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Polarization of prompt J/ψ in proton-proton collisions at RHIC

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Within the framework of the nonrelativistic QCD (NRQCD) factorization approach, we compute the polarization of prompt J/ψ produced at the Brookhaven's Relativistic Heavy-Ion Collider from proton-proton collisions at the center-of-momentum energy $\sqrt{s} = 200$ GeV. The perturbative contributions are computed at leading order in the strong coupling constant. The prediction reveals that the color-singlet contribution severely underestimates the PHENIX preliminary data for the differential cross section integrated over the rapidity range $|y| < 0.35$ and its contribution is strongly transversely polarized, which disagrees with the PHENIX preliminary data. After including the color-octet contributions, we find that the NRQCD predictions for both the cross section and polarization over the transverse-momentum range 1.5 GeV $< p_T <$ 5 GeV (1.5 GeV $< p_T <$ 2 GeV) integrated over the rapidity range $|y| < 0.35$ ($1.2 < |y| < 2.2$) agree with the data within errors.

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In the mid-1990s, the Collider Detector at Fermilab (CDF) Collaboration at the Fermilab Tevatron observed remarkable surplus of the *prompt* J/ψ and $\psi(2S)$ production at large transverse momenta (p_T) [1,2]. Based on the nonrelativistic quantum chromodynamics (NRQCD) factorization approach [3], Braaten and Fleming explained the large cross section by introducing the color-octet gluon fragmentation mechanism, which is the NRQCD extension of the color-singlet version proposed in Ref. [4]. According to the proposal [5], the prompt spin-triplet S-wave charmonia are dominantly produced from the color-octet spin-triplet S-wave charm-anticharm pairs $[c\bar{c}_8(^3S_1)]$ that are fragmented from the gluons at large p_T.

Using the approximate heavy-quark spin symmetry of the NRQCD Lagrangian, Cho and Wise predicted that the spin-triplet S-wave charmonia H must be transversely polarized at large p_T [6], if the color-octet gluon fragmentation is the dominant source in that region. Subsequently, phenomenological polarization predictions for the prompt $\psi(2S)$ [7–9] and J/ψ [10,11] at the Tevatron were carried out. The result is that these states are the more transversely polarized the larger p_T is [7–11] and the rise of the transverse polarization for the J/ψ is slower than that of the $\psi(2S)$ because of the feed-downs from the P-wave spin-triplet states χ_{cJ} for $J = 0$, 1, and 2 [10,11]. Therefore, the observation of transverse H at large p_T is an important independent confirmation of the color-octet gluon fragmentation mechanism.

However, the run-I CDF measurement with an integrated luminosity of about 110 pb^{-1} [12] was in dramatic contradiction to these predictions. To make matters even more confusing, the run-II CDF data of about 800 pb^{-1} [13] neither agree with the predictions nor their own run-I measurement. The prompt J/ψ's from run-II CDF data are almost unpolarized and even show a moderate increase in the longitudinal fraction from $p_T = 5$ to 30 GeV [13].

Further theoretical studies include analyses at higher orders in the strong coupling α_s for the color-singlet [14–18] and for the color-octet [19] channels and the relativistic corrections [20]. Even after those corrections, the color-octet mechanism still contributes to the production rate significantly. Recent color-singlet-model calculations of the polarization of *direct* J/ψ at next-to-leading order (NLO) in α_s predict strong longitudinal polarization [16,17], which disagree with the run-II CDF data over the whole range of p_T. These disagreements have cast doubt on our current understanding of the charmonium production mechanism and lead one to analyze hadroproduction of charmonia at various circumstances.

