Effects of the large gluon polarization on $xg_1^d(x)$ and $J/\psi$ productions at polarized ep and pp collisions

T. Morii
Faculty of Human Development, Division of Sciences for Natural Environment and Graduate School of Science and Technology, Kobe University, Nada, Kobe 657, Japan

S. Tanaka
Faculty of Human Development, Division of Sciences for Natural Environment, Kobe University, Nada, Kobe 657, Japan

and

T. Yamanishi
Graduate School of Science and Technology, Kobe University, Nada, Kobe 657, Japan

Abstract

The recent SMC data of $xg_1^d(x)$ are reproduced with the large polarized gluons. To study further the polarized gluon distribution in a proton, we calculate the spin–dependent differential cross section for $J/\psi$ leptoproductions and the two–spin asymmetry for $J/\psi$ hadroproductions. Its experimental implication is discussed.

---

†E–mail morii@JPNYITP.BITNET
††E–mail yamanishi@cphys.cla.kobe-u.ac.jp
There have been several theoretical interpretations on the “proton spin crisis” [1, 2]. Among them, there is an interesting idea that gluons contribute significantly to the proton spin through the $U_A(1)$ anomaly [3]. In this description the amount of the proton spin carried by quarks is not necessarily small. The integrated value of the spin–dependent gluon ($\Delta G(Q^2)$) inside a proton concomitantly becomes as large as $5 \sim 6$ at $Q^2_0 = 10.7\text{GeV}^2$ (EMC value).

Recently, the E581/704 collaboration at Fermilab [4] measured the two–spin asymmetries $A_{\pi^0}^{\text{LL}}(\bar{p}p)$ for inclusive $\pi^0$–production in $pp$ and $\bar{p}p$ collisions of longitudinally polarized beams on longitudinally polarized targets at $\sqrt{s} = 20\text{GeV}$. By comparing the measured asymmetries $A_{\pi^0}^{\text{LL}}(p\bar{p})$ with the theoretical predictions given by Ramsey et al. [5], the E581/704 collaboration concluded that the large gluon polarization inside a proton was ruled out at 95% CL by the data. However, in recent papers [6, 7], it has been emphasized that large $\Delta G(Q^2)$ can still be consistent with the experimental data for both cases of $pp$ and $\bar{p}p$ collisions if one adopts the spin–dependent gluon distribution function which is large for $x < 0.1$ but small for $x \geq 0.1$. In addition, Vogelsang and Weber [7] have studied the reliability of perturbative QCD predictions for $A_{\pi^0}^{\text{LL}}(\bar{p}p)$ by taking the intrinsic $k_T$–smearing effects into account and concluded that the results remain still valid. Accordingly the E581/704 data do not necessarily rule out the large gluon polarization but strongly constrain the shape of the spin–dependent gluon distributions.

However, is the polarized gluon contribution really so large in a proton? In order to confirm this, it is very important to measure, in experiments, physical quantities in special processes which are sensitive to the magnitude of spin–dependent gluon distribution.

In this work, we study the effect of the possible large gluon polarization in interesting processes. To examine the effect of the large gluon distribution, we take, as a typical example, our previous model [6] which has a large polarized gluon distribution,

$$\delta G(x, Q^2 = 4\text{GeV}^2) = C x^{0.6}(1 - x)^{14} G(x, Q^2 = 4\text{GeV}^2).$$

where a constant $C = 6.208$ is determined so as to fit the experimental integrated value of $g_1^p(x, Q^2)$, i.e., $\int_0^1 g_1^p(x, Q^2)dx = 0.126$ (EMC data) [8]. $G(x, Q^2)$ is the spin–independent gluon
distribution function with “B_” parameterization by KMRS\cite{9}. The spin–dependent gluon
distribution given by eq.(1) takes a large integrated value : \( \Delta G(Q^2_0) \equiv \int_0^1 \delta G(x, Q^2_0) dx = 6.14. \)
In literature\cite{2, 10}, people have discussed many examples of large \( \Delta G(Q^2_0) \) which also fit well
to EMC \( g_1^p(x) \) data. Compared with these distributions of polarized gluons, the distribution
given by eq.(1) is very special since it is large for \( x < 0.1 \) but small for \( x \geq 0.1 \). In the
previous work\cite{6}, we could explain satisfactorily the EMC data \( (g_1^p(x)) \) and the E581/704 data
\( (A_{LL}^{\pi^0}(\vec{p} \cdot p)) \) by using eq.(1).

