Bottomonium production in $\bar{p}p$ annihilation

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The cross sections for production of bottomonium states χ_b, Υ as resonances in direct channel $\bar{p}p$ annihilation are estimated. It is shown that the observation of such states in $\bar{p}p$ annihilation by their decay products $\chi_b \to \gamma\Upsilon$, $\Upsilon \to e^+e^-$ $(\mu^+\mu^-)$ is realistic in experiments with an antiproton storage ring and a gaseous jet target at a luminosity $L=10^{32}$ cm^{-2} sec^{-1} and a beam monochromaticity $\Delta p/p = 10^{-5}$.

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The experimental study of bottomonium production in $\bar{p}p$ annihilation $\bar{p}p \to \chi_b, \Upsilon, \Upsilon', \ldots$ would be of great interest. In such measurements, it would be possible to determine the total widths of χ_b states and partial decay widths χ_b, Υ, Υ' into $\bar{p}p$, which is very hard to realize in any other way. The knowledge of the χ_b total widths is essential for checking QCD and potential models (see, e.g., [1]); the results of the measurements of the partial decay widths χ_b, Υ, $\Upsilon', \ldots$ into $\bar{p}p$ are even more important, since after comparison with the corresponding data on χ_c, J/ψ, ψ' they could be used as a crucial test for the perturbative theory of exclusive processes in QCD (see [2]).

Also of extreme interest would be the measurements of the angular distributions γ and e^+e^- $(\mu^+\mu^-)$ in sequential decays $\bar{p}p \to \chi_b$, $\chi_b \to \gamma\Upsilon$, $\Upsilon \to e^+e^-$ $(\mu^+\mu^-)$. The problem is that the χ_1 and χ_2 states are generally produced as aligned in $\bar{p}p$ annihilation and the degree of alignment is determined by the production mechanism (gluon fusion, nonperturbative mechanism, resulting in the effective $\bar{q}q\chi$ interaction at large distances, etc.). The measurements of the angular distributions γ and e (μ) make it possible to determine this alignment and, therefore, to find the mechanism of χ_b production in $\bar{p}p$ annihilation [3,4]. The comparison with the analogous data for the χ_c states would allow one to clarify how the χ production mechanism changes with quark mass increase. (For χ_c, the nonperturbative mechanism could be expected, for χ_b—the gluon fusion.)

Up to now, the opinion has prevailed that the observation of the annihilation $\bar{p}p \to \chi_b$, Υ is nonrealistic, because the corresponding cross sections are too small. In the present work, I will try to demonstrate that this is not so and that the study of these processes is possible in future antiproton storage rings.

Let us assume that the energy spread in the antiproton beam is smaller than the total χ_b width and estimate the cross section $\bar{p}p \to \chi_b$ at the peak:

$$\sigma(\bar{p}p \to \chi_b)_{\text{peak}} = \frac{4\pi(2j+1)}{m_\chi^2 - 4m_p^2} B(\chi_b \to \bar{p}p) ,$$
$$B(\chi_b \to \bar{p}p) = \frac{\Gamma(\chi_b \to \bar{p}p)}{\Gamma_{\chi,\text{tot}}} . \tag{1}$$

I start with the estimate of $\Gamma(\chi_b \to \bar{p}p)$ by the quark counting rule formulas using the experiment Fermilab E760 data on the annihilation cross sections $\bar{p}p \to \chi_{2c}$, $\bar{p}p \to \chi_{1c}$. According to these data [5,6],

$$\sigma(\bar{p}p \to \chi_{2c})_{\text{peak}} \approx 200 \text{ nb} ,$$
$$\sigma(\bar{p}p \to \chi_{1c})_{\text{peak}} \approx 100 \text{ nb} , \tag{2}$$

$$\Gamma_{\text{tot}}(\chi_{2c}) = 1.98 \pm 0.17 \pm 0.07 \text{ MeV} ,$$
$$\Gamma_{\text{tot}}(\chi_{1c}) = 0.88 \pm 0.11 \pm 0.08 \text{ MeV} . \tag{3}$$

It follows from (1)–(3) that the partial $\chi_{1,2c}$ decay widths are equal to

$$\Gamma(\chi_{2c} \to \bar{p}p) \approx 150 \text{ eV} ,$$
$$\Gamma(\chi_{1c} \to \bar{p}p) \approx 100 \text{ eV} . \tag{4}$$

