Prompt lepton production in upsilon and t-quarkonium decays

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(Received 3 July 1984)

We have calculated the lepton-energy distributions and invariant-mass-squared distributions for the decay of upsilon and t-quarkonium mesons into leptons $+X$ via either c or b quarks as on-shell intermediate states. We also predict the branching ratios for those decays.

I. INTRODUCTION

Decays of bound states of heavy quarks provide a good process to make quantitative tests of perturbative quantum chromodynamics (QCD). This is due to the relatively large masses of the constituent quarks which require the interaction energy to be large, forcing the strong-coupling constant to be small (asymptotic freedom). In this paper we discuss the three-gluon decay modes of the upsilon and t-quarkonium mesons. One of the gluons subsequently produces a heavy-quark pair, one or both of which then decay semileptonically.

An interesting possibility is that these prompt leptons can be used as a signal of charm and/or bottom production. Using perturbative QCD, we have calculated branching ratios and lepton-energy distributions for the Υ or t-quarkonium $\rightarrow 3G \rightarrow q\bar{q}X \rightarrow l^+l^-X$. We find that the branching ratios for the case when the $q\bar{q}$ pair is $c\bar{c}$ or $b\bar{b}$ are small but in principle measurable. The lepton-energy distribution and invariant-mass distribution of the lepton pair are quite distinct and should be easily distinguishable from the background.

In Sec. II A, we discuss the model we use to describe the upsilon and t-quarkonium and present the QCD expressions for the lowest-order contributions to the decay processes described above. In Sec. II B, we show the distributions and branching ratios obtained from these expressions.

II. CALCULATIONS AND RESULTS

A. The model

The vector mesons are assumed to be $J^P=1^-$ bound states of two heavy quarks, $b\bar{b}$ or $t\bar{t}$, each of which carries half the mass of the meson. This means the q and $\bar{q}$ are treated as though they are free particles. The meson is assumed to decay at rest in the laboratory system into three gluons, one of which produces a quark-antiquark pair. The quark and the antiquark subsequently decay weakly into leptons. The decay of a particle-antiparticle bound state into (or via) three gauge field quanta has been discussed in several different contexts.[1-4] (References 1 and 2 discuss production of photons and/or gluons *per se.* Reference 3 considers production of a lepton pair, via a photon, with two gluons. Reference 4 considers jet formation from three gluons, or two gluons with a photon.) We have, for reasons of convenience, recalculated the decay amplitude and have written the square of the amplitude in a manifestly symmetric form. The differential rate for the strong-interaction part of this process (Fig. 1) is given by

$$\frac{d\Gamma}{d\Omega}=\frac{256}{3}F_c\frac{(4\pi\alpha_s)^4\,|\psi(0)|^2}{(M_V)^2}\frac{|A|^2}{(k^2D_3D_4D_4)^2}\,, \tag{1}$$

where

$$F_c=\frac{(N_c{}^2-4)(N_c{}^2-1)}{32N_c{}^2}=\frac{5}{36}\,,$$

M_V=mass of the vector meson, and $\psi(0)$ is the bound-state wave function at the origin. $|\psi(0)|^2$ is determined from the electronic partial width via the relation

$$\Gamma(\Upsilon\rightarrow e^+e^-)=16\pi\alpha^2e_q{}^2[1-16\alpha_s/(3\pi)]\frac{|\psi(0)|^2}{M_V{}^2}\,, \tag{2}$$

where α is the fine-structure constant and e_q is the relative quark charge ($e_q=\frac{1}{3}$ for the b quark). The amplitude can be obtained from the one given in Eq. (A6) of Ref. 5 by crossing the P_3 and P_4 momenta in that expression to the outgoing channel. The square of the amplitude is given by

$$|A|^2=m^2L_{\mu\nu}H_{\mu\nu}\,, \tag{3}$$

where m is the mass of one of the outgoing quarks,

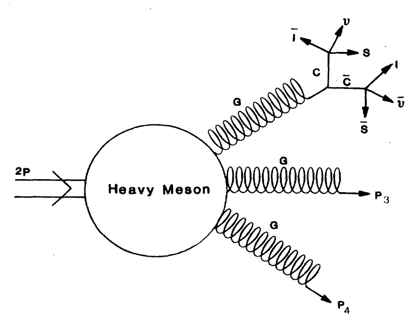

FIG. 1. The decay of the heavy vector meson into three gluons, one of which pair produces a heavy-quark—antiquark pair which subsequently decay to leptons.

