[\ln(2M/m_e) - 1/2\right] \simeq 0.093$ and σ is the machine dispersion. Using $\sigma \simeq 1.5$ MeV and eqs. (7) and (8) we finally obtain

$$\tilde{\sigma}(M) \simeq 38 \text{ nb}, \qquad (10)$$

which corresponds to about 40 units of R $(\sigma_{\mu\bar{\mu}}(9.4) \simeq 98$ nb)

The leptonic widths for the $\Upsilon'(10.0)$ and $\Upsilon''(10.4)$ can be estimated in analogy to eq. (4). We obtain $\Gamma(\Upsilon' \longrightarrow e\bar{e}) \simeq .65$ keV and $\Gamma(\Upsilon'' \longrightarrow e\bar{e}) \simeq .55$ keV, having assumed a level splitting of 50-100 MeV of the two S--states with the two lowest and almost degenerate D-states, coupled to e^-e^+ via $^3S_1 - {}^3D_1$ mixing. Then, by appropriate rescaling, we slightly modify the estimates of ref. (3), obtaining $\Gamma(\Upsilon' \longrightarrow \text{dir. had}) \simeq 14$ keV, $\Gamma(\Upsilon' \longrightarrow \text{all}) \simeq 26$ keV, $\Gamma(\Upsilon'' \longrightarrow \text{dir. had}) \simeq 11$ keV and $\Gamma(\Upsilon'' \longrightarrow \text{all}) \simeq 28$ keV. In the case $\Upsilon \equiv (t\bar{t})$, starting from $\Gamma(\Upsilon \longrightarrow e\bar{e}) \simeq 4.8$ keV (eq. (6)) a similar procedure could be used to estimate the various widths.

We now turn to Υ's production in hadronic collisions and, more generally, consider first dilepton production. An explicit scaling model for this process was presented[7,14] some years ago based on the idea of generalized vector dominance. The model showed scaling for e. m. as well strong interactions and an increase of the average transverse momentum with the mass. This latter feature is now constistent with the experimental indications[15], and supported by explicit calculations[16] in QCD.

A simple scaling law for the hadronic production cross sections follows directly from the correspondence (duality) between the two mechanism of lepton pairs production, namely the vector meson formation[7,14] and direct $q\bar{q}$ annihilation[6]. Denoting by $\sigma^V(s)$ and $d\sigma^{\mu\bar{\mu}}/dQ^2$ the corresponding production cross sections, then

$$B(V \longrightarrow \mu\bar{\mu})\ \sigma^V(s)\,\delta(Q2-m_V^2) \propto B(V \longrightarrow \text{dir. had})\frac{\langle R_V\rangle}{R}\frac{d\sigma^{\mu\bar{\mu}}}{dQ^2} = \tag{11}$$

$$= B(V \longrightarrow \text{dir. had})\frac{\langle R_V\rangle}{R}\frac{1}{Q^4}F(Q^2/s),$$

for any species $V(V=\varrho,\omega\ ,\varphi\ ,J,\cdots)$. Integrating over Δm_V^2 and using (1), one gets ($s \gg m_V^2$)

$$\frac{m_V^3}{\Gamma_d^V}\ \sigma^V(s) \propto Q^3\,\frac{d\sigma^{\mu\bar{\mu}}}{dQ} = F(Q^2/s), \tag{12}$$

where Γ_d^V is the direct hadronic width of the state V. Eq. (12) then leads to relate the production cross sections of different vector mesons as ($s \gg\gg m_V^2$, $s' \gg m_{V'}^2$)

$$\frac{m_V^3}{\Gamma_d^V}\ \sigma^V(s) = \frac{m_{V'}^3}{\Gamma_d^{V'}}\ \sigma^{V'}(s'=s\ \frac{m_{V'}^3}{m_V^2}). \qquad (13)$$

This simple scaling law was also suggested by Gaisser et al.[17] on dimensional grounds, with $\Gamma'_d = \Gamma$. They showed the agreement of (13) with data for ϕ, J and ψ' production. In this latter case the direct hadronic width ($\Gamma_d^{\psi'} \simeq$ 20 keV) instead of the total width is important to fix the right scale. The scaling behaviour of the cross sections is summarized in Fig. 1[17]. Furthermore, the comparis on with the scaling behaviour of $Q^3\ d\sigma^{\mu\bar{\mu}}/dQ$ for $pp \longrightarrow \mu\bar{\mu} + X$, shown in Fig. 2, indicates clearly the existence of the same universal curve for both resonance and dilepton pairs production, in agreement with eq. (12).

