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Nuclear Effects on Polarized Structure Function of Deuteron*

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Abstract Polarized deep inelastic scattering is a powerful tool for studying the internal refined information about the parton structure of the proton and deuteron. By means of the spin-dependent quark distributions in 6-quark clusters extended from a pQCD model, the polarized structure function of deuterons is investigated. Nuclear effects due to the presence of spin-1 isosinglet 6-quark clusters in the deuteron is obtained. It can be found that the calculated results with nuclear effects can better fit the SLAC E155 experimental data than that without nuclear effects.

Key words nuclear effect, deuteron, quark cluster, polarized structure function

Inelastic lepton scattering from nucleons (nuclei) has been used over the past thirty years to obtain an ever-increasing knowledge of the distribution of the partons that make up the nucleon (bound nucleon), namely gluons and up, down, strange, and perhaps charmed quarks. It is one of the great successes of QCD that the same parton distribution can be used to describe the unpolarized inelastic structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$. The parton distribution functions depend on x, the fractional momentum carried by the struck parton, and Q^2, the four-momentum transfer squared of the exchanged virtual photon, as well as many other high energy physical processes. In 1982, the European Muon Collaboration (EMC)[1] discovered in unpolarized deep inelastic scattering the difference of the structure function for a bound nucleon measured on a nuclear target and that of a free nucleon. This phenomenon is well-known as the EMC effect, which implies that the quark distributions are different for a bound and a free nucleon.

The F_1 and F_2 structure functions are sensitive to the helicity-averaged parton distributions. Recent improvements in polarized lepton beams and targets have made it possible to make increasingly accurate measurements of two additional structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$, which depend on the difference in parton distributions with helicity either aligned or anti-aligned with the spin of the parent particles[2]. In the naive quark-parton model (QPM), the nucleon is composed of quarks which have no orbital angular momentum, and there are no polarized gluons present. In this simple picture, the unpolarized structure function $F_1(x, Q^2)$ and polarized structure function $g_1(x, Q^2)$ can be simply expressed as the charge weighed sum and difference between momentum distributions for quark helicities aligned parallel ($q^\uparrow$) and antiparallel ($q^\downarrow$) to the longitudinally polarized nucleon:

$$F_1(x, Q^2) = \frac{1}{2}\sum_i e_i^2[q_i^\uparrow(x, Q^2) + q_i^\downarrow(x, Q^2)], \tag{1}$$

$$g_1(x, Q^2) = \frac{1}{2}\sum_i e_i^2[q_i^\uparrow(x, Q^2) - q_i^\downarrow(x, Q^2)] \equiv \frac{1}{2}\sum_i e_i \Delta q_i(x, Q^2). \tag{2}$$

The charge of quark flavor u, d, and s is denoted by

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e_i and $q_i^{\uparrow(\downarrow)}(x, Q^2)$ are the quark plus antiquark momentum distribution.

In 1987, the EMC reported results from a polarized muon-proton scattering experiment at CERN which puzzled the particle and nuclear physics communities. Contrary to the prediction of the naive quark model, the EMC found that a small fraction of the proton spin is attributed to the spins of the quarks (the socalled "spin crisis")[3]. Subsequent precision measurements are consistent with the original experimental results, but the theoretical interpretation has become more complex. It is now believed that in additional to the quarks, the orbital angular momentum and gluons may contribute significantly to the proton's spin. The polarized structure functions are interesting not only in opening a new degree of freedom with which to explore the detailed structure of the nucleon, but also for making a precise test of QCD via Bjorken sum rule which is a strict QCD prediction[4].