Recently, the spin–dependent structure function of deutron \( g_1^d(x) \) has been measured by the
SMC group at CERN\cite{11} using polarized muon beams on polarized deuteron targets. Here,
to examine the large gluon polarization, we apply eq.(1) to the SMC data together with the
spin–dependent quark distribution functions\cite{12}. The results are shown in fig.1, in which one
can see that the distribution eq.(1) is consistent with the SMC data even though \( \Delta G \) is large.
Note that we have no free parameters in calculating \( g_1^d(x) \).

Now, let us get into the consideration of the physical quantities in the specific processes
which are sensitive to the spin–dependent gluon distributions. In this work, we present two
interesting quantities which predominantly depend on the spin–dependent gluon distributions :
one is the spin–dependent differential cross section of inelastic \( J/\psi \) productions in polarized
electron–polarized proton collisions and the other is the two–spin asymmetry of \( J/\psi \) produc-
tions in polarized proton–polarized proton collisions.

First, we consider the inelastic \( J/\psi \) production in polarized ep collisions\cite{4}. The cross
sections of this process are directly related to the distribution of polarized gluons. Since we
are considering the region where the \( J/\psi \) particles are produced via the photon–gluon fusion,
\( \gamma^* g \rightarrow J/\psi g \), shown in fig.2, we take the kinematic region as\cite{14}
\[
  z = \frac{p_{J/\psi} \cdot p_p}{Q \cdot p_p} < 0.8 , \quad \frac{p_T^2}{m_{J/\psi}^2} > 0.1 ,
\]
where \( p_T \) is the transverse momentum of the produced \( J/\psi \). \( Q, p_{J/\psi} \) and \( p_p \) represent the
\footnote{The \( J/\psi \) productions in unpolarized ep collisions have been studied by Stirling and his collaborators\cite{13}.}
four–momenta of the (virtual) photon, $J/\psi$ and the proton, respectively. $z \to 1$ is in the elastic domain and for $p_T \to 0$ the multiple soft gluon emission must be considered. The spin–dependent differential cross section for the subprocess $\gamma^* g \to J/\psi g$ is

$$
\frac{d\Delta \hat{\sigma}}{dt} = \frac{1}{4} \left[ \frac{d\hat{\sigma}_{++}}{dt} - \frac{d\hat{\sigma}_{+-}}{dt} + \frac{d\hat{\sigma}_{-+}}{dt} - \frac{d\hat{\sigma}_{--}}{dt} \right] = \frac{8\pi m_{J/\psi}^3 \alpha_S^2 \Gamma_{ee}^2}{3\alpha} \frac{\hat{s}^2 (\hat{s} - m_{J/\psi}^2)^2 - \hat{t}^2 (\hat{t} - m_{J/\psi}^2)^2 - \hat{u}^2 (\hat{u} - m_{J/\psi}^2)^2}{(\hat{s} - m_{J/\psi}^2)^2 (\hat{t} - m_{J/\psi}^2)^2 (\hat{u} - m_{J/\psi}^2)^2},
$$

(3)

where $\frac{d\hat{\sigma}_{++}}{dt}$, for instance, denotes that the helicity of the virtual photon is positive and that of the gluon negative, and $\Gamma_{ee}$ is the leptonic decay width of $J/\psi$, $\Gamma_{ee} = 5.36$keV. $\hat{s}, \hat{t}$ and $\hat{u}$ are Mandelstam variables. At the hadron level $\gamma^* p \to J/\psi X$, we can calculate the differential cross section as

$$
\frac{d\Delta \sigma}{dt} = \int \delta G(x, Q^2) \frac{d\Delta \hat{\sigma}}{dt} dx,
$$

