Estimate on Spin Asymmetry for Drell-Yan Process at Fermilab with Tensor-Polarized Deuteron

S. KUMANO\textsuperscript{1,2,3} and Qin-Tao SONG\textsuperscript{1,3}

\textsuperscript{1}KEK Theory Center, Institute of Particle and Nuclear Studies, KEK, 1-1, Oho, Tsukuba, Ibaraki, 305-0801, Japan
\textsuperscript{2}J-PARC Branch, KEK Theory Center, Institute of Particle and Nuclear Studies, KEK, and Theory Group, Particle and Nuclear Physics Division, J-PARC Center, 203-1, Shirakata, Tokai, Ibaraki, 319-1106, Japan
\textsuperscript{3}Department of Particle and Nuclear Physics, Graduate University for Advanced Studies (SOKENDAI), 1-1, Oho, Tsukuba, Ibaraki, 305-0801, Japan

E-mail: qintao@post.kek.jp

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There are four new structure functions for the spin-1 deuteron in comparison with the ones for the spin-1/2 proton, and they are called $b_1$, $b_2$, $b_3$, and $b_4$. The twist-2 structure functions $b_1$ and $b_2$ are expressed by tensor-polarized parton distribution functions in the deuteron. HERMES measurements of $b_1$ are much different from the prediction of the standard deuteron model with D-state admixture. It indicates that the structure functions $b_1$ and $b_2$ probe an interesting new aspect in the deuteron. There is an approved experiment at JLab to measure $b_1$ and it is expected to start in 2019. On the other hand, the measurement of tensor-polarized distributions is under consideration at Fermilab by the Drell-Yan process with the unpolarized proton beam and tensor-polarized deuteron target. It is expected to provide crucial information on tensor-polarized antiquark distributions. Since the distributions are small quantities, it is important to estimate the tensor-polarized spin asymmetry theoretically to find experimental feasibility for an actual proposal at Fermilab.

KEYWORDS: Drell-Yan process, spin asymmetry, tensor structure, quark, gluon, QCD

1. Introduction

The quark model was proposed by M. Gell-Mann and G. Zweig in 1964 to classify numerous hadron states, and the quark model works successfully to explain major hadron properties. In this naive quark model, spins of ground-state hadrons such as the proton are carried by quarks. However, the European Muon Collaboration discovered that only a small fraction of the spin is carried by the quarks in the proton. Analyses of subsequent experiments suggest that the fraction is only 20-30%, and it is inconsistent with the naive quark-model prediction. This spin puzzle of proton suggests that the contributions from gluon spin and partonic orbital angular momenta should not be zero. Therefore, a more sophisticated description is necessary to reveal the proton spin structure beyond the naive quark model. In order to solve the spin puzzle of the proton, it is necessary to know the gluon-spin and orbital-angular-momentum contributions. Recently, generalized parton distributions are widely investigated, and they provide a possible way to solve the proton puzzle in the orbital-angular-momentum part.

There is a similar case in the deuteron as the proton spin puzzle. The deuteron was originally considered as a bound state of proton and neutron in S wave. The experimental magnetic moment of deuteron is consistent with the S-wave proposal, because the magnetic moment of deuteron is almost equal to the sum of magnetic moments of proton and neutron. Later, the electric quadrupole moment was observed by experiment, which indicated that the deuteron cannot be the pure S-wave state. Then
the deuteron was considered as an S-D mixture state, and the D-wave contribution is a very small fraction. This D-state admixture proposal is widely accepted. However, a HERMES experiment in 2005 [1] showed that the twist-2 function \(b_1\) is not as small as the prediction in the S-D mixture picture [2–4]. The \(b_1\) function is expressed by the tensor-polarized parton distribution functions (PDFs), which could contain the D-wave contribution in deuteron. However, the standard S-D mixture can not explain the experimental data. There are several theoretical studies for the unexpected \(b_1\) of the deuteron such as six quarks configuration of the deuteron [5], shadowing effects of the nucleus [6–8], effects of \(\pi\) exchange between proton and neutron [5]. At this stage, the structure function \(b_1\) and the tensor-polarized PDFs are not understood in spite of these theoretical ideas. In this work, we propose a possible way to clarify tensor-polarized antiquark distributions in the Drell-Yan process [9], and it may provide crucial information to find a mechanism for solving the issue.