On the basis of (13) we now turn to estimate the Υ production cross section. We have

$$B(\Upsilon \longrightarrow \mu\bar{\mu})\frac{d\sigma^{\Upsilon}}{dy}(s)\Big/_{y=0} \simeq \left(\frac{m_J^3}{m_\Upsilon^3}\right) B(\Upsilon \longrightarrow \text{dir})\ \frac{\Gamma(\Upsilon \longrightarrow \mu\bar{\mu})}{\Gamma(J \longrightarrow \mu\bar{\mu})} \times$$
$$\left\{ B(J \longrightarrow \mu\bar{\mu})\ \frac{d\sigma^J}{dy}\Big/_{y=0}(s'=s\frac{m_J^2}{m_\Upsilon^2})\right\}, \qquad (14)$$

and using eqs. (7-8) for the case $\Upsilon \equiv (b\bar{b})$,

$$\left\{ B(\Upsilon \longrightarrow \mu\bar{\mu})\ \frac{d\sigma^{\Upsilon}}{dy}\Big/_{y=0}(s)\right\} \simeq 6.5\times 10^{-3} \left\{ B(J \longrightarrow \mu\bar{\mu})\frac{d\sigma^J}{dy}\Big/_{y=0}(s' = s\frac{m_J^2}{m_\Upsilon^2})\right\}. \qquad (15)$$

The Υ production at 400 GeV/c ($\sqrt{s} \simeq 27.4$ GeV) is therefore related to J/ψ production at $\sqrt{s'} \simeq 9$ GeV, where $d\sigma^J/dy/_{y=0} \simeq 10^{-33}\ cm^2$[18]. The strong energy dependence of $d\sigma^J$ in region, and possible thresholds effects, which have been neglected in eqs. (14-15) are both sources of some uncertainty. At ISR energies the situation should be much cleaner

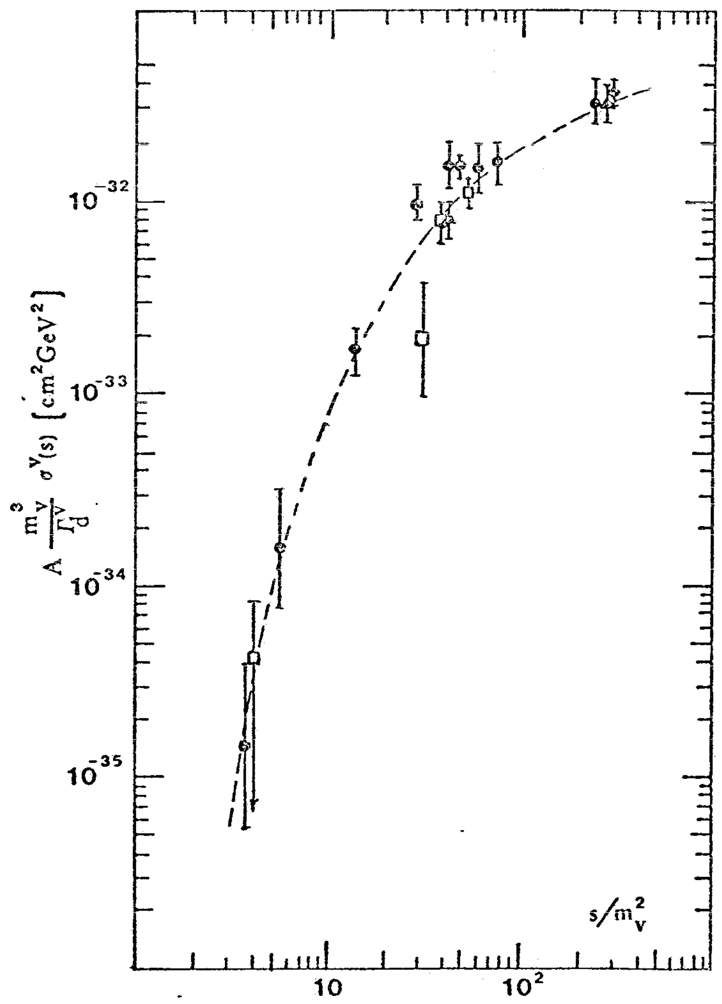

FIG. 1 - Evidence for scaling in inclusive vector meson production (pp $\rightarrow$VX). ^V_d is the direct hadronic width of state V. The constant A has the value A $\simeq$ 2 x 10^{-7}. The experimental data(18) refer to (▲) φ , (●) J/Ψ , (◘) Ψ' production respectively. The curve drawn through the points is the same appearing in Fig. 2.

