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Laboratori Nazionali di Frascati

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ON $\overline{p}p$ DECAY WIDTHS OF HEAVY QUARKONIUM STATES

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Abstract

We discuss the decay widths and branching ratios of charmonium and bottomonium levels into $\overline{p}p$ final states. The values of these widths and corresponding branching ratios determine quarkonia production cross-sections as s-channel resonances in $\overline{p}p$ annihilation. From the known values of charmonia decay widths into differnt channels and using non-relativistic formulas for S-, P- and D-state transitions into gluons we obtain the predictions for decay widths of $^1P_1$, and $^3D_1$ charmonium levels into $\overline{p}p$ final state. To estimate $\overline{p}p$ decay widths for $^3P_0$, $^3D_2$, $^3D_3$ and $^1D_2$ charmonium levels we made some plausible assumptions on dependence of the amplitude of gluon transition into $\overline{p}p$ state on angular momentum and parity. Than, using the energy behavior of the amplitude of $\overline{p}p$ annihilation into gluons given by non-perturbative quark-gluon model we come to estimates of $\overline{p}p$ decay widths and branching ratios for 2^1S_0 level of charmonium and S- and P-levels of bottomonium.

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Production of quarkonium states as s-channel resonances in $\bar{p}p$ annihilation is the only way to study C-odd levels with quantum numbers not equal to 1^{--}. Moreover, the production of C-even P-wave states of charmonium in $\bar{p}p$ collisions allowed to determine their total widths much more exactly than in radiative decays of $\psi'(2S)$ meson[1]. The production of bottomonium levels in $\bar{p}p$ annihilation could discriminate between perturbative and non-perturbative mechanisms of their production[2].

Existing estimates[3,4] of decay widths and branching ratios of heavy quarkonium into $\bar{p}p$ final state based on perturbative QCD are strongly dependent on proton wave function which is known in perturbative QCD only at asymptotics. Moreover, in the case of charmonium there must exist a very significant non-perturbative corrections[5], which may be important even for bottomonium case[6,7]. A phenomenological attempt[8] to obtain an estimate the charmonium $^3D_1$-state decay width into $\bar{p}p$ state, as it will be shown below, is incorrect because of missed numerical factor.

n this paper we use existing experimental data[9] on different decay widths of charmonia and non-relativistic formulas for charmonium decays into gluon states[10-12] to obtain the widths of transitions $(Q\bar{Q}) \to gluons$. Using experimental data on $\bar{p}p$ decay widths of charmonium and some assumptions on angular momentum and parity dependence of transition $gluons \to \bar{p}p$ we get the estimates of unknown $\bar{p}p$ decay widths of S-, P- and D-wave states of charmonium which are shown in Table I.

Table I

state	2^1S_0	$^3P_0$	$^1P_1$	$^3D_1$	$^3D_2$	$^3D_3$	$^1D_2$
Γ(eV)	1400	1600	60	500	30	200	100
$B \cdot 10^3$	0.24	0.12	0.12	0.02	0.025	< 0.05	0.15

Our predictions for charmonium are larger than those based on perturbative QCD[3,4].

To obtain predictions for bottomonium we use existing data on $\bar{p}p$ decay widths of charmonia, and non-perturbative quark-gluon string model[13-16] for energy dependence of gluon transitions into $\bar{p}p$ final state. Results for S- and P-waves of bottomonium are shown in Table II.

Table II

state	$^3S_1$	2^3S_1	3^3S_1	2^3P_0	2^3P_1	2^3P_2	2^1P_1
$\Gamma(\mathrm{eV}) \cdot 10^3$	$100 \div 30$	$40 \div 10$	$20 \div 5$	$60 \div 16$	$11 \div 3$	$15 \div 4$	$11 \div 3$
$B \cdot 10^7$	$20 \div 6$	$8 \div 2$	$8 \div 2$	1.1÷.3	1.1÷.3	1.1÷.3	1.1÷.3

For bottomonium our results are about one order of magnitude less than the results of paper[7].

The transition $(Q\bar{Q}) \to p\bar{p}$ shown in Fig. 1 can be separated into two different parts: the perturbative decay of quarkonium $(Q\bar{Q})$ state into gluons and subsequent, presumably non-perturbative, transition of gluons into $\bar{p}p$ state.