The quark counting rule formulas state that $\Gamma(\chi \to \bar{p}p) \sim m_\chi^{-9}$ [2]. Using (4), we find

$$\Gamma(\chi_{2b} \to \bar{p}p) \approx 0.0150 \text{ eV} ,$$
$$\Gamma(\chi_{1b} \to \bar{p}p) \approx 0.01 \text{ eV} . \tag{5}$$

The quark counting rule formulas, which, perhaps, correctly describe the m_χ dependence of $\Gamma(\chi \to \bar{p}p)$ in the bottomonium region, are hardly satisfactory in the region of charmonium. The simplest argument in favor of this statement is that each of the six quarks produced in $\chi \to \bar{p}p$ decay shares only 600 MeV of energy. The other argument demonstrating that the perturbation theory on which the quark counting rule is based is inapplicable to the calculations of χ_c widths, due to the fact that the first (in $1/m_c$) nonperturbative correction to the hadronic χ_c width, calculated in Ref. [7], appears to be larger than the main perturbative term. (Even for χ_b, it comprises about 30% [7].)

Even larger nonperturbative effects are expected for

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partial widths $\chi_c \to \bar{p}p$. It is easy to estimate their sign. Suppose that the quark counting rule formulas correctly describe the m_χ dependence of $\Gamma(\chi \to \bar{p}p)$ in the χ_b region. According to them, $\Gamma(\chi \to \bar{p}p)$ is steeply increasing with decreasing m_χ, like m_χ^{-9}. (The proton mass is neglected in comparison with m_χ.) Such a dependence, however, cannot continue up to relatively small values of m_χ since it would result in unreasonably large values of $\Gamma(\chi \to \bar{p}p)$. Therefore, the true curve normalized to the same value in the χ_b region, as the quark counting curve, is more flat than the latter in the region of small m_χ (curve b in Fig. 1). When both curves are normalized to the same value in the χ_c region, as was done above, then the true curve results in higher values of $\Gamma(\chi_b \to \bar{p}p)$ in comparison with the quark counting curve (curve c in Fig. 1).

To quantitatively estimate this effect, let us compare the result of measuring the ratio $\Gamma(\psi' \to \bar{p}p)/\Gamma(J/\psi \to \bar{p}p)$ with its value calculated according to the quark counting rule. Experimentally [8],

$$R_{\psi\,\mathrm{expt}} = \left. \frac{\Gamma(\psi' \to \bar{p}p)}{\Gamma(J/\psi \to \bar{p}p)} \right|_{\mathrm{expt}} = 0.33 \pm 0.11 \; . \tag{6}$$

The quark counting rule predicts the same mass dependence for ψ-state widths as for χ states, which gives

$$(R_\psi)_{\mathrm{quark\ count}} = \left[\frac{m_{J/\psi}}{m_{\psi'}} \right]^9 = 0.21 \; . \tag{7}$$

(As was shown in Ref. [2], the electromagnetic interaction contribution to the decay $J/\psi \to \bar{p}p$ is small.) A correction must be introduced into Eq. (7) due to the fact that ψ' is the radial excitation in the $\bar{c}c$ system and the decay probabilities ratio ψ' and J/ψ into $\bar{p}p$ is proportional to the ratio

$$\frac{|\psi_{\psi'}(0)|^2}{|\psi_{J/\psi}(0)|^2} = \frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)} \frac{m_{\psi'}}{m_{J/\psi}} = 0.53 \; . \tag{8}$$

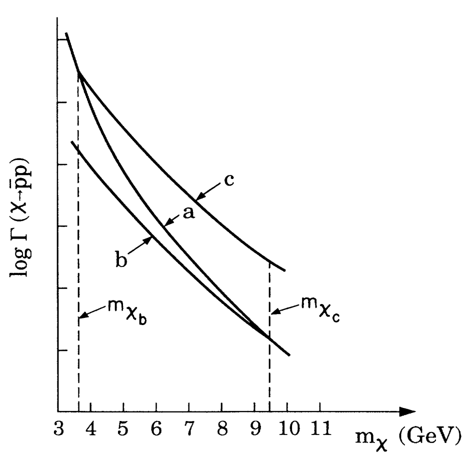

FIG. 1. m_χ dependence of $\Gamma(\chi \to \bar{p}p)$: (a) the quark counting curve; (b) the true curve normalized to coincidence with the quark counting curve at m_{χ_b}; (c) the true curve normalized to coincidence with the quark counting curve at m_{χ_c}.

