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A.V.Sidorov[1], M.V.Tokarev[2]

NUCLEAR EFFECT IN DEUTERON, Q^2-EVOLUTION OF $F_3^N(x,Q^2)$ STRUCTURE FUNCTION AND GROSS—LLEWELLYN SMITH SUM RULE

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[1]E-mail: sidorov@thsun1.jinr.dubna.su
[2]E-mail: tokarev@sunhe.jinr.dubna.su

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1 Introduction

The CCFR collaboration has recently reported on new high statistics data of the nucleon structure function $F_3^N(x, Q^2)$ [1, 2]. The experiment has been carried out using a neutrino beam at the Fermilab Tevatron. The data together with the previous ones [3, 4] make it possibile to analyze in detail the Q^2-dependence of the nucleon structure function within the framework of QCD and to verify the Gross-Llewellyn Smith (GLS) sum rule [5]. The theoretical analysis of the data was made by the members of the CCFR collaboration [6] using the direct integration of the Altarelli-Parisi equation [7]. The Q^2-evolution of the moments of the structure function F_3^N based on the solution of the corresponding renormalization-group equation was carried out in [5, 8]. The method of SF reconstruction over their Mellin moments based on SF expansion over the Jacobi polynomials [9, 10, 11] was used in [5]. The method was shown to be very effective to control higher perturbative QCD corrections and to investigate sensitivity of the parameter $\Lambda_{\overline{MS}}$ to them.

Note that the nuclear effects themselves (Fermi motion, off-mass corrections, shadowing etc.) are very important to extract nucleon deep-inelastic structure functions (F_2^N, g_1^N, F_3^N) from experimental data for deuteron and heavy nucleus. They should be included in the joint QCD analysis of nucleon structure functions.

The nuclear effect of relativistic Fermi motion for the spin-independent - F_2^D structure function in the covariant approach in the light cone variables [12] was analyzed in [13]. The covariant approach in the light-cone variables is based on the relativistic deuteron wave function (RDWF) with one nucleon on mass shell. The RDWF depending on one variable - the virtuality of nucleon $k^2(x, k_\perp)$, can be expressed via the Dpn vertex function $\Gamma_a(x, k_\perp)$. This model has been successfully used for the description of the deuteron electromagnetic formfactors and some processes involving polarized and unpolarized deuteron [12, 14]. As shown in [13], the structure function ratio $R_F^{D/N} = F_2^D/F_2^N$ increases with x and reaches 6% at $x \simeq 0.7$. The dependence of $R_F^{D/N}$ on x is similar to the EMC one on heavy nucleus. The same relativistic approach and the deuteron model have been used [15] to describe the spin-dependent structure function g_1^D and to estimate a nuclear effect in the $\vec{\mu} + \vec{D} \rightarrow \mu + X$ process. It has been found that the ratio $R_g^{D/N} = g_1^D/g_1^N$ is practically independent of x and Q^2 over a wide kinematic range of $x = 10^{-3} - 0.7$, $Q^2 = 1 - 80\ (GeV/c)^2$ and attains ~ 0.9. The obtained results on the ratios $R_F^{D/N}$, $R_g^{D/N}$ allow one to consider that the used deuteron model takes into account correctly the spin structure of deuteron and relativistic Fermi motion of nucleon in the deuteron. Therefore the study of the effect of relativistic Fermi motion for the SF xF_3^D in the proposed relativistic approach is also actual and can give important information on the nucleon and deuteron structure.

In the present paper the covariant approach in the light-cone variables and the deuteron model [12] are used to consider the deep-inelastic neutrino-deuteron scattering and to estimate a nuclear effect in this process. We have calculated the deuteron SF $F_3^D(x, Q^2)$ and compared results with available experimental data [4]. The dependence of the structure function ratio $R_F^{D/N}(x, Q^2) = F_3^D(x, Q^2)/F_3^N(x, Q^2)$ on x and Q^2 is investigated. This ratio characterizes the nuclear effect in the deuteron for the $\nu + D \rightarrow \mu^- + X$ process. The ratio $R_F^{D/N}$ is practically independent of Q^2 over a wide kinematic range of $x = 10^{-3} - 0.7$, $Q^2 = 1 - 500\ (GeV/c)^2$. We have supposed that the ratio $R_F^{D/N}$ reproduces approximately the ratio $R_F^{A/N}$ and the former has been used for the QCD analysis of experimental data of the CCFR collaboration. The Q^2 dependence of the GLS sum rule is verified with taking nuclear effect into account. The correction $(\delta S/S)_{GLS}$ for the GLS integral $S_{GLS}(x,Q^2)$ is found.

