NUCLEAR EFFECTS ON THE SPIN-DEPENDENT STRUCTURE FUNCTIONS

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We address the question how the spin-dependent nucleon structure function $g_1(x,Q^2)$ gets modified when the nucleon is bound inside a nucleus. We analyze the influence of nuclear interactions using the $\Delta-\pi$ model, known to describe well the unpolarized effect, and the free polarized parton distributions. The results for the neutron in ^{3}He and proton in ^{3}H, ^{7}Li and ^{19}F are presented, showing significant changes in the parton spin distributions and in their moments. Scattering processes off polarized ^{7}Li are suggested which could justify these theoretical calculations and shed more light on both nuclear spin structure and short distance QCD.

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1.

The influence of nuclear effects on the nucleon structure functions received enormous interest after the measurement by the European Muon Collaboration [1] of the ratio of structure functions:

$$R(x,Q^2)=\frac{F_2^{N/\mathrm{Fe}}(x,Q^2)}{F_2^{N/\mathrm{D}}(x,Q^2)}\,, \tag{1.1}$$

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followed by a series of experiments [2] confirming the nontrivial changes of the parton densities due to the nuclear environment. Many theoretical models have described correctly the Bjorken x and A-dependence [3] starting sometimes from quite different assumptions. It is therefore not easy to tell what is the underlying dynamics of the "EMC effect". In the search for new tests a polarized version of the effect was proposed some time ago [4]. In this paper we take into account theoretical and experimental progress in the knowledge of the nucleon spin.

We will study corrections to the spin-dependent structure function $g_1^N(x,Q^2)$ (where N denotes proton or neutron) by calculating deviation from unity of the ratio:

$$R_{\uparrow}^{A}(x,Q^2) = \frac{g_1^{N/A}(x,Q^2)}{g_1^N(x,Q^2)}\,. \tag{1.2}$$

Such quantity has become important due to the use of light nuclei (^{2}D, ^{3}He) in the extraction of the neutron structure function $g_1^n(x,Q^2)$ (SMC [5], E143 [6], E154 [7], HERMES [8]). The definition of $g_1^{N/A}(x,Q^2)$ requires some attention. It is the structure function of a single, polarized nucleon inside the nucleus. One should keep in mind that polarizing the nucleus, in general, results in a complicated spin combinations of nucleons and it is thus not easy to extract $g_1^{N/A}(x,Q^2)$. Only in selected cases and to certain approximation the polarization of the nucleus is equivalent to the polarization of the nucleon in the same direction. The nuclei we have chosen (^{3}He, ^{3}H and ^{7}Li, ^{19}F) are good examples of such situation.

2.

The model which describes correctly the x and A-dependence of the unpolarized EMC effect was proposed in Ref. [9]. Here we extend it to the polarized case.

We recall conventional picture of nucleus as a system of nucleons and non-nucleonic objects: Δ isobars [10] and excess pions [11] and assume that polarized deep-inelastic scattering may occur either from constituents of the nucleons or from constituents of the Δ isobars. Excess pions are spinless and do not contribute directly to polarized scattering. The momentum distributions of non-nucleonic objects come from standard nuclear physics calculations [12, 13] and are in this sense independent of the model. Such construction of the model has an important advantage: we do not have to worry what the proposed mechanism does to low energy nuclear physics.

Another important assumption is that nucleons, Δ isobars and pions contribute incoherently to the structure function of the nucleus. Thanks to that we can write the "effective nucleon" structure function in the nucleus as a sum of convolutions of isolated hadron structure functions with momentum distributions taken from nuclear physics

$$g_1^{N/A}(x,Q^2) = \int\limits_x^A \frac{dz}{z} f^N(z) g_1^N\left(\frac{x}{z}, Q^2\right) + \int\limits_x^A \frac{dz}{z} f^\Delta(z) g_1^\Delta\left(\frac{x}{z}, Q^2\right), \quad (2.1)$$

where Q^2 is the negative momentum transfer squared and

$$z = A\frac{k_+^\alpha}{k_+^A}, \qquad \alpha = N,\, \Delta,\, \pi \quad (2.2)$$

denotes light-cone $\left(k_+ = k_0 + k_\parallel\right)$ momentum fraction per nucleon of the interacting nucleon, Δ isobar or pion. The distribution functions $f^\alpha(z)$ satisfy the following sum rules:

$$\int\limits_0^A dz\ f^N(z) \ = \ 1 - \langle n_\Delta \rangle\,, \quad (2.3)$$

$$\int\limits_0^A dz\ f^\Delta(z) \ = \ \langle n_\Delta \rangle\,, \quad (2.4)$$

$$\int\limits_0^A dz\ f^\pi(z) \ = \ \langle n_\pi \rangle\,, \quad (2.5)$$

as well as the momentum conservation law

$$\sum_\alpha \int\limits_0^A dz\ z f^\alpha(z) = \sum_\alpha \langle z_\alpha \rangle = 1\,. \quad (2.6)$$

Eqs. (2.3), (2.4) represent baryon number conservation law, with $\langle n_\Delta \rangle$ and $\langle n_\pi \rangle$ defined as average numbers of Δ isobars and excess pions in nucleus, respectively.

Let us precisely discuss each contribution entering Eq. (2.1).

2.1.

