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Polarized proton-deuteron Drell-Yan processes and parton distributions

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We show in general that there are 108 structure functions in the proton-deuteron Drell-Yan processes. However, there exist only 22 finite ones after integrating the cross section over the virtual-photon transverse momentum $\vec{Q}_T$ or after taking the limit $Q_T \to 0$. There are 11 new structure functions in comparison with the ones of the proton-proton reactions, and they are related to the tensor structure of the deuteron. Parton-model analyses indicate an important tensor structure function $V_T^{UQ_0}$, which can be measured by a quadrupole spin asymmetry. The Drell-Yan process has an advantage over lepton reactions in finding tensor polarized antiquark distributions. We hope that our studies will be realized in the next-generation RHIC-Spin project and other ones.

1. Introduction

Spin structure of the proton has been investigated through polarized deep inelastic lepton scattering. It is now interesting to investigate other aspects of spin physics. For example, the deuteron is a spin-one particle, so that it has tensor structure which does not exist in the proton. The deuteron target is often used in the deep inelastic scattering; however, the purpose is to extract the "neutron" structure functions in the deuteron. We had better shed light on the deuteron spin structure itself rather than just use it for finding the neutron information. There are some initial studies on the spin-one structure functions. In the lepton scattering on the deuteron, there exist new structure functions, b_1, b_2, b_3, and b_4. However, the polarized proton-deuteron (pd) reaction had not been studied at all in connection with the deuteron structure functions. The major purpose of this work is to investigate the general formalism of the polarized pd Drell-Yan processes [1]. In particular, we list all the possible structure functions in the reactions. Then, the processes are also analyzed in a naive parton model [2]. Another purpose is to facilitate future deuteron projects such as the polarized deuteron reactions at RHIC.

The tensor structure function is a new field of high-energy spin physics. Because it has not been measured experimentally, it is a unique opportunity to test our present understanding of spin physics. Furthermore, it may reveal an unexpected aspect of hadron structure. There is a possibility that the polarized proton-deuteron reaction is realized in the future experimental projects.

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2. Structure functions and spin asymmetries

Because the polarized high-energy pd Drell-Yan process had not been studied, we should first discuss in general what kind of structure functions are investigated [1]. Two independent formalisms are studied. The first one is a spin-density formalism and the second is a hadron-tensor formalism. In the first method, we express structure functions by the helicity amplitudes and Clebsch-Gordan coefficients. Then, imposing Hermiticity, parity conservation, and time-reversal invariance, we find that 108 structure functions exist. In comparison with the proton-proton (pp) reactions, there are 60 new functions. If the cross section is integrated over the lepton-pair transverse momentum $\vec{Q}_T$, there are only 22 ones and the others vanish. There are 11 new functions in addition to the ones of the pp reactions, and they are associated with the tensor structure of the deuteron. In the second method, possible Lorentz index expressions are found for the hadron tensor $W^{\mu\nu}$ by the combinations of available Lorentz vectors and pseudovectors. The $Q_T \to 0$ case indicates that the following 22 structure functions also exist:

$$\begin{array}{l} W_{0,0}\,,\ \ V_{0,0}^{LL},\ \ V_{0,0}^{TT},\ \ V_{0,0}^{UQ_0},\ \ V_{0,0}^{TQ_1},\ W_{2,0},\ \ V_{2,0}^{LL},\ \ V_{2,0}^{TT},\ \ V_{2,0}^{UQ_0},\ V_{2,0}^{TQ_1},\ \ U_{2,1}^{TU}, \\ U_{2,1}^{TQ_0},\ \ U_{2,1}^{UT},\ \ U_{2,1}^{LQ_1},\ \ U_{2,1}^{TQ_2},\ \ U_{2,1}^{TL},\ \ U_{2,1}^{LT},\ \ U_{2,1}^{UQ_1},\ \ U_{2,2}^{UQ_2},\ \ U_{2,2}^{TT},\ \ U_{2,2}^{TQ_1},\ \ U_{2,2}^{LQ_2}. \end{array} \tag{1}$$

The functions W, V, and U are an unpolarized structure function, a polarized one without the spin factors in the hadron tensor, and a polarized one with the spin factor. The subscripts of these structure functions indicate, for example, that $W_{L,M}$ is obtained by $\int d\Omega\, Y_{LM}\, d\sigma/(d^4Q\, d\Omega) \propto W_{L,M}$ in the unpolarized reaction. The superscripts indicate the polarization states of A and B: e.g. $U_{L,M}^{pol_A\, pol_B}$. The superscripts U, L, and T show unpolarized, longitudinally polarized, and transversely polarized states. The quadrupole polarizations Q_0, Q_1, and Q_2 are specific in the reactions with a spin-1 hadron, and they are associated with the spherical harmonics Y_{20}, Y_{21}, and Y_{22} as shown in Figs. 1, 2, and 3. They are the polarizations in the xz, yz, and xy planes. The 11 structure functions with the superscripts Q_0, Q_1, and Q_2 do not exist in the pp reactions.