2 Model of Relativistic Deuteron

The cross section of deep-inelastic neutrino-deuteron scattering in a one-photon approximation is expressed via the imaginary part of the forward scattering amplitude of the virtual W-boson on the deuteron - $W^D_{\mu\nu}$. The latter is related to the deuteron structure functions $F^D_{1,2,3}(\nu,Q^2)$ as follows

$$W^D_{\mu\nu} = -(g_{\mu\nu} - q_\mu q_\nu/q^2)\cdot F^D_1 + p^*_\mu p^*_\nu \cdot F^D_2/\nu + i\epsilon_{\mu\nu\alpha\beta}\, q^\alpha p^\beta \cdot F^D_3/\nu. \quad (1)$$

Here q,p are the momenta of W-boson and deuteron, M is the deuteron mass, $Q^2 = -q^2 > 0, \nu = (pq), p^*_\mu = p_\mu - q_\mu(pq)/q^2$.

In a relativistic impulse approximation (RIA) the forward scattering amplitude of the virtual W-boson on the deuteron $A^D_{\mu\nu}$ is expressed via a similar scattering amplitude on the nucleon $A^N_{\mu\nu}$ as follows

$$A^D_{\mu\nu}(q,p) = \int \frac{d^4k_1}{(2\pi)^4 i} Sp\{A^N_{\mu\nu}(q,k_1)\cdot T(s_1,k_1)\}. \quad (2)$$

Here $T(s_1,k_1)$ is the amplitude of forward $\bar{N} - D$ scattering and the notation $s_1 = k^2 = (p-k_1)^2$ is used. Integration is carried out with respect to the active nucleon momentum k_1. Integral (2) is calculated in the light-cone variables ($k_\pm = k_0 \pm k_3, k_\perp$). The peculiar points of integrand (2) on the plane of the complex variable $k_\perp$ are due to the peculiarities of the nucleon virtualities k_1^2 and k^2. Some of the peculiarities are due to the propagators $\sim (m^2 - k_1^2)^{-1}$, $(m^2 - k^2)^{-1}$. The others are related to the Dpn vertex and the amplitude $A^N_{\mu\nu}$.

The integral is not zero if the region of integration on k_+ is restricted

$$0 < k_+ < p_+ - k_+. \quad (3)$$

Taking into account only a nucleon pole in the unitary condition for the amplitude $T(s_1,k_1)$ and the relation between the RDWF and the vertex function $\Gamma_\alpha(k_1)$: $\psi(k_1) = \Gamma_\alpha\cdot(m+\hat{k}_1)^{-1}$, the antisymmetrical part of the deuteron tensor $W^D_{\mu\nu}$ can be written as

$$W^D_{\mu\nu} = W^{\alpha\beta}_{\mu\nu}\cdot\rho^{(S)}_{\alpha\beta} \quad (4)$$

$$W^{\alpha\beta}_{\mu\nu} = \int \frac{d^4k}{(2\pi)^4 i}\delta(m^2-k^2)\theta(k_0)\theta(p_+ - k_+)\; Sp\{w^N_{\mu\nu}\cdot\bar{\psi}^\alpha(k_1)\cdot(m+\hat{k})\cdot\psi^\beta(k_1)\}. \quad (5)$$

Here the θ-function and light-cone variables are used. The tensor $\rho^{(S)}_{\alpha\beta}$ is the symmetrical part of the deuteron polarization density matrix. The symmetrical part of the deuteron tensor $W^D_{\mu\nu}$ is expressed in the form similar to (4,5). The vertex function $\Gamma_\alpha(k_1)$ is defined by 4 scalar functions $a_i(k_1^2)$ and takes the form [16]

$$\Gamma_\alpha(k_1) = k_{1\alpha}[a_1(k_1^2) + a_2(k_1^2)(m+\hat{k}_1)] + \gamma_\alpha[a_3(k_1^2) + a_4(k_1^2)(m+\hat{k}_1)]. \quad (6)$$

The relativization procedure of the deuteron wave function ψ_α has been proposed and the scalar functions $a_i(k_1^2)$ have been constructed in [17]. The functions a_i were parametrized as the sum of pole terms. Some pole positions and residues were found from the comparison of our RDWF with the known nonrelativistic one in the nonrelativistic limit. For the latter the Paris wave function [18] was taken. The other parameters were fixed from the description of the static characteristics of the deuteron (electric charge - $G_e(0) = 1(e)$, magnetic - $G_m(0) = \mu_D(e/2M)$ and quadrupole - $G_Q(0) = Q_D(e/M^2)$ moments) in the relativistic impulse approximation.

