Double Spin Asymmetries in $P$-wave Charmonium Hadroproduction

W.-D. NOWAK, A. TKABLADZE

DESY Zeuthen, D-15738 Zeuthen, Germany

Abstract

We discuss the double spin asymmetries in $P$-wave charmonium hadroproduction with non-zero transverse momenta at fixed target energies, $\sqrt{s} \simeq 40 \text{ GeV}$, within the framework of the factorization approach. The size of the asymmetries and the projected statistical errors in a future option of HERA with longitudinally polarized protons scattering off a polarized target (HERA-$\vec{N}$) are calculated. Measurements of the $\chi_{c1}$ and $\chi_{c2}$ decays into dilepton plus photon should allow to distinguish between different parametrizations for the polarized gluon distribution in the proton. At higher energies ($\sqrt{s} = 200 \text{ GeV}$) the situation appears less favourable with the presently envisaged integrated luminosities of the polarized RHIC collider.

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1 Introduction

The study of spin asymmetries in the production of heavy quarkonium states in polarized nucleon-nucleon collisions should provide important information about the spin structure of the nucleon. Heavy quark-antiquark production processes occur at small distances and the subprocess level cross sections can be calculated perturbatively. On one hand, charmonium production asymmetries are expected to be sensitive to the polarized gluon distribution function in the proton, since heavy quark systems are mainly produced in gluon-gluon fusion subprocesses. On the other hand, it is essential to investigate in more detail the heavy quark-antiquark pair hadronization phase. To this end, observation of charmonium production in experiments with polarized beams is expected to provide additional tests for existing models.

The Factorization Approach (FA) based on the Nonrelativistic QCD (NRQCD) turns out to be a most rigorous framework to study heavy quarkonium production and decay processes [1]. According to the FA the inclusive production cross section for a quarkonium state $H$ in the process

$$ A + B \rightarrow H + X $$

(1)

can be factorized as

$$ \sigma(A + B \rightarrow H) = \sum_n \frac{F_n}{m_Q^{n-4}} \langle 0 | O_n^H | 0 \rangle, $$

(2)

where the short-distance coefficients, $F_n$, are associated with the production of the heavy quark pair in the color and angular momentum state $[n]$. This part of the production cross section involves only momenta of the order of the heavy quark mass and larger and can be calculated perturbatively. The heavy quark-antiquark pair production process occurs at small distances, $1/m_Q$, and is factorized from the hadronization phase which takes place at large distances, $1/(m_Q v^2)$, where $m_Q$ is the heavy quark mass. Here $v$ is the average velocity of heavy constituents in the quarkonium, with $v^2 \simeq 0.3$ for charmonium and $v^2 \simeq 0.1$ for bottomonium systems. The vacuum matrix elements of NRQCD operators, $\langle 0 | O_n^H | 0 \rangle$, describe the evolution of the quark-antiquark state $[n]$ into the final hadronic state $H$. These matrix elements cannot be calculated perturbatively, but the relative importance of long distance matrix elements in powers of velocity $v$ can be estimated using the NRQCD velocity scaling rules [2]. This formalism implies that quark-antiquark color octet intermediate states are allowed to contribute to heavy quarkonium production and decay processes at higher order in the velocity expansion. Therefore, in the FA the complete structure of the quarkonium Fock space is taken into account while in the old approach, in the Color Singlet Model (CSM) [3], only the dominant Fock state is considered, which consists of a color singlet quark-antiquark pair in a definite angular-momentum state of the final hadron (the leading term in the velocity expansion).

The predicted shape of the $p_T$ distribution of the $^3S_1(8)$ intermediate octet state production cross section indicates that $J/\psi$ and $\psi'$ production at large $p_T$ observed at the Tevatron (FNAL) can be explained in the FA [4, 5]. Recent investigations have shown that the contribution of color octet states to the charmonium production cross section is very important at fixed target energies, $\sqrt{s} \simeq 30 - 60$ GeV, and reduces existing discrepancies between experimental data and predictions of the CSM [6].