$$L_{\mu\nu}=p_{1\mu}p_{2\nu}+p_{1\nu}p_{2\mu}-(k^2/2)g_{\mu\nu}\ , \tag{4}$$

$$H_{\mu\nu}=(k^2g_{\mu\nu}-k_\mu k_\nu)\left[(p_3\cdot p_4)^2\left[\frac{B_1{}^2}{2m^2}-k^2\right]+k\cdot p_3k\cdot p_4\left[2p_3\cdot p_4-\frac{k\cdot p_3k\cdot p_4}{2m^2}\right]\right]$$
$$-B_1(2q_\mu q_\nu+p_3\cdot p_4T_{\mu\nu})-2\left[(p_3\cdot p_4)^2(T_{\mu\nu}^{(3)}+T_{\mu\nu}^{(4)})+\frac{B_1}{4m^2}(4p\cdot p_3p\cdot p_4)T_{\mu\nu}\right]\ , \tag{5}$$

with $B_1=2m^2-k^2/2$, $q_\mu=k\cdot p_3p_{4\mu}-k\cdot p_4p_{3\mu}$,

$$T_{\mu\nu}=2g_{\mu\nu}k\cdot p_3k\cdot p_4+k^2(p_{3\mu}p_{4\nu}+p_{4\mu}p_{3\nu})-k\cdot p_3(k_\mu p_{4\nu}+k_\nu p_{4\mu})-k\cdot p_4(k_\mu p_{3\nu}+p_{3\mu}k_\nu)\ , \tag{6}$$

and

$$T_{\mu\nu}^{(i)}=g_{\mu\nu}(k\cdot p_i)^2+k^2p_{\mu i}p_{\nu i}-(k\cdot p_i)(k_\mu p_{i\nu}+k_\nu p_{i\mu}),\quad i=3,4\ . \tag{7}$$

The propagators are given by

$$D_3=2p\cdot p_3\ , \tag{8a}$$

$$D_4=2p\cdot p_4\ , \tag{8b}$$

and

$$D_k=2p\cdot k-k^2\ , \tag{8c}$$

where $2p$ is the momentum of the incoming vector meson.

The differential leptonic decay rate of the b or c quark is given by the phenomenological expression[6]

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx}=4856.7x^{3.4}(1-x/0.53)^{3.6}\ , \tag{9}$$

where $\Gamma=$ total width and x is the fraction of energy carried away by either lepton. x is measured in the rest frame of the decaying quark.

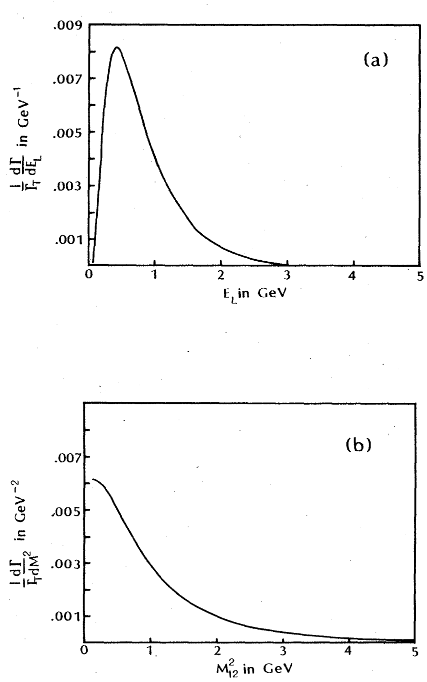

FIG. 2. (a) The energy distribution of either of the outgoing leptons measured in the rest frame of the upsilon for the process $\Upsilon\to GGc\bar{c}\to\mu^+\mu^-X$. (b) The invariant-mass squared of the $\mu^+\mu^-$ pair for the process described in (a).

B. Predictions of the model

1. Upsilon decay

The energy distribution of either of the outgoing massive leptons as measured in the rest frame of the upsilon is shown in Fig. 2(a) for the process $\Upsilon\to GGc\bar{c}\to\mu^+\mu^-+X$. In this and all subsequent figures, the distributions were generated using the mass of the muon. However, there is no significant difference in the distributions when the mass of the electron is used in place of that of the muon. The energy distributions for the less massive leptons (e,μ) are easily distinguishable from that of the tau, since the position, width and amplitude of the peak in the energy distribution are dependent to some extent on the mass of the lepton.

In Fig. 2(b) the invariant-mass squared $M_{12}{}^2$ of the two charged leptons is plotted. The shape of the distribution for large $M_{12}{}^2$ is sensitive to the rest mass of the two leptons. The smaller rest mass (electron mass) produces a broader tail for the $M_{12}{}^2$ distribution than does the larger rest mass (muon mass). However, the branching ratios are the same in both cases.

In Table I, we give the predicted branching ratio for the decay of the upsilon via the process shown in Fig. 1.

2. t-quarkonium

We have calculated the lepton-energy distribution and invariant-mass-squared distribution for two different decay channels. In Figs. 3(a) and 3(b), we have plotted these distributions for the process $(t\bar{t})\to GGc\bar{c}\to\mu^+\mu^-+X$, and

TABLE I. Branching ratios.

