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THE DECAY OF THE UPSILON INTO PHOTONS AND GLUONS*

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ABSTRACT

The hadronic decays of heavy quark–antiquark 1^3S_1 resonances such as the ψ/J or Υ can provide an ideal laboratory for studying the properties of gluon jets. We discuss the predictions of QCD perturbation theory for gluon jet structures, hadronic multiplicities, fragmentation distributions, and angular distributions. In particular the channel $(Q\bar{Q}) \rightarrow \gamma + X$, whose rate, spectrum, and angular distribution are predicted in lowest order, should allow the study of the jet and resonance structure produced via two intermediate gluons.

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It is generally anticipated that the recent discovery[1] of the upsilon Υ structure in the reaction $pp \to \mu^+\mu^- X$ at $\mathcal{M}_{\mu^+\mu^-} \sim 9.5$ GeV signals the existence of at least one new quark flavor. The upsilon Υ and its predicted associated excited states are expected to be investigated further with the next generation of e^+e^- storage rings. In this letter we discuss possibilities for studying specific properties of gluon jets utilizing the hadronic and electromagnetic decays of heavy $Q\bar{Q}$ resonances such as the Υ and ψ/J. The existence of gluon quanta, as yet unconfirmed by experiment, is a central feature of quantum chromodynamics (QCD). The decay of the upsilon, in particular the channel $\Upsilon \to \gamma + X$, should provide an ideal environment to verify the existence and measure the properties of gluon jets.

The hadronic width of a ground state $J^P = 1^-$ $Q\bar{Q}$ analogue of the ψ/J is expected to be narrow in QCD since the hadronic decay must proceed via an intermediate state consisting of at least 3 color-octet gluons. [2] Treating the gluons as massless, the standard color SU(3) predictions for the total hadronic and electromagnetic decay widths from Fig. 1a are[2]

$$\Gamma_{had} = \frac{40}{81\pi} (\pi^2 - 9) \frac{\alpha_c^3}{M^2} \, |R(0)|^2 \tag{1}$$

and

$$\frac{\Gamma_{had}}{\Gamma_{e^+e^-}} = \frac{5(\pi^2 - 9)\alpha_c^3}{18\pi\alpha^2} \; \frac{(2/3)^2}{(e_Q/e)^2} \tag{2}$$

where $R(0)$ is the bound state wave function at $r = 0$, α_c is the color fine-structure constant, and e_Q is the charge of the quark.

Assuming that the production of a virtual gluon leads to a collimated-hadronic jet (analogous to "quark" jets in $e^+e^- \to q\bar{q} \to$ hadrons), then the final hadronic state in $e^+e^- \to \Upsilon \to$ hadrons is expected to consist of 3 coplanar, non-collinear hadronic jets in the e^+e^- cm system. [3] Event by event the produced hadrons should tend to lie within a pancake-like cylinder in momentum space. The plane defined by minimizing the components of momentum of the hadrons in the normal direction (or defined via the construction of a quadrupole tensor [4]) will correspond to the production plane of the 3 virtual gluons. We note that to order m_e^2/s, the resonance is produced in the $J_z = \pm 1$ state relative to the e^+e^- direction. We then can predict from QCD the angular distribution

$$\frac{dN}{d\cos\theta^*} = \frac{3}{16}\,(3-\cos^2\theta^*) \tag{3}$$

where θ^* is the cm angle for the normal of the plane relative to the e^+e^- beam direction. This prediction is independent of the momentum partition of the gluon jets. The mean value of transverse momentum normal to the plane gives a measure of the transverse momentum fluctuations of gluon jets.

Unlike quarks, gluons produce hadronic jets whose leading particles are neutral in the mean and have a relatively soft hadronic spectrum. Perturbation theory calculations for $g \to q\bar{q} \to Hq\bar{q}$ suggest [5]

$$D_{H/g}(x) \sim (1-x)\left(D_{H/q}(x) + D_{H/\bar{q}}(x)\right) \tag{4}$$

where H is any hadron. Furthermore since the gluon octet has a stronger color charge than the quark color triplet, relatively more hadrons may be produced in the consequent color-neutralization process. A simple SU(3) color calculation[6] predicts that the hadronic rapidity plateau associated with a gluon jet is 9/4 larger than that associated with a quark jet. A comparison of the $e^+e^- \to$ hadron multiplicity on and off the Υ resonance will be a crucial test of this idea. Neglecting the effect of quark flavor, the total multiplicity (due to 3 gluons) at $s = m_\Upsilon^2$ will be at least 9/4 of the multiplicity off-resonance for collinear events (zero sphericity), to as large as 27/8 of the multiplicity measured in e^+e^- annihilation (due to $e^+e^- \to u\bar{u}$ or $d\bar{d}$) at $s = 4/9\, m_\Upsilon^2$. Thus in such a picture the mean charged multiplicity may jump to ~ 11 to 15 at the Υ compared to 5 or 6 just below resonance production.

