Possible studies of gluon transversity in the spin-1 deuteron at hadron-accelerator facilities

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Abstract

Chiral-odd gluon transversity distribution could shed light on a new aspect of hadron physics. Although we had much progress recently on quark transversity distributions, there is no experimental measurement on the gluon transversity. The gluon trasversity does not exist in the spin-1/2 nucleons and it exists in the spin-1 deuteron. Therefore, it could probe new hadron physics in the deuteron beyond the basic bound system of a proton and a neutron because the nucleons cannot contribute directly. Here, we explain that the gluon transversity can be measured at hadron accelerator facilities, such as Fermilab and NICA, in addition to charged-lepton scattering measurements at lepton accelerator facilities by showing cross sections of the proton-deuteron Drell-Yan process as an example.

1 Introduction

There are tensor-polarized structure functions for spin-1 hadrons, such as the deuteron, in addition to the polarized ones for the spin-1/2 nucleons. The twist-2 tensor-polarized structure function b_1 was measured by the HERMES collaboration [1]. We have been investigating structure functions of spin-1 hadrons theoretically [2–12]. On the other hand, there are future experimental projects to measure these new structure functions at various accelerator facilities. The structure function b_1 will be measured at the Jefferson laboratory (JLab) [13], and there

is a letter of intent to measure the gluon transversity also at JLab [14]. These polarized-deuteron structure functions will be also investigated at Fermilab [15,16] and Nuclotron-based Ion Collider fAcility (NICA) [17] with the polarized-deuteron target and beam, respectively. Furthermore, they should be also investigated at future electron-ion colliders in US and China.

Recently, there was much progress in the quark transversity distribution on both theoretical and experimental sides. Global analyses of experimental data were done and optimum quark transversity distributions were proposed. However, there is no experimental measurement on the gluon transversity. The gluon transversity is a chiral-odd distribution, which needs a helicity-flip for a gluon in the gluon-hadron helicity amplitude. Namely, the two-unit of spin $\Delta s = 2$ is necessary, so that the hadron spin should be equal to one or larger, and it does not exist in the spin-1/2 nucleons. Because of this property, the gluon transversity is a unique distribution for probing the non-nucleonic component in the deuteron, it could provide a new hadron-physics information beyond a simple bound system of nucleons.

There is an experimental plan to measure the gluon transversity at JLab by measuring the azimuthal angle dependence of the deuteron spin polarization. Since there are a number of hadron accelerators in operation and will be built in the near future, it is nice that gluon transversity experiments will be done as independent and complementary measurements to the JLab one. These projects were not possible until recently because there was no theoretical formalism with the gluon transversity for hadron-facility experiments. Considering this situation, we provided such a formalism for the gluon transversity studies at the hadron accelerator facilities by taking the proton-deuteron Drell-Yan process as an example [11,12]. In the near future, we expect that the gluon transversity experiments will be realized at Fermilab [15,16] and NICA [17] by using proton and deuteron beams.

2 Linear polarization of spin-1 deuteron

The gluon transversity is defined by linear polarizations for the spin-1 deuteron and also the gluon. Although the linear polarization is often used for photon, it is rarely used for hadron polarizations, so that it is briefly explained in this section. The spin-1 deuteron polarizations are described by the polarization vectors defined by $\vec{E}_{\pm} = (\mp 1, -i, 0)/\sqrt{2}$, $\vec{E}_0 = (0, 0, 1)$, $\vec{E}_x = (1, 0, 0)$, and $\vec{E}_y = (0, 1, 0)$. The polarizations $\vec{E}_+$, $\vec{E}_0$, and $\vec{E}_-$ indicate the spin states with the z component of spin $s_z = +1$, 0, and -1; $\vec{E}_x$ and $\vec{E}_y$ are linear polarizations. The spin vector $\vec{S}$ and tensor T_{ij} are written by these polarization vectors, and then they are parametrized in the deuteron rest frame as

$$\vec{S} = \text{Im}(\vec{E}^* \times \vec{E}) = (S_T^x, S_T^y, S_L),$$

$$T_{ij} = \frac{1}{3}\delta_{ij} - \text{Re}(E_i^* E_j) = \frac{1}{2}\begin{pmatrix} -\frac{2}{3}S_{LL} + S_{TT}^{xx} & S_{TT}^{xy} & S_{LT}^x \\ S_{TT}^{xy} & -\frac{2}{3}S_{LL} - S_{TT}^{xx} & S_{LT}^y \\ S_{LT}^x & S_{LT}^y & \frac{4}{3}S_{LL} \end{pmatrix}.$$

(1)

The parameters S_T^x, S_T^y, S_L, S_{LL}, S_{TT}^{xx}, S_{TT}^{xy}, S_{LT}^x, and S_{LT}^y are assigned to express the vector and tensor polarizations of the spin-1 deuteron. The convariant forms S^μ and $T^{\mu\nu}$ are given in Refs. [11,12].