(4)

where $\delta G(x, Q^2)$ is the spin–dependent gluon distribution function. $x$ is the fraction of the proton momentum carried by the initial state gluon and is given as

$$
x = \frac{1}{s_T} \left( \frac{m_{J/\psi}^2}{z} + \frac{p_T^2}{z(1-z)} \right),
$$

(5)

where $\sqrt{s_T}$ is the total energy in photon–proton collisions. We express eq.(4) in terms of observable variables as

$$
\frac{d^2 \Delta \sigma}{dz dp_T^2} = \frac{8\pi \alpha_S^2 m_{J/\psi}^2 \Gamma_{ee} z (1-z) x \delta G(x, Q^2)}{3\alpha \left( m_{J/\psi}^2 (1-z) + p_T^2 \right)^2} \times \frac{1}{(m_{J/\psi}^2 + p_T^2)^2} \left[ \frac{(1-z)^4}{m_{J/\psi}^2 (1-z)^2 + p_T^2)^2} - \frac{z^4 p_T^4}{(m_{J/\psi}^2 + p_T^2)^2 m_{J/\psi}^2 (1-z)^2 + p_T^2)^2} \right].
$$

(6)

Using $\alpha_S(m_{J/\psi}) = 0.4$ together with the large polarized gluon distribution eq.(11), we can estimate the spin–dependent differential cross section eq.(13). At HERA energy $\sqrt{s_T} = 185$GeV, $d^2 \Delta \sigma/dz dp_T^2$ vs. $p_T^2$ is shown in fig.3 for various values of $z$. As shown in eq.(14), this distribution is directly proportional to the magnitude of the polarized gluon distribution. Therefore, by detecting it with high precision, one can get to know how large the gluon polarization is. We
hope that our present predictions would be tested in the forthcoming HERA experiments for polarized electron–polarized proton collisions.

Another interesting quantity is the $x$ dependence of the spin–dependent differential cross section which would also be measured in the forthcoming experiments. By rewriting eq.(6), we can get

$$
\frac{d\Delta \sigma}{dx} = x\delta G(x, Q^2)\delta f(x, x_{\text{min}}),
$$

(7)

with

$$
\delta f(x, x_{\text{min}}) = \frac{16\pi\alpha^2\Gamma_{J/\psi} x_{\text{min}}^2}{3\alpha m_{J/\psi}^3 x^2}
$$

$$
\times \left[ \frac{x - x_{\text{min}}}{(x + x_{\text{min}})^2} + \frac{2x_{\text{min}}x \ln \frac{x}{x_{\text{min}}}}{(x + x_{\text{min}})^3} - \frac{x + x_{\text{min}}}{x(x - x_{\text{min}})} + \frac{2x_{\text{min}} \ln \frac{x}{x_{\text{min}}}}{(x - x_{\text{min}})^2} \right],
$$

(8)

where $x_{\text{min}} \equiv m_{J/\psi}^2/s_T$. $\delta f$ is a function which is sharply peaked in $x$ just above $x_{\text{min}}$. A numerical calculation derives $x_{\text{peak}} = 1.53x_{\text{min}}$. Fig.4 shows the $x$ dependence of $d\Delta \sigma/dx$ calculated using eq.(7) at various energies including relevant HERA energies. As $\delta f$ has a sharp peak, the observed cross section $d\Delta \sigma/dx$ directly reflects the spin–dependent gluon distribution near $x_{\text{peak}}$. As is seen from eq.(7), $d\Delta \sigma/dx$ is linearly dependent on the spin–dependent gluon distribution. Thus, if $\delta G(x)$ is small or vanishing, $d\Delta \sigma/dx$ is necessarily small. We are eager for the result in fig.4 being checked in the future experiments.