The calculation of (5) in the light-cone variables gives the final expression for the deuteron SF F_3^D

$$F_3^D(\alpha, Q^2) = \int_\alpha^1 dx\ d^2k_\perp\ \Delta(x, k_\perp) \cdot F_3^N(\alpha/x, Q^2). \tag{7}$$

The nucleon SF is defined as $F_3^N = (F_3^{\nu N} + F_3^{\bar{\nu} N})/2$, $\alpha = -q^2/2(pq)$. The function $\Delta(x, k_\perp)$ describes the left (right)-helicity distribution for an active nucleon (antinucleon) that carries away the fraction of deuteron momentum $x = k_{1+}/p_+$ and transverse momentum $k_\perp$. It is expressed via the RDWF $\psi_\alpha(k_1)$ as follows

$$\Delta(x, k_\perp) \propto Sp\{\bar{\psi}^\alpha(k_1) \cdot (m + \hat{k}) \cdot \psi^\beta(k_1) \cdot \hat{q} \cdot \sigma^{\mu\nu} \cdot \gamma_5 \cdot \rho_{\alpha\beta}^{(S)} \cdot \epsilon_{\mu\nu\gamma\delta} q^\gamma p^\delta\}, \tag{8}$$

where $\rho_{\alpha\beta}^{(S)}$ is the polarization density matrix for unpolarized deuteron. Note that in the approach using the distribution function $\Delta(x, k_\perp)$ includes not only usual S- and D-wave components of the deuteron but also a P-wave component. The latter describes the contribution of $N\bar{N}$-pair production. The contribution of this mechanism is small over a low momentum range ($x < 1$), but it might be considerable in a high momentum one ($x > 1$).

3 Structure Function $F_3^D(x, Q^2)$

In the relativistic impulse approximation the deuteron SF F_3^D is defined by equation (6). We calculate F_3^D using the RDWF [17]. The parametrization of the nucleon SF F_3^N and parton distributions are taken from [8, 19, 20, 21].

Figure 1 shows the dependence of $xF_3^D(x, Q^2)$ on x at $Q^2 = 3, 10, 500\ (GeV/c)^2$. The displacement of the curves to a low x-range with increasing Q^2 is observed. The SF xF_3^D decreases at $x < 0.1$ and increases at $x > 0.1$ with growing Q^2. The experimental data for xF_3^D [4] at $Q^2 = 3, 11\ (GeV/c)^2$ are shown in Figure 2 too. Taking into account large errors an agreement between the calculated results and the experimental data to be considered reasonable. We would like to note that the general shape of the deuteron SF is similar to the nucleon one.

Figure 2 presents the results for xF_3^D obtained with different parton distributions [19, 20, 21]. In the parton model the nucleon SF is expressed via the momentum distributions of valence quarks $xF_3^N = xu_V + xd_V$. One can see from Figure 2 that all curves practically coincide. Note also that the calculated curves lie above the ones obtained with parametrization xF_3^N [8] at $x < 4 \cdot 10^{-2}$. We consider that high statistics experimental data for a deuteron SF xF_3^D are extremely important to obtain independent and complementary information on valence quark distributions - $u_V(x, Q^2)$, $d_V(x, Q^2)$ and to choose between different nucleon models.

