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Bottomonium polarization in hadroproduction

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Abstract

The polarization of the Υ and χ_{b2} mesons in hadron hadron collisions is considered. It is shown that both states are produced with a noticeable polarization which allows to use forthcoming data of DESY HERA-B and of the RHIC collider experiments to discriminate between the different mechanisms of heavy quarkonia production. © 1999 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

In the last few years there has been growing interest in the study of heavy quarkonia production and decay processes. The factorization approach (FA), based on nonrelativistic QCD (NRQCD) [1] allows one to explain *qualitatively* the production of J/ψ and ψ' mesons at large transverse momenta at the Tevatron [2,3].

In extension of the color singlet model (CSM) [4], the NRQCD FA implies that the heavy quarkonium can be produced through color octet quark-antiquark states. The relative importance of the different intermediate states, color octet and color singlet, can be defined by the velocity scaling rules [5]. In this picture the heavy quarkonium production and decay processes are considered as a double series in the QCD coupling constant, α_S, and the relative velocity of constituents in the heavy quarkonium, v. The transformation of the intermediate quark-antiquark pair into the final hadronic state is parameterized by long distance matrix elements. The latter can not be calculated in the framework of perturbative QCD and thus have to be extracted from data. Once this is done, the predictions for other processes can be made. However, until now, the universality of NRQCD factorization approach has not been validated. Large theoretical uncertainties do not allow to use the existing experimental data for extracting the color octet matrix elements with sufficient accuracy. Predicted cross sections depend strongly on the factorization and/or renormalization scales as well as on the mass of the heavy quark [6,7]. Resummation of higher order terms in v is necessary near the kinematical boundaries, where cross sections are sensitive to the momentum carried away by soft gluons in the hadronization phase (for more details see [8] and the references therein).

As it turns out, a study of spin effects in heavy quarkonium physics provides powerful tools to test

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the NRQCD factorization approach. The polarization of final states or the spin asymmetries in polarized reactions, being the ratios of cross sections, do not depend strongly on the above mentioned phenomenological parameters and on the color octet long distance matrix elements characterizing the hadronization phase.

The production of heavy quarkonium in polarized experiments in the framework of the NRQCD FA was studied in Refs. [9,10]. The spin asymmetries depend not only on the heavy quarkonium production mechanism but also on the gluon polarization in the nucleon. These results are reliable in the study of the quarkonium production mechanism only when the polarized gluon distribution is known and contributes significantly to the observable asymmetries.

Another spin dependent observable showing less theoretical uncertainties and therefore being more promising for testing the NRQCD FA is the polarization of quarkonium in the final state. In recent papers it was suggested to measure the polarization of quarkonia; in J/ψ and ψ' production at the Tevatron [6,11,12], in J/ψ photoproduction [13], and in Υ production at fixed target energies [14–16]. Production of charmonium in fixed target reactions was analyzed in details in [7,17].

Recently Kharzeev and Jaffe suggested to use the photon angular distribution from the decay of $\chi_{c2} \to J/\psi + \gamma$ [18] for testing the NRQCD FA. As we show below, the contribution of color octet states is negligible in P-wave charmonium production and hence the measurement of the χ_{c2} polarization can not provide valuable information about the color octet mechanism. On the other hand, the main contribution in the production of the bottomonium P-wave states is expected from the $^3S_1^{(8)}$ color octet state [7]. In the present paper we calculate the polarization of the Υ and χ_{b2} states at fixed target and RHIC collider energies and consider the possibilities to discriminate different mechanisms for heavy quarkonium production.

2. χ_{b2} production

The photon angular distribution (after integration over the azimuthal angle was carried out) can be expressed in the χ_J-meson rest frame as

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \alpha_\gamma \cos^2\theta, \tag{1}$$

where θ is the polar angle relative to the hadron beam axis.