Next, we discuss the two–spin asymmetry $A_{LL}$ for inclusive $J/\psi$ productions in polarized proton–polarized proton collisions. Since the $J/\psi$ productions come out only via gluon–gluon fusion processes at the lowest order of QCD diagrams, this quantity is sensitive to the spin–dependent gluon distribution in a proton. Let us define the $A_{LL}^{J/\psi}(pp)$ as

$$
A_{LL}^{J/\psi}(pp) = \frac{[d\sigma(p_+p_+ \rightarrow J/\psi X) - d\sigma(p_+p_- \rightarrow J/\psi X)]}{[d\sigma(p_+p_+ \rightarrow J/\psi X) + d\sigma(p_+p_- \rightarrow J/\psi X)]} = \frac{Ed\Delta \sigma/d^3p}{E d\sigma/d^3p},
$$

(9)

where $p_+(p_-)$ denotes that the helicity of a proton is positive (negative). In eq.(9), the numerator (denominator) represents the spin–dependent (spin–independent) differential cross section.
for the hard-scattering parton model and is given by

\[ E \frac{d\Delta \sigma}{d^3p} = \frac{1}{\pi} \int_{x_a^{\min}}^1 dx_a \delta G(x_a, Q^2) \delta G(x_b, Q^2) \left( \frac{x_a x_b}{x_a - x_1} \right) \frac{d\Delta \sigma}{dt}(\hat{s}, \hat{t}, \hat{u}), \]  

(10)

\[ E \frac{d\sigma}{d^3p} = \frac{1}{\pi} \int_{x_a'^{\min}}^1 dx_a G(x_a, Q^2) G(x_b, Q^2) \left( \frac{x_a x_b}{x_a - x_1} \right) \frac{d\sigma}{dt}(\hat{s}, \hat{t}, \hat{u}), \]  

(11)

where \( x_a \) is the momentum fraction in the proton \( a \) and

\[ x_1 = \frac{e^y}{\sqrt{s}} \sqrt{m_{J/\psi}^2 + p_T^2}, \quad x_2 = \frac{e^{-y}}{\sqrt{s}} \sqrt{m_{J/\psi}^2 + p_T^2}, \]

\[ x_b = \frac{x_a x_2 s - m_{J/\psi}^2}{s(x_a - x_1)}, \quad x_a^{\min} = \frac{x_1 - \tau}{1 - x_2}. \]

Here \( y \) is the rapidity of the produced \( J/\psi \) particle and \( \tau \equiv m_{J/\psi}^2/s \). As \( J/\psi \) particles are produced via \( gg \rightarrow J/\psi \) \( g \), differential cross sections of the subprocess included in eqs. (10) and (11) are formulated in the framework of perturbative QCD [13]. Then we get

\[ \frac{d\Delta \hat{\sigma}}{dt} = \frac{5\pi \alpha_s^3(Q^2)|R(0)|^2 m_{J/\psi}}{9 \hat{s}^2} \times \left[ \frac{\hat{s}^2}{(\hat{t} - m_{J/\psi}^2)^2(\hat{u} - m_{J/\psi}^2)^2} - \frac{\hat{t}^2}{(\hat{u} - m_{J/\psi}^2)^2(\hat{s} - m_{J/\psi}^2)^2} - \frac{\hat{u}^2}{(\hat{s} - m_{J/\psi}^2)^2(t - m_{J/\psi}^2)^2} \right], \]

(12)

\[ \frac{d\hat{\sigma}}{d\hat{t}} = \frac{5\pi \alpha_s^3(Q^2)|R(0)|^2 m_{J/\psi}}{9 \hat{s}^2} \times \left[ \frac{\hat{s}^2}{(\hat{t} - m_{J/\psi}^2)^2(\hat{u} - m_{J/\psi}^2)^2} + \frac{\hat{t}^2}{(\hat{u} - m_{J/\psi}^2)^2(\hat{s} - m_{J/\psi}^2)^2} + \frac{\hat{u}^2}{(\hat{s} - m_{J/\psi}^2)^2(t - m_{J/\psi}^2)^2} \right], \]

