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Structure of Deuteron by Polarized Proton-Deuteron Drell-Yan Process

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There are additional spin observables for the deuteron, in comparison with the spin-1/2 proton, because of its spin-1 nature, and they are tensor-polarized structure functions. In 2005, the HERMES collaboration observed the tensor structure function b_1 in the deep inelastic scattering (DIS) process with a polarized deuteron, and this measurement is different from the standard deuteron prediction. Furthermore, there was an interesting indication that a finite antiquark tensor polarization exists. These results suggest that the structure function b_1 could probe an interesting new aspect in the deuteron. In the near future, b_1 will be accurately measured by at JLab (Thomas Jefferson National Accelerator Facility) and the Drell-Yan experiment is now under consideration at Fermilab by using the unpolarized proton beam and tensor-polarized deuteron target. In this work, we provide theoretical predictions for the spin asymmetry in the Fermilab Drell-Yan experiments by using optimum tensor-polarized parton distribution functions to explain the HERMES measurement.

KEYWORDS: Tensor structure, deuteron, spin asymertry, Drell-Yan, QCD

1. Introduction

Deuteron structure has been studied by hadron degrees of freedom. The deuteron is a bound state of proton and neutron mainly in S wave, and the existence of a finite electric quadrupole moment indicates that the deuteron should also contain D wave. Therefore, the deuteron is a S-D mixture state, and the D-wave contribution is very small. It is interesting to investigate the tensor structure in terms of quark and gluon degrees of freedom. In 2005 the HERMES collaboration made the first measurement of the tensor structure function b_1 for the deuteron [1]. However, the measurement shows that b_1 is much larger than the conventional convolution-model prediction with the S-D mixture [2–5]. It indicates that the tensor structure of deuteron is not understood in the parton level.

There is an approved experiment to measure b_1 by the deep inelastic scattering (DIS) at JLab (Thomas Jefferson National Accelerator Facility) and it will start soon. This accurate experiment will help us to understand the tensor structure of deuteron. The structure function b_1 is expressed by the tensor-polarized parton distribution functions (PDFs); however, the separation of antiquark distributions is not obvious solely from the DIS measurements. Since the understanding of the tensor-polarized antiquark distributions could be essential for clarifying the discrepancy between the HERMES data and the convolution-model predictions, it is important to measure them experimentally. Fortunately, it is possible in the Fermilab-E1039 experiment by the Drell-Yan process with a tensor-polarized deuteron target. The purpose of our research is to calculate the tensor-polarized spin asymmetries of the Drell-Yan process [6] because there was no theoretical estimate to be used for an experimental proposal and future comparison with the data.

2. Tensor structure functions in DIS with polarized deuteron

The tensor structure of the deuteron can be investigated in charged-lepton DIS with the polarized deuteron, and the hadron tensor of the deuteron is defined as

$$\begin{aligned}
W_{\mu\nu}^{\lambda_f\lambda_i} &= \int \frac{d^4x}{4\pi M} e^{iqx} \left\langle p\,\lambda_f | J_\mu(x) J_\nu(0) | p\,\lambda_i \right\rangle \\
&= -F_1 \hat{g}_{\mu\nu} + \frac{F_2}{M\nu}\hat{p}_\mu \hat{p}_\nu + \frac{ig_1}{\nu}\epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + \frac{ig_2}{M\nu^2}\epsilon_{\mu\nu\lambda\sigma} q^\lambda (p\cdot q s^\sigma - s\cdot q p^\sigma) \\
&\quad - b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}),
\end{aligned} \tag{1}$$

where M, p, and q are deuteron mass, deuteron momentum, and virtual-photon momentum, λ_i and λ_f indicate spin states of the deuteron, and the details of other notations are found in Refs. [2,7].

There are eight structure functions in Eq. (1). The structure functions F_1, F_2, g_1 and g_2 exist in the spin-1/2 nucleon, whereas b_1, b_2, b_3 and b_4 are new structure functions for the spin-1 deuteron. In the patron picture, b_1 is expressed by the tensor-polarized PDFs $\delta_T q_i = q_i^0 - (q_i^{+1} + q_i^{-1})/2$, where the superscript $(\pm 1, 0)$ indicates the deuteron spin state and the subscript i is the quark flavor, as $b_1 = \frac{1}{2}\sum_i e_i^2 \left[\delta_T q_i(x, Q^2) + \delta_T \bar{q}_i(x, Q^2)\right]$. There is also an interesting sum rule for b_1 [8],

$$\int dx b_1(x) = -\lim_{t\to 0} \frac{5}{24} t F_Q(t) + \frac{1}{9}\int dx \left[4\delta_T \bar{u}(x) + 4\delta_T \bar{d}(x) + \delta_T \bar{s}(x)\right], \tag{2}$$

where $F_Q(t)$ is the electric quadrupole form factor. The nonzero measurement of b_1 integral indicates the existence of finite tensor-polarized antiquark distributions, and this was suggested by the HERMES collaboration [1]:

$$\int_{0.002}^{0.85} dx b_1(x) = [1.05 \pm 0.34 \pm 0.35] \times 10^{-2},\ [0.35 \pm 0.10 \pm 0.18] \times 10^{-2}, \tag{3}$$

where the first integral is obtained in the measured kinematical range and the second one by imposing the constraint $Q^2 > 1$ GeV^2. It should be also noted that the measured HERMES b_1 values are much larger in magnitude than the standard convolution-model estimates, and it may be considered as a deuteron tensor-structure puzzle.