A possibly even more interesting channel to investigate is $\Upsilon \to (\gamma + g + g) \to \gamma +$ hadrons, where the photon is produced directly rather than via π^0 or η decays, etc. The branching ratio computed from the perturbation theory diagrams in Fig. 1b is

$$B_\gamma = \frac{\Gamma(\Upsilon \to \gamma gg)}{\Gamma(\Upsilon \to ggg)} = \frac{\alpha}{\alpha_c}\, C\left(\frac{e_Q}{e}\right)^2 \tag{5}$$

where C = 36/5 is a color SU(3) factor[7] and α_c is determined from Eq. (2). For $\alpha_c = 0.2$, $B_\gamma = 3\%$ for a quark charge of 1/3 and 12% for a quark charge of 2/3. Measurement of the photon decay spectrum is thus sensitive to a nontrivial SU(3) color factor, as well as the quark charge. To lowest order in α_c the distribution in photon momenta is identical to that for ortho-positronium[8]

$$\frac{dN^0}{dx}(\Upsilon \to \gamma X) = \frac{2}{\pi^2 - 9}\left[\frac{x(1-x)}{(2-x)^2} - \frac{2(1-x)^2}{(2-x)^3}\ln(1-x) + \frac{2-x}{x} + \frac{2(1-x)}{x^2}\ln(1-x)\right] \tag{6}$$

where $x = 2\omega/M_\Upsilon$. This continuum spectrum is graphed in Fig. 2. Unlike backgrounds, the spectrum monotonically increases as $x \to 1$. Thus measurements of the hard photon distribution $d\Gamma/dx\,(\Upsilon \to \gamma + X)/\Gamma_{hadronic}$ for large x (see Eq. (10)) will provide a straightforward but crucial test of QCD. We also can predict the angular distribution of hard photons relative to the e^+e^- beam direction

$$\frac{dN}{d\cos\theta_\gamma} = \frac{3}{8}\,(1+\cos^2\theta_\gamma)\,, \qquad (x_\gamma \to 1) \tag{7}$$

where $\cos\theta_\gamma = \hat{p}_\gamma \cdot \hat{p}_{e^+}$. Thus the photons are emitted preferentially along the beam axis.

The decay $\Upsilon \to \gamma + X$ can in principle allow a study of the final state from two gluon jets over a full range of kinematics $\mathcal{M}_X^2 < M_\Upsilon^2$. The invariant mass squared of the hadronic recoil system is $\mathcal{M}_X^2 = (p_\Upsilon - k)^2 = M_\Upsilon^2(1-x)$. Thus the entire mass spectrum of the two gluon system X can be scanned at one beam energy from the observation of the photon spectrum (see Fig. 2). One expects to find the hadrons aligned along a jet axis in the recoil system rest frame. The comparison to the normal $e^+e^- \to q\bar{q}$ jet system at the same invariant mass should be illuminating. It will be particularly interesting to compare: (a) the leading particle spectra to check Eq. (4), (b) the average transverse momentum of particles relative to the jet axis, and (c) the produced hadron multiplicity. The multiplicity comparison for quark versus gluon jets will allow for a definitive test of the hypothesis that the initial magnitude of color separation directly controls the production of hadrons, and check whether the value of 9/4 predicted for the ratio of hadronic plateaus is correct. [6]

It should also be noted that the gluon-gluon system can couple to any C = + neutral isoscalar resonance including the η_c, η_Υ, η^o, η', as well as bound states of gluons predicted by many confining formulations of QCD.[9] Knowledge of branching ratios for such processes as $\Upsilon \rightarrow \eta_c + \gamma$ can lead to important constraints on the di-gluon wavefunction. These resonances will lead to a modification of the lowest order continuum spectrum $dN^o/d\mathcal{M}_X^2$ given by Eq. (6):

$$\frac{dN}{d\mathcal{M}_X^2}(\Upsilon \rightarrow \gamma + X) = \left[1 + \rho(\mathcal{M}_X^2)\right]\frac{dN^o}{d\mathcal{M}_X^2} \tag{8}$$

where by usual duality arguments one expects

$$\int d\mathcal{M}^2 \rho(\mathcal{M}^2) = 0 \tag{9}$$

integrated over a local region about the resonance. (See Fig. 2.)

