Nuclear Effects in Polarized Proton-Deuteron Drell-Yan Processes *

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The longitudinally polarized Drell-Yan process is one of the most powerful tools to probe the structure of hadrons. By means of the recent formalism of the polarized proton-deuteron (pd) Drell-Yan, we calculate the ratio of the proton-deuteron Drell-Yan cross section to the proton-proton (pp) one $\Delta \sigma_{pd}/2\Delta \sigma_{pp}$ in the polarized case. The theoretical results can be compared with future experimental data to confirm the nuclear effect due to the 6-quark cluster in deuteron.

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One of the most active areas of research in nuclear and particle physics during last several decades is the study of quark and gluon distributions in the nucleon and nuclei. Several major surprises were discovered in deep-inelastic scattering (DIS) experiments which profoundly changed our views of the partonic substructure of hadrons. [1] In 1982, the European Muon Collaboration (EMC) [2] discovered in unpolarized deep inelastic scattering the difference between the structure function for a bound nucleon measured on a nuclear target and that of a free nucleon. This phenomenon is known as the EMC effect, which implies that the quark distributions are different for a bound and a free nucleon. The polarized structure functions [3] are interesting not only in opening a new degree of freedom with which to explore the detailed structure of the nucleon(nuclei), but also for making a precise test of QCD via Bjorken sum rule which is a strict QCD prediction. [4]

The production of lepton pairs in hadron collisions, the Drell-Yan Process, [5] is also one of the most powerful tools to probe the structure of the nucleon and nuclei. Its parton model interpretation is straightforward — the process is induced by the annihilation of a quark-antiquark pair into a virtual photon which subsequently decays into a lepton pair. The Drell-Yan process in proton-proton or proton-nucleus collisions therefore provides a direct probe of the quark distribution in the nucleon and nuclei. It is further natural to expect that a measurement of the Drell-Yan cross section in polarized proton-nucleon (nuclei) collision will yield information of the polarized quark distribution in the nucleon (nuclei), which is an alternative method to the DIS.

It has been commonly considered that the nuclear effects in deuteron are neglected, and its structure functions are regarded as the sum of the structure functions of the proton and neutron. However, Gomez et al. [6] found that the deuteron has a significant EMC effect. In addition, the E665 experimental result [7] suggested the presence of nuclear shadowing effects in deuteron. The analysis by Epele et al. [8] also shows a significant nuclear effects due to the composite nature of the deuteron.

Since the experimental discovery of the EMC effect, many theoretical models have been put forward to explain it. [9] The quark cluster model (QCM) [10] is one of these models. The quark cluster model assumes that the nucleus is composed of a combination of ordinary nucleons plus some fraction of 6-quark cluster (the overlap of two nucleons). The valence and sea quark distribution functions in the 6-quark cluster, which can be determined from counting rules, have a dependence on $x$ different from those in nucleons. Benesh and Vary [11] examined the implications of the QCM for the spin-dependent structure function of the deuteron and 3He. They gave the deuteron polarized structure function by using the presence of 6-quark clusters in the deuteron wave function. However, there were no detailed quark spin distributions in 6-quark clusters by them. Several years ago, Brodsky et al. [12] provided a reasonable description of the spin-dependent quark distributions of the nucleon in a pQCD based model. Schmidt and Yang have extended this analysis to the description of the spin-dependent quark distributions in a 6-quark cluster. [13]

In the previous work [14], by means of the polarized quark distributions in a 6-quark cluster, the nuclear effects on polarized structure function in deuteron have been investigated. It is found that the calculated results with nuclear effects can better fit the SLAC E155 experimental data [15] than that without nuclear effects. In order to investigate further the nuclear effects in deuteron, we show an alternative way by combining the polarized proton-deuteron Drell-Yan data with the proton-proton data in the polarized case.

Recently, Hino and Kumano discuss a general formalism [16] and a parton-model analysis [17] of the

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polarized pd Drell-Yan process. Using the theoretical formalism, the ratio of the polarized pd Drell-
Yan cross section to the polarized pp one $\Delta \sigma_{pd}/2\Delta \sigma_{pp}$ has been studied \cite{16} by them. However, the deuteron structure functions are treated by simple summations of proton and neutron ones without considering the nuclear effects in deuteron. In this Letter, we first investigate the nuclear-effects in polarized pd Drell-Yan process by measuring the ratio of the cross section to the polarized pp one $\Delta \sigma_{pd}/2\Delta \sigma_{pp}$, and taking advantage of the formalism.