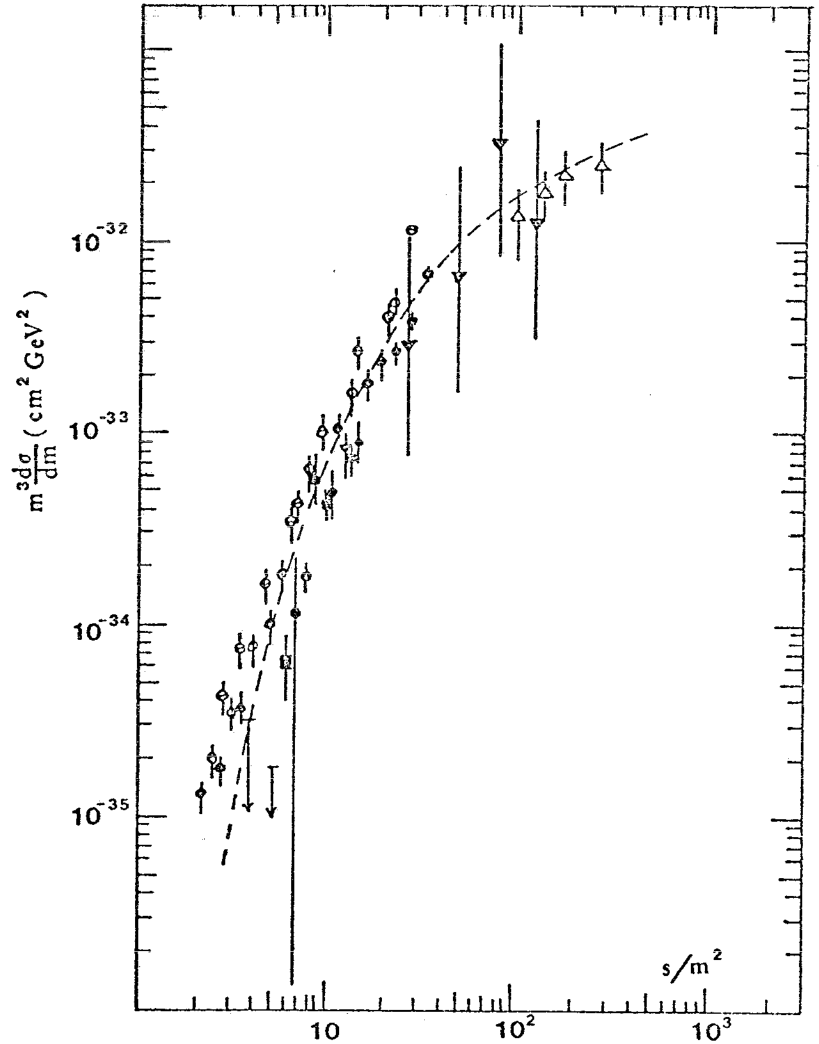

FIG. 2 - Evidence for scaling in inclusive lepton pair production (pN $\rightarrow$ $1\bar{1}$X). The figure is taken from ref. (19). The "experimental" points shown have been obtained from actual data by using a quark-parton model to extrapolate into unobservable regions of longitudinal momentum. The curve drawn through the points is the same appearing in Fig. 1.

and eq. (15) predicts (at $\sqrt{s} \simeq 50$ GeV) a production rate two orders of magnitude larger.

We obtain

$$B(\Upsilon \longrightarrow \mu\bar{\mu}) \frac{d\sigma^{\Upsilon}}{dy}/_{y=0}(s \simeq 750) \simeq 4.5 \times 10^{-37}\ cm^2, \qquad (16)$$

which agrees, within a factor of two, with the experimental value[(1)] $B_{\mu\bar{\mu}}\, d\sigma/dy/_{y=0} \simeq 2 \times 10^{-37}$. In the case $\Upsilon \equiv (t\bar{t})$ we would have found $B_{\mu\bar{\mu}}\, d\sigma/dy/_{y=0} \simeq 10^{-36}\ cm^2$. We therefore conclude that the charge of the new constituent quark is likely to be -1/3.

The ratios of the cross sections for Υ, Υ' and Υ'' are estimated to be ($s=750$ GeV^2)

$$B_{\mu\bar{\mu}}\, d\sigma^{\Upsilon} : B_{\mu\bar{\mu}}\, d\sigma^{\Upsilon'} : B_{\mu\bar{\mu}}\, d\sigma^{\Upsilon''} \simeq 1 : 0.32 : 0.15\ . \qquad (17)$$

The coincide with those found by Ellis et al.[(3)], in spite of the differences in the various partial widths, as given above. Experimentally they are observed[(1)] to be $1 : (0.37 \pm 0.04) : (0.06 \pm 0.04)$. In the case of $\Upsilon \equiv (t\bar{t})$ we would have found the ratios 1 : 0.21 : 0.09, about fifty per cent larger than those in ref. (3). Then the observed ratio (Υ/Υ') again favors the choice $\Upsilon \equiv b\bar{b}$.