Much of the above analysis is applicable to decays of the ψ: the main difference here is that the gluon energy is too low to produce clean jet-like events. The calculation of the shape and rate for $\psi \rightarrow \gamma_{prompt} + X$ should still be valid: in perturbation theory QCD predicts $\Gamma(\psi \rightarrow \gamma_{prompt} + X)/\Gamma_{had} \cong 12\%$. [10] Further, although it will be difficult to see the low x part of the spectrum dN/dx (Eq. (6)) due to the substantial background from π^o and η decays, the high x part of the spectrum may be amenable to measurement. Together, Eq. (5) and (6) predict

$$\frac{1}{\Gamma_{had}}\frac{d\Gamma}{dx}(Q\bar{Q} \rightarrow \gamma_{prompt} + X) \cong 0.12\left(\frac{0.2}{\alpha_c}\right)\left(\frac{e_Q/e}{2/3}\right)^2 \frac{dN^o}{dx} \tag{10}$$

where dN^o/dx is given by Eq. (6). Observation of a γ-spectrum in agreement with Eq. (10) would be a striking confirmation of our ideas of the Zweig-violating decays of heavy $Q\bar{Q}$ states.

The most critical experimental constraint necessary for the $\Upsilon \to \gamma + X$ measurements will be the veto of backgrounds for $\Upsilon \to \pi^o$, η^o, etc., together with good spacial resolution to avoid overlapping photons. This will be relatively easier for $x \to 1$ where the direct photon signal peaks compared to the characteristically observed rapidly falling backgrounds. Furthermore, the direct photons will be generally unaccompanied by hadrons traveling in the same direction, ameliorating the spacial resolution problem.

It will also be of interest to measure the virtual photon decay, $\Upsilon \to \gamma X \to e^+e^-X$, in order to check the photon-mass dependence of the $\Upsilon \to \gamma gg$ amplitude. One expects from Fig. 1b that the distribution will scale as dq^2/q^2 for q^2 small compared to the heavy quark mass squared.

We conclude by summarizing: decays of heavy $(Q\bar{Q})$ ground state resonances such as the $\Upsilon(9.4)$ should be dominated by three-jet events, with a multiplicity on the resonance peak markedly different than off the peak. The decay rate for Υ (or ψ) $\to \gamma$ + two "gluon" jets will be an important laboratory for testing our ideas of gluon fragmentation and the relation between color separation and hadronic multiplicity. Finally, the rate for $\psi \to \gamma_{prompt} + X$ and the high-x part of the γ spectrum are uniquely calculable in QCD: their measurements will provide an important test of our ideas about Zweig-violating decays of heavy $Q\bar{Q}$ systems.

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Figure Captions

Fig. 1 (a) QCD model for the total hadronic rate $\Gamma \sim \alpha_c^3$ of a $Q\bar{Q}$ bound state.

(b) Dominant contribution to the prompt photon decay rate $\Gamma_\gamma \sim \alpha\, \alpha_c^2$. Diagrams (c) and (d) are suppressed by additional factors of α_c^2 and α_c^4 respectively.

Fig. 2 Hadronic mass spectrum predicted for the decay $(Q\bar{Q}) \to \gamma X$, with $s = M^2_{Q\bar{Q}}$. The solid line is the continuum prediction from QCD, Eq. (4). Resonances which couple strongly to the digluon system will modulate the spectrum at $\mathcal{M}_X^2/s = 1-x$ as indicated schematically by the dotted line ($\Upsilon \to \eta_c \gamma$). The kinematic limit is $x \le 1-4m_\pi^2/s$.