Despite the obvious successes of the NRQCD in explaining large $p_T$ charmonium production at the Tevatron, some experimental data contradict the Color Octet Model (COM) predictions. In particular, theoretical predictions disagree with measurements of the polarization of $J/\psi$ and
$\psi'$ particles produced at fixed target energies \cite{8} and the COM prediction for the yield ratio of $\chi_{c1}$ and $\chi_{c2}$ states remains too low \cite{8}. One possible solution for these discrepancies was proposed by Brodsky et al. \cite{9} suggesting that higher twist processes, when more than one parton from projectile or target participate in the reaction, might give a significant contribution to low $p_T$ production of $J/\psi$ and $\chi_{c1}$ states. Problems exist also in charmonium photoproduction at HERA. The color octet contribution underestimates the inelastic $J/\psi$ photoproduction cross section at large values of $z$ ($z = E_{J/\psi}/E_\gamma$ in the laboratory frame) \cite{10}.

Unlike the color singlet long distance matrix elements, each connected with the subsequent hadronic non-relativistic wave function at the origin, color octet long distance matrix elements are unknown and have to be extracted from experimental data. The NRQCD factorization approach implies universality, i.e. the values of long distance matrix elements extracted from different experimental data sets must be the same. However, due to the presently rather large theoretical uncertainties \cite{11,13} and the unknown size of higher twist process contributions \cite{9} the existing experimental data does not allow to check the FA universality, yet.

This fact motivated us to look for other processes with less theoretical uncertainties to test the COM. The observation of spin asymmetries in the production of charmonium states can be used for these purposes \cite{12} as well as measurements of the $J/\psi$ polarization in unpolarized hadron-hadron collisions and electroproduction \cite{9,13,14}.

In the present article we consider double spin asymmetries in $P$-wave charmonium production at non-zero $p_T$ in the NRQCD factorization approach. The double spin asymmetry in $J/\psi$ hadroproduction has been studied recently taking into account color octet intermediate states \cite{12,13}. The asymmetries in the production of $\chi_{cJ}$ states at small $p_T$ were considered in refs. \cite{14,15}. As already mentioned above, at small values of $p_T$ large contributions from higher twist effects are expected \cite{9} and the presently available theoretical predictions are not reliable enough to allow extraction of information about polarized parton distributions or to check the COM. Morii et al. considered asymmetries in the production of $\chi_{cJ}$ states at RHIC energies taking into account only fragmentation type contributions for color octet intermediate states \cite{17}. However, since the cross section for the production of charmonium states falls steeply with increasing $p_T$ the statistical errors becomes too large at those values of $p_T$ where the fragmentation approach can be applied, especially at at small energies $\sqrt{s} \simeq 50$ GeV. In contrast to this approach, our calculations \cite{18} use the exact expressions for the cross sections of intermediate color octet states in different helicity states of the initial partons, to estimate the expected spin asymmetries in the production of $\chi_{cJ}$ states as well as the projected errors.

The article is organized as follows. In the next section subprocess level asymmetries for possible intermediate octet and singlet states and corresponding long-distance color octet parameters are considered. In section 3 numerical results are presented for spin asymmetries in production of $\chi_{cJ}$ states at HERA-$\bar{N}$ \cite{23}, one of the future options of HERA; an experiment using an internal polarized nucleon target in a possibly later polarized HERA beam at $\sqrt{s} \simeq 40$ GeV. For comparison, we also consider the expected asymmetries in the production of $\chi_{cJ}$ states in similar spin physics experiments at the RHIC collider \cite{21} at $\sqrt{s} = 200$ GeV.

### 2 Asymmetries at the Subprocess Level

The two-spin asymmetry $A_{LL}$ for inclusive $\chi_{cJ}$ production is defined as

$$A_{LL}(pp) = \frac{d\sigma(p_+p_+ \rightarrow \chi_{cJ}) - d\sigma(p_+p_- \rightarrow \chi_{cJ})}{d\sigma(p_+p_+ \rightarrow \chi_{cJ}) + d\sigma(p_+p_- \rightarrow \chi_{cJ})} = \frac{E_d\Delta\sigma/d^3p}{E_d\sigma/d^3p}.$$ (3)
where the subscript in $p_+(p_-)$ indicates the sign of the helicity projection onto the direction of the proton. The production of each quarkonium state receives contributions from both color octet and color singlet states. In leading order $v^2$ only one color octet state contributes to the production of $\chi_{cJ}$ states, namely $^3S_1(8)$. Unlike direct $J/\psi$ production, leading color octet and color singlet contributions to P-wave charmonium production scale equally in $v^2, O(v^5)$, and the subleading corrections are only of the order $O(v^9)$. To calculate the production asymmetries only leading order color octet contribution are taken into account.