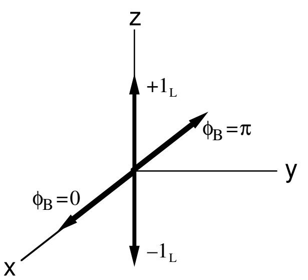

Figure 1. Polarization Q_0.

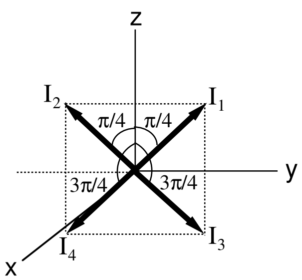

Figure 2. Polarization Q_1.

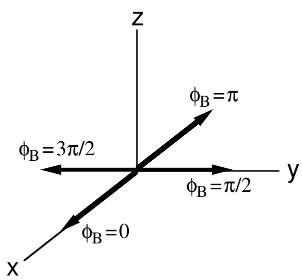

Figure 3. Polarization Q_2.

In the pp Drell-Yan processes, merely the following unpolarized, longitudinal, and transverse combinations exist: $<\sigma>$, A_{LL}, A_{TT}, A_{LT}, and A_T. In addition, the quadrupole spin asymmetries exist in the pd reactions. Our formalism indicates that the following fifteen quantities could be investigated:

$$
\begin{aligned}
&<\sigma>,\ A_{LL},\quad A_{TT},\quad A_{LT},\quad A_{TL},\quad A_{UT},\quad A_{TU},\\
&A_{UQ_0},\quad A_{TQ_0},\ A_{UQ_1},\ A_{LQ_1},\ A_{TQ_1},\ A_{UQ_2},\ A_{LQ_2},\ A_{TQ_2},
\end{aligned}
\tag{2}
$$

where the subscript U indicates the unpolarized state. These asymmetries are expressed in terms of the structure functions in Eq. (1). For example, A_{UQ_0} is measured with the unpolarized proton and the Q_0-type tensor polarized deuteron. It is written by the structure functions $V_{0,0}^{UQ_0}$, $V_{2,0}^{UQ_0}$, $W_{0,0}$, and $W_{2,0}$:

$$
A_{UQ_0} = \frac{1}{2<\sigma>}\left[\sigma(\bullet,0_L) - \frac{\sigma(\bullet,+1_L)+\sigma(\bullet,-1_L)}{2}\right] = \frac{2\,V_{0,0}^{UQ_0} + (\frac{1}{3} - cos^2\theta)\,V_{2,0}^{UQ_0}}{2\,W_{0,0} + (\frac{1}{3} - cos^2\theta)\,W_{2,0}}\,, \tag{3}
$$

where $\bullet$ indicates the unpolarized case.

3. Parton-model analysis

In the previous section, it is shown in Eq. (1) that there exist the 22 structure functions. These functions are measured by the spin asymmetries in Eq. (2). Next, we try to understand the physics meaning of these structure functions, particularly the new tensor polarized ones, in a naive parton model [2].

The hadron tensor $W^{\mu\nu}$ is written by the quark and antiquark correlation functions. They are expressed in terms of possible combinations of Lorentz vectors and pseudovectors with the constrains of Hermiticity, parity conservation, and time-reversal invariance. We find that new tensor distributions are involved in the correlation function $\Phi[\gamma^+]$. It is particularly important that the leading-twist tensor distribution δq is found in our analysis, and it is expressed by the "unpolarized" quark distribution $[\mathcal{P}(x)_\lambda]$ in a spin-1 hadron with helicity λ as

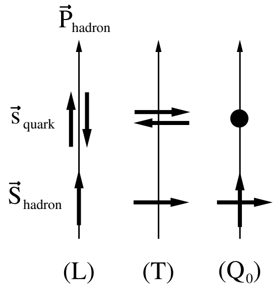

Figure 4: Longitudinally polarized, transversity, and tensor polarized distributions ($\bullet$=unpolarized).

$$
\delta q(x) = \frac{1}{2}\left[\mathcal{P}(x)_{\lambda=0} - \frac{\mathcal{P}(x)_{\lambda=+1}+\mathcal{P}(x)_{\lambda=-1}}{2}\right]. \tag{4}
$$