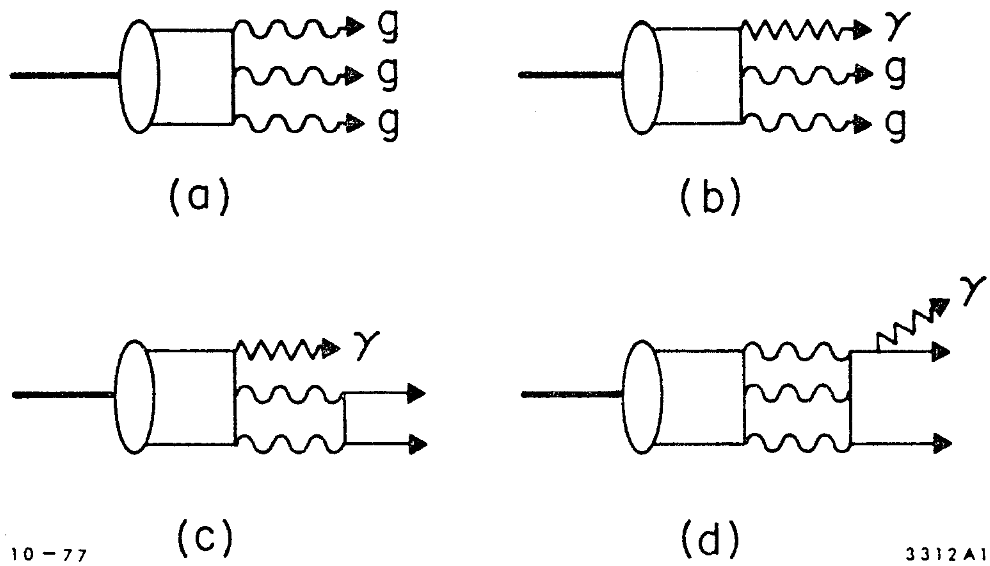

Fig. 1

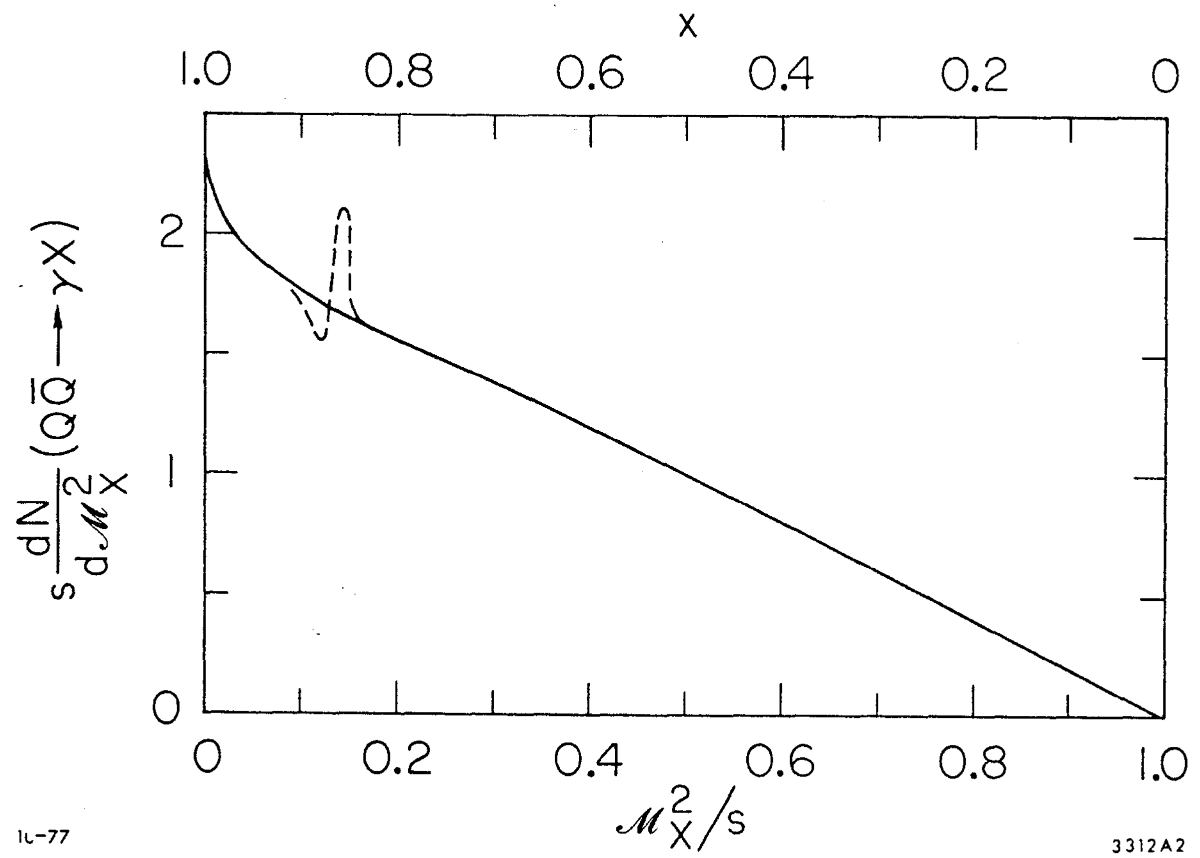
x
1.0
0.8
0.6
0.4
0.2
0
2
1
0
$s\frac{dN}{d\mathcal{M}_X^2}(Q\bar{Q}\rightarrow\gamma X)$
0
0.2
0.4
0.6
0.8
1.0
$\mathcal{M}_X^2/s$
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Fig. 2