We now turn briefly to estimate the photo production cross sections for Υ (9.4). As in the previous case, we will make use of a simple scaling law for the hadronic cross sections. From the dual picture of deep inelastic scattering[(8)], we have

$$m_V^2\ \sigma_{VN}(s) = f(s/m_V^2), \qquad (18)$$

where the r.h.s. reduces to a constant ($s \gg m_V^2$) for the diffractive component of σ_{VN}. Then the simple scaling law follows in photo production

$$\frac{d\sigma^V}{dt}(s)/_{t=t_{min}} \sim \frac{1}{m_V^5}\ \Gamma^V_{e\bar{e}}\ f(s/m_V^2) \qquad (19)$$

Eq. (19) is displayed in Fig. 3 for varions vector mesons(*). The consistency of the scaled exitation curves of ϱ, ϕ, J/ψ and ψ' with a universal curve is quite remarkable.

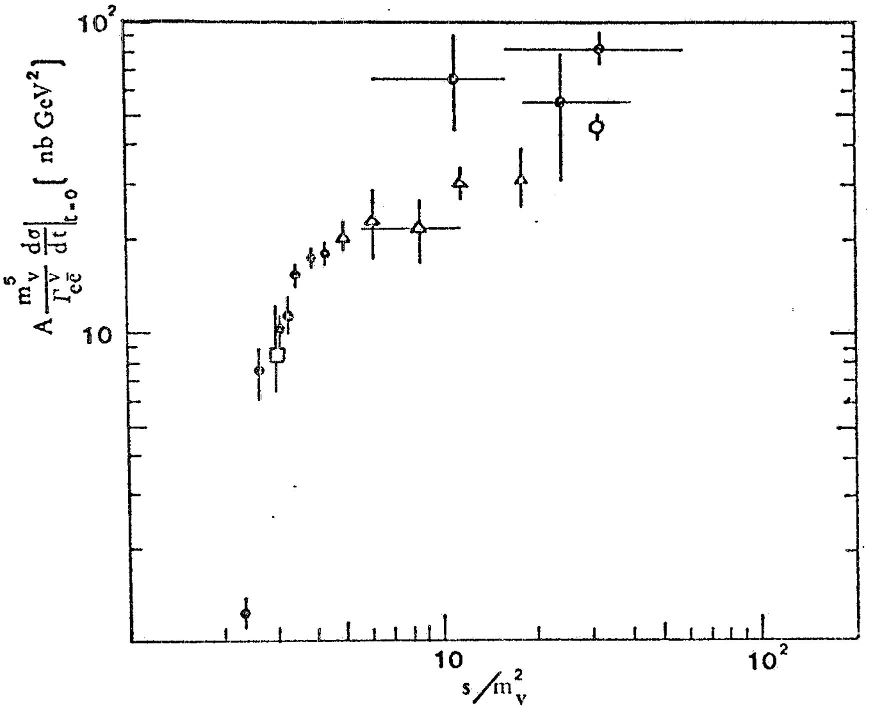

FIG. 3 - Evidence for scaling in photo-production of vector mesons. The constant A has the value $A \simeq 1.68 \times 10^{-8}$. The experimental data[20] refer to (o) ϱ, (Δ) φ, ($\bullet$) J/ψ and ($\square$) ψ' production respectively.

On the basis of (19) the photoproduction cross section for $\Upsilon(9.4)$ at high energies, e.g. $k_\gamma = 150$ GeV is estimated to be ($\Upsilon \equiv b\bar{b}$)

$$\frac{d\sigma}{dt}\Big/_{t=t\min} (\gamma p \longrightarrow \Upsilon p) \simeq 10 \text{ pb/GeV}^2, \tag{20}$$

and four times higher if $\Upsilon \equiv t\bar{t}$.

To summarize, we have estimated the Υ production cross sections in e^+e^- annihilation, hadronic collisions and photo production on the ba

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(*) For consistency we have taken into account only the diffractive component of the ϱ cross section.

sis of simple scaling laws which follow directly from duality arguments, and agree with experimental data for lower mass vector mesons. Our results suggest the charge of the new constituent quark is likely to be -1/3.

After this work was completed, an interesting paper appeared[21], where the same duality ideas were applied to Υ production in e^+e^- annihilation, and in particular our eq. (17) was also derived.

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