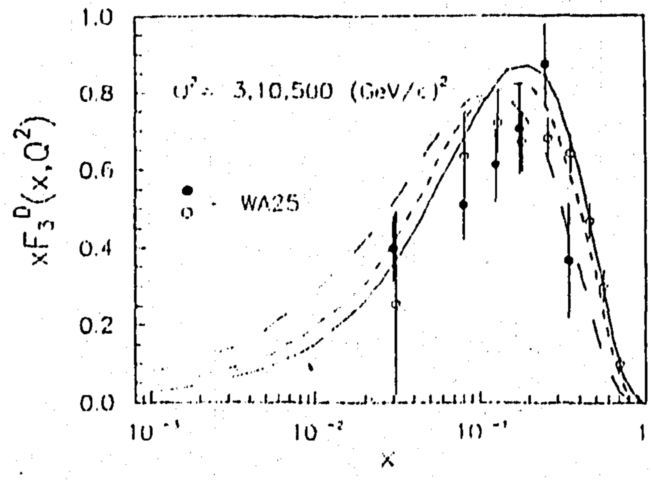

Figure 1. Deep-inelastic deuteron structure function $xF_3^D(x,Q^2)$. Theoretical results have been obtained with the nucleon parametrization xF_3^N taken from [8] : —— - 3 $(GeV/c)^2$, - - - - 10 $(GeV/c)^2$, — — - 500 $(GeV/c)^2$. Experimental data [4]: •−3 $(GeV/c)^2$, ∘ − 11 $(GeV/c)^2$.

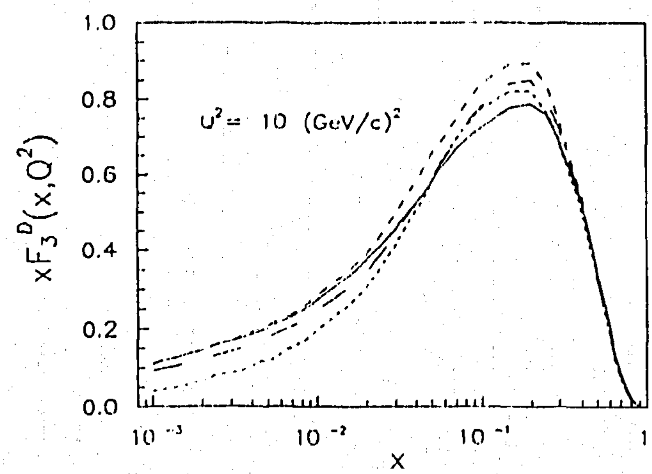

Figure 2. Deep-inelastic deuteron structure function $xF_3^D(x,Q^2)$. Theoretical results have been obtained with the parton distributions taken from: - - - [8], – – – [19], — — [20], —— [21].

4 Nuclear Effect in the Deuteron

The nuclear effect in a deuteron for the $\nu + D \to \mu^- + X$ process is described by the ratio $R_F^{D/N}(x,Q^2) = F_3^D(x,Q^2)/F_3^N(x,Q^2)$. Figure 3 shows the dependence of the $R_F^{D/N}$ ratio on x. It has been found that the ratio $R_F^{D/N}$ is practically independent of the parametrization of the parton distributions [19, 20, 21] and the nucleon SF [8] over a wide kinematic range of $x = 10^{-3} - 0.7$, $Q^2 = 1 - 500\ (GeV/c)^2$. The curve has an oscillatory feature and cross-over point $x_0 : R_F^{D/N}(x_0) = 1$, $x_0 \simeq 0.03$. The effect of relativistic Fermi motion decreases with x at $x < 6 \cdot 10^{-3}$.

Thus, the obtained results give us evidence that the function $R_F^{D/N}$ is a universal one. Defined by the structure of the RDWF, it can be used to extract the nucleon SF F_3^N from the experimentally known deuteron one

$$F_3^N(x,Q^2) = [R_F^{D/N}(x)]^{-1} \cdot F_3^D(x,Q^2). \qquad (9)$$

The obtained results (Fig.3) clearly demonstrate that the nucleon SF F_3^N extracted from deuteron data can be modified by nuclear medium.

The performed analysis of the nuclear correction for the nucleon SF also allows one to consider the influence of the nuclear effect on the GLS sum rule [22]:

$$S_{GLS} = \int_0^1 F_3^N(x)dx. \qquad (10)$$

In the parton model the nucleon SF can be expressed via the valence u_V, d_V parton distributions and the sum rule (10) can be written as follows

$$S_{GLS}(x,Q^2) = \int_x^1 [u_V(y,Q^2) + d_V(y,Q^2)]dy. \qquad (11)$$

The value of the integtal tends to the parton model prediction $S_{GLS}(x) \to 3$ at $x \to 0$.