2. Tensor-Polarized Structure Function \(b_1\)

There are two major methods to investigate the tensor structure functions of deuteron. One is deep inelastic scattering (DIS), and the other is Drell-Yan process. In the charged-lepton DIS process with the polarized deuteron, there are 8 structure functions in the hadron tensor

\[
W^{J\lambda_l\lambda_i}_{\mu\nu}(x,q^2) = \frac{1}{4\pi M} \int d^4 x e^{i (q \cdot x)} \langle p \lambda_f | J_\mu(x) J_\nu(0)| p \lambda_i \rangle
\]

\[
= - F_1 \hat{g}_{\mu\nu} + F_2 \hat{p}_\mu \hat{p}_\nu + \frac{ig_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda \hat{s}^\sigma + \frac{ig_2}{M^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q) s^\sigma - s \cdot q p^\sigma
\]

\[
- b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}).
\] (1)

Here, \(M, \nu, p\), and \(q\) are hadron mass, hadron momentum, and momentum transfer, \(\hat{s}\) is the spin vector of the spin-1 hadron, \(\nu\) is defined by \(\nu = p \cdot q/M\), and \(\epsilon_{\mu\nu\lambda\sigma}\) is an antisymmetric tensor with the convention \(\epsilon_{0123} = +1\). The initial and final spin states of the deuteron are denoted as \(\lambda_i\) and \(\lambda_f\), respectively. The notations \(\hat{g}_{\mu\nu}\) and \(\hat{p}_\mu\) are defined by \(\hat{g}_{\mu\nu} = g_{\mu\nu} - q_\mu q_\nu/q^2\), \(\hat{p}_\mu = p_\mu - (p \cdot q/q^2) q_\mu\). The expressions of \(r_{\mu\nu}, s_{\mu\nu}, t_{\mu\nu}\), and \(u_{\mu\nu}\) are found in Refs. [2, 10]. The structure functions \(F_1, F_2, g_1\), and \(g_2\) exist in the hadron tensor of a spin-1/2 hadron as well, while \(b_1, b_2, b_3\) and \(b_4\) are the new quantities for a spin-1 hadron.

The twist-2 structure functions \(b_1\) and \(b_2\) are related to each other by the relation \(2xb_1 = b_2\) in the Bjorken scaling limit. In the parton picture, \(b_1\) has a similar expression as \(F_1\),

\[
F_1 = \frac{1}{2} \sum_i e_i^2 \left[ q_i(x, Q^2) + \bar{q}_i(x, Q^2) \right], \quad b_1 = \frac{1}{2} \sum_i e_i^2 \left[ \delta_T q_i(x, Q^2) + \delta_T \bar{q}_i(x, Q^2) \right],
\] (2)

where \(\delta_T q_i(x, Q^2) = q_i^0 - (q_i^{+1} + q_i^{-1})/2\) is the tensor-polarized PDFs, and \(q_i^0\) indicates an unpolarized quark distribution with flavor \(i\) in the deuteron spin state \(\lambda\). If we integrate \(b_1\) by the Bjorken variable \(x\), we can get a sum rule \(\int dx b_1(x) = -\lim_{x \to 0} (5/24) i F_Q(t) = 0 [11]\) from the valence-quark part; however, if there are finite \(\delta_T \bar{q}(x)\) distributions, it becomes \(\int dx b_1(x) = (1/9) \int dx \left[ 4\delta_T \bar{u}(x) + 4\delta_T \bar{d}(x) + \delta_T \bar{s}(x) \right]\). Therefore, a finite sum indicates that there exist tensor-polarized distributions for antiquarks in the deuteron.