It has been commonly considered that the nuclear effects in the deuteron are negligibale, and its structure functions is regarded as the sum of the structure functions of the proton and neutron. However, Gomez et al[5] found that the deuteron has a significant EMC effect. In addition, the E665 experimental result[6] suggests the presence of nuclear shadowing effects in the deuteron. The analysis by Epele et al[7] also shows a significant nuclear effect 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[8]. The work by Lassila and Sukhatme[9] shows that the quark cluster model (QCM) can give a good unified explanation for the experimental data of the EMC effect in whole x region. Spin-dependent effects in the QCM of the deuteron and ^{3}He were investigated by Benesh and Vary[10]. But there were no detailed 6-quark clusters quark distribution by them. Several years ago, Brodsky, Burkardt and Schmidt provided a reasonable description of the spin-dependent quark distributions of the nucleon in a pQCD based model[11]. We extended this analysis to the description of the spin-dependent quark distributions in a 6-quark cluster[12]. Within this framework, the ratio of the deuteron structure function to the free nucleon structure function can be well described. In this paper, by means of the polarized quark distributions in a 6-quark cluster and the isospin symmetry in the deuteron, the nuclear effects of polarized structure function in the deuteron is investigated.

According to Ref.[12], in the region $z \to 1$, where z is the lightcone momentum fraction carried by a given quark or antiquark in the 6-quark cluster ($0 \leqslant z \leqslant 1$), pQCD can give rigorous predictions for the behavior of distribution functions. In particular, it predicts the helicity retention which means that the helicity of a valence quark will match that of the parent quark cluster. Explicitly the quark distributions of a spin-1 isosinglet 6-quark cluster satisfy the counting rule[13]

$$Q_6(z) \sim (1-z)^p, \tag{3}$$

where $p = 2n - 1 + 2\Delta s_z$, n is the minimal number of the spectator quarks and $\Delta S_z = \left| S_z^q - s_z^6 \right| = 1/2$ or $3/2$ for parallel or anti-parallel quark and the 6-quark cluster helicities, respectively. More specifically, following Ref.[11], spin distributions for the nonstrange quarks in the 6-quark cluster are parameterized as

$$Q_6^{\uparrow}(z) = \frac{1}{z^{\alpha}}[A_6(1-z)^{10} + B_6(1-z)^{11}], \tag{4}$$

$$Q_6^{\downarrow}(z) = \frac{1}{z^{\alpha}}[C_6(1-z)^{12} + D_6(1-z)^{13}]. \tag{5}$$

Here $Q = q + \bar{q}$, and $q = u + d$. The effective QCD Pomeron intercept $\alpha = 0.8$ is introduced to reflect the Regge behavior at low z. Since the nucleon overlap region is small, we make the assumption that in the formation of the 6-quark cluster the quarks retain approximately the total helicity and momentum they had in the nucleons. Therefore we can fix the parameters by using the following conditions: one condition is the requirement that the sum rules converge at $z \to 0$; the second condition is the values of the integral of the polarized quark distribution $\Delta Q_6 = 0.68$ which is $2(\Delta u + \Delta d)$ of the nucleon[14]; the third condition reflects the fact that the momentum fraction z_Q carried by the quark and antiquark of a 6-quark cluster should be half of that for a single nucleon, i.e., $z_Q = \frac{1}{2}(x_u + x_d) = 0.2605$[15]. This leaves us with one unknown parameter, which is chosen to be C_6. The three constraints give the solution set

$$A_6 = 0.9937 C_6 + 8.9047, \tag{6}$$

$$B_6 = -1.0948 C_6 - 6.3505, \tag{7}$$

$$D_6 = -1.1011 C_6 + 2.5542. \tag{8}$$

The probabilistic interpretation of the parton distributions $Q_6^\uparrow$ and $Q_6^\downarrow$ gives the bounds

$$0 < C_6 < 25.26. \tag{9}$$

Similarly, the strange quark and anti-quark distributions are parameterized as

$$S_6^\uparrow(z) = \frac{1}{z^{\alpha'}}[A_s(1-z)^{12} + B_s(1-z)^{13}], \tag{10}$$

$$S_6^\downarrow(z) = \frac{1}{z^{\alpha'}}[C_s(1-z)^{14} + D_s(1-z)^{15}], \tag{11}$$