![Graphs of subprocess level asymmetries for $^3S_1(octet)$, $^3P_0(singlet)$, $^3P_1(singlet)$, and $^3P_2(singlet)$](image)

Figure 1: The subprocess level asymmetries for $^3P_0$, $^3P_1$, and $^3P_2$ color singlet, as well as for $^3S_1(8)$ color octet state.

We consider the production of $\chi$ states at non-zero values of transverse momentum, $p_T > 1.5$ GeV. The leading contribution to the production of charmonium states at those values of transverse momentum comes from the $2 \to 2$ subprocesses. The leading order subprocesses, $2 \to 1$, should not contribute to the quarkonium production with $p_T > 1.5$ GeV because these transverse
momenta cannot be caused by internal motion of partons in the nucleon. The contribution of higher twist processes is also expected to be small at $p_T > 1.5$ GeV.

For the calculation of the expected asymmetries for color octet and singlet states of a $(c \bar{c})$-pair we consider the following subprocesses:

$$
\begin{align*}
g + g & \rightarrow (c \bar{c}) + g \\
g + q & \rightarrow (c \bar{c}) + q \\
q + \bar{q} & \rightarrow (c \bar{c}) + g
\end{align*}
$$

(4)

The asymmetries for all these subprocesses were calculated in ref. [12]. The values of those giving a significant contribution to the production of $\chi_{cJ}$ states are presented in Fig. 1 in dependence on the two dimensionless quantities $\eta = 4m_c^2/\hat{s}$ and $x_T = p_T/p_{\text{max}}$, where $m_c$ is the charm quark mass, $\hat{s}$ the c.m. energy in the parton-parton system, and $p_{\text{max}}$ is the maximum momentum of the produced state in the subprocess. Figure 1 shows only the gluon-gluon fusion subprocess asymmetries because they give the main contribution to the hadron level asymmetry.

The color singlet long distance matrix elements are connected to quarkonia wave functions at the origin:

$$
\langle 0 | O^{\chi_{cJ}}_{1} (3P_J) | 0 \rangle = \frac{3N_c}{2\pi} (2J + 1) | R'(0) |^2 = 3.2 \cdot 10^{-1} GeV^3.
$$

(5)

This value was used in [6] for fitting the CDF data on $J/\psi$ production through $\chi_{cJ}$ states and corresponds to the Buchmüller-Tye type potential solution tabulated in [21]. For the color octet long distance matrix element the following value extracted from CDF data was used [6]:

$$
\langle 0 | O^{\chi_{cJ}}_{8} (3S_1) | 0 \rangle = 9.8 \cdot 10^{-3} GeV^3,
$$

(6)

As shown in ref. [13] the variation of the renormalization and/or the factorization should lead to large uncertainties when fitting the color octet parameters. The fit results for long distance color octet matrix elements can be affected also by higher $v^2$ corrections (so called ‘trigger bias’ effect) [11]. Therefore care is required when using at fixed target energies the value for this parameter extracted from CDF. The influence of these uncertainties on the expected asymmetries will be discussed in the next section.

3 Results and Discussion

The characteristic value of the partonic $x$ in the production of $(c \bar{c})$ pairs can be obtained from the relation $x_1x_2 \simeq (4m_c^2 + p_T^2)/s \simeq 0.01$ at HERA-$N$. This means that the typical value of $x_{\text{gluon}}$ that can be probed by measuring the spin asymmetry in charmonium production is about $x_{\text{gluon}} \simeq 0.1$. We used three different sets of Gehrmann and Stirling (GS) parametrizations [22] for polarized parton distribution functions (PDF) that are different in the region
to show the sensitivity of the spin asymmetries in the production of $\chi_{cJ}$ states on the
gluon polarization in the nucleon: the sets A and B of the NLO GS parameterization and the
LO parameterization set A. In Fig. 2 the polarized gluon densities from these parametrizations
are shown at $Q^2 = 10$ GeV$^2$, which is the appropriate value in the kinematical region considered.
As can be seen, the three chosen sets exhibit somewhat different values for the polarized gluon
distribution function at partonic $x$ values around 0.1. We note that, although the calculations of
subprocess level cross sections are performed in leading order, the NLO set of the parametrization
was used to probe different shapes of the polarized gluon distribution.