Recently, the PHENIX Collaboration at the Brookhaven's Relativistic Heavy-Ion Collider (RHIC) reported the cross section [21] and the polarization [22] of the *inclusive* J/ψ production in pp collisions at the center-of-momentum (CM) energy $\sqrt{s} = 200$ GeV. The data also contain the J/ψ's from the B decay, which occupy a tiny fraction ($0.036^{+0.025}_{-0.023}$) of the total rate [23]. Therefore, the inclusive charmonium cross section should be essentially the same as the prompt one. There are several theoretical analyses on the J/ψ production in pp collisions at RHIC. Several years ago, Cooper, Liu, and Nayak reported the NRQCD prediction for the production rate for prompt J/ψ [24,25], which agrees with the run-3 PHENIX data [26,27]. The authors of Ref. [28] explained the J/ψ production rate with two phenomenological parameters of a new production mechanism so-called *s-channel cut* [29]. However, the s-channel-cut prediction for the polarization disagrees with the PHENIX preliminary data for the large-rapidity region $1.2 < |y| < 2.2$ while that for $|y| < 0.35$ is consistent with the measurement [22,30]. Furthermore, Artoisenet and Braaten [31] showed that the s-channel cut can be identified with the charm-pair rescattering and is not a dominant mechanism for charmonium production in high-energy collisions. Very recently, Brodsky and Lansberg carried out calculations for direct J/ψ in the color-singlet model at NLO in α_s [32], including contributions from cg fusion. They obtained a rapidity distribution in good agreement with the PHENIX data [32] under the assumption that about 40% of the J/ψ events come from higher resonances.

In this paper, we present a quantitative analysis of the cross section and the polarization of prompt J/ψ produced in pp collisions at $\sqrt{s} = 200$ GeV using the NRQCD factorization formalism [3]. The perturbative contributions are computed at leading order (LO) in α_s. By including both the color-singlet and color-octet contributions, we find that the NRQCD predictions for both the cross section and polarization agree with the data within errors.

The schematic form of the NRQCD factorization formula for the differential cross section of the polarized charmonium H_λ with momentum P and spin quantum number λ is given by

$$d\sigma^{H_\lambda(P)} = d\sigma^{c\bar{c}_n(P)}\langle O_n^{H_\lambda(P)}\rangle, \tag{1}$$

where the summation is assumed over the index n for the color and angular momentum states of the $c\bar{c}$ pair. The short-distance coefficients $d\sigma^{c\bar{c}_n(P)}$, which are insensitive to the long-distance nature of the quarkonium, are calculable using perturbative QCD. The nonperturbative nature of the H is factorized into the NRQCD matrix elements $\langle O_n^{H_\lambda(P)}\rangle$. The matrix elements are, in general, tensors depending on P and the polarization tensor of the H_λ. After using the symmetries of NRQCD, one can reduce these polarized matrix elements $\langle O_n^{H_\lambda(P)}\rangle$ in terms of the scalar matrix elements $\langle O_n^H\rangle$ that are independent of P and λ. The numerical importance of the NRQCD matrix elements can be estimated based on the velocity-scaling rules of NRQCD [3]. For the spin-triplet S-wave quarkonia $H = J/\psi$ or $\psi(2S)$, the most important matrix elements are $\langle O_1^H({}^3S_1)\rangle$ for the color-singlet state, and $\langle O_8^H({}^1S_0)\rangle$, $\langle O_8^H({}^3S_1)\rangle$, and $\langle O_8^H({}^3P_0)\rangle$ for the color-octet states, respectively. Because prompt J/ψ's include the samples that come from the decay of $\psi(2S)$ and χ_{cJ}, we also have to consider the production of χ_{cJ}. For the χ_{cJ}, the matrix elements $\langle O_1^{\chi_{c0}}({}^3P_0)\rangle$ and $\langle O_8^{\chi_{c0}}({}^3S_1)\rangle$ are equally important.

In the PHENIX experiment of pp collisions, they probe a moderate p_T range, where the fragmentation effect is negligible [25]. Therefore, the production of H should be dominated by the fusion contributions. Then the differential cross section for H_λ is expressed as

$$d\sigma^{H_\lambda(P)} = f_{i/p} \otimes f_{j/p} \otimes d\hat{\sigma}_{ij}^{c\bar{c}_n(P)}\langle O_n^{H_\lambda(P)}\rangle, \tag{2}$$

where $f_{i/p}(x, \mu)$ is the parton distribution function (PDF) and the sums over the partons i and j are implied. Here, x and μ are the longitudinal momentum fraction of the parton and the factorization scale, respectively.