In Ref.\cite{18}, the longitudinally-polarized pd cross section is given by

$$\Delta \sigma_{pd} = \sigma(\uparrow_L, -1_L) - \sigma(\uparrow_L, +1_L) \propto -\frac{1}{4} \left[ 2V_{1,0}^{LL} \right],$$

where the subscripts of $\uparrow_L, +1_L$, and $-1_L$ indicate the longitudinal polarization, $\sigma(p_{ol}, p_{ol})$ indicates the cross section with the proton polarization $p_{ol}$, and the deuteron one $p_{ol}$. The longitudinally polarized structure functions $V_{1,0}^{LL}$ and $V_{2,0}^{LL}$ are defined in Ref.\cite{18}. The subscripts $l$ and $m$ of the expression $V^{LL}_{lm}$ indicate that it is obtained by the integration $\int d\Omega y_{im} \Delta \sigma_{pd}$, and the superscript LL means that proton and deuteron are both longitudinally polarized. The $\theta$ is the polar angle of the final lepton $\mu^\pm$. A parton model should be used for discussing relations between the structure functions and polarized parton distributions. In the following, we employ the expression which is obtained by integrating the cross section over the virtual-photon transverse momentum $Q_T$. According to Ref.\cite{19}, it is given by

$$\Delta \sigma_{pd} \propto \sum_f e_f^2 \left[ \Delta q_f(x_1) \Delta \bar{q}_f^d(x_2) + \Delta \bar{q}_f(x_1) \Delta q_f^d(x_2) \right],$$

where $\Delta q_f(\Delta \bar{q}_f^d)$ and $\Delta \bar{q}_f(\Delta q_f^d)$ are the longitudinally-polarized quark and antiquark distribution function in the proton (deuteron). The subscript $f$ indicates quark flavor, and $e_f$ is the corresponding quark charge; $x_1$ and $x_2$ are the momentum fractions of proton (deuteron) carried by the quark or anti-quark.

If we disregard the nuclear effects in deuteron and assume isospin symmetry for proton and neutron, the polarized quark distribution functions in deuteron can be expressed as

$$\Delta u^d = \Delta u + \Delta d, \; \Delta d^d = \Delta d + \Delta u, \; \Delta s^d = 2\Delta s, \; \Delta \bar{u}^d = \Delta \bar{u} + \Delta \bar{d}, \; \Delta \bar{d}^d = \Delta \bar{d} + \Delta \bar{u}, \; \Delta \bar{s}^d = 2\Delta \bar{s},$$

where $\Delta u(d, s)$ is polarized quark distribution function, and $\Delta \bar{u}(\bar{d}, \bar{s})$ is polarized anti-quark distribution function in proton. Similarly, the pp Drell-Yan cross section is given by simply substituting $q^d(\bar{q}^d)$ with $q(\bar{q})$. Therefore, the ratio of the pd cross section to the pp one is then obtained to be

$$R_{pd} = \frac{\Delta \sigma_{pd}}{2\Delta \sigma_{pp}}$$

$$= \frac{\sum_f e_f^2 \left[ \Delta q_f(x_1) \Delta \bar{q}_f^d(x_2) + \Delta \bar{q}_f(x_1) \Delta q_f^d(x_2) \right]}{\sum_f e_f^2 \left[ \Delta q_f(x_1) \Delta \bar{q}_f(x_2) + \Delta \bar{q}_f(x_1) \Delta q_f(x_2) \right]}.$$ \hspace{2cm} (4)

The behaviour of $R_{pd}$ at two $x_F$ extreme limits has been analysed by Kumano and Miyama,\cite{18} If two extreme limits ($x_F = x_1 - x_2 \to \pm 1$) are taken in Eq.\hspace{2cm} (4) with the assumption $\Delta u(x \to 1) \gg \Delta d(x \to 1)$,\cite{12,20} the ratio becomes

$$R_{pd}(x_F \to +1) = \frac{1}{2 \left[ 1 + \frac{\Delta \bar{d}(x_2)}{\Delta \bar{u}(x_2)} \right]} \left. \right|_{x_2 \to 0},$$

$$R_{pd}(x_F \to -1) = \frac{1}{2 \left[ 1 + \frac{\Delta \bar{d}(x_1)}{4\Delta \bar{u}(x_1)} \right]} \left. \right|_{x_1 \to 0}. \hspace{2cm} (5)$$