3. Spin asymmetry in the Drell-Yan process with unpolarized proton and tensor-polarized deuteron

The tensor structure of the deuteron can also be investigated by the proton-deuteron Drell-Yan process at Fermilab, where the unpolarized proton beam (120 GeV) is provided by the Main Injector and the deuteron target is tensor polarized. It is much easier to study the antiquark tensor-polarized distributions by the Drell-Yan process. The hadron tensor is complicated in comparison with that of DIS, because there exists more than 100 structure functions in the polarized Drell-Yan processes. Among spin asymmetries, A_Q [9, 10] is the most important asymmetry for probing the deuteron tensor structure, and it is expressed as

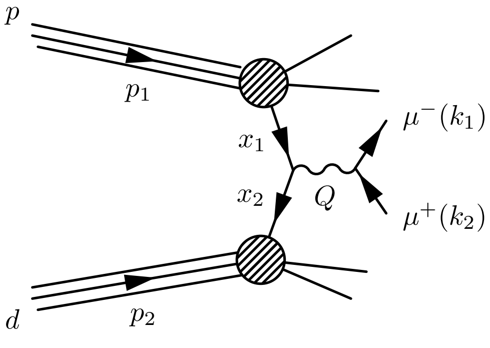

Fig. 1. Drell-Yan process with tensor-polarized deuteron.

$$A_Q = \frac{1}{\langle\sigma\rangle}\left[\sigma(\bullet, 0) - \frac{\sigma(\bullet, +1) + \sigma(\bullet, -1)}{2}\right], \tag{4}$$

where ± and 0 are the spin states of the deuteron, and • indicates the unpolarized proton. Namely, the spin asymmetry A_Q shows the cross section difference with different deuteron spin states, and it will disappear if the deuteron were in purely S wave. In the parton model, A_Q is related to the tensor-polarized PDFs of the deuteron as

$$A_Q = \frac{\sum_i e_i^2 \left[q_i(x_1)\delta_T \bar{q}_i(x_2) + \bar{q}_i(x_1)\delta_T q_i(x_2)\right]}{\sum_i e_i^2 \left[q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1) q_i(x_2)\right]}. \tag{5}$$

At large $x_F (= x_1 - x_2)$, the terms $\bar{q}_i(x_1)\delta_T q_i(x_2)$ and $\bar{q}_i(x_1)q_i(x_2)$ can be neglected in comparison with $q_i(x_1)\delta_T \bar{q}_i(x_2)$ and $q_i(x_1)\bar{q}_i(x_2)$, respectively, and the asymmetry becomes simpler, $A_Q = \sum_i e_i^2 \left[q_i(x_1)\delta_T \bar{q}_i(x_2)\right] / \sum_i e_i^2 \left[q_i(x_1)\bar{q}_i(x_2)\right]$. Therefore, the tensor-polarized antiquark distributions can be obtained by measuring A_Q, and this is the advantage of using the Drell-Yan process.

4. Results

Here, we present the theoretical estimates for the spin asymmetries $A_Q(x_1, x_2)$ [6] of proton-deuteron Drell-Yan process in the Fermilab E-1309 experiment. In Fig. 1, quark and antiquark annihilate into dimuon through the virtual photon. x_1 and x_2 are the momentum fractions of quark and antiquark, respectively. $M_{\mu\mu}^2 = Q^2 = (k_1 + k_2)^2 = x_1 x_2 s$, where $s = (p_1 + p_2)^2$ is the center-of-mass energy. In the E1309 experiment of Fermilab, the beam is 120 GeV unpolarized proton of the Main Injector and the target is a polarized deuteron.

In order to obtain the spin asymmetries $A_Q(x_1, x_2)$, the unpolarized PDFs are taken from the MSTW code [11] in the leading order of the running-coupling constant α_s. As for the initial tensor-polarized PDFs, the only available choice is the parameterization [12] based on HERMES data. In this parameterization, two sets are provided in order to find the impact of tensor-polarized antiquark distributions. There are no tensor-polarized antiquark distributions at the initial energy scale $Q_0^2 = 2.5$ GeV^2 in set 1, whereas finite tensor-polarized antiquark distributions exist in set 2 even at the initial energy scale. The set-2 parameterization should be more reliable in the sense that it agrees with the HERMES measurements of b_1. The tensor-polarized distributions at other energy scales can be obtained by the DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations.