We proceed to compute the differential cross section for the H_λ. In order to make a prediction that is consistent with that for the Tevatron [10], we follow the strategies of Ref. [10] except that we neglect the fragmentation. We include the parton processes $ij \to c\bar{c} + k$, with $i, j = g, q, \bar{q}$ and $q = u, d, s$, and neglect heavy partons like c and b. Corresponding LO parton cross sections $d\hat{\sigma}$ of order α_s^3 are given in Refs. [9,11,33]. The numerical values for the relevant NRQCD matrix elements are given in Table I of Ref. [10].[1] For the PDF's, we choose MRST98LO [34] as the default value and CTEQ5L [35] for comparison. We use the transverse mass $m_T = (4m_c^2 + p_T^2)^{1/2}$ as a common scale for the factorization scale and the renormalization scale with the charm-quark mass $m_c = 1.5$ GeV. We evaluate α_s from the one-loop formula using the value of $\Lambda_{\rm QCD}$ given in each PDF set [34,35]. We estimate theoretical uncertainties in our numerical calculations following Ref. [10]. The errors are from the matrix elements in Table I of Ref. [10] and from the variations of μ and m_c within the ranges $\frac{1}{2}m_T$–$2m_T$ and 1.45–1.55 GeV with the central values m_T and 1.5 GeV, respectively. The errors in PDF are estimated by taking the difference between MRST98LO and CTEQ5L. We put the color-octet ${}^1S_0$ and ${}^3P_0$ matrix elements as $\langle O_8^H({}^1S_0)\rangle = xM_r^H$, $\langle O_8^H({}^3P_0)\rangle/m_c^2 = (1-x)M_r^H/r$ and vary x from 0 to 1 with the central value $\frac{1}{2}$. All of the errors listed above are added in quadrature.

One of the most convenient measures of the polarized cross section for the spin-triplet S-wave quarkonium H is the variable α defined by

$$\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L), \tag{3}$$

where σ_T (σ_L) is the cross section for the transversely (longitudinally) polarized H. For the complete transverse

[1]The color-octet matrix elements $\langle O_8^H({}^1S_0)\rangle$ and $\langle O_8^H({}^3P_J)\rangle$ are determined not separately but as a linear combination $M_r^H = \langle O_8^H({}^1S_0)\rangle + r\langle O_8^H({}^3P_0)\rangle/m_c^2$ which depends on the variable r given in Ref. [10].

(longitudinal) case, $\alpha = +1\ (-1)$. If the H is unpolarized, then $\alpha = 0$.[2] In the recent PHENIX analysis [22], they used the hadron CM frame like the CDF analyses [13,21]. Employing the method given in Refs. [10,11], one can compute the polarized cross sections σ_T and σ_L in the hadron CM frame from Eq. (2). Substituting these results to Eq. (3), we obtain α.

Our prediction for the differential cross section for the prompt J/ψ is shown in Fig. 1 as a function of p_T against the PHENIX preliminary data [22].[3] The rate is averaged over the midrapidity region and its explicit normalization is given by

$$\frac{B_{ee}}{2\pi p_T}\langle d^2\sigma/dydp_T\rangle_y = \frac{B_{ee}}{2\pi p_T(2Y)}\int_{-Y}^{Y}\frac{d^2\sigma}{dydp_T}dy, \quad (4)$$

where $Y = 0.35$ is the rapidity cut and B_{ee} is the branching fraction for $J/\psi \to e^+e^-$. The shaded band indicates the NRQCD prediction at order α_s^3. The dominant source of the theoretical uncertainties is from the scale μ, which produces errors of about 78% (94%) at $p_T = 1.5$ GeV (5 GeV). The variation of m_c produces errors of about 11% (2%) at $p_T = 1.5$ GeV (5 GeV). The remaining contributions from the matrix elements, x, and PDF's produce errors of about 11% (4%) at $p_T = 1.5$ GeV (5 GeV).