The polarizations of the spin-1 deuteron are summarized in Table 1 by showing the polarization $\vec{E}$ and the polarization parameters for the longitudinal, transverse, and linear polarizations of the deuteron. For example, the longitudinal polarization contains not only the longitudinal polarization parameter S_L but also the tensor polarization S_{LL}. The transverse polarization has the transverse-polarization parameter $S_T^{x,y}$, the tensor polarization S_{LL}, and the linear polarization S_{TT}^{xx}. The linear polarization has both the tensor polarization S_{LL} and the linear polarization S_{TT}^{xx}. Therefore, for extracting the gluon transversity $\Delta_T g$ associated

Table 1: Longitudinal, transverse, and linear polarizations of the deuteron, polarization vectors, and parameters of spin vector and tensor [11, 12, 17]. The other parameters vanish in the considered polarizations ($S_{TT}^{xy} = S_{LT}^x = S_{LT}^y = 0$). The gluon transversity distribution is associated with the polarization parameter S_{TT}^{xx}.

Polarizations	$\vec{E}$	S_T^x	S_T^y	S_L	S_{LL}	S_{TT}^{xx}
Longitudinal $+z$	$\frac{1}{\sqrt{2}}(-1, -i, 0)$	0	0	$+1$	$+\frac{1}{2}$	0
Longitudinal $-z$	$\frac{1}{\sqrt{2}}(+1, -i, 0)$	0	0	-1	$+\frac{1}{2}$	0
Transverse $+x$	$\frac{1}{\sqrt{2}}(0, -1, -i)$	$+1$	0	0	$-\frac{1}{4}$	$+\frac{1}{2}$
Transverse $-x$	$\frac{1}{\sqrt{2}}(0, +1, -i)$	-1	0	0	$-\frac{1}{4}$	$+\frac{1}{2}$
Transverse $+y$	$\frac{1}{\sqrt{2}}(-i, 0, -1)$	0	$+1$	0	$-\frac{1}{4}$	$-\frac{1}{2}$
Transverse $-y$	$\frac{1}{\sqrt{2}}(-i, 0, +1)$	0	-1	0	$-\frac{1}{4}$	$-\frac{1}{2}$
Linear x	$(1, 0, 0)$	0	0	0	$+\frac{1}{2}$	-1
Linear y	$(0, 1, 0)$	0	0	0	$+\frac{1}{2}$	$+1$

with S_{TT}^{xx}, the linear polarization asymmetry $E_x - E_y$ needs to be taken. Alternatively, the transverse polarizations could be used if the $S_T^{x,y}$ and S_{LL} terms are removed by appropriate polarization combinations or calculated by using corresponding PDFs [11, 12].

3   Gluon transversity

The longitudinally-polarized and transversity distributions are defined for quarks and gluons by matrix elements of nonlocal operators as

$$\Delta q(x) = \int \frac{d\xi^-}{4\pi} e^{ixp^+\xi^-} \langle p s_L | \bar{\psi}(0)\gamma^+\gamma_5\psi(\xi) | p s_L \rangle_{\xi^+=\vec{\xi}_\perp=0},$$

$$\Delta_T q(x) = \int \frac{d\xi^-}{4\pi} e^{ixp^+\xi^-} \langle p s_{Tj} | \bar{\psi}(0) i\gamma_5 \sigma^{j+}\psi(\xi) | p s_{Tj} \rangle_{\xi^+=\vec{\xi}_\perp=0},$$

$$\Delta_T g(x) = \varepsilon_{TT,\alpha\beta} \int \frac{d\xi^-}{2\pi} xp^+ e^{ixp^+\xi^-} \langle p E_x | A^\alpha(0)A^\beta(\xi) | p E_x \rangle_{\xi^+=\vec{\xi}_\perp=0}, \tag{2}$$

by using the lightcone coordinates. Here, Δq is the longitudinally-polarized quark distribution function, and $\Delta_T q$ and $\Delta_T g$ are quark and gluon transversity distributions. The p is the hadron momentum, the s_L and s_{Tj} ($j = 1$ or 2) indicate longitudinal and transverse polarizations, E_x is the linear polarization, ψ and A^μ are the quark and gluon fields, and x is the momentum fraction carried by a parton. The gauge links for the color gauge invariance are not explicitly written. The transverse parameter $\varepsilon_{TT}^{\alpha\beta}$ is defined by $\varepsilon_{TT}^{11} = +1$ and $\varepsilon_{TT}^{22} = -1$.