We also provide error-band estimates in this work. There are 3 parameters involved in the initial tensor-polarized parton distributions in set 2 [12]. For a physical quantity $f(x)$, its error $\delta f(x)$ is expressed as

$$[\delta f(x)]^2 = \Delta\chi^2 \sum_{i,j} \left[\frac{\partial f(x)}{\partial \xi_i}\right]_{\hat{\xi}} H_{ij}^{-1} \left[\frac{\partial f(x)}{\partial \xi_j}\right]_{\hat{\xi}}, \tag{6}$$

where H_{ij} is the Hessian matrix, ξ_i is a parameter, and $\hat{\xi}$ is the minimum parameter set. Here, we adopt $\Delta\chi^2 = 1$ in showing the error bands. Expanding χ^2 around the minimum parameter set $\hat{\xi}$, we can express $\Delta\chi^2$ by the Hessian matrix, $\Delta\chi^2 = \chi^2(\hat{\xi} + \delta\hat{\xi}) - \chi^2(\hat{\xi}) = \sum_{i,j} H_{ij}\delta\xi_i\delta\xi_j$.

The spin asymmetries $A_Q(x_1, x_2)$ are shown in the left panel of Fig. 2 for both set 1 and set 2 at typical momentum fractions $x_1 = 0.2$, $x_1 = 0.4$ and $x_1 = 0.6$ [6]. We find that the spin asymmetries are a few percent for both sets. If x_2 is very small, the differences between the set-1 and the set-2 results are large. This is because the spin asymmetries $A_Q(x_1, x_2)$ are very sensitive to the tensor-polarized antiquark distributions in this region as discussed in Sec. 3. The set-2 asymmetries should be more reliable since the existence of finite tensor-polarized antiquark distributions is in agreement with the HERMES data.

In order to indicate typical errors of our estimates, we show the asymmetries $A_Q(x_1, x_2)$ in the right panel of Fig. 2 at the typical energy scale $Q^2 = 30$ GeV^2. Even if the error bands are considered, the asymmetries are of the order of a few percent and they obviously deviate from 0. It validates the

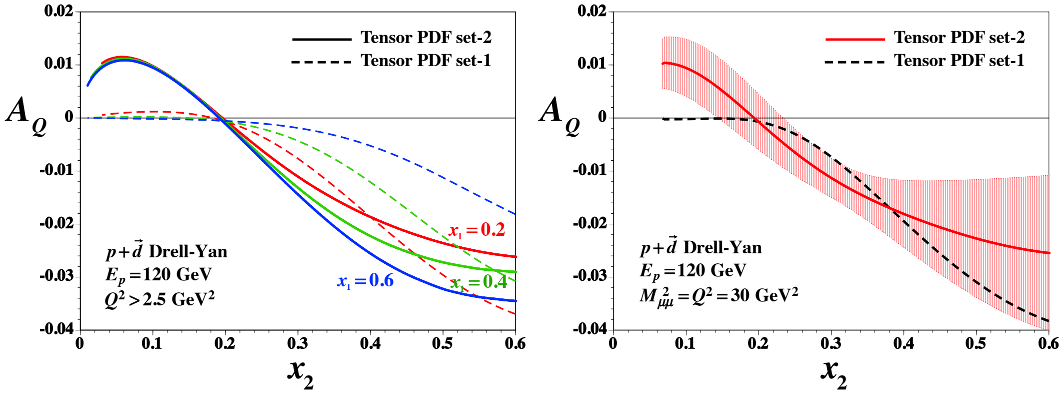

Fig. 2. Left panel: Spin asymmetries $A_Q(x_1, x_2)$ are estimated at typical momentum fractions $x_1 = 0.2$, $x_1 = 0.4$, and $x_1 = 0.6$. Right panel: Spin asymmetries $A_Q(x_1, x_2)$ are estimated at the typical energy scale $Q^2 = 30$ GeV^2 [6].

importance of the Fermilab Drell-Yan experiment to probe the tensor structure of the deuteron, in particular the tensor-polarized antiquark distributions. In addition to the Fermilab-E1039 experiment, such a Drell-Yan experiment is possible at hadron-accelerator facilities such as BNL-RHIC, CERN-COMPASS, J-PARC, GSI-FAIR, and IHEP in Russia.

5. Summary

The tensor-polarized parton distributions are important physical quantities, and they can reflect interesting dynamical aspects of deuteron including the D-wave contribution. The tensor structure of the deuteron can be studied by DIS and Drell-Yan process, while it is much easier to get the tensor-polarized antiquark distributions in the Drell-Yan process. In this work, the tensor-polarized spin asymmetries A_Q were theoretically calculated for the proton-deuteron Drell-Yan process at Fermilab, and we obtained a few percent values. We hope that the Fermilab-E1309 experiment will be realized and a new field of hadron spin physics will be explored in future.

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