Figure 4 shows the dependence of the GLS integral $S_{GLS}(x,Q^2)$ on x for $Q^2 = 3$ and 500 $(GeV/c)^2$. The integral increases with Q^2 at $x < 0.01$ and decreases at $x > 0.01$. It should be noted that the obtained value of $S_{GLS}(x,Q^2)$ at $x = 10^{-3}$ is lower than the expected one from the GLS sum rule. For $Q_0^2 = 3$ and 500 $(GeV/c)^2$ we have obtained $S_{GLS}(x = 10^{-3}) = 2.41$ and 2.66, respectively. The CCFR group result at the scale $Q^2 = 3\ (GeV/c)^2$ is $S_{GLS} = 2.50 \pm 0.018(stat) \pm 0.078(syst)$ [2].

We have used the result on the $R_F^{D/N}$ ratio to estimate the nuclear correction for the GLS integral

$$S_{GLS}(x,Q^2) = \int_x^1 F_3^N(y,Q^2)dy. \qquad (12)$$

The obtained results for the correction $(\delta S/S)_{GLS}$, where $\delta S_{GLS} = S_{GLS}^{R=1}(Q^2) - S_{GLS}^{R=F_3^D/F_3^N}$, due to the nuclear effect of Fermi motion are given in Figure 4. It is seen that the nuclear correction is less than 1% at $x < 0.4$.

5 The QCD Analysis of xF_3^N Structure Function and GLS Sum Rule

In this section we perform the QCD analysis of the xF_3^N experimental data [1, 2] taking into account the nuclear effect ratio. We consider as a first approximation that $R_F^{Fe/N} = R_F^{D/N} \equiv$

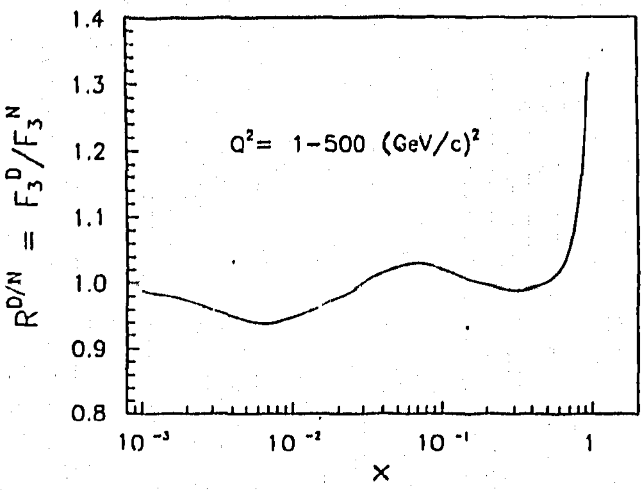

Figure 3. The $R_F^{D/N} = F_3^D/F_3^N$ ratio of the structure functions for deep-inelastic neutrino-deuteron scattering.

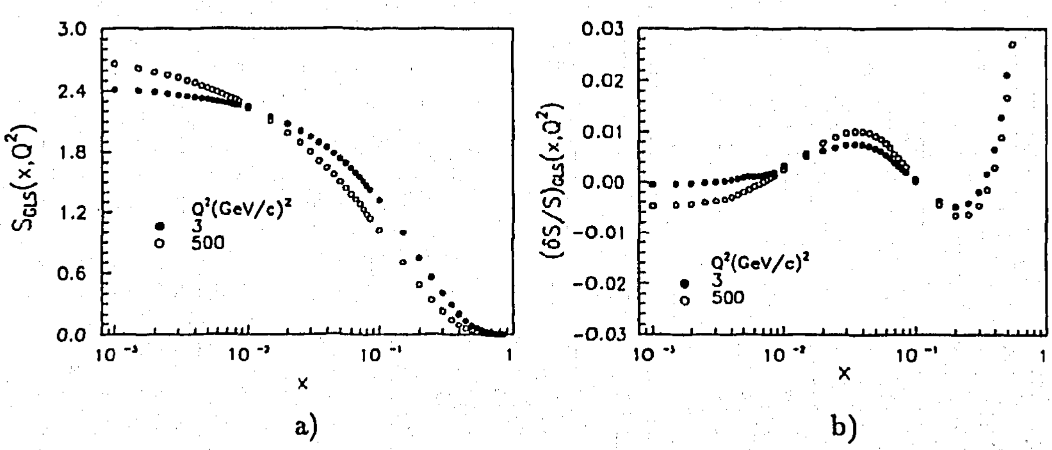

Figure 4. The Gross-Llewellyn Smith integral $S_G(x,Q^2)$ and the correction $(\delta S/S)_{GLS}$ due to the nuclear effect.