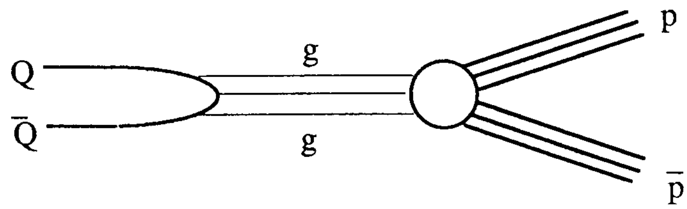

FIG. 1

According to diagram shown in Fig. 1 we write down the expression for $\Gamma[(Q\bar{Q}) \to p\bar{p}]$ in the form:

$$\Gamma[(Q\bar{Q}) \to p\bar{p}] = \Gamma[(Q\bar{Q}) \to gluons] B(gluons \to p\bar{p}) \tag{1}$$

For ${}^1S_0$ $\eta_c(1S)$ level

$$\Gamma({}^1S_0 \to gluons) = \Gamma^{tot}({}^1S_0). \tag{2}$$

For ${}^3S_1$ $J/\psi(1S)$ resonance

$$\begin{aligned} \Gamma({}^3S_1 \to gluons) = \Gamma^{tot}({}^3S_1) - \Gamma({}^3S_1 \to \mu^+\mu^-) - \Gamma({}^3S_1 \to e^+e^-) - \\ -\Gamma({}^3S_1 \to \gamma^* \to hadrons) - \Gamma({}^3S_1 \to \gamma\, {}^1S_0) - \Gamma({}^3S_1 \to \gamma gg) \end{aligned} \tag{3}$$

For 2^3S_1 $\psi'(2S)$ meson

$$\begin{aligned} \Gamma(2^3S_1 \to gluons) = \Gamma^{tot}(2^3S_1) - \Gamma(2^3S_1 \to \mu^+\mu^-) - \Gamma(2^3S_1 \to e^+e^-) - \\ -\Gamma(2^3S_1 \to \gamma^* \to hadrons) - \Gamma(2^3S_1 \to \gamma\, {}^1S_0) - \Gamma(2^3S_1 \to \gamma gg) - \\ -\Gamma(2^3S_1 \to {}^1S_0\ hadrons) - \sum_J \Gamma(2^3S_1 \to \gamma\, {}^3P_J) \end{aligned} \tag{4}$$

And for ${}^3P_J$ $\chi_{cJ}(1P)$ levels

$$\Gamma({}^3P_J \to gluons) = \Gamma^{tot}({}^3P_J) - \Gamma({}^3P_J \to \gamma\, {}^3S_1) \tag{5}$$

The decay widths of C-even states into $\gamma\gamma$ final states are small and not included into eq.s (2) and (5). The values of $\Gamma[(Q\bar{Q}) \to gluons]$ for known charmonium states extracted from experimental data[1,9] are shown in Table III.

Table III

state	$^1S_0$	$^3S_1$	2^3S_1	$^3P_0$	$^3P_1$	$^3P_2$
Γ(MeV)	$10.3\pm3,8$	$.054\pm.004$	$.031\pm.003$	13.5 ± 3.3	$.47\pm.08$	$1.48\pm.18$

When obtaining the data on $^3S_1$ and 2^3S_1 states shown in Table III we used the ratio:

$$\frac{\Gamma(^3S_1\to\gamma gg)}{\Gamma(^3S_1\to ggg)}=0.10\pm0.04 \qquad (6)$$

for charmonium[17].
Note that the ratio

$$\frac{\Gamma(^3P_0\to gg)}{\Gamma(^3P_2\to gg)}=9.1\pm2.5 \qquad (7)$$

from Table III contradicts non-relativistic theoretical prediction[10]:

$$\frac{\Gamma(^3P_0\to gg)}{\Gamma(^3P_2\to gg)}=\frac{15}{4} \qquad (8)$$

The known values of $\Gamma[(Q\bar{Q})\to gluons]$ for bottomonium states are shown in Table IV.