The deuteron structure function \(b_1\) was measured by HERMES Collaboration in 2005, and the experimental measurement of \(b_1\) is not as small as the prediction by the standard convolution model with the S-D admixture [1]. Therefore, a new mechanism could be necessary to explain the tensor structure of the deuteron in terms of quark and gluon degrees of freedom. The integrals of \(b_1\) are also provided by the HERMES data as

\[
\int_{0.002}^{0.85} dx b_1(x) = \left[ 1.05 \pm 0.34(stat) \pm 0.35(sys) \right] \times 10^{-2}, \quad \left[ 0.35 \pm 0.10(stat) \pm 0.18(sys) \right] \times 10^{-2},
\] (3)
where the first value is obtained in the measured range and the second is in the range of \( Q^2 > 1 \text{ GeV}^2 \). The nonzero measurements of the \( b_1 \) integral support the existence of tensor-polarized distributions for antiquark quarks \( \delta_T \bar{q}(x) \). In future, the structure function \( b_1 \) can be measured at JLab (Thomas Jefferson National Accelerator Facility), and this should provide us important information on the tensor structure of deuteron.

3. Tensor-Polarized Spin Asymmetry in Proton-Deuteron Drell-Yan Process

Another possible way to study the tensor structure of the deuteron is the Drell-Yan process. It is much better in probing \( \delta_T \bar{q}(x) \) directly. In the Fermilab E1309 experiment, the beam is unpolarized proton (120 GeV, Main Injector) and the target is polarized deuteron. The proton-deuteron Drell-Yan process \( p + d \rightarrow \mu^+ \mu^- + X \) is schematically shown in Fig. 1, where the center-of-mass energy is \( s = (p_1 + p_2)^2 \), and the dimuon-mass squared is given by \( M_{\mu\mu}^2 = Q^2 = x_1 x_2 s \).

There are many spin asymmetries in the proton-deuteron Drell-Yan process, but the most important one is new tensor-polarized asymmetry \( A_{Q} \) (\( \equiv 2A_{UQ_0} \)) defined by [12, 13]

\[
A_Q = \frac{1}{\langle \sigma \rangle} \left[ \sigma(\bullet, 0) - \frac{\sigma(\bullet, +1) + \sigma(\bullet, -1)}{2} \right],
\]

for studying the tensor-polarized PDFs. Here, \( \pm \) and 0 are for the deuteron spin states and \( \bullet \) indicates the unpolarized proton. In the leading-order (LO) parton model, it is expressed by the PDFs

\[
A_Q = \frac{\sum_i c_i^2 \left[ q_i(x_1) \delta_T \bar{q}_i(x_2) + \bar{q}_i(x_1) \delta_T q_i(x_2) \right]}{\sum_i c_i^2 \left[ q_i(x_1) \bar{q}_i(x_2) + \bar{q}_i(x_1) q_i(x_2) \right]}.
\]

A finite spin asymmetry \( A_Q \) reflects the existence of tensor-polarized distributions \( \delta_T \bar{q}(x) \) and \( \delta_T q(x) \) in the deuteron. At the large \( x_F = x_1 - x_2 \) region, we have the relations \( q_i(x_2) \delta_T \bar{q}_i(x_2) \gg \bar{q}_i(x_1) \delta_T q_i(x_2) \) and \( q_i(x_1) \bar{q}_i(x_2) \gg \bar{q}_i(x_1) q_i(x_2) \), so that the spin asymmetry of \( A_Q \) becomes

\[
A_Q = \frac{\sum_i c_i^2 \left[ q_i(x_1) \delta_T \bar{q}_i(x_2) \right]}{\sum_i c_i^2 \left[ q_i(x_1) \bar{q}_i(x_2) \right]}.
\]

In this case, the existence of asymmetry \( A_Q \) at large \( x_F \) region indicates the tensor-polarized antiquark distributions \( \delta_T \bar{q}(x) \). The Drell-Yan process has a merit to measure the antiquark tensor-polarized distributions directly from the measurement of the asymmetry \( A_Q \). In particular, this proton-deuteron Drell-Yan experiment is under consideration in the Fermilab E1309 experiment as a future project.

