A PROBE OF OZI SUPPRESSION

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The process $Q\bar{Q}$ to 1^+1^- + hadrons is studied. The Ore–Powell formula is generalized for massive photons. It is pointed out that the behaviour of the decay rate in the large q^2 region depends strongly on dynamics. This reaction may also provide means to determine the weak neutral couplings of heavy quarks.

We study quarkonium decays into lepton pair and hadrons. The contribution of QCD annihilation diagram (see fig. 1a) has been calculated as a function of invariant mass (q^2) of the lepton pair, giving a generalization of the Ore-Powell formula [1,2]. The QCD diagram, however, might not give the dominant contribution in the large q^2 region, where final state interactions are not included and are expected to be important. In view of this we have made an estimate, unfortunately very model dependent, of final state interaction effects. This kind of contributions may overwhelm those of the QCD diagram by orders of magnitude for large q^2. In the most optimistic case the process could be easily observable also in the large q^2 region.

So we emphasize the importance of studying the high q^2 region experimentally. Even an upper bound on the branching fraction might provide important information about the nature of OZI suppression.

In case the most optimistic expectations are fulfilled in which the OZI suppression is relaxed at relatively large q^2 we have the fascinating possibility of determining the weak neutral coupling of heavy quarks. As described below a rate measurement would be sufficient.

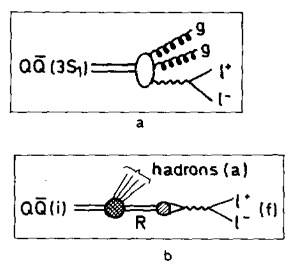

Fig. 1. (a) Lowest order diagram in QCD for the process $Q\bar{Q}(3S_1) \to gg + \ell^+\ell^-$. (b) Diagram representing possible final state interactions for the process $(Q\bar{Q}) \to$ hadrons + $\ell^+\ell^-$.

In QCD perturbation theory in lowest order, the process $Q\bar{Q} \to 1^+1^-$ + hadrons is described by the annihilation diagram of fig. 1a. The cumbersome but straightforward calculation yields [‡1]

$$\Gamma(^3S_1 \to \gamma^* gg) = \Gamma(^3S_1 \to \gamma gg) * f(q^2), \qquad (1)$$

where $f(z)$ function is a result of integration

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[‡1] The calculation has been done by computer, using REDUCE

$$f(q^2) = \frac{1}{\pi^2 - 9} \int_0^{1-\omega} dx_1 \int_{1-w-x_1}^{(1-w-x_1)/(1-x_1)} dx_2$$

$$\times F(x_1, x_2, w), \quad w = q^2/4M^2_{\text{quark}}. \tag{2}$$

The function $F(x_1, x_2, w)$ is symmetric in x_1, x_2 and has the form

$$F(x_1, x_2, w) = \sum_{n=0}^{4} a_n w^n / [x_1^2 x_2^2 (x_2 - 2w)^2], \tag{3a}$$

where $x_1 + x_2 + x_3 = 2$ and the coefficients a_n can be given as follows

$$a_0 = [x_1^4 + 2x_1^3 x_2 - 4x_1^3 + \tfrac{3}{2} x_1^2 x_2^2$$

$$- 9x_1^2 x_2 + 7x_1^2 + \tfrac{13}{2} x_1 x_2 - 6x_1 + 1] + (x_1 \leftrightarrow x_2),$$

$$a_1 = [4x_1^3 + \tfrac{1}{4} x_1^2 x_2^2 + 5x_1^2 x_2 - 10x_1^2$$

$$- 7x_1 x_2 + 10x_1 - 2] + (x_1 \leftrightarrow x_2),$$

$$a_2 = [x_1^2 x_2 + 6x_1^2 + 3x_1 x_2 - 8x_1 + \tfrac{3}{2}] + (x_1 \leftrightarrow x_2),$$

$$a_3 = [x_1 x_2 + 4(x_1 + x_2) - 2],$$

$$a_4 = 1. \tag{3b}$$

At $w = 0$ we reproduce the well-known Ore-Powell formula. The integration (2) has been done numerically, subsequently the function $f(q^2)$ has been approximated by a polynom and the total rate $\Gamma(^3S_1 \to gg\,\ell^+\ell^-)$ has been calculated analytically