In the region $p_T > 1.5$ GeV, the NRQCD prediction agrees with the data within theoretical uncertainties. The curve for the central value tends to overestimate (underestimate) the data in the region $p_T < 3$ GeV (> 3 GeV). In Fig. 1, the color-singlet contribution at LO in α_s is displayed as a band surrounded by a solid curve, which severely underestimates the data over the whole range of p_T. In the lower p_T region, the fixed-order calculation of order α_s^3 fails to give reliable predictions. In order to extend the prediction to the lower p_T region, one must include the order-α_s^2 $2 \to 1$ parton processes, its NLO contribution of order α_s^3, and multiple soft-gluon emissions that should be resummed,[4] which are out of the scope of this work.

Our results for the α of the prompt J/ψ integrated over the midrapidity region $|y| < 0.35$ is shown in Fig. 2 against the PHENIX preliminary data [22]. The shaded band represents the NRQCD prediction and the band surrounded by a solid curve is that for the color-singlet contribution. The uncertainties of α are computed in the same manner as those of the differential cross section in Fig. 1. In this case, a large portion of the uncertainties cancel because α is computed as the ratio of polarized cross sections. In contrast to the cross section, the dominant sources of the errors are the matrix elements, x, and PDF's that account for 99% in total.

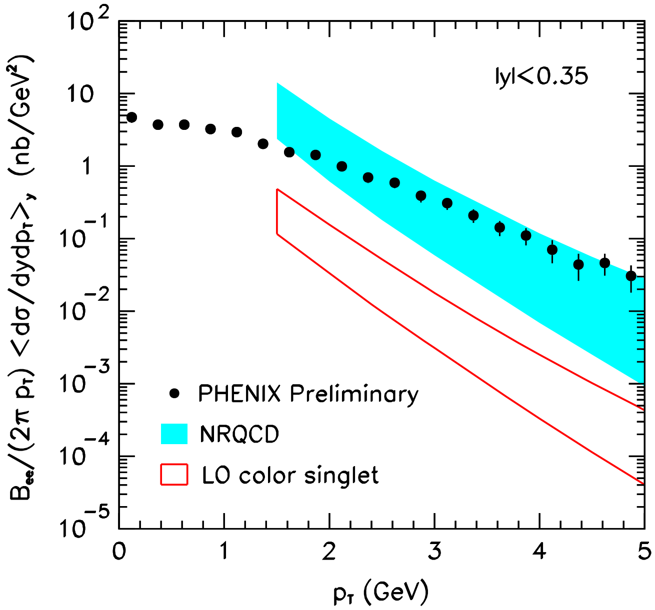

FIG. 1 (color online). The differential cross section of prompt J/ψ in pp collisions at $\sqrt{s} = 200$ GeV as a function of p_T in units of nb/GeV^2 against the PHENIX preliminary data [22] for the inclusive J/ψ. The shaded band represents the NRQCD prediction and the band surrounded by a solid curve is the color-singlet contribution at LO in α_s.

We predict that the prompt J/ψ is almost unpolarized or slightly longitudinally polarized in the range 1.5 GeV $< p_T <$ 5 GeV. Although the NRQCD prediction has large theoretical uncertainties, it agrees with the two data points within errors. As we have expected, the fragmentation dominance does not occur and, therefore, a strong transverse polarization is not observed. The color-singlet contribution is strongly transversely polarized with small uncertainties, which is disfavored by the data.

The polarization variable α for the large-rapidity region $1.2 < |y| < 2.2$ was also measured by the PHENIX Collaboration at $p_T = 1.6$ GeV as $\alpha = 0.02 \pm 0.16$ [22]. Our predictions of the color-singlet model and NRQCD are $\alpha_{\text{color-singlet}} = 0.19 \pm 0.03$ and $\alpha_{\text{NRQCD}} = 0.15 \pm 0.10$, respectively. On the other hand, one can compare the differential cross section in the large-rapidity range near $p_T = 1.6$ GeV. We find that $f(1.6\text{ GeV})_{\text{color-singlet}} = 0.08 \pm 0.05$ nb/GeV^2 and $f(1.6\text{ GeV})_{\text{NRQCD}} = 2.24 \pm 1.82$ nb/GeV^2, where $f(p_T)$ is the same as the right side of Eq. (4) except that the average is over the range $1.2 < |y| < 2.2$. The color-singlet model prediction severely underestimates the differential cross section and the NRQCD prediction agrees with data in both α and $f(p_T)$ in the large-rapidity region.