![Figure 3](image-url)

Figure 3: a) $\chi_{c1}$ and b) $\chi_{c2}$ production asymmetries versus transverse momentum at $\sqrt{s} = 40$ GeV. The
solid (dashed) line correspond to set A (B) of the NLO GS parametrization and the dash-dotted line
to set A of the leading order GS parametrization. The dotted line represents the expected asymmetry
calculated only in the CSM for the set A of the NLO parametrization.

Figs. 3 and 4 show the expected production asymmetries for $\chi_{cJ}$ states at $\sqrt{s} = 40$ GeV
(HERA-$\vec{N}$). Figures 3a and 3b also include projected statistical uncertainties on the asymmetry
$\delta A_{LL}$, estimated at HERA-$\vec{N}$ from $[19]$ by

$$\delta A_{LL} = 0.17/\sqrt{\sigma(p\bar{b})};$$

where 100% efficiency is assumed. This relation is based upon an integrated luminosity of
240 $pb^{-1}$ and beam and target polarizations of $P_B = 0.6$ and $P_T = 0.8$, respectively $[22]$. The
error bars are obtained by using integrated cross sections over bins $\Delta p_T = 0.5$ GeV (for the
first three points) and $\Delta p_T = 1$ GeV (for the other two ones). Note that it is easier to measure
asymmetries for $\chi_{c1}$ and $\chi_{c2}$ states due to their large branching ratios for decays into $J/\psi$ plus
photon (27% for $\chi_{c1}$ and 13.5% for $\chi_{c2}$). These branching ratios and the $J/\psi$ decay branching
ratios into $l^+ l^-$ ($l = e, \mu$) are taken into account in the calculations of the projected statistical
errors for the production of $\chi_{c1}$ and $\chi_{c2}$ states. Due to the small branching ratio of the $\chi_{c0}$ decay
through $J/\psi$, $6.6 \cdot 10^{-3}$, the projected statistical errors of an asymmetry measurement for this
state are too large.

In Figs. 3 and 4, the asymmetries for set A and set B of the NLO GS parametrization are
represented by solid and dashed lines, respectively, whereas the dash-dotted lines correspond to
set A of the LO parametrization. The asymmetries coming only from color singlet intermediate
states expected for the set A of NLO GS parametrization are additionally shown in Figs. 3 and
4 by dotted lines. Note that for the set C of the NLO GS parametrization all asymmetries are less than 1% and practically unobservable, hence they are not shown. For the mass of the charm quark the value $m_c = 1.48$ GeV was taken and the parton distribution functions are evaluated on the factorization scale $\mu = \sqrt{p_T^2 + 4m_c^2}$. The strong coupling constant is calculated by the one-loop formula with 4 active flavors ($\Lambda_{QCD} = 200$ MeV).

In all three parameterizations for the polarized parton distribution functions the gluon-gluon fusion process gives the dominant contribution to $\Delta \sigma$ in the kinematical region considered. The quark-gluon subprocesses contribute only to about 10% (for both color octet and color singlet states) and the contribution of quark-antiquark annihilation subprocesses is less than 1%.

The contribution of the color octet $3S^1_1$ state does practically not change the $\chi_{c0}$ production asymmetry coming from the color singlet intermediate state. For $\chi_{c1}$, the influence of the octet contribution becomes larger with increasing $p_T$. As seen from Fig. 1, the asymmetries for color singlet $3P_2$ and color octet $3S^1_1$ states have different sign. By this reason the color octet contribution, compared to the color singlet one, changes the asymmetry of the $\chi_{c2}$ state more than in the case of $\chi_{c0}$ and $\chi_{c1}$. Moreover, due to the ‘trigger bias’ effect the corresponding color octet long distance matrix element may be approximately two times larger and hence the contribution of the color octet states to the asymmetries may even increase.

In the inclusive case the kinematics of the $2 \rightarrow 2$ subprocess cannot be reconstructed completely. Hence only indirect information on the gluon polarization of the nucleon can be obtained by measuring the spin asymmetry in inclusive $\chi_{cJ}$ production. As can be seen from Figs. 3 and 4, the expected asymmetries for all $\chi_c$ states strongly depend on the size of the polarized gluon distribution function in the region $x_{gluon} \geq 0.1$. At HERA-$\vec{N}$ the size of the $\chi_{c1}$ and $\chi_{c2}$ asymmetries compared to the projected statistical errors will allow to draw conclusions on the polarized gluon distribution function.