In Ref. [18], using the QCD multipole expansion [19], angular distributions for the decay of χ_{c2} with the different spin projections were found:

$$\begin{aligned} W(J_z = \pm 2) &\propto 1 + \cos^2\theta, \\ W(J_z = \pm 1) &\propto 1 - \tfrac{1}{3}\cos^2\theta, \\ W(J_z = 0) &\propto 1 - \tfrac{3}{5}\cos^2\theta. \end{aligned} \tag{2}$$

The polarization of the χ_2 can be calculated using the spin orientation of the intermediate quark-antiquark pair. The color singlet $^3P_2$ state produced in the gluon-gluon fusion subprocess has the spin projection $J_z = \pm 2$ [17]. Thus, in the CSM $\alpha_\gamma = 1$ is obtained.

In leading order in v only one color octet state, $^3S_1^{(8)}$, contributes to χ_2 production. In lowest order in α_S, the state $^3S_1^{(8)}$ can only be produced in the quark-antiquark annihilation subprocess. Although the process $gg \to {}^3S_1(8)$ is allowed by conservation laws [2], it vanishes in leading order in α_S.

To calculate the contribution of the $^3S_1^{(8)}$ color octet channel in the process $q\bar{q} \to \chi_2(J_z)$ we follow the helicity decomposition procedure developed in [21] and use spin symmetry, rotational invariance, and the vacuum saturation approximation. The result reads:

$$\begin{aligned} &\hat{\sigma}\left(q\bar{q} \to \chi_2(J_z)\right) \\ &\quad = \frac{8\pi^3\alpha_s^2}{45 m_b^3 s}\,\delta\!\left(x_1 x_2 - \frac{4m_Q^2}{s}\right)\langle \mathcal{O}_8^{\chi_2}(^3S_1)\rangle \\ &\qquad \times \sum_{S_z} |\langle 2\, J_z | J_z - S_z, S_z\rangle|^2 \left(1 - \delta_{S_z 0}\right). \end{aligned} \tag{3}$$

The same result was obtained in [22] assuming that

[2] The Landau-Yang theorem does not forbid this process, as it was mentioned in [20], since the two initial gluons are in the antisymmetric color state.

the process ${}^3S_1^{(8)} \to \chi_2$ is realized via choromoelectric dipole transition.

From Eq. (3) one obtains the relative production rates of χ_2 with the different spin projections, $\pm 2 : \pm 1 : 0 = 2:1:1/3$. Averaging the distributions from Eq. (2) according to the relative yield of χ_2 with the corresponding J_z, we obtain the value of the angular distribution parameter, $\alpha_\gamma = 0.44$.

Now we show that the meson state χ_{c2} is produced mainly from the intermediate color singlet states and the contribution from the color octet mechanism is negligible. The color octet matrix elements parameterizing the transition ${}^3S_1^{(8)} \to \chi_{cJ}$ are small compared to the corresponding color singlet matrix elements of P-wave states [7,20]. As we have mentioned above, in leading order in α_S, the ${}^3S_1^{(8)}$ octet state is produced in the quark-antiquark annihilation subprocess. But for charmonium production the quark-antiquark luminosity is small compared to the gluon-gluon luminosity even at fixed target energies ($\sqrt{s} \simeq 40$ GeV). Consequently, the contribution of color octet states to χ_{c2} production is negligible and the photon angular distribution parameter α_γ is determined only by the color singlet mechanism, i.e. $\alpha_\gamma \simeq 1$.

The situation for the bottomonium states is more subtle. In χ_{b2} production the main contribution is expected from the intermediate color octet state, ${}^3S_1^{(8)}$. The color octet matrix elements describing the ${}^3S_1^{(8)} \to \chi_{bJ}$ transition are larger than the corresponding color singlet matrix elements [7,20]. In addition, the quark-antiquark luminosity is larger compared to the charmonium case because of the larger mass of the $(b\bar{b})$ pair. In Table 1 the χ_{b2} production cross sections in gluon-gluon fusion and quark-antiquark annihilation subprocesses at different energies are presented. These cross sections are calculated using the GRV LO parton distribution functions [23] evaluated at the factorization scale $Q^2 = 4m_b^2$; the b-quark mass is chosen to be $m_b = 4.9$ GeV. The long distance color octet and color singlet parameters are taken from [7].