$$\Gamma(^3S_1 \to gg\,\ell^+\ell^-) \approx \frac{2\alpha}{3\pi} (\ln M_v/2\mu - 1.04)\,\Gamma(^3S_1 \to gg\gamma) \tag{4}$$

where M_v is the mass of the quarkonium and μ denotes the mass of the leptons. The total rate is enhanced by the log factor $\ln(M_v/\mu)$ given by the conversion of the almost real photons to lepton pairs. As such these events carry now new dynamical information as compared with the normal radiative decays. However, since they are characterized by collinear leptons and therefore easily detectable, they provide independent means for an accurate determination of the radiative decays.

An analysis of the large q^2 region ($q^2 > 1$ GeV^2), where the logarithmic enhancement is no longer dominant is more interesting because it gives a new independent test of perturbative QCD. In this region the branching ratio given by the diagram of fig. 1a is

$$\frac{\Gamma(^3S_1 \to gg\mu^+\mu^-, q^2 > 1)}{\Gamma(^3S_1 \to \text{direct hadrons})} \approx 2.3 \times 10^{-4}\, Q_q^2, \tag{5}$$

where Q_q is the electric charge of the heavy quark. This ratio is independent from the wave function of the quarkonium and has only logarithmic dependence on the heavy quark mass.

In the larger q^2 region, where the emitted hadron system is relatively soft, other mechanisms than the annihilation one can also contribute. For example (see fig. 1b)

$$Q\bar{Q} \to \text{hadrons} + (Q\bar{Q})' \tag{6}$$
$$\hookrightarrow \mu^+\mu^-$$

The QCD contribution in the region $\sqrt{q^2} \geqslant 0.8\, M_v$ (in lack of phase space, smooth behaviour in q^2) is tiny.

$$B_L = \frac{\Gamma(^3S_1 \to gg\,\ell^+\ell^-, \sqrt{q^2} \geqslant 0.8\, M_v)}{\Gamma(^3S_1 \to \text{hadrons})_{\text{direct}}}$$

$$\approx 0.7 \times 10^{-5} \frac{Q_q^2}{\alpha(s)}\, \epsilon^2 \tag{7}$$

where ϵ is $(M_v - \sqrt{q^2})/M_v$. At the top quark ($M_v \lessapprox 40$ GeV) we obtain $B_L \approx 0.8 \times 10^{-6}$.

The role of possible final state interactions (hatched blob in fig. 1b), expected to be important in the high q^2 region, is very difficult to estimate. The most conservative lower bound is obtained by mimicing the $\psi' \to \psi 2\pi$ calculation for the hadronic vertex coupling assuming that

$$g^2(M_v^2, q^2, 1/R^2) \approx g^2_{\psi' \to \psi 2\pi}(M^2_{\psi'}, M^2_{\psi}, 1/R^2), \tag{8}$$

where R is the relevant length scale for the bound state. For logarithmic potential one expects this coupling to be independent of the quarkonium mass [3]. In the large q^2 region the q^2 dependence might be also negligible ‡2.

‡2 Assuming the validity of some pole dominance models, the contributions of different radially excited states to overlap integrals have alternating sign, but an exact cancellation is not expected.

With our normalization the observed value of $g^2_{\psi'\to\psi\pi\pi}$ is

$$\frac{g^2_{\psi'\psi\pi\pi}}{4\pi}\frac{1}{64\pi^2} = 1.4 \times 10^{-2} \qquad (9)$$

the effective matrix element being defined as $T_{fi} = g\epsilon'_\mu \epsilon^\mu$. The resonance formula corresponding to fig. 1b reads

$$\Gamma = \frac{1}{\pi}\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{\Gamma^{i\to R}(q^2)\,\Gamma^{R\to f}(q^2)\sqrt{q^2}}{(q^2 - M_v^2)^2 + M_v^2\Gamma^2}, \qquad (10)$$

where $\Gamma^{i,R}(q^2)$ has the structure of the decay width of $\psi' \to \psi\pi\pi$ scaled to the corresponding kinematical region, $\Gamma^{R,f}(q^2)$ is the leptonic width of the relevant quarkonium state. For the top quark the branching ratio B_L equals $(1 - 3) \times 10^{-6}$ depending on the choice of the leptonic width. This result, however, must be a serious underestimate for two reasons. (a) The small value of the effective coupling (9) is in part at least due to the presence of an Adler zero [4]. This is not the case for this inclusive process and some exclusive channels as well. (b) An inclusive reaction expected to be substantially larger than a particular channel. We conclude that a branching ratio as large as $B_L \sim 10^{-3}$ is not excluded by phenomenological considerations.

