On the properties of *t*-quarkonium decay

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The decays of the 1^3S_1 state of $t\bar{t}$ (T-meson) have been estimated. It is shown that the multiplicity in direct hadron decays of the T-meson should be twice as large as in phonon events because of the cascade multiplication of gluons. The appearance of the T-meson in e^+e^- annihilation are discussed briefly.

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Five types of quarks—*u*, *d*, *s*, *c*, *b*—have now already been discovered, and present-day concepts make it reasonable for the existence of at least one more, sixth quark *t* with a charge $e_t = 2/3$. Hopes for the existence of a "gluon factory" are tied to the $t\bar{t}$ system—*t*-quarkonium. It is assumed that a study of the decays of T-quarkonium will make it possible to examine in detail the properties of gluons and their hadronization process.

In this paper we shall consider the expected properties of the decays of the lightest vector state (1^3S_1) of *t*-quarkonium, which we will denote by T. We shall be concerned with the ratio of the various decays, the multiplicity of the final hadrons and the possibilities of observing the T-meson.

We can attempt to describe all quarkonium decays in terms of the wave function or, in the final analysis, in terms of the potential between the quarks. Such an approach has been pursued especially vigorously for charmonium $c\bar{c}$ (see, for example, Ref. 1 for a general description of this work). If the potential is assumed to be universal, then charmonium calculations can be transferred to systems of heavier quarks.[2] However, the problem of choosing the potential and its universality still has no definite solution (see Ref. 3 for a recent discussion of this problem). Therefore we will use another, semiphenomenological approach.

As is known, the total width Γ_{tot} of vector quarkonium contains several contributions.

1) Decays into lepton pairs e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ give a combined width of $2\Gamma_{e^+e^-}$ for the J/ψ-meson and $3\Gamma_{e^+e^-}$ for the v-meson or heavier quarkoniums.

2) The contribution of electromagnetic hadronic decays ($Q\bar{Q}\to\gamma^*\to$hadrons) is equal to $\Gamma_h^{(\gamma)} = R\Gamma_{e^+e^-}$, where $R = \sigma(e^+e^-\to\text{hadrons})/\sigma(e^+e^-\to\mu^+\mu^-)$ near the quarkonium peak.

3) The width of the direct hadronic decays ($Q\bar{Q}\to 3g\to$hadrons) is equal to (see, for example, Ref. 1)

$$\Gamma_h^{(dir)} = \frac{10}{81\, e_Q^2}\,\frac{\pi^2-9}{\pi}\,\frac{\alpha_s^3}{\alpha^2}\,\Gamma_{e^+e^-}, \qquad (1)$$

where e_Q is the electrical charge of the quark, $\alpha_s = g_s^2/4\pi$ is the quarkonium interaction constant.

4) Radiation decays ($Q\bar{Q}\to\gamma 2g\to\gamma +$ hadrons) have a width

$$\Gamma_{\gamma h} = \frac{8}{9}\,\frac{\pi^2-9}{\pi}\,\frac{\alpha_s^2}{\alpha}\,\Gamma_{e^+e^-}. \qquad (2)$$

Let us note that α_s may not be the same as the coefficient in the Coulomb-like part of the effective potential.

5) The width of the $1^3S_1\to\gamma + 1^1S_0$ is relatively small for charmonium[4] and probably also for heavier quarkoniums. We shall ignore it.

We shall make use of the empirical relationship

$$\Gamma_{e^+e^-} = c_Q^2\ \text{const}, \qquad (3)$$

valid for ρ, ω, ϕ, J/ψ, v. After assuming that in the transition from one quarkonium to another α_s varies in accordance with the usual logarithmic formula of quantum chromodynamics (see, for example, Ref. 1), we can now calculate the t-quarkonium decays.

The results are shown in Table I. The initial values are underlined. The interval $M_T = 35$–50 GeV of possible mass values is taken for the T-meson. A comparison of

TABLE 1. Quarkonium decay widths.