As it is obvious from Table 1, the main contribution to the χ_{b2} production cross section at HERA-B energy ($\sqrt{s} \simeq 40$ GeV) is due to the quark-antiquark annihilation subprocess, i.e. angular distribution parameter is expected to be $\alpha_\gamma \simeq 0.44$. The relative contribution of the gluon-gluon fusion subprocess in the total cross section increases for RHIC collider energies and correspondingly increases the value of α_γ. At $\sqrt{s} = 500$ GeV α_γ is found to be 0.7.

Table 1
Cross sections for χ_{b2} production through different subprocesses at HERA-B and RHIC energies in NRQCD FA.

$\sqrt{s}$ (GeV)	$\sigma(q\bar{q} \to {}^3S_1^{(8)} \to \chi_{b2})$ (nb)	$\sigma(gg \to \chi_{b2})$ (nb)
40	0.4	0.033
200	11	5.5
300	18	13
500	30	33

In the color evaporation model (CEM) [24] spin-orbital and color quantum numbers of intermediate quark-antiquark states are irrelevant, and gluon emission during the hadronization phase is assumed to be unsuppressed. This model predicts that all the quarkonium states are produced unpolarized. Averaging the values of the angular distribution parameter in Eqs. (2), one obtains $\alpha_\gamma \simeq 0.15$ for unpolarized χ_2 production. This value does not depend on the energy and is the same for charmonium and bottomonium states.

As we can conclude from the above analysis, the differences between the predictions of different mechanisms for the parameter α_γ, which describes the polarization of χ_{b2}, are large enough to use them as a test for NRQCD FA and extract information about the color octet intermediate state.

Although the color octet contribution is negligible in the production of the P-wave charmonium, the measurement of the χ_{c2} polarization can provide a possibility to discriminate the color singlet mechanism versus the CEM. On the other hand, care has to be taken in the interpretation of the χ_{c2} polarization data. It is not excluded that the mass of the charm quark is not large enough to apply the NRQCD factorization approach to the charmonium production and decay processes. Because of the rather large value of v^2, about 0.3 for the charmonium system, the Fock states at high order of v^2 may contribute significantly and thus can not be neglected. For example, data on J/ψ polarization in hadroproduction at fixed target energies contradict to the NRQCD FA as well as to color singlet model predictions [7,17]. One of the reasons for this discrepancies could be higher twist effects when more than one

Table 2
Cross sections for Υ production through different subprocesses at HERA-B and RHIC energies in the NRQCD FA.

$\sqrt{s}$ (GeV)	$gg \to \Upsilon g$ (nb)	$gg \to {}^1S_0^{(8)}, {}^3P_{0,2}^{(8)} \to \Upsilon$ (nb)	$gg \to \chi_{b2} \to \Upsilon\gamma$ (nb)	$q\bar{q} \to {}^3S_1^{(8)} \to \chi_{b2} \to \Upsilon\gamma$ (nb)
40	0.002	0.01	0.016	0.24
200	0.9	1.9	2.7	6.82
300	2.44	4.3	6.3	10.6
500	6.8	11.4	16.4	17.8

parton from one or another hadron is involved in the hard process [17].