It is found that the flavor-asymmetric distribution $\Delta \bar{u} - \Delta \bar{d}$ can be extracted by finding the deviation from 1 at $x_F \to \pm 1$ or from $5/8$ at $x_F \to -1$. However, $R_{pd}$ in other $x_F$ regions are not so promising in the flavor asymmetry, and can be used to find the $x$ dependence of the polarized quark distribution function in deuteron so that the nuclear effects in deuteron can be shed light on.

Now let us turn to investigate the nuclear effects in polarized proton-deuteron Drell-Yan process. In the quark cluster model, the presence of 6-quark cluster is used to understand the nuclear effects in deuteron. Therefore, when we take account of the nuclear effects in deuteron and employ isospin symmetry, the polarized quark distribution function in deuteron can be written as

$$\Delta u^d = p_5(\Delta u + \Delta d) + p_6 \Delta u^6,$$

$$\Delta d^d = p_3(\Delta d + \Delta u) + p_6 \Delta d^6,$$

$$\Delta s^d = 2p_3 \Delta s + p_6 \Delta s^6,$$

$$\Delta \bar{u}^d = p_5(\Delta \bar{u} + \Delta \bar{d}) + p_6 \Delta \bar{u}^6,$$

$$\Delta \bar{d}^d = p_3(\Delta \bar{d} + \Delta \bar{u}) + p_6 \Delta \bar{d}^6,$$

$$\Delta \bar{s}^d = 2p_3 \Delta \bar{s} + p_6 \Delta \bar{s}^6,$$

$$p_5 = \left( p_5 - p_6 \right) - \frac{1}{2} \left( p_d - p_{pd} \right),$$

$$p_6 = p_{0s} + p_{0d}, \hspace{2cm} (7)$$

where $p_s = 0.957$ and $p_d = 0.043$ denote the probabilities for finding the deuteron in an s or d wave, respectively; $p_{0s} = 0.047$ and $p_{0d} = 0.007$ are the probabilities for creating a 6-quark cluster in the s- and d-states. $\Delta \bar{u}^6$ ($\Delta \bar{d}^6$) given in Refs.\cite{13,14} is polarized quark (anti-quark) distribution function in the 6-quark cluster. Benesh and Bary\cite{10} obtained the values of $p_d$, $p_{0s}$, and $p_{0d}$ by the s- and d-state wave function for the deuteron.