It agrees with the definition in the lepton-deuteron scattering [3]. In the naive parton-model analysis, we find 19 structure functions. However, there exist only four finite structure functions by the $\vec{Q}_T$ integration and the others vanish. In the following, the $\vec{Q}_T$ integrated results are shown. First, the cross section is

$$
\begin{aligned}
\frac{d\sigma}{dx_A\,dx_B\,d\Omega} = \frac{\alpha^2}{4\,Q^2}\Bigg[& (1+\cos^2\theta)\left\{\overline{W}_T + \frac{1}{4}\lambda_A\lambda_B\,\overline{V}_T^{LL} + \frac{2}{3}\left(2\,|\vec{S}_{BT}|^2 - \lambda_B^2\right)\overline{V}_T^{UQ_0}\right\}\\
& + \sin^2\theta\,|\vec{S}_{AT}|\,|\vec{S}_{BT}|\cos(2\phi-\phi_A-\phi_B)\,\overline{U}_{2,2}^{TT}\Bigg]\,,
\end{aligned}
\tag{5}
$$

where $\overline{W} = \int d^2\vec{Q}_T\, W$ and the same for $\overline{V}$ and $\overline{U}$. The four finite structure functions are expressed by the parton distributions in the process q(in p)+$\bar{q}$(in d)$\rightarrow \ell^+ + \ell^-$ as

$$\overline{W}_T = \frac{1}{3}\sum_a e_a^2\, q_a(x_A)\, \bar{q}_a(x_B)\ , \qquad \overline{V}_T^{LL} = -\frac{4}{3}\sum_a e_a^2\, \Delta q_a(x_A)\, \Delta\bar{q}_a(x_B)\ ,$$
$$\overline{U}_{2,2}^{TT} = \frac{1}{3}\sum_a e_a^2\, \Delta_T q_a(x_A)\, \Delta_T\bar{q}_a(x_B)\ , \qquad \overline{V}_T^{UQ_0} = \frac{1}{3}\sum_a e_a^2\, q_a(x_A)\, \delta\bar{q}_a(x_B)\ . \tag{6}$$

The unpolarized, longitudinally-polarized, transversity, and tensor-polarized distributions are expressed by q_a, Δq_a, $\Delta_T q_a$, and δq_a with the quark flavor a, respectively. The tensor distribution can be investigated by the unpolarized-quadrupole Q_0 asymmetry

$$A_{UQ_0} = \frac{\overline{V}_T^{UQ_0}}{\overline{W}_T} = \frac{\sum_a e_a^2\, [\, q_a(x_A)\, \delta\bar{q}_a(x_B) + \bar{q}_a(x_A)\, \delta q_a(x_B)\,]}{\sum_a e_a^2\, [\, q_a(x_A)\, \bar{q}_a(x_B) + \bar{q}_a(x_A)\, q_a(x_B)\,]}\ , \tag{7}$$

where the contribution from the process $\bar{q}$(in A)+q(in B)$\rightarrow \ell^+ + \ell^-$ is added. This equation suggests that the tensor polarized distributions are found by the Drell-Yan experiment if the unpolarized distributions are well known in the proton. In the large x_F region, the term $\bar{q}_a(x_A)\, \delta q_a(x_B)$ is neglected so that the antiquark tensor polarization $\delta\bar{q}$ could be extracted. It could be also found in the lepton scattering by studying a deviation from the b_1 sum rule [4]; however, the Drell-Yan process has an advantage over the lepton reactions in the sense that the antiquark distributions $\delta q_a(x)$ are found rather easily. In addition, the antiquark flavor asymmetries $\Delta\bar{u}/\Delta\bar{d}$ and $\Delta_T\bar{u}/\Delta_T\bar{d}$ can be investigated by combining the pd Drell-Yan data with the pp data in the same way as the unpolarized case [5] because the polarized pd Drell-Yan formalism is now completed in Refs. [1,2].

4. Summary

We have found that there exist 108 structure functions in the pd Drell-Yan processes; however, the number becomes 22 after integrating the cross section over the transverse momentum $\vec{Q}_T$ or after taking the limit $Q_T \rightarrow 0$. The new structure functions are associated with the tensor structure of the deuteron. The naive parton-model analyses indicate the important structure function $V_T^{UQ_0}$, which is expressed by the unpolarized distributions of the proton and the tensor polarized ones of the deuteron. The pd Drell-Yan is particularly useful for finding the tensor polarized antiquark distributions. There are a variety of interesting topics on the polarized pd reactions. We hope that our studies will be realized experimentally.

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