(13)

with

\[ \hat{s} = x_a x_b s, \quad \hat{t} = -x_a x_2 s + m_{J/\psi}^2, \quad \hat{u} = -x_b x_1 s + m_{J/\psi}^2, \]

where \( R(0) \) is the value of the radial S-wave function at the origin. For estimation of \( A_{LL}^{J/\psi}(pp) \), we choose two different sets of the spin-dependent gluon distributions. One is the large polarized gluon distribution in eq. (11). The other is the vanishing one \( \delta G(x, Q_0^2) = 0 \). Setting \( y = 0 \) with the definition \( Q^2 = m_{J/\psi}^2 + p_T^2 \) and using Duke–Owens parametrization (set 1) [14] as the spin-independent gluon distribution function, we plot \( A_{LL}^{J/\psi}(pp) \) as a function of the transverse momenta of the \( J/\psi \) at \( \sqrt{s} = 20 \) and 100GeV in fig.5. We see that the large polarized gluon
distribution in the range $0 < x < 0.1$ contributes much to $A_{LL}^{J/\psi}(pp)$ at moderate $p_T$ regions ($p_T \gtrsim 1\text{GeV}$). Note that here we do not consider the very small $p_T$ regions ($p_T < 1\text{GeV}$) where soft gluon effects of QCD can not be neglected. For large $p_T$ regions (for example, $p_T > 3\text{GeV}$ ($15\text{GeV}$) for $\sqrt{s} = 20\text{GeV}$ ($100\text{GeV}$)) the increase of $A_{LL}^{J/\psi}(pp)$ is seen even for the case of the vanishing gluon distribution, $\delta G(x, Q^2_0) = 0$, because of the $Q^2$ evolution of gluon distribution functions. But in these regions the $A_{LL}^{J/\psi}$ predicted with the large gluon polarization is not so significantly different from that with the vanishing one and hence we would not be able to find practically the difference between them. On the other hand, for moderate $p_T$ regions ($p_T \gtrsim 1\text{GeV}$) the predictions for two cases are quite different and would be tested easily in experiments. Therefore we can get knowledge of $\Delta G$ by measuring $A_{LL}^{J/\psi}$ for moderate $p_T$ regions.

In summary, we have examined the effect of the large gluon polarization on some physical quantities in special processes which are sensitive to the magnitude of gluon polarizations. By using the large polarized gluon distribution, $\Delta G(Q^2_0) = 6.14$, which is consistent with both the EMC data and the E581/704 data, we could reproduce successfully the recent SMC data of $xg_1^d(x)$ without free parameters.

Furthermore, in order to test the effects of large gluon polarizations in other processes, we have calculated, using the large polarized gluon distribution, some interesting quantities, \textit{i.e.} $d^2\Delta\sigma/dzdp_T$ and $d\Delta\sigma/dx$ for $J/\psi$ leptoproductions, $A_{LL}^{J/\psi}(pp)$ for $J/\psi$ hadroproductions. Since $d^2\Delta\sigma/dzdp_T$ and $d\Delta\sigma/dx$ are directly proportional to the polarized gluon distribution, one can easily examine the magnitude of the gluon polarization by measuring these quantities in experiments. Furthermore, as for $A_{LL}^{J/\psi}(pp)$, there would be a good chance to find the large polarized gluon in moderate $p_T$ regions ($p_T \gtrsim 1\text{GeV}$). The $J/\psi$ productions in polarized ep and pp collisions considered here can therefore serve as a very clean probe of the polarized gluon densities in a proton. We hope these predictions would be tested in the forthcoming experiments.
References

[1] R. L. Jaffe and A. V. Manohar, Nucl. Phys. **B337** (1990) 509; G. Altarelli, Polarized electroproduction and the spin of the quarks inside the proton, International School of Subnuclear Physics, 27th Course (Erice, August 1989), CERN–TH–5675/90; G. G. Ross, Polarized nucleon structure functions, in : Proc. XIV International Symposium on Lepton and Photon Interactions (Stanford, August 1989), ed. M. Riordan (World Scientific, 1990) p.41.

[2] G. Altarelli and W. J. Stirling, Particle World **1** (1989) 40.