Table IV

state	$^3S_1$	2^3S_1	3^3S_1	2^3P_0	2^3P_1	2^3P_2
Γ(KeV)	41 ± 2	21 ± 4	12 ± 1.4	400 ± 140	63 ± 17	100 ± 20

When obtaining the data shown in Table IV we used in the case of bottomonium for the ratio eq.(6) the value[18]:

$$\frac{\Gamma(^3S_1\to\gamma gg)}{\Gamma(^3S_1\to ggg)}=(2.79\pm0.15)\% \qquad (9)$$

For n^3S_1 states the ratio:

$$\frac{\Gamma(^3S_1\to ggg)}{\Gamma(^3S_1\to\mu^+\mu^-)}=\frac{5}{18}\left(\frac{M}{2m_Q}\right)^2\frac{(\pi^2-9)[\alpha_s(m_Q)]^3}{\pi\alpha^2}[1+1.6\frac{\alpha_s(m_Q)}{\pi}], \qquad (10)$$

where M is the mass of the n^3S_1 resonance, does not depend on the quarkonium wave function in the origin.

The corresponding ratio for $^3D_1$ level has the form[10-12]:

$$\frac{\Gamma(^3D_1 \to ggg)}{\Gamma(^3D_1 \to \mu^+\mu^-)} = \frac{304}{45}\left(\frac{M}{2m_Q}\right)^2 \frac{[\alpha_s(m_Q)]^3}{\pi\alpha^2} L \cdot \left[1 + \left(\frac{107\pi^2}{9728} + \frac{509}{912}\right)L^{-1} - \frac{233}{190}\frac{e^{-L}}{L}\right] \quad (11)$$

here $L = \ln(M/\Delta)$, where Δ is the inverse mean radius of quarkonium: $\Delta = \langle r \rangle^{-1}$. Corrections of the order of α_s to eq.(11) are unknown.

Eq.(11) contains large numerical factor before the ratio α_s^3 / α^2 with respect to eq.(10), which was not taken into account in paper[8].

The well-known descrepancy between the theoretical expectations for ratios of eq.(10) for 1^3S_1 and 2^3S_1 levels of charmonium and experimental values is reduced by the factor $(M/2m_c)^2$ in eq.(10). With this factor taken into account the double ratio

$$\frac{\Gamma[\psi'(2S) \to ggg]}{\Gamma[\psi'(2S) \to e^+e^-]} \Big/ \frac{\Gamma[J/\psi \to ggg]}{\Gamma[J/\psi \to e^+e^-]} = 1.42 \quad (12)$$

instead of 1 and fits very well the experimental number 1.44 ± 0.15. In the case of $\Upsilon(1S)$, and $\Upsilon(3S)$ states the corresponding ratios are equal:

$$1 : (1.23 \pm 0.2) : (0.89 \pm 0.15) \quad (13)$$

and have to be compared with mass-corrected ratios

$$1 : 1.12 : 1.20 \quad (14)$$

Experimental values from eq.(13) agree both with eq.(14) and unity. The more detailed discussion of this problem is out of the scope of present paper.

Now we can calculate the magnitudes of $B(gluons \to p\bar{p})$ (see eq.(1)) from experimental data on $\Gamma[(c\bar{c}) \to p\bar{p}]$ and the values of $\Gamma[(c\bar{c}) \to gluons]$ given in Table III at energies of charmonium resonances. These values depend on quarkonium quantum numbers and are given in Table V.

Table V

state, J^P	$^1S_0, 0^-$	$^3S_1, 1^-$	$2^3S_1, 1^-$	$^3P_1, 1^+$	$^3P_2, 2^+$
$B \cdot 10^3$	1.2 ± 0.4	3.6 ± 0.3	1.7 ± 0.5	0.15 ± 0.03	0.12 ± 0.02

The $\bar{p}p$ decay widths of $^1P_1$ and $^3D_1$ charmonium states can be estimated now without any additional assumptions. For P_1 wave charmonia transitions into hadrons we have the relation[10,19]:

$$\frac{\Gamma(^1P_1 \to hadrons)}{\Gamma(^3P_1 \to hadrons)} = \frac{5}{6}. \tag{15}$$

