Detect $\Delta G$ at BNL-RHIC via Double Quarkonium Production

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The double spin asymmetry for exclusive $J/\psi$ pair production in the polarized $p^{-}p$ collisions at RHIC is investigated. Our study shows that the asymmetry in this process is measurable at RHIC-SPIN experiments in the near future, and, hence it can be used to determine the gluon distribution function $\Delta G(x)$ in the polarized nucleon.

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Since the first measurement of the polarized structure function by the European Muon Collaboration [1], an enormous amount of researches have been done on the nucleon spin structure both experimentally and theoretically. The unpolarized deep inelastic scattering (DIS) experiments show that the gluon shares a large portion of the parent proton’s momentum. However, how the gluons share the spin of proton is still an open question. In the conventional DIS process, the gluon contributions are the Quantum Chromodynamics (QCD) higher order effects and we cannot avoid some ambiguities coming from e.g. the factorization scheme dependence, when determining the polarized gluon distributions. Although there are some efforts [2,3] to parameterize them, it seems difficult to obtain clear understanding of the role of gluons.

Therefore, it is desirable to study other processes than DIS in which a direct measurement of the polarized gluon is possible. It is now expected that the polarized proton-proton collisions (RHIC-Spin) at BNL relativistic heavy-ion collider RHIC will provide copious experimental data to unveil the polarized parton distributions. Since the major emphasis and strength of RHIC-Spin is to measure the gluon polarization, it is important and interesting to investigate various processes which are attainable experimentally to this aim.

Up to now, three processes are considered to be promising for measuring the polarized gluons, which are thought to be feasible at RHIC technically. Those are

- High-$p_T$ Prompt Photon Production
- Jet production
- Heavy Flavor Production

There are some advantages and disadvantages in each of these processes. The prompt photon production with polarized beams at RHIC is a useful process, but we must know precisely the quark distributions from the polarized DIS experiments. For jet and heavy flavor production, the effects of hadronization and higher order corrections are not yet well controlled theoretically. For detailed discussions, see recent review paper in Ref. [4]. Therefore, to develop more practical ways for measuring the gluon polarization at RHIC experiments is one of the urgent theoretical tasks today.

The quarkonium production and decays have long been taken as ideal processes to investigate the nature of QCD. Due to the approximately non-relativistic nature, the heavy quark and antiquark bound state is considered as one of the simplest system in QCD. The very clean signals of quarkonium leptonic decays lead to the experimental observations with a high precision, and therefore the quarkonium may play a crucial role in investigating many quantities and phenomena, e.g. the parton distribution, the QGP and even new physics.

However, it should be pointed out that although the heavy quarkonium physics has been investigated for about thirty years, theoretical description of quarkonium production is still premature. Conventionally, the so-called color-singlet model (CSM) was widely employed in the study of heavy quarkonium production and decays [5]. In CSM, it is assumed that the $Q\bar{Q}$ pair produced in a high energy collision will bind to form a given quarkonium state only if the $Q\bar{Q}$ pair is created in color-singlet state with the same quantum numbers as the produced bound states; as well, in the quarkonium decays the annihilating $Q\bar{Q}$ pair will be in short distance and singlet with the same quantum numbers as its parent bound states. It is assumed in CSM that the production amplitudes can be factorized into short distance and long distance parts. The short distance sector is perturbative QCD applicable, while all the long distance nonperturbative effects are attributed to a single parameter, the

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wave function. Nevertheless, color-singlet factorization is only an ad hoc hypothesis. There are no general arguments to guarantee such a naive assumption to be held up to higher order radiative corrections. Recently, from the Fermilab Tevatron data collected in the 1992-1993 run, CDF group found [6–8] that the large-$p_T$ $J/\psi(\psi')$ were produced much more than the leading order(LO) CSM predictions. This phenomenon was referred as "$\psi$-surplus" production or "$\psi$-anomaly".

In order to explain the experimental results of $\psi$ surplus production, the color-octet mechanism(COM) [9] was proposed based on a novel effective theory, the non-relativistic QCD(NRQCD) [10]. According to COM the produced $c\bar{c}$ pair in color-octet configuration may also evolve into $\psi$ via radiation or absorption of soft gluons. For details, readers are recommended to reference [10]. The appearance of this new quarkonium production mechanism brought deep effects on the quarkonium physics. Having achieved the first-step success in explaining the CDF data, the color-octet mechanism encounters also difficulties in other processes [11]. As discussed in Ref. [12], the extent of importance of color-octet contributions in charmonium production remains unfixed for the time being. Therefore, to use quarkonium as probes to investigate new physics, one should really take the large ambiguities remaining in color octet matrix elements and higher order corrections into consideration, especially for charmonium system.