3. Υ production

A measurement of the Υ polarization can also be used to obtain information about the relative weight of the color octet mechanism. In leptonic decays the polarization of the S-state quarkonium is determined by the polar angle distribution of the leptons with respect to the beam direction in the meson rest frame. This distribution has the same form as the photon angular distribution in case of the χ_2-state decay, Eq. (1). The angular distribution parameter α can be related to ξ, the fraction of longitudinally polarized Υ mesons:

$$\alpha = \frac{1-3\xi}{1+\xi} = \begin{cases} 1 \text{ for } \xi = 0 \\ -1 \text{ for } \xi = 1 \end{cases} \tag{4}$$

This fraction depends on the mechanism and the particular subprocess of Υ production. Channels with dominating contributions to Υ hadroproduction at small p_T (with the corresponding values of α and ξ) are listed below:

i) Direct Υ production through the color singlet state, $gg \to \Upsilon g$; the ratio of longitudinally and transversely polarized quarkonia $\xi = 0.23$ and $\alpha \simeq 0.25$ [17].

ii) Direct Υ production through color octet states, $gg \to {}^1S_0^{(8)}, {}^3P_{0,2}^{(8)} \to \Upsilon$. For the intermediate scalar state, ${}^1S_0^{(8)}$, $\xi = 1/3$ and $\alpha = 0$; for intermediate P-wave states $\xi = 1/7$ and $\alpha = 0.75$ [7].

iii) Υ production from χ_{b2} decay, the CSM, $gg \to \chi_{b2} \to \Upsilon\gamma$. The χ_{b2} at small p_T are produced with spin projection $J_z = \pm 2$ and Υ coming from χ_{b2} is purely transversely polarized, $\alpha = 1$ [17].

iv) Υ production from χ_{b2} decay through the color octet state, $q\bar{q} \to {}^3S_1^{(8)} \to \chi_{b2} \to \Upsilon\gamma$. In this case Υ mesons are produced with sizeable transverse polarization, $\alpha = 0.24$ [14].

Cross sections of Υ production for each particular subprocess are shown in Table 2. In our calculations we used the formulae for cross sections obtained in [7] and values of the long distance matrix element parameters extracted from the Tevatron data [20]. All the cross sections depend strongly on the mass of b-quark and the factorization scale, but the relative yield of Υ from different subprocesses is practically insensitive to these parameters.

The expected polarization of Υ mesons at different energies can be obtained by weighting all subprocesses with their partial cross sections, see Table 3.

The range of the parameter α in Table 3 is due to different possible choices of the parameters for the long distance color octet matrix elements, $\langle \mathcal{O}_8^{J/\psi}({}^1S_0) \rangle$ and $\langle \mathcal{O}_8^{J/\psi}({}^3P_0) \rangle$. We note that only their combination is fitted from experimental data [7]. For the lower values of α the main contribution is assumed to come from the octet S-state. Higher values correspond to the opposite case, when the parameter for the evolution of octet P-wave states, $\langle \mathcal{O}_8^{J/\psi}({}^3P_0) \rangle$, is dominating. Our results for Υ polarizatiuon are in agreement with the predictions of Ref. [16].

Since the Υ polarization is expected to be large in the NRQCD factorization approach, while the CEM predicts unpolarized Υ production, $\alpha = 0$, it is possible to test both these mechanisms at DESY HERA-B or RHIC collider.

Table 3
Parameter α for the Υ polarization at different energies.

$\sqrt{s}$ (GeV)	α
40	0.28–0.31
200	0.37–0.49
300	0.4 –0.54
500	0.43–0.59

Despite the lower statistics, bottomonium provides a more useful device for testing NRQCD FA than the charmonium system. Because of the large mass of the *b*-quark the higher twist effects are expected to be suppressed [17]. Contributions of higher Fock states in bottomonium production are more suppressed than in case of charmonium; the relative velocity for the bottomonium family is about $v^2 \simeq 0.1$.

In conclusion, we have considered the polarized production of χ_{b2} and Υ states at different energies. The main contribution in the production of bottomonium states is expected from the quark-antiquark annihilation subprocess through the color octet intermediate state, ${}^3S_1^{(8)}$. The photon angular distribution in the χ_{b2} decay is expected to be different from those predicted by the CEM or the color singlet model alone. This allows one not only to test the NRQCD factorization approach but to obtain information about the significance of the color octet intermediate states. In addition, it will be intriguing to measure the predicted rise of Υ and χ_{b2} polarization parameters with increasing energy.

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