with

$$A_s = 0.9959C_s - 3.6213, \tag{12}$$

$$B_s = -1.0678C_s + 3.9005, \tag{13}$$

$$D_s = -1.0720C_s + 0.2792. \tag{14}$$

Here $\alpha' = 1$ Regge behavior for sea quarks is adopted. The probabilistic interpretation of the parton distributions $S_6^\uparrow$ and $S_6^\downarrow$ requires

$$3.637 < C_s < 3.879. \tag{15}$$

The values of C_6 and C_s can be obtained by fitting the experimental data from Fermilab E665[6] and SLAC[5], which is the ratio of the deuteron structure function to the free nucleon structure function. If we consider only the contributions of non-strange quarks, we find the value $C_6 = 10$. The strange quark in the 6-quark clusters in the deuteron only gives a very small modification, and there is no significant change in its effect when the free parameter C_s varies in the admissible range $[3.637, 3.879]$. In the following calculation we use $C_6 = 9.5$, $C_s = 3.8$.

Now we begin with the discussion of the application of the quark-cluster model to polarized DIS with the deuteron. Without taking into account of the nuclear effects due to the presence of 6-quark clusters in the deuteron, only the depolarization of the proton and neutron in the d-wave component of the deuteron wave function. The spin-dependent structure function can be written as

$$g_1^D(x) = \left(p_s - \frac{1}{2}p_d\right)\frac{[g_1^p(x) + g_1^n(x)]}{2}, \tag{16}$$

where $p_s = 0.957$ and $p_d = 0.043$ denote the probabilities for finding the deuteron in an s or d wave, respectively. In the presence of 6-quark clusters, $g_1^D(x)$ can be given by[10]

$$g_1^D(x) = \left[(p_s - p_{6s}) - \frac{1}{2}(p_d - p_{6d})\right] \times \frac{[g_1^p(x) + g_1^n(x)]}{2} + \frac{1}{2}p_6 g_1^6\left(\frac{x}{2}\right), \tag{17}$$

where $p_{6s} = 0.047$ and $p_{6d} = 0.007$, the probabilities for creating a 6-quark cluster in the s-and d-states, were calculated by Benesh and Bary[10], $p_6 = p_{6s} + p_{6d}$ and g_1^6 is the spin-dependent structure function of a spin-1, isosinglet 6-quark cluster,

$$g_1^6(z) = \frac{1}{18}[5\Delta Q_6(z) + 2\Delta S_6(z)], \tag{18}$$

where $\Delta Q_6(z) = Q_6^\uparrow(z) - Q_6^\downarrow(z)$ and $\Delta S_6(z) = S_6^\uparrow(z) - S_6^\downarrow(z)$.

Employing Eq. (16) and (17), we can calculate the polarized structure function g_1^D without nuclear effects and with nuclear effects, and obtain the xg_1^D in order to compare with the experimental data. In our calculation, the polarized parton distribution functions for the proton are taken from the new version of the LSS (Lead-Sidorov-Stamenev) parameterization[16]. The neutron structure function g_1^n can be obtained by means of the isospin symmetry, i.e. $\Delta u^p(x) = \Delta d^n(x)$, $\Delta d^p(x) = \Delta u^n(x)$, $\Delta s^p(x) = \Delta s^n(x)$.

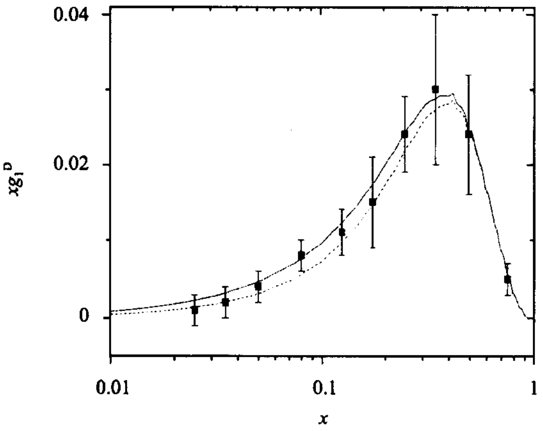

Fig.1. The xg_1^D and the comparison with the SLAC E155[17]. The solid curve corresponds to including contributions of the 6-quark clusters, i.e. nuclear effects. The dashed curve denotes the results without 6-quark clusters in the deuteron.