In addition, the measurement of $\chi_{c1}$ and $\chi_{c2}$ asymmetries provides a good opportunity to discriminate between two possible mechanisms of heavy quarkonium production: the NRQCD factorization approach and the Color Evaporation Model (CEM) [24]. As can be seen from Fig. 3b, the $\chi_{c2}$ production asymmetry is negative at smaller values of transverse momentum where the gluon-gluon fusion subprocess contribution to $\Delta \sigma$ is dominant. In spite of the positive contribution of the color octet state $3S^1_1$ to $\Delta \sigma$, the $\chi_{c2}$ production asymmetry remains negative as in the CSM, i.e. in the NRQCD approach the double spin asymmetries for $\chi_{c1}$ and $\chi_{c2}$ states have different sign. In contrast, in the CEM the asymmetries for all charmonium states are expected to be the same. Such a comparison is possible even when shape and size of the polarized gluon distribution in the proton are not yet known. The only requirement is that the gluon polarization is large enough to generate observable $\chi_{c1}$ and $\chi_{c2}$ asymmetries.

For comparison we have also calculated the expected double-spin asymmetries for the production of $\chi_{c1}$ and $\chi_{c2}$ states at RHIC energies. The results are given in Fig. 5 for the c.m.s. energy

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Figure 4: Expected asymmetries for $\chi_{c0}$ production at HERA-$\vec{N}$ for different GS parameterizations as explained in Fig. 3.
\( \sqrt{s} = 200 \text{ GeV} \). The statistical errors are calculated with the anticipated integrated luminosity of 320 \( pb^{-1} \) assuming 100\% efficiency and \( P_B P_T \approx 0.5 \). As can be seen by comparing Fig. 3 and Fig. 5, the expected asymmetries decrease with increasing c.m.s. energy for a given parameterization of polarized parton distribution functions. Moreover, the anticipated integrated luminosities at HERA-\( \vec{N} \) and RHIC lead to a smaller discrimination power at higher energy.

![Figure 5](image)

Figure 5: a) \( \chi_{c1} \) and b) \( \chi_{c2} \) production asymmetries versus transverse momentum at \( \sqrt{s} = 200 \text{ GeV} \). The solid (dashed) line correspond to set A (B) of the NLO GS parametrization. The dotted line represents the expected asymmetry calculated only in CSM for the set A of the NLO parametrization.

One of the main parameters of the factorization approach is the mass of the charm quark. As in the case of \( J/\psi \) production [12], the expected asymmetries for \( \chi_{cJ} \) states are practically insensitive to the value of the charm quark mass. Therefore, the double spin asymmetry in \( \chi_{cJ} \) production, unlike the cross section, should be free from uncertainties caused by the unknown mass of intermediate color octet states. Moreover, the asymmetries do not strongly depend on the renormalization scale, unlike the production cross sections [13]. The effects of intrinsic transverse momentum smearing on the asymmetries in the production of charmonium states were also investigated. Such an effect is very important for the cross section of \( J/\psi \) photoproduction at HERA collider energies [25], however its influence to asymmetries is far below the size of the projected statistical errors shown in Figs. 3 and 5.

4 Conclusions

Double spin asymmetries expected in hadroproduction of heavy quarkonium \( P \)-wave states in polarized proton-proton collisions were investigated. To reduce the contribution from possible higher twist corrections [4] the production of \( \chi_{cJ} \) mesons was considered at non-zero transverse momenta, \( p_T > 1.5 \text{ GeV} \) unlike the calculations of [15, 16], where only the lowest order subprocesses \( 2 \to 1 \) were taken into account.

The size of the expected asymmetries in conjunction with the projected statistical uncertainties at HERA-\( \vec{N} \) (\( \sqrt{s} \approx 40 \text{ GeV} \)) will allow to distinguish between different parametrizations for polarized parton distribution functions, specifically between the NLO GS sets A and B [22]. At RHIC, higher than hitherto planned integrated luminosities would be required to do so.

The asymmetries for the production of the \( \chi_{c1} \) and \( \chi_{c2} \) states in the transverse momentum range \( 1.5 < p_t < 3 \text{ GeV} \) exhibit different signs in the NRQCD factorization approach. In
contrast to this, the color evaporation model predicts identical double spin asymmetries for all charmonium states. This should allow to discriminate between these different mechanisms of heavy quarkonia production if the gluon polarization is sufficiently large and $\chi_c$ asymmetries become observable.

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