The longitudinally-polarized quark distribution functions are given by the difference between the quark distributions with spin parallel to the hadron spin and the ones with antiparallel spin: $\Delta q(x) = q_+(x) - q_-(x)$ for the helicity operator $\Pi_\parallel = \Sigma_\parallel/2$ with $\vec{\Sigma} = \gamma_5\gamma_0\vec{\gamma}$. The transversity distribution is expressed as $\Delta_T q(x) = q_\uparrow(x) - q_\downarrow(x)$, where $\uparrow$ and $\downarrow$ indicate parallel and anti-parallel quark polarizations defined by the polarization operator $\tilde{\Pi}_\perp = \gamma_0\Sigma_\perp/2$ [11,12] in the transversely polarized hadron. Equation (2) indicates that the gluon transversity is the distribution of linearly-polarized gluon distribution difference in the linearly-polarized deuteron

$$\Delta_T g(x) = g_{\hat{x}/\hat{x}}(x) - g_{\hat{y}/\hat{x}}(x), \tag{3}$$

where $\hat{y}/\hat{x}$ indicate the gluon linear polarization ε_y in the deuteron with the polarization E_x.

Structure functions of hadrons are expressed by the imaginary part of parton-hadron forward scattering amplitudes $A_{\Lambda_i \lambda_i, \Lambda_f \lambda_f}$ in Fig. 1, where the initial and final hadron helicities are shown by Λ_i and Λ_f and parton ones are by λ_i and λ_f. These helicities satisfy the conservation relation $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$. The polarized quark and gluon distribution functions defined in Eq. (2) are expressed by the helicity amplitudes as

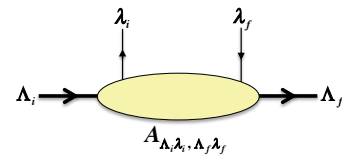



Figure 1: Parton-hadron forward scattering amplitudes.

$$\Delta q(x) \sim \text{Im}\,(A_{++,++} - A_{+-,+-}), \quad \Delta_T q(x) \sim \text{Im}\,A_{++,--}, \quad \Delta_T g(x) \sim \text{Im}\,A_{++,--}. \quad (4)$$

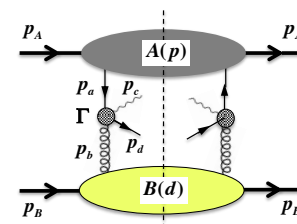
Both quark and gluon transversity distributions are given by the amplitudes with the helicity flips for both quark (gluon) and hadron. Since the nucleon is spin 1/2, the quark-helicity flip is possible and it has the quark transversity distribution. However, the hadron spin should be one or larger for allowing the helicity flip of two units for the gluon, so that the gluon transversity does not exist in the nucleon. As a spin-1 hadron or nucleus, the deuteron is most appropriate for experimental investigations because it is a stable and simple nucleus. These facts suggest a unique purpose for investigating the gluon transversity of the deuteron. The deuteron is a weak bound system of a proton and a neutron; however, these nucleons cannot contribute to the gluon transversity directly. Therefore, if a finite distribution is found experimentally, it sheds light on any new hadron physics beyond the simple bound system of nucleons.

4 Proton-deuteron Drell-Yan process and gluon transversity

The purpose of our research is to propose a possibility to investigate the gluon transversity at hadron accelerator facilities. As an example, we made the theoretical formalism for the proton-deuteron Drell-Yan process $p + d \rightarrow \mu^+ \mu^- + X$ with the linearly-polarized deuteron [11, 12]. There are many subprocesses which contribute to the Drell-Yan cross section as typically shown in Figs. 2 and 3 for the subprocesses $q\bar{q} \rightarrow \gamma^* g$ and $qg \rightarrow \gamma^* q$. The upper proton blob and the lower deuteron blob indicate the collinear correlation functions, which are expressed by various parton distribution functions (PDFs). The proton is not polarized, so that only the unpolarized PDFs of the proton are needed for estimating the cross section. On the other hand, we consider the linear polarizations E_x and E_y for the deuteron, and their asymmetry $d\sigma(E_x) - d\sigma(E_y)$ is calculated. We take the z axis as the proton momentum direction. The differential cross section is calculated for the variables $\tau = M_{\mu\mu}^2 / s = Q^2/s$, the dimuon

Figure 2: $q\bar{q} \rightarrow \gamma^* g$ subprocess.

Figure 3: $qg \rightarrow \gamma^* q$ subprocess.