[According to the quark counting rule, $\Gamma(1\,^3S_1 \to e^+e^-) \sim m^{-1}$.] With the account of this correction, the theoretical value of R found by the quark counting rule is equal to

$$(R_\psi)_{\mathrm{theor,quark\ count}} = 0.11 \tag{9}$$

and is three times smaller than the experimental one. So, indeed, the experimental curve of the m dependence of $\Gamma(\psi \to \bar{p}p)$ in the charmonium region decreases much slower than the quark counting curve. [The effective power k in $\Gamma(\psi \to \bar{p}p) \sim m^{-k}$ is equal to $k = 2.7 \pm 2.2$, but not to $k = 9$, as in quark counting.] Strictly speaking, in addition to the power m dependence, the quark counting formulas are proportional to the logarithmic factor $\alpha_s^6(m)$. The formal account of this factor would result in an even larger (by 40%) disagreement of theory with experiment, i.e., to smaller values of k.

It is natural to expect a similar deviation of the true curve from the quark counting curve in the charmonium region also for C-even states. It is clear that such strong deviations from the quark counting formulas [by a factor of 3 when $\Gamma(\psi \to \bar{p}p)$ decreases by a factor of 5 according to quark counting] will not stop abruptly with increasing m. In the mass interval from χ_c to χ_b, $\Gamma(\chi \to \bar{p}p)$ decreases by a factor of 10^4. From the above considerations, I estimate that the true values of $\Gamma(\chi_b \to \bar{p}p)$ are at least an order of magnitude larger than the values calculated according to the quark counting rule: i.e.,

$$\Gamma(\chi_{2b} \to \bar{p}p) \sim \Gamma(\chi_{1b} \to \bar{p}p) \sim 0.1-0.2 \text{ eV} \; . \tag{10}$$

[This estimate would follow, e.g., if we account for the proton mass and, instead of m_χ^{-9} dependence, suppose the dependence $\sim (m_\chi + 2m_p)^{-9}$.] The α_s dependence of $\Gamma(\bar{p}p) \sim \alpha_s^6(m_\chi)$, which would result in a threefold decrease of $\Gamma(\chi \to \bar{p}p)$ in the interval of m_χ from 4 to 10 GeV, is neglected because it is masked by a much stronger deviation from the power dependence $\sim m_\chi^{-9}$—compare the corresponding remark above when discussing $\psi \to \bar{p}p$ decays.

Taking the total $\Gamma\chi_b$ widths to be equal to $\Gamma\chi_{2b} \approx 100$ keV, $\Gamma\chi_{1b} \approx 25$ keV [1], we find

$$\sigma_{\mathrm{peak}}(\bar{p}p \to \chi_{1b}) \sim \sigma_{\mathrm{peak}}(\bar{p}p \to \chi_{2b}) \sim 0.5-1 \text{ nb} \; . \tag{11}$$

The χ_b production in $\bar{p}p$ annihilation at the χ_b resonance peak can be found by observing the decays $\chi_b \to \gamma\Upsilon$, $\Upsilon \to e^+e^-$, $\mu^+\mu^-$. For such an experiment, an antiproton storage ring with an energy ~ 55 GeV, a gaseous jet target, and a beam monochromaticity not worse than $\Delta p/p = 10^{-5}$ are necessary. If the luminosity of this installation is $L = 10^{32}$ cm^{-2} sec^{-1} (such a luminosity is supposed for the gaseous jet target in CERN SuperLEAR [9]), then one may expect to observe $\bar{p}p \to \chi_{2b}(\chi_{1b}) \to \gamma\Upsilon$, $\Upsilon \to e^+e^- + \mu^+\mu^-$ at the rate of 50–100 events/day.

For the C-odd bottomonium states, the estimates analogous to those presented above give

$$\sigma(\bar{p}p \to \Upsilon) \sim 0.2-0.5 \text{ nb} \; , \tag{12}$$

and at the same luminosity the number of events of $\bar{p}p \to \Upsilon \to e^+e^- + \mu^+\mu^-$ would be about 100 events/day.

If the background in these experiments is smaller than in the Fermilab experiments on χ_c production [5], where the background cross section of e^+e^- production was about 10 pb/MeV [10], what could be expected, then, probably, is that the background would not be too dangerous.

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