R. Experimental high statistics data on the $R_F^{A/D}(x,Q^2) = F_3^A/F_3^D$ ratio are required for a more detailed analysis of the nuclear structure function xF_3^A.

We shall use the method based on the SF expansion over the set of the Jacobi polynomials. This method has been developed in [9]-[11] and applied to analyze the xF_3^N data of the CCFR collaboration in [10, 11, 23, 24]. Using a simple shape of the SF at fixed momentum transfer Q_0^2

$$xF_3^N(x,Q_0^2) = Ax^b(1-x)^c(1+\gamma x), \tag{13}$$

and involving the experimental points with $Q^2 > 10\ (GeV/c)^2$ in the analysis in order to avoid the HT and TMC contribution, we have determined in the NLO of QCD the values of free parameters A,b,c,γ and $\Lambda_{\overline{MS}}$. The results are presented in Tables 1 and 2 for different points Q_0^2.

Table 1. The results of the NLO QCD fit of the CCFR xF_3^N SF data for $f = 4$, $Q^2 > 10\ (GeV/c)^2$, with the corresponding statistical errors. $\chi^2_{d.f.}$ is the χ^2-parameter *normalized to the degree of freedom d.f.*. Expansion over 12 Jacobi polynomials is used

	$R = F_3^{Fe}/F_3^N$			$R = 1$		
$Q_0^2\ (GeV/c)^2$	$\chi^2_{d.f.}$	$\Lambda^{(4)}_{\overline{MS}}$	S_{GLS}	$\chi^2_{d.f.}$	$\Lambda^{(4)}_{\overline{MS}}$	S_{GLS}
3	77.8/60	202±26	2.346	74.6/60	206 ± 35	2.414
5	77.2/60	202±33	2.371	74.1/60	209 ± 33	2.454
10	75.7/60	204±36	2.413	73.8/60	211 ± 36	2.504
100	74.8/60	207±34	2.527	75.0/60	211 ± 34	2.642
500	75.3/60	206±35	2.595	76.8/60	209 ± 30	2.719

A stable value of $\Lambda^{(4)}_{\overline{MS}}$ is in agreement with the result of [5] and is not sensitive to nuclear effects. The value of the GLS sum rule is calculated for different points Q_0^2 as a first Mellin moment of the quark distribution

$$S_{GLS}(0,Q^2) = \int_0^1 \frac{dx}{x} Ax^b(1-x)^c(1+\gamma x). \tag{14}$$

The systematic error of S_{GLS} is about ±0.2. (More details of the fit procedure see in [5].)

The Q^2–dependence of the GLS sum rule is in qualitative agreement with perturbative QCD predictions and with the results of [5] with fixed γ and equal to 0.

The difference $\delta S_{GLS}(Q^2) = S_{GLS}^{R=1}(Q^2) - S_{GLS}^{R=F_3^{Fe}/F_3^N}(Q^2)$ characterizes the contribution of the nuclear effect and increases from 0.057 to 0.124 while Q^2 changes from 3 to 500 $(GeV/c)^2$, respectively.

This fact is strongly related to a complicated behaviour of the ratio R at small x and a large contribution of this region to the GLS sum rule.

Table 2. The parameters of the SF distribution $xF_3^N(x,Q_0^2) = Ax^b(1-x)^c(1-\gamma x)$ at $Q_0^2 = 3\ (GeV/c)^2$

	$R = F_3^{Fe}/F_3^N$	$R = 1$
A	7.311 ± 0.187	6.898 ± 0.250
b	0.852 ± 0.012	0.819 ± 0.019
c	3.298 ± 0.055	2.491 ± 0.111
γ	-0.079 ± 0.074	-0.867 ± 0.067