(virtual photon) transverse momentum squared $\vec{q}_T^2$, its azimuthal angle ϕ, and rapidity y in the center-of-mass frame. Here, $M_{\mu\mu}$ is the dimuon mass, and s is the center-of-mass energy squared. For the linear polarization asymmetry $E_x - E_y$, we obtained the leading cross-section expression by integrating over the momentum fraction x_a for partons in the proton as

$$\frac{d\sigma_{pd \rightarrow \mu^+ \mu^- X}}{d\tau\, d\vec{q}_T^2\, d\phi\, dy}(E_x - E_y) = -\frac{\alpha^2 \alpha_s C_F q_T^2}{6\pi s^3} \cos(2\phi) \int_{\min(x_a)}^1 dx_a \frac{1}{(x_a x_b)^2 (x_a - x_1)(\tau - x_a x_2)^2}$$
$$\times \sum_q e_q^2 x_a [q_A(x_a) + \bar{q}_A(x_a)] x_b \Delta_T g_B(x_b), \quad (5)$$

where α is the fine structure constant, α_s is the QCD running coupling constant, C_F is the color factor $C_F = (N_c^2 - 1)/(2N_c)$ with $N_c = 3$, and e_q is the quark charge. The momentum

fraction x_b is given by $x_b = (x_a x_2 - \tau)/(x_a - x_1)$, and the kinematical minimum of x_a is $\min(x_a) = (x_1 - \tau)/(1 - x_2)$ with $x_1 = e^y \sqrt{(Q^2 + \vec{q}_T^2)/s}$ and $x_2 = e^{-y} \sqrt{(Q^2 + \vec{q}_T^2)/s}$. The $q_A(x_a)$ and $\bar{q}_A(x_a)$ are quark and antiquark distribution functions in the proton, and $\Delta_T g(x_b)$ is the gluon transversity.

The absolute value of the cross section in Eq. (5) is shown in Fig. 4 for the Fermilab kinematics with $p_p = 120$ GeV by taking $\phi = 0$, $y = 0.5$, and $q_T = 0.5$ or 1.0 GeV as the function of the dimuon-mass squared $M_{\mu\mu}^2$. Here, the CTEQ14 PDFs are used for the unpolarized PDFs of the proton, and the NNPDF1.1 is used for the gluon transversity by boldly assuming that the longitudinally-polarized gluon distribution is equal to the gluon transversity. Because of this bold assumption, the cross section and the following spin asymmetry could be overestimated. The cross section $d\sigma(E_x + E_y)$ can be calculated by using the unpolarized PDFs of the proton and deuteron with the assumption of neglecting the small tensor-polarized PDF part, and the calculated spin assymmetry $d\sigma(E_x - E_y)/d\sigma(E_x + E_y)$ is shown in Fig. 5. The asymmetries are typically a few percent. If a finite value is found experimentally, it could create a new field of hadron and nuclear physics beyond the simple bound system of nucleons. Therefore, we hope that such an experiment is realized in future. In fact, this experiment will be proposed within the Fermilab-E1039 experiment [15, 16], and a similar J/ψ experiment should be possible in the NICA project.

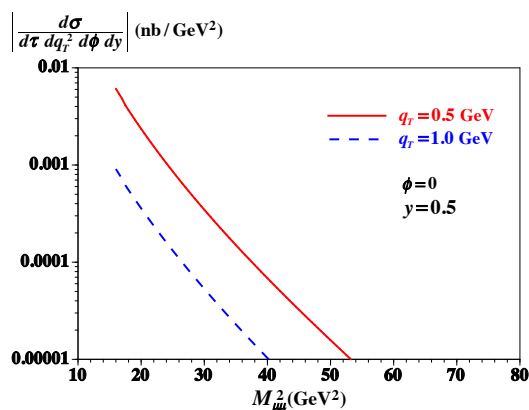



Figure 4: Proton-deuteron Drell-Yan cross section for the linear-polarization asymmetry $E_x - E_y$.

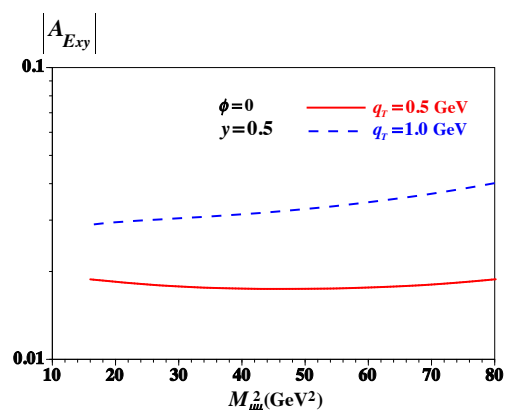



Figure 5: Spin asymmetry $d\sigma(E_x - E_y)/d\sigma(E_x + E_y)$.

5 Conclusion

The gluon transversity has not been measured yet experimentally. If a finite distributions is found, it indicates the existence of new hadronic physics. In this work, we showed the general formalism to investigate the gluon transversity at hadron accelerator facilities by taking the Drell-Yan process as an example. In the 2020's, we expect that the gluon transversity will be measured at JLab, Fermilab, NICA, and other accelerator facilities, so that it could become an exciting field of hadron physics in the near future.

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