In calculating \( A_Q(x_1, x_2) \), the unpolarized distributions of proton and deuteron are taken from the MSTW PDFs in the LO [14]. As for the tensor-polarized distributions of deuteron, we use the parameterizations of Ref. [15] for explaining the HERMES data at the average scale \( Q^2 = 2.5 \text{ GeV}^2 \). There are two analysis types for the parameterizations. In set 1, there is no tensor-polarized antiquark distribution at \( Q^2 = 2.5 \text{ GeV}^2 \). With finite tensor-polarized antiquark distributions, the set-2 tensor-polarized PDFs can explain the HERMES data better than those of set 1. Moreover, the experimental measurements of the \( b_1 \) integral in Eq. (3) also indicate that the tensor-polarized antiquark distributions are necessary at the initial scale. By using the DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations [2], the tensor-polarized distributions can also be obtained at larger \( Q^2 \) scales for the Drell-Yan process [9]. The evolved tensor-polarized PDFs are shown for the set 2 in Fig. 2 at \( Q^2 = 30 \text{ GeV}^2 \) as an example. It is interesting that we found a finite tensor-polarized gluon distribution at \( Q^2 = 30 \text{ GeV}^2 \), even though they are set to be zero at the initial scale. The spin asymmetries of set 1 and set 2 are shown in Fig. 3 at the momentum fractions \( x_1 = 0.2, x_1 = 0.4 \) and
$x_1 = 0.6$ [9]. The asymmetries of both set 1 and set 2 are a few percent. At the small region of $x_2$, the set-1 results are very different from those of set 2, because the antiquark tensor-polarized distributions become more important in the small $x_2$ region. The set-2 asymmetries should be more reliable since the tensor-polarized distributions can explain the HERMES data well. Based on our asymmetry estimates, the Fermilab E1309 Collaboration is considering to measure this tensor-polarization asymmetry.

4. Summary

The tensor-polarized parton distributions can be investigated by the new structure function $b_1$ and spin asymmetry $A_Q$ in the Drell-Yan process for the deuteron. They should shed light on a new spin physics, namely tensor structure in terms of quark and gluon degrees of freedom. In this work, we showed the theoretical estimates on the spin asymmetry $A_Q$, and it is of the order of a few percent. In future, those quantities could be measured by Jlab ($b_1$) and Fermilab ($A_Q$), and they are expected to clarify the puzzle of deuteron tensor structure.

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References

[1] A. Airapetian et al. [HERMES Collaboration]: Phys. Rev. Lett. 95 (2005) 242001.
[2] P. Hoodbhoy, R. L. Jaffe and A. Manohar: Nucl. Phys. B 312 (1989) 571.
[3] R. L. Jaffe and A. Manohar: Nucl. Phys. B 321 (1989) 343.
[4] H. Khan and P. Hoodbhoy: Phys. Rev. C 44 (1991) 1219.
[5] G. A. Miller: Phys. Rev. C 89 (2014) 045203.
[6] N. N. Nikolaev and W. Schafer: Phys. Lett. B 398 (1997) 245 Erratum: [Phys. Lett. B 407 (1997) 453].
[7] J. Edelmann, G. Piller and W. Weise: Z. Phys. A 357 (1997) 129.
[8] K. Bora and R. L. Jaffe: Phys. Rev. D 57 (1998) 6906.
[9] S. Kumano and Q. T. Song: Phys. Rev. D 94 (2016) 054022.
[10] S. Kumano: J. Phys. Conf. Ser. 543 (2014) 012001.
[11] F. E. Close and S. Kumano: Phys. Rev. D 42 (1990) 2377.
[12] S. Hino and S. Kumano: Phys. Rev. D 59 (1999) 094026.
[13] S. Hino and S. Kumano: Phys. Rev. D 60 (1999) 054018.
[14] A. D. Martin, W. J. Stirling, R. S. Thorne and G. Watt: Eur. Phys. J. C 63 (2009) 189.
[15] S. Kumano: Phys. Rev. D 82 (2010) 017501.