[3] G. Altarelli and G. G. Ross, Phys. Lett. **B212** (1988) 391; R. D. Carlitz, J. C. Collins and A. H. Mueller, Phys. Lett. **B214** (1988) 229; A. V. Efremov and O. V. Teryaev, Dubna preprint E2-88-287 (1988).

[4] D. L. Adams et al., FNAL E581/704 Collab., Phys. Lett. **B261** (1991) 197.

[5] G. Ramsey and D. Sivers, Phys. Rev. **D43** (1991) 2861.

[6] K. Kobayakawa, T. Morii and T. Yamanishi, Z. Phys. **C59** (1993) 251.

[7] W. Vogelsang and A. Weber, Phys. Rev. **D45** (1992) 4069.

[8] J. Ashman et al., EMC Collab., Phys. Lett. **B206** (1988) 364; Nucl. Phys. **B328** (1989) 1.

[9] J. Kwiecinski, A. D. Martin, W. J. Stirling and R. G. Roberts, Phys. Rev. **D42** (1990) 3645.

[10] Z. Kunszt, Phys. Lett. **B218** (1989) 243; H. Y. Cheng and S. N. Lai, Phys. Rev. **D41** (1990) 91; M. Glück, E. Reya and W. Vogelsang, Phys. Rev. **D45** (1992) 2552.

[11] B. Adeva et al., SMC Collab., Phys. Lett. **B302** (1993) 533.
[12] K. Kobayakawa, T. Morii, S. Tanaka and T. Yamanishi, Phys. Rev. D46 (1992) 2854.

[13] A. D. Martin, C. -K. Ng and W. J. Stirling, Phys. Lett. B191 (1987) 200; S. M. Tkaczyk, W. J. Stirling and D. H. Saxon, DESY HERA Workshop (1987), preprint RAL–88–041.

[14] E. L. Berger and D. Jones, Phys. Rev. D23 (1981) 1521.

[15] R. Gastmans, W. Troost and T. T. Wu, Nucl. Phys. B291 (1987) 731.

[16] D. W. Duke and J. F. Owens, Phys. Rev. D30 (1984) 49.
Figure captions

Fig. 1: The dependence of the spin–dependent deuteron structure function in term of $xg_1^d(x, Q^2)$ on $x$ at $Q^2 = 4.6\text{GeV}^2$. Experimental data are taken from [11].

Fig. 2: The lowest order QCD diagram for the inelastic $J/\psi$ leptoproduction in polarized electron–polarized proton collisions.

Fig. 3: The differential cross section $d^2\Delta\sigma/dzd\not{p}_T^2$ vs. $\not{p}_T^2$ at $\sqrt{s_T} = 185\text{GeV}$ for various values of $z$. The curves are predicted using the large polarized gluon distribution function eq.(1) in the inelastic domain region $p_T^2/m_J^2/\psi > 0.1$. $Q^2$ is typically taken to be $m_J^2/\psi$.

Fig. 4: The distribution $d\Delta\sigma/dx$ as a function of $x$ for different values of $\sqrt{s_T}$ is predicted using eq.(1) as the spin–dependent gluon distribution.

Fig. 5: Using $\Delta G(Q_0^2) = 6.14$ and $\Delta G(Q_0^2) = 0$, the two–spin asymmetries $A_{LL}^{J/\psi}(pp)$ for $y = 0$ (namely, $\theta = 90^\circ$ where $\theta$ is the production angle of $J/\psi$ in the CMS of a colliding proton) calculated as a function of transverse momenta $p_T$ of $J/\psi$ at (a) $\sqrt{s} = 20\text{GeV}$, and (b) $\sqrt{s} = 100\text{GeV}$. The solid (dashed) curve corresponds to $\Delta G(Q_0^2) = 6.14$ ($\Delta G(Q_0^2) = 0$).
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9309336v1
This figure "fig1-2.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9309336v1
This figure "fig1-3.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9309336v1
This figure "fig1-4.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9309336v1
This figure "fig1-5.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9309336v1
This figure "fig1-6.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9309336v1