In literature, a series of efforts have been made so far for measuring the polarized parton distributions through quarkonium production processes [13–17]. Unfortunately, most of previous investigations were not directly applied to the RHIC experiments and are spoiled by the uncertainties aforementioned. In this work, we show that the exclusive double heavy quarkonium production in the polarized proton-proton collision would be one of the ideal processes to measure the polarized gluon distributions and may play at least a supplemental role to the presently proposed program at RHIC. Due to being an exclusive process that can not be realized in COM, the uncertainties remaining in color-octet matrix elements are ruled out for our concern, which enables us to make more precise predictions. In addition, the double quarkonium production also has several advantages in reducing theoretical uncertainties from other sources. That is, (1) The concerned quantity, the asymmetry, is almost independent of the relativistic corrections and non-perturbative uncertainties, which is normally not negligible in the study of charmonium system. The reason is that these kinds of uncertainties appearing in both numerator and denominator in the definition of asymmetry may cancel out. (2) The higher order QCD corrections can be well controlled by applying a suitable $p_T$ cut for the charmonium system, because the the strength of strong interaction here highly correlates to the transverse momenta of final states. (3) At RHIC energy, especially for $p - p$ collision, the $q\bar{q}$ annihilation process is reasonably negligible compared to the prevailing gluon-gluon fusion process. Therefore, the double-quarkonium stands as a very sensitive system for measuring gluon polarizations.

Years ago, there were discussions of observing the gluon polarization by means of exclusive double $J/\psi$ production [18,19]. However, the main concerns there were not on RHIC physics, and analytical expressions were not presented for more extensive use.

![FIG. 1. Typical Feynman diagrams for $g + g \to J/\psi + J/\psi$. The topological groups (A) and (B) show up in the photon-photon to double charmonium production process. The group (C) is necessary in guaranteeing the gauge invariance.](image-url)
and in the following, the parity conservation is taken for granted. In terms of the gluon densities and the partonic cross sections, this asymmetry reads,

$$A = \frac{\int dx_1 dx_2 d\Delta \sigma G(x_1, Q^2) \Delta G(x_2, Q^2)}{\int dx_1 dx_2 d\Delta \sigma G(x, Q^2) G(x_2, Q^2)} ,$$  

(3)

where \( \Delta G(x, Q^2) = G_+(x, Q^2) - G_-(x, Q^2) \) and \( G_+(x, Q^2) = G_+(x, Q^2) + G_-(x, Q^2) \) are the polarized and unpolarized gluon distributions defined at the scale \( Q^2 \). The unpolarized (polarized) partonic cross section \( \bar{\sigma} \) (\( \Delta \bar{\sigma} \)) is defined as,

$$\bar{\sigma} = \frac{1}{4} \sum_{\lambda, \lambda'} \bar{\sigma} (\lambda, \lambda'), \quad \Delta \bar{\sigma} = \frac{1}{4} \sum_{\lambda, \lambda'} \lambda' \lambda \bar{\sigma} (\lambda, \lambda').$$  

(4)

The concerned process, as schematically presented in Figure 1, gives the polarized partonic differential cross section as

$$\frac{d\Delta \bar{\sigma}}{dt} = \frac{-16 \alpha_s^4 |R(0)|^4}{81 \pi^4 (m^2 - t)^4 (m^2 - u)^4} \times \left[ 2744 m^{24} - 1520 m^{22} (t + u) + m^{20} (32110 t^2 + 90076 t u + 32110 u^2) - 16 m^{18} (2025 t^3 + 12673 t^2 u + 12673 t u^2 + 2025 u^3) + 2 t^4 (3494 - 908^3 u + 1374^2 t^2 - 908 t u - 349 t^4) + 4 m^{16} (3903 t^4 + 5792 t^3 + 117766 t^2 u^2 + 5792 t^2 u^3 + 3903 u^4) - 4 m^{14} (510^5 t^2 + 36713 t^4 u + 36713 t^4 u + 135685 t^2 u^2 + 135685 t^2 u^3 + 36713 t^4 u^3 + 510 u^5) + m^{12} (-241 t^6 + 86000 t^5 u + 364313 t^4 u^2 + 594840 t^3 u^3 + 364313 t^2 u^4 + 586000 t u^5 - 1461 u^6) + 4 m^2 t^2 u^2 (9^7 - 505 t^2 + 44 t^2 u + 55 t^3 u^3 + 55 t^3 u^3 + 4 t^3 u + 9 u^7) + 2 m^9 (381 t^7 - 7111 t^6 u + 83783 t^5 u^2 - 83783 t^5 u^3 - 180639 t^4 u^3 - 83783 t^2 u^3 + 7111 t u^5 + 381 u^7) + m^8 (-79 t^8 + 1272 t^7 u + 54526 t^6 u^2 + 156224 t^5 u^3 + 163850 t^4 u^4 + 156224 t^3 u^5 + 54526 t^2 u^6 + 1272 t u^7 + 79 u^8) + m^4 t (36 t^8 + 1471 t^7 u + 9764 t^6 u^2 + 12863 t^5 u^3 + 7196 t^4 u^4 + 12863 t^3 u^5 + 9764 t^2 u^6 + 1471 t u^7 + 36 t u^8) + 2 m^6 (2 t^9 + 17 t^8 u + 5151 t^7 u^2 + 25947 t^6 u^3 + 24439 t^5 u^4 + 24439 t^4 u^5 + 25947 t^3 u^6 + 5151 t^2 u^7 + 17 t u^8 + 2 u^9) \right] ,$$

where \( R(0) \) is the wave function of \( J/\psi \) at the origin and \( m \) is the rest mass of \( J/\psi \); \( s, t \) and \( u \) are the Mandelstam variables for the partonic system. The sum of our results for different helicity combinations gives the unpolarized partonic differential cross section, \( \bar{\sigma} \) in (4), which agrees with the results in Refs. [21,22].