The theoretical results are given in Fig.1. In this figure, the solid curve denote the xg_1^D with the nuclear effect due to 6-quark clusters, the dashed curve corresponds to not considering the 6-quark clusters. The experimental data are taken from the SLAC E155 experiment, which are the new precision measurements of the deuteron spin structure function xg_1^D[17] obtained from the deep inelastic scatterings by 48.3GeV electrons on polarized deuterons in the kinematic range $0.01 < x < 0.9$ and $1 < Q^2 <$

$40\mathrm{GeV}^2$. In the range $0.48 < x < 0.9$, the calculated results with nuclear effects are almost the same as that without considering the 6-quark cluster. In the range $0.01 < x < 0.48$, the xg_1^D with nuclear effects are within error bars of the presently available data. Obviously, it can be found that the calculated results with nuclear effects can better fit the SLAC E155 experimental data than that without nuclear effects. Therefore, on the one hand, we suggest more accurate polarized deep inelastic scattering experiments on the deuteron in order to confirm the nuclear effects. On the other hand, the nuclear effects in the deuteron could be further observed in the future polarized proton-deuteron Drell-Yan process at FNAL, HERA and RHIC[18].

References

1 EMC Collab, Aubert J J et al. Phys. Lett., 1983, **B123**:275

2 Abe K et al. Phys. Rev., 1998, **D58**:112003

3 Lampe B, Reya E. Phys. Rep., 2000, **332**:1

4 Bjorken J D. Phys. Rev., 1966, **148**:1467

5 Gomez J et al. Phys. Rev., 1994, **D49**:348

6 Fermilab E665 Collaboration, Adams M R et al. Phys Rev. Lett., 1995, **75**:1466

7 Epele L N et al. Phys. Lett., 1992, **B275**:155

8 Thomas A W. Nucl. Phys., 1991, **B532**:177

9 Lassila K E, Sukhatme U P. Phys. Lett., 1985, **B209**:343

10 Benesh C J, Vary J P. Phys. Rev., 1991, **C44**:2175

11 Brodsky S J, Burkardt M, Schmidt I. Nucl. Phys., 1995, **B441**:197

12 Schmidt I, YANG J J. Eur. Phys. J., 2001, **C20**:63

13 Brodsky S J, Lepage G P. in Proceedings 1979 Summer Inst. on Particle Physics, SLAC (1979); Gunion J F. Phys. Rev., 1974, **D10**:242; Blankenbecler, Brodsky S J. Phys. Rev., 1974, **D10**:2973

14 Stiegler U. Phys. Rep., 1996, **277**:1

15 Martin A D, Stirling W J, Roberts R G. Phys. Lett., 1993, **B306**:145; Phys. Rev., 1994, **D50**:6734

16 Leader E, Sidorov A V, Stamenov D B. Eur. Phys. J., 2002, **C23**:479

17 Anthony P L et al. Phys. Lett., 1999, **B463**:339

18 DUAN Chun-Gui et al., chin phys. Lett., to be pnblished

氘核极化结构函数的核效应*

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摘要 极化深度非弹性散射是研究质子、氘核内部部分子精细结构的有利工具. 利用基于微扰QCD模型得到的6夸克集团内部自旋夸克的分布函数,研究了氘核极化结构函数的核效应. 发现考虑了核效应后的氘核极化结构函数比没有考虑核效应的结果能更好地符合SLAC E155的实验数据.

关键词 核效应 氘核 夸克集团 极化结构函数

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