Decay mode	$\Gamma(M\to q\bar{q}X)/\Gamma_{\text{total}}$
$\Upsilon\to c\bar{c}X$	0.007 9
$(t\bar{t})\to c\bar{c}X$	0.039 49
$(t\bar{t})\to b\bar{b}X$	0.022 6

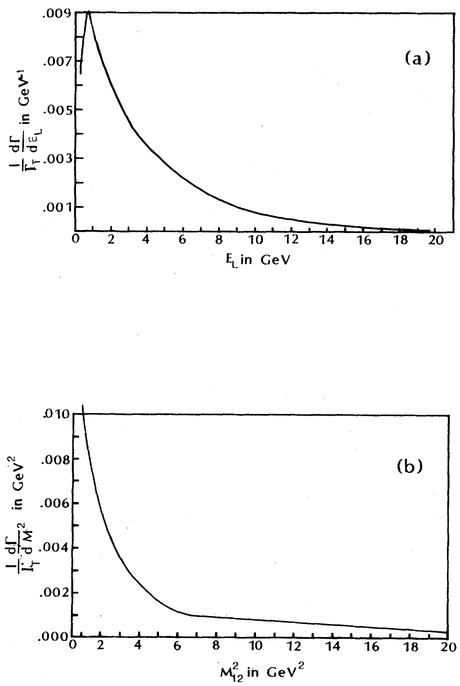

FIG. 3. (a) The energy distribution of either of the outgoing leptons measured in the rest frame of the $(t\bar{t})$ system for the process $(t\bar{t})\to GGc\bar{c}\to\mu^+\mu^-X$. (b) The invariant-mass squared of the $\mu^+\mu^-$ pair for the process described in (a).

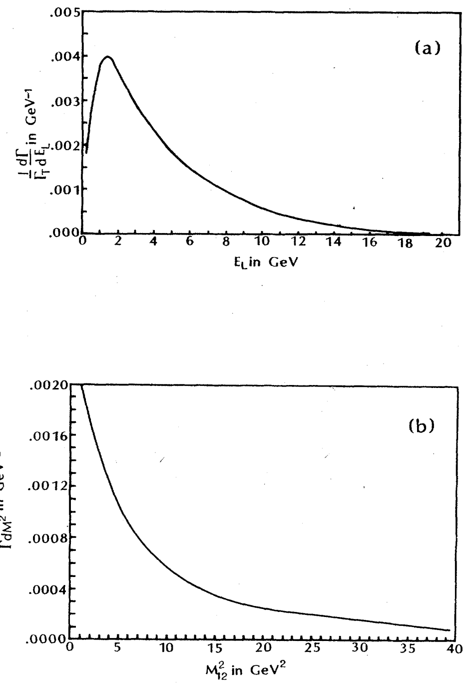

FIG. 4. (a) The energy distribution of either of the outgoing leptons measured in the rest frame of the $(t\bar{t})$ for the process $(t\bar{t})\to GGb\bar{b}\to\mu^+\mu^-X$. (b) The invariant-mass squared for the $\mu^+\mu^-$ pair for the process described in (a).

in Figs. 4(a) and 4(b) we have similar plots for $(t\bar{t})\to GGb\bar{b}\to\mu^+\mu^-+X$. Comparing Figs. 3(a) and 4(a), we see that they are very similar except that the $b\bar{b}$ channel distribution peaks at a slightly higher energy and has a somewhat higher tail due to phase-space effects. The invariant-mass-squared distributions, Figs. 3(b) and 4(b), show a higher and narrower peak in the $c\bar{c}$ channel than in the $b\bar{b}$ channel at the low-mass-squared end of the distribution because of the wider range of momenta available to the c quarks.

The branching ratios for the two channels are given in Table I. The larger value for the $c\bar{c}$ channel is expected on the basis of phase-space considerations.

III. CONCLUSIONS

The results presented here, plus those of Ref. 3, will be useful in sorting out the various contributions to prompt lepton production in the decay of heavy-vector mesons. The hope that prompt massive-lepton production could be used to signal charm production in heavy-vector-meson decay is somewhat diminished by the smallness of the branching ratios for the processes investigated in this paper. Nevertheless, as machine energies and luminosities increase, the decays of heavy vector mesons may provide a viable means of studying sequential decays of the heavy quarks.

ACKNOWLEDGMENTS

This research was supported in part at Indiana University by the U.S. Department of Energy under Contract No. DE-AC02-84ER40125 and at the University of Alabama by the U.S. Department of Energy under Contract No. DE-FG05-84ER40141. One of us (B.H.) would like to thank the Theory Group at Fermilab for its hospitality during the period when much of this work was carried out.

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