With all ingredient sets as given above, we can numerically calculate the ratio of the polarized pd Drell-
Yan cross section to the pp one $\Delta \sigma_{pd}/2\Delta \sigma_{pp}$ with nuclear effects and without nuclear effects in deuteron.
In our calculation, the polarized parton distribution functions for proton are taken from the new version of the Lead-Sidorov-Stamenev (LSS) leading-order (LO) parameterizations. In Fig. 1, the theoretical results are given with taking centre-of-mass energy \( \sqrt{s} = 50 \) GeV and dimuon mass \( M_{\mu\mu} = 5 \) GeV. The dotted-dashed curve denotes the \( R_{pd} \) with the nuclear effects due to 6-quark clusters in deuteron, and the dotted curve corresponds to the case with no consideration the 6-quark clusters. In Fig. 2, the Drell-Yan cross section ratio \( R_{pd} \) is calculated at \( \sqrt{s} = 200 \) GeV and \( M_{\mu\mu} = 5 \) GeV, and the results without nuclear effects are almost equal to those at \( \sqrt{s} = 50 \) GeV. The comparison of Fig. 1 with Fig. 2 indicates that the nuclear effects in deuteron become more significant in higher center-of-mass energy and large \( x_F \) region. The \( R_{pd} \) at high energy decrease in comparison with that at low energy in large \( x_F \) region. For example, our calculated \( R_{pd} \) with nuclear effects is respectively 0.989 at \( \sqrt{s} = 50 \) GeV and 0.917 at \( \sqrt{s} = 200 \) GeV when \( x_F = 0.75 \). The reason is that the probed \( x_2 \) at high collision energy is smaller than that at low collision energy, and the shadowing effect in deuteron become important in small \( x_2 \) region. In addition, at large \( x_F = x_1 - x_2 \), the \( \Delta \sigma_f(x_1) \) terms in Eq. (4) can be neglected because \( \Delta \sigma_f(x_1) \) goes to zero at large \( x_1 \). Subsequently, the \( R_{pd} \) depends mainly on the \( \Delta \sigma_f(x_1) \) terms in Eq. (4); \( x_2 \) is very much small at large \( x_F \), the \( \Delta \sigma_f(x_2) \) varies very slowly with \( x_2 \), so that \( R_{pd} \) have mainly dependence on the variable \( x_1 \). In our calculation, we can find from Figs. 1 and 2 that the \( R_{pd} \) approaches nearly constant in the region \( x_F > 0.6 \). It is shown that \( R_{pd} \) does not vary almost with \( x_1 \) in the region \( x_F > 0.6 \). This is an interesting question. The detailed analysis can not be given about \( R_{pd} \) dependence on \( x_1 \) or \( x_2 \) respectively because the ratio of \( R_{pd} \) employed here depends on \( x_F \), and the theoretical derivation does not obtained currently of \( \frac{\Delta \sigma_f}{\Delta \sigma_{pd}}(pd) \) dependence on \( x_1 \) and \( x_2 \) in analogy with the unpolarized Drell-Yan process. Further studies along this direction are in progress.

In summary, we have investigated the longitudinally polarized Drell-Yan cross section ratio \( \Delta \sigma_{pd}/2\Delta \sigma_{pp} \) by means of the recent formalism for the polarized pd Drell-Yan process. We find that the difference between \( R_{pd} \) with nuclear effects and without nuclear effects in the range \( x_F > 0.08 \) is larger at higher center-of-mass energy, and this makes it possible to confirm further the nuclear effects in deuteron. It is shown that the information on the nuclear effects in deuteron can be extracted in the future experiment. Although there is not experiments for the polarized pd Drell-Yan at this stage, we suggest precise experimental research on this reaction at FNAL, HEAR, and RHIC, which makes us well understand the nuclear effects in deuteron.

References

[1] Peng J C 2003 Preprint hep-ph/0301053
[2] EMC Collab, Aubert J J et al 1983 Phys. Lett. B 123 275
[3] Lampe B and Reya E 2000 Phys. Rep. 332 1
[4] Bjorken J D 1966 Phys. Rev. 148 1467
[5] Drell S D and Yan T M 1970 Phys. Rev. Lett. 25 336
[6] Duan C G et al 2003 Eur. Phys. J. C 29 557
[7] Duan C G et al 2002 Chin. Phys. Lett. 19 485
[8] Gomez J et al 1994 Phys. Rev. D 49 348
[9] Adams M R et al (Fermilab E665 Collaboration) 1995 Phys. Rev. Lett. 75 1466
[10] Epele I N et al 1992 Phys. Lett. B 275 155
[11] Thomas A W 1991 Nucl. Phys. B 532 177
[12] Lassila K E and Sukhatme U P 1985 Phys. Lett. B 209 343
[13] Benesch C J and Vary J P 1991 Phys. Rev. C 44 2175
[14] Brodsky S J, Bubalid M and Schmidt I 1995 Nucl. Phys. B 441 197
[15] Schmidt I and Yang J J 2001 Eur. Phys. J. C 20 63
[16] Duan C G, Shi L J, Li G L and Yang J J 2004 High Energy Phys. Nucl. Phys. Phys. B 281 117 (in Chinese)
[17] Anthony F L et al 1999 Phys. Lett. B 463 339
[18] Hino S and Kumano S 1999 Phys. Rev. D 59 094026
[19] Hino S and Kumano S 1999 Phys. Rev. D 59 054018
[20] Leader E, Sidorov A V and Stameno D B 2002 Eur. Phys. J. C 23 479
[21] Gunion J F 1974 Phys. Rev. D 10 242