Conclusion

We have considered a deep-inelastic neutrino-deuteron scattering in the framework of the covariant approach in the light-cone variables. The spin-dependent structure function $F_3^D(x,Q^2)$ has been calculated and compared with experimental data. The results are in reasonable agreement with the data. The estimate of the effect of relativistic Fermi motion in the deuteron described by the ratio $R_F^{D/N}$ is obtained. It is an important argument that nuclear medium alters considerably the structure of a free nucleon in the process. The procedure of extraction of the nucleon SF $F_3^N(x,Q^2)$ takes the relativistic deuteron structure into account correctly and can be used to analyze other experimental data. The QCD prediction for Q^2 dependence of S_{GLS}^{QCD} is given by $S_{GLS}^{QCD}(Q^2) = 3\,[1-\alpha_s(Q^2)/\pi + O(\alpha_s^2(Q^2)) + O(1/Q^2)]$. For $Q^2 = 3$ and $500\ (GeV/c)^2$ and for the corresponding value of $\Lambda_{\overline{MS}}^{(4)}$ taken from Table 1 S_{GLS}^{QCD} has been found to be 2.665 and 2.846, respectively. These values are higher than the results presented in Table 1 for the corresponding concrete values of Q^2 and $\Lambda_{\overline{MS}}^{(4)}$, and the situation is in qualitative agreement with the results of [5]. One can see from Figure 4(a,b) that the $R_F^{D/N}$ ratio applied directly to the parametrization of SF obtained in [8] without taking nuclear effect into account, slightly changes the GLS sum rule. On the other hand, the results presented in Table 1 show, that the QCD analysis taking the $R_F^{D/N}$ ratio into account affects considerably the GLS sum rule over a wide region of Q^2 and especially at high Q^2. Therefore for the QCD analysis of SF and precise determination of the GLS sum rule which is important for comparison of higher order perturbative QCD predictions [25], nuclear effect should be taken into account in addition to a higher twist contribution and target mass corrections.

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Сидоров А.В., Токарев М.В. E2-95-90

Ядерный эффект в дейтроне, Q^2-эволюция структурной функции $F_3^N(x,Q^2)$ и правило сумм Гросса—Льюеллина Смита

Рассматривается процесс глубоконеупругого рассеяния нейтрино на дейтроне в рамках ковариантного подхода в переменных светового конуса. В релятивистском импульсном приближении на основе релятивистской волновой функции дейтрона вычисляется структурная функция $F_3^D(x,Q^2)$. Результаты расчетов сравниваются с экспериментальными данными. Исследуется отношение структурных функций $R_F^{D/N} = F_3^D/F_3^N$, описывающее ядерный эффект в дейтроне, в зависимости от x и Q^2. Оценена величина ядерного эффекта, обусловленная фермиевским движением нуклонов. Проверено правило сумм Гросса—Льювеллина Смита и исследована зависимость интеграла $S_{GLS}(x,Q^2)$ от x и Q^2. Проведена Q^2-эволюция структурной функции xF_3^N в рамках КХД с учетом ядерного эффекта для $S_{GLS}(x,Q^2)$ и показано, что ядерный эффект должен учитываться при проверке правила сумм Гросса—Льювеллина Смита.

Работа выполнена в Лаборатории высоких энергий и Лаборатории теоретической физики им. Н.Н.Боголюбова ОИЯИ.

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Sidorov A.V., Tokarev M.V. E2-95-90

Nuclear Effect in Deuteron, Q^2-Evolution of $F_3^N(x,Q^2)$ Structure Function and Gross—Llewellyn Smith Sum Rule

Deep-inelastic neutrino-deuteron scattering in the covariant approach in the light-cone variables is considered. The deuteron structure function $F_3^D(x,Q^2)$ is calculated in the relativistic impulse approximation on the basis of the relativistic wave function. The results are compared with available experimental data. The nuclear effect of relativistic Fermi motion described by the ratio $R_F^{D/N} = F_3^D/F_3^N$ is estimated. The dependence of the ratio on x and Q^2 is investigated. The dependence of the Gross—Llewellyn Smith integral $S_{GLS}(x,Q^2)$ on x and Q^2 is considered. On the basis of the QCD analysis of the xF_3^N structure function the correction for $S_{GLS}(x,Q^2)$ due to the nuclear effect is estimated and it is shown that the nuclear effect should be taken into account to verify the Gross—Llewellyn Smith sum rule.

The investigation has been performed at the Laboratory of High Energies and the Bogoliubov Laboratory of Theoretical Physics, JINR.

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Редактор Э.В.Ивашкевич. Макет Р.Д.Фоминой

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