If this result obtains it implies a softening of OZI suppression at large q^2. This is an interesting possibility. It seems to us that studying the available data sample the existence or absence of this effect can be verified. Even an experimental upper limit will constraint the form the Zweig suppression mechanism one must have at *all* q^2,

If the OZI rule turns out not to be effective in the large q^2 region, we have the possibility of determining the weak neutral axial coupling of heavy quarks. To this effect we consider the reaction (see fig. 2)

$$Q\bar{Q}(^3S_1) \to \text{C-odd hadron state} + \ell^+\ell^-. \qquad (11)$$

From experimental point of view a relevant state can be e.g. ω or ϕ and any number of π^0. Because of *C*-parity, the process requires the exchanges of two photons, therefore the ratio of the electromagnetic and weak decay rates becomes of order $O(4\alpha^4/(G_F m_q^2\pi)^2)$

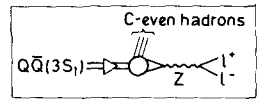

Fig. 2. Diagram for the weak decay of heavy quarkonium.

$\approx 1/m_q^4$ (in GeV) where m_q is the quark mass. The background due to direct electromagnetic processes can be shown to be negligible as well, by choosing an appropriate geometry, in the PETRA, PEP energy region. It is amusing to point out that in this process the weak interactions are dominant over the electromagnetic at relatively lower energies and no delicate interference measurement is needed.

To estimate the relevant branching ratio we have calculated the rate of the process $Q\bar{Q}(^3S_1) \to \gamma + \mu^+\mu^-$ in the standard nonrelativistic quarkonium model. We have obtained for the branching ratio

$$BR = \frac{\Gamma(^3S_1 \to \gamma\mu^+\mu^-)}{\Gamma_{tot}} = \frac{\Gamma(^3S_1 \to \gamma\mu^+\mu^-)}{\Gamma(^3S_1 \to \mu^+\mu^-)} BR^{lepton}$$

$$= (2\alpha/3\pi)\,(G_F m_q^2/4\pi\alpha)^2\, BR^{lepton} \qquad (12)$$

Numerically

$$BR = (1.5 \times 10^{-3}) \cdot (1.53 \times 10^{-8} m_q^4) \cdot (2 - 5) \times 10^{-2}$$

In case of the process with hadrons (11), in place of the factor $2\alpha/3\pi$ in eq. (12) we have a factor given by the OZI suppression. Following the argument of the previous section this factor may be larger than $2\alpha/3\pi$ in the relatively high q^2 region (albeit the phase space is smaller). In the optimistic case of setting it equal to 0.1 we obtain $BR_{weak} \approx (3 - 7.5) \times 10^{-10} m_q^4$ (in GeV). So for a heavy quark of mass 20 GeV we have $BR \approx (0.8\text{–}2) \times 10^{-5}$. Even with some further reduction the process (11) might be observable with present luminosities. We are aware that our optimistic estimate is on shaky ground, but we want to emphasize that if it is measurable it would give probably the only way to determine the $Z\bar{t}t$ couplings.

We hope to have demonstrated the importance of the process $Q\bar{Q} \to 1^+1^- +$ hadrons, both for the understanding the mechanism of the OZI rule and for the possibility to study weak decay of heavy quarkoniums.

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References

[1] A. Ore and J.L. Powell, Phys. Rev. 75 (1949) 1969.

[2] V.A. Novikov et al., Phys. Rep. 41C (1978) 1 and further references therein.

[3] K. Gottfried, in: Proc. 1977 Intern. Symp. on Lepton and photon interactions at high energies (Hamburg, August 1977);
see also J. Ellis et al., Nucl. Phys. B131 (1977) 285.

[4] L.S. Brown and R.N. Cahn, Phys. Rev. Lett. 35 (1975) 1;
D. Morgan and M.R. Pennington, Phys. Rev. D12 (1975) 1283.