Our results in Fig. 2 are the first NRQCD predictions that can be compared with the PHENIX results for the p_T distributions of the polarization [22]. Our p_T distribution for the production rate shown in Fig. 1 integrated over the midrapidity range agrees with a previous result in Ref. [25]

[2] The polarized cross section varies depending on the spin quantization axis [36,37].

[3] The PHENIX preliminary data quoted in Fig. 1 do not include an additional global systematic error of 10%.

[4] See, for example, Refs. [38,39] and references therein.

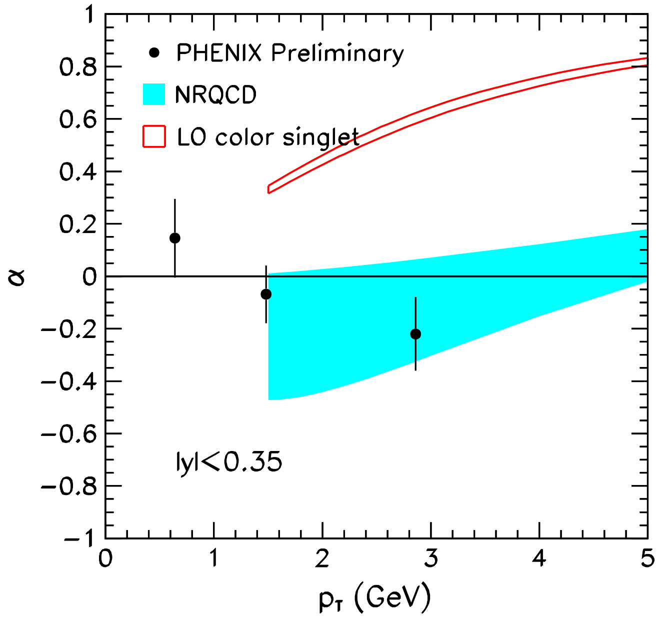

FIG. 2 (color online). The polarization parameter α for the prompt J/ψ in pp collisions at $\sqrt{s} = 200$ GeV as a function of p_T against the PHENIX preliminary data [22] for the inclusive J/ψ. The shaded band represents the NRQCD prediction and the band surrounded by a solid curve is the color-singlet contribution at LO in α_s.

within errors. Very recently, Brodsky and Lansberg computed the rapidity distribution of J/ψ integrated over p_T within the color-singlet model at NLO in α_s. Unfortunately, we are unable to compare our results directly with those in Ref. [32] because they did not calculate the p_T distribution and because our LO calculation breaks down at small p_T so we cannot calculate the rapidity distribution integrated over the whole p_T range.

In conclusion, we have provided the NRQCD predictions for the p_T distribution of the differential cross section and the polarization variable α for the prompt J/ψ produced in pp collisions at $\sqrt{s} = 200$ GeV. The short-distance processes were computed at the fixed-order α_s^3. We have chosen the numerical values for the nonperturbative NRQCD matrix elements that were fit to the prompt J/ψ cross section measured at the Tevatron and were used to compute the NRQCD prediction for the α at the Tevatron. The prediction reveals that the color-singlet contribution severely underestimates the data for the differential cross section. The NRQCD predictions for both the cross section and polarization agree with the data within errors over the range 1.5 GeV $< p_T <$ 5 GeV (1.5 GeV $< p_T <$ 2 GeV) integrated over the rapidity range $|y| < 0.35$ ($1.2 < |y| < 2.2$). Our fixed-order calculation breaks down for p_T below 1.5 GeV. In order to extend the NRQCD prediction to the lower p_T region, one must include the $2 \to 1$ processes at NLO accuracies and resum large logarithms from soft-gluon emissions. It would be exciting to see whether the future NRQCD prediction at this region agrees with the measured PHENIX preliminary data at the lowest p_T bin.

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