In the following, we investigate the spin asymmetry in the RHIC-Spin experiment at \( \sqrt{s} = 500 \text{ GeV} \) which is the planned highest RHIC energy. In our numerical calculations, the scale \( Q^2 \) of the parton distribution function and the strong coupling constant is taken to be the transverse momentum of \( J/\psi \) for the \( p_T \) distributions.

Whereas, in the calculation of the angular distribution of the spin asymmetries and the integrated cross sections, the scale is taken to be \( Q^2 = m^2 \). The nonrelativistic relation \( m = 2 m_c, \text{ with } m_c = 1.5 \text{ GeV} \), is used and \( |R(0)|^2 = 0.8 \text{ GeV}^3 \).

We plot in Figure 2 the double spin asymmetry versus the transverse momentum of \( J/\psi \) with respect to the proton beams with different sets of the GS parameterizations [2], and in Figure 3 the angular distribution of the asymmetry in the parton center-of-mass frame. The charmonium pair exclusive production happens only through the color-singlet scheme as shown in Figure 1 and so it is feasible to reconstruct the parton center-of-mass system in experiment. To be consistent with the use of the GS polarized distributions, we use the MRST parameterization [23] for the unpolarized gluon distribution. From results shown in Figures 2 and 3, it is clear that the asymmetries obtained with different parameterizations diverse quite much.

We notice that to observe the spin asymmetry both in \( p_T \) and angular distributions, a high luminosity is required. Nevertheless, having a relatively high accuracy in theory, even with a few experimental events our results may tell something about the gluon polarization inside the proton. From diagrams 2 and 3 it is easy to figure out that the charmonium pairs are produced mainly in low \( p_T \) and the forward direction relative to the beams, where the set C gives a small asymmetry compared to sets A and B.
In order to estimate the event rate for the $J/\psi$ pair productions, we calculate the total cross section with different parton parameterizations. The results are collected in table I. As expected, the discrepancies among these predictions are not very large. Here, the notation $\sigma_{\mu^+\mu^-}$ means that the branching ratio of $B(\psi \rightarrow \mu^+\mu^-) = 0.0588$, as the practical measuring mode to reconstruct the charmonium state, is included. From the predicted cross sections, we see that with the integrated luminosity of 800 pb$^{-1}$ in the future run of RHIC, there will be thousands of $J/\psi$ pair events to be detected, which can certainly give us some information on the gluon polarization in the nucleon.

To conclude, in this work we have shown that the exclusive $J/\psi$ (quarkonium) pair production at RHIC may stand as a novel process in measuring the gluon spin distributions inside the polarized nucleon. The large mass of heavy quark guarantees that perturbative calculation is applicable to this process; the asymmetry, rather than cross sections, eliminates large amount of uncertainties which come from the non-perturbative hadronization and relativistic corrections. The higher order QCD corrections may be properly controlled by employing a suitable $p_T$ cut. We have also discussed the feasibility of observing the double spin asymmetry via this process. Our results show that for the time being the accumulated data with low achievable fraction of polarization in the RHIC beam are not yet enough to analyze this process for the purpose of measuring the gluon helicity distributions. However, in the future run with colliding energy of 500 GeV and the accumulated luminosity 800 pb$^{-1}$, the $J/\psi$ pair events can be surely detected and the gluon polarization could be measured. With the expected upgrade of RHIC in future, the $J/\psi$ pair production may become a promising process with very clean signal and less theoretical uncertainties in uncovering the nucleon spin structures.

Finally, it should be mentioned that there are two kinds of backgrounds which may interfere with the measurement of our proposed process. The first is the contribution of higher excited quarkonium states feeddown to double $J/\psi$. Which is not negligibly small generally speaking, however, for pair production they are doubly suppressed. The second is the quarkonium pairs production through color-octet mechanism, which is known to be the dominant $J/\psi$ pair production scheme at high energy and large $p_T$ via $gg \rightarrow gg$ hard interaction and with both final state gluons fragmenting to color-octet intermediate states and then evolving into quarkonia nonperturbatively. Nevertheless, in both cases the $J/\psi$ pairs are not exclusively produced, hence, experimentally they can be excluded with care.

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\begin{table}[h]
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\begin{tabular}{lll}
\hline
 & $\sigma_{\mu^+\mu^-}$ & $\sigma_{\mu^+\mu^-}(|p_T| > 1\text{ GeV})$ \\
\hline
CTEQ5L [24] & 11.8 pb & 7.3 pb \\
MRST [23] & 6.5 pb & 4.3 pb \\
GRV [25] & 7.4 pb & 4.7 pb \\
\hline
\end{tabular}
\caption{Total cross sections for $J/\psi$ pair production at RHIC with $\sqrt{s} = 500$ GeV, evaluated with different parton distributions.}
\end{table}

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