Using $^3P_1$ branching ratio into $\bar{p}p$ final state from Table V we have:

$$\Gamma(^1P_1 \to \bar{p}p) = 60 \pm 12 \text{ eV}. \tag{16}$$

To estimate $\Gamma(^3D_1 \to ggg)$ we use eq.(10) and (11). The double ratio does not depend on wave functions and their derivatives in the origin and on coupling constants:

$$\frac{\Gamma(^3D_1 \to ggg)}{\Gamma(^3D_1 \to e^+e^-)} \Big/ \frac{\Gamma(2^3S_1 \to ggg)}{\Gamma(2^3S_1 \to e^+e^-)} = = \frac{608}{25(\pi^2-9)} L \cdot \left[1 + \left(\frac{107\pi^2}{9728} + \frac{509}{912}\right) L^{-1} - \frac{233}{190}\frac{e^{-L}}{L}\right]. \tag{17}$$

At $M = 3.8$ GeV and $\Delta = 0.24$ GeV[20] we have for the right-hand side of eq. (17) the value of 78.5. Using e^+e^- width of $\psi(3770)$ resonance (we neglect here with mixing of 2^3S_1 and $^3D_1$ states) and data on $\psi'(2S)$ resonance we obtain $\Gamma(^3D_1 \to ggg) = 300 \pm 50$ KeV and

$$\Gamma(^3D_1 \to \bar{p}p) = 500 \pm 150 \text{ eV}. \tag{18}$$

To make a next step we have to apply a non-perturbative model for gluon transistion into $\bar{p}p$ final state. The problem of inverse process, $\bar{p}p$ annihilation into gluons, was discussed in paper[16] in the frame of quark-gluon string model[13-15]. In this model $\bar{p}p$ annihilation is described by diagrams shown in Fig. 2.

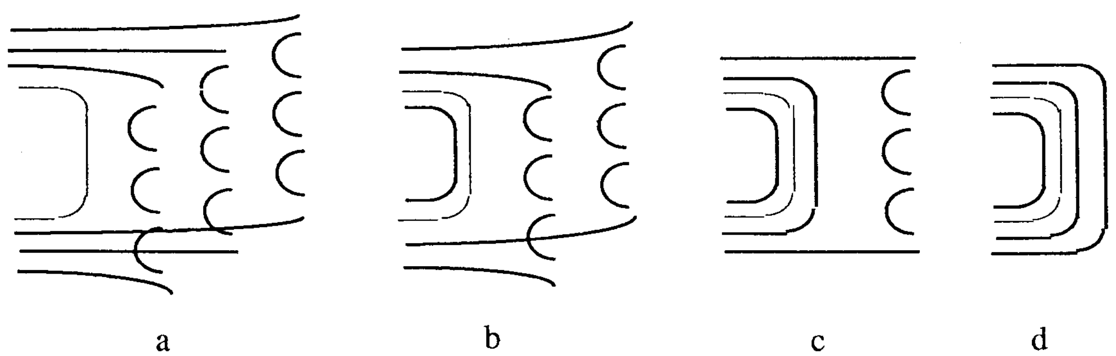

FIG. 2

The diagram shown in Fig. 2a which gives the main contribution to $\bar{p}p$ annihilation at high energies corresponds to so called string junction, which appears inside baryons due to gauge invariance[21]. The $\bar{p}p$ annihilation cross-section corresponding to this diagram decreases with energy as $s^{-1/2}$. The second diagram presents the process with annihilation of one quark-antiquark pair in addition to string junctions annihilation. Because of this additional annihilation this diagram decreases with energy faster, like s^{-1}. The diagram in Fig. 2d describes $\bar{p}p$ annihilation into pure gluon state. The amplitude of this process has Regge behavior:

$$T(s,t) \propto (s/s_0)^{\alpha_N(t)-1}, \qquad (19)$$

where $\alpha_N(t)$ is baryon Regge trajectory, $s_0 = 2{,}25\ \mathrm{GeV}^2$ [22] and s is the invariant mass of $\bar{p}p$ pair or the mass of quarkonium resonance.

Partial wave amplitude with fixed total angular momentum J depends on energy s like

$$T_J(s) \propto (s/s_0)^{\alpha_N(0)-1} \frac{1}{\alpha'_N(0)\ln(s/s_0)}, \qquad (20)$$

where $\alpha_N(0) = -(0.2 \div 0.5)$ and $\alpha'_N(0) = 1\ \mathrm{GeV}^{-2}$. Eq.(20) leads to the energy dependence of $B(gluons \to \bar{p}p)$.

$$B(gluons \to \bar{p}p) \propto [T_J(s)]^2 \propto (s/s_0)^{-(2.4 \div 3)} \cdot [\ln(s/s_0)]^{-2} \qquad (21)$$

Now we can estimate the $\bar{p}p$ decay widths of n^3S_1 and 2^3P_1 and 2^3P_2 bottomonium levels. Using the experimental data from Table IV, the energy dependence eq.(21) and $B(gluons \to \bar{p}p)$ for J/ψ resonance with the same quantum numbers from Table V we obtain the results shown in Table II.