$Q\bar{Q}$	Γ (keV)	Γ_h (keV)	$\Gamma_h^{(dir)}$ (keV)	Γ_h (keV)	Γ_{tot} (keV)	R	
J/ψ	4.8	12	42.3	5.4	69	2.5	0.18
Υ	1.2	4.4	20.6	0.84	29.5	3.7	0.14
T	4.8	19	11 – 9.5	2	46.5 – 45	4	0,115 – 0,11

the calculations for v with the measured values $\Gamma^{v}_{e^+e^-} = 1.33 \mp 0.14$ keV,[5] $\Gamma^{v}_{\rm tot} = 45^{+38}_{-14}$ keV [6] shows the degree of reliability of the numbers obtained.

The question of the multiplicity of the hadrons in the t-quarkonium decays is extremely interesting. For direct decays it can be estimated by the relation[7]

$$n^T_{ch} \approx \frac{3}{2}\,\frac{9}{4}\,\Delta n^{e^+e^-}_{ch}\left(W = \frac{2}{3}M_T\right) + n^{J/\psi}_{ch}\,. \tag{4}$$

It is assumed that the excess of n^T_{ch} over $n^{J/\psi}_{ch}$ is caused by the emission of a large number of relatively soft gluons by the three initial high-energy gluons. A similar, cascade multiplication of the gluons specific to QCD, emitted by the quarks, is apparently responsible for the increase of the multiplicity in the e^+e^- hadrons outside the resonances.[8] Equation (4) reflects the relationship between gluon emission by gluons and by quarks. In it $\Delta n^{e^+e^-}_{ch}(W)$ is the increase of the multiplicity in the e^+e^- annihilation as the energy increases from ~ 2 GeV to W; the coefficient 3/2 takes account of the transition from two jets to three, and the coefficient 9/4 takes account of the higher probability of soft gluon emission by a gluon than by a quark.[9] Equation (4) gives a reasonable estimate ($n_{ch} \approx 8$–10) for direct v decays. For a T-meson in the mass M interval from 35 to 50 GeV the estimate of n^T_{ch} varies from ≈ 30 to ≈ 40. It is twice the multiplicity which is to be expected[7,10] for phonon events and for T decay via a photon. It would be very interesting to verify this consequence of the cascade multiplication of gluons.

Let us discuss briefly the possibilities of observing the T-meson. With the emission of soft photons taken into account, the ratio of the maximum cross section at the resonance peak to the background in the channel $e^+e^- \to$hadrons is[11]

$$1 + \frac{1}{R}\,\frac{9}{2\alpha^2}\sqrt{\frac{\pi}{2}}\,\frac{\Gamma_{e^+e^-}\Gamma_h}{\sigma\Gamma_{tot}}\left(\frac{2\sqrt{2}\,\sigma}{M_T}\right)^{\beta},\quad \beta = \frac{4\alpha}{\pi}\left(\ln\frac{M_T}{m_e} - \frac{1}{2}\right),$$

where $\Gamma_h = \Gamma^{(\gamma)}_h + \Gamma^{(dir)}_h + \Gamma_{\gamma h}$, and σ is the energy spread in the beams. In the $e^+e^- \to \mu^+\mu^-$ channel this ratio is equal to

$$1 + \frac{9}{2\alpha^2}\sqrt{\frac{\pi}{2}}\,\frac{(\Gamma_{e^+e^-})^2}{\sigma\Gamma_{tot}}\left(\frac{2\sqrt{2}\,\sigma}{M_T}\right)^{\beta}.$$

For $\sigma(\text{MeV}) = 22\times 10^{-3}\, M_T^2\, (\text{GeV})^2$ (this corresponds to the PETRA apparatus) we obtain the result that the cross section maximum exceeds the background by a factor of 2–2.5 in the hadronic channel and a factor of 1.5–2 in the muon channel. Thus, the measurement of the leptonic width and the reconstruction of the total width will apparently not be too difficult a problem.

Direct hadronic and radiation decays of the T-meson are the most interesting for studying gluons. But because of asymptotic freedom, $\Gamma_h^{(dir)}$ amounts to only $\sim(1/3)\,\Gamma_h$, and $\Gamma_{\gamma h} \approx 0.06\ \Gamma_h$. The role of direct decays can be enhanced by selecting events with large multiplicity or, for example, with large sphericity.

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