To predict $\bar{p}p$ decay width of $\eta_c(2S)$ resonance with the mass 3594 MeV[9] we used the value $\Gamma[\eta_c(2S) \to gg] = 5.8 \pm 2.2$ MeV obtained from the equation:

$$\frac{\Gamma[\eta_c(2S) \to gg]}{\Gamma[\eta_c(1S) \to gg]} = \frac{|R_{2S}(0)|^2}{|R_{1S}(0)|^2} = \frac{\Gamma[\psi'(2S) \to e^+e^-]}{\Gamma[J/\psi(1S) \to e^+e^-]} \cdot \frac{M^2_{\psi'}}{M^2_{J/\psi}} \qquad (22)$$

Using the data from Table 5 and eq.(21) we come to the value:

$$\Gamma[\eta_c(2S) \to \bar{p}p] = 1.4 \pm 0.7\ \mathrm{KeV} \qquad (23)$$

To obtain estimates for $^3P_0$, $^3D_2$, $^3D_3$ and $^1D_2$ states we have to make some assumptions on the behavior of $B(gluons \to \bar{p}p)$ for quantum numbers 0^+, 2^- and 3^-.

From Table V it follows that $B(gluons \to \bar{p}p)$ for negative parity waves is about of order of magnitude higher than these for positive parity. We will assume that

$B(gluons \to \bar{p}p)$ for 2^- and 3^- waves are approximately the same as for 0^- and 1^- waves while $B(gluons \to \bar{p}p)$ for 0^+ state is the same as for 1^+ and 2^+ states.

Using the ratios[12]:

$$\frac{\Gamma(^3D_2 \to ggg)}{\Gamma(^3D_1 \to ggg)} = \frac{9}{76}\left(1 - 1.45L^{-1} + 2.19\mathrm{e}^{-L}L^{-1}\right) \quad (24)$$

and

$$\frac{\Gamma(^3D_3 \to ggg)}{\Gamma(^3D_1 \to ggg)} = \frac{9}{19}\left(1 - 0.48L^{-1} + 0.47\mathrm{e}^{-L}L^{-1}\right) \quad (25)$$

where $L = \ln(M/\Delta) = 2.77$ was defined above, we obtain for $\Gamma(^3D_2 \to ggg)$

$$\Gamma(^3D_2 \to ggg) = 0.062 \cdot \Gamma(^3D_1 \to ggg) = 19 \pm 3 \text{ KeV} \quad (26)$$

and the values for $\Gamma(^3D_3 \to \bar{p}p)$ and $\Gamma(^3D_3 \to \bar{p}p)$ decay widths shown in Table I.

To calculate $\Gamma(^1D_2 \to gg)$ and $\Gamma(^1D_2 \to \bar{p}p)$ we use the ratio[10-12]:

$$\frac{\Gamma(^3D_2 \to ggg)}{\Gamma(^1D_2 \to gg)} = \frac{5}{3\pi}\,\alpha_s(m_c^2)L\left(1 - 0.78L^{-1} + .0.97\mathrm{e}^{-L}L^{-1}\right) \quad (27)$$

With $\alpha_s(m_c^2) = 0.29$[18] and value of $L = \ln(M/\Delta) = 2.77$ we have:

$$\Gamma(^1D_2 \to gg) = 60 \pm 10 \text{ KeV} \quad (28)$$

and

$$\Gamma(^1D_2 \to \bar{p}p) = 100 \pm 30 \text{ eV} \quad (29)$$

When calculating the branching ratios for $^3D_2$ and $^1D_2$ charmonium states shown in Table I we used the results of papers[23-26] on transitions of these states into low-lying charmonium levels.

The predicted values of $\bar{p}p$ decay widths and branching ratios of $^1D_2$ and $^3D_2$ charmonium states make it feasible to detect these states in E-760 experiment.

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