In the parton model our fundamental quantity of interest, the spin-dependent nucleon structure function g_1^N, can be expressed in terms of differences between the number densities of quarks with spin parallel and anti-parallel to the longitudinally polarized parent nucleon:

$$g_1^N(x) = \frac{1}{2}\sum_{q=1}^{N_f} e_q^2 \left\{ \Delta q^N(x) + \Delta\overline{q}^N(x) \right\} , \tag{2.7}$$

where

$$\Delta q^N(x) = q_\uparrow^N - q_\downarrow^N , \quad \Delta\overline{q}^N(x) = \overline{q}_\uparrow^N - \overline{q}_\downarrow^N . \tag{2.8}$$

In the Leading-Order (LO) QCD above functions become Q^2-dependent. In the Next-to-Leading Order (NLO) g_1^N can be written as:

$$\begin{aligned} g_1^N(x,Q^2) \;=\; & \frac{1}{2}\sum_{q=1}^{N_f} e_q^2 \Bigg\{ \Delta q^N(x,Q^2) + \Delta\overline{q}^N(x,Q^2) + \frac{\alpha_s\left(Q^2\right)}{2\pi} \\ & \times \left[\Delta C_q \otimes \left(\Delta q^N + \Delta\overline{q}^N\right) + \frac{1}{N_f}\Delta C_g \otimes \Delta g \right](x,Q^2) \Bigg\} , \end{aligned} \tag{2.9}$$

where Δg is polarized gluon density ($\Delta g = g_\uparrow - g_\downarrow$), $\alpha_s\left(Q^2\right)$ is QCD running coupling constant and N_f denotes the number of active flavors. The spin-dependent Wilson coefficients ΔC_q and ΔC_g in the $\overline{\text{MS}}$ scheme can be found in Ref. [14]. The convolution $\otimes$ is defined as usual by

$$\left(f \otimes g\right)(x) \equiv \int_x^1 \frac{dz}{z} f(z) g\left(\frac{x}{z}\right) . \tag{2.10}$$

In ^{3}He with the wave function entirely in S state, two protons have opposite spins and all the spin is carried by neutron. But in realistic ^{3}He nucleus higher partial waves (S' and D) in the ground state wave function lead to the spin depolarization. Effective polarization of neutron in ^{3}He is estimated in [15] to decrease to $\mathcal{P}_n = (86 \pm 2)\%$, whereas effective polarization of single proton is $\mathcal{P}_p = (-2.8 \pm 0.4)\%$. Thanks to these quantities one can write the spin-dependent structure function $g_1^N(x,Q^2)$ from Eq. (2.1) as

$$g_1^N(x,Q^2) = \mathcal{P}_n g_1^n(x,Q^2) + 2\mathcal{P}_p g_1^p(x,Q^2) \tag{2.11}$$

for neutron in ^{3}He and as

$$g_1^N(x,Q^2) = \mathcal{P}_n g_1^p(x,Q^2) + 2\mathcal{P}_p g_1^n(x,Q^2) \tag{2.12}$$

for proton in ^{3}H. In the case of ^{7}Li we assumed that it consists of ^{4}He, where two protons and two neutrons have opposite spins, and of ^{3}H, in which we treat the spin depolarization like in Eq. (2.12).

2.2.

For nuclei with $A > 6$ we use an approximate formula [11] reproducing the effect of Fermi motion:

$$f^N(z) = \frac{3}{4}\left(\frac{m_N}{k_\mathrm{F}}\right)^3 \left[\left(\frac{k_\mathrm{F}}{m_N}\right)^2 - (z-1)^2\right], \tag{2.13}$$

for

$$-\frac{k_\mathrm{F}}{m_N} \leq z-1 \leq \frac{k_\mathrm{F}}{m_N}, \tag{2.14}$$

and $f^N(z) = 0$ otherwise. The possible corrections to this distribution turn out to be of little importance in our problem. The Fermi momenta k_F for various nuclei can be found in Ref. [16]. Here m_N is the nucleon mass.

The distribution $f^N(z)$ for ^{3}He has been extracted from Ref. [13] and assumed to describe also ^{3}H. It is worth to note that one can calculate $f^N(z)$ from nucleon momentum distribution $\rho_N(\vec{k})$ (easily accessible in terms of conventional nuclear theory) using approximate relationship [17]:

$$f^N(z) = \int d^3\vec{k}\ \rho_N(\vec{k})\,\delta\left(z - \frac{k_{\|} + \sqrt{\vec{k}^2 + m_N^2}}{m_N}\right). \tag{2.15}$$

2.3.

Even though the pions are spinless and do not directly enter Eq. (2.1), their influence comes through the sum rule (2.6) since baryons share the momentum with pions. Effectively, this requires replacement (in Eq. (2.13) and next) of $z-1$ by $z-1+\langle z_\pi\rangle$, where $\langle z_\pi\rangle$ is average momentum carried by pions (all distributions are then peaked at $1-\langle z_\pi\rangle$).

2.4.

The Δ isobar structure function $g_1^\Delta(x,Q^2)$, required in Eq. (2.1), is not known from experiment. A phenomenological construction has been presented in Ref. [10] and can be extended to the spin-dependent case in a straightforward way. We start from writing the valence part of proton and neutron polarized structure functions as:

$$g_{1v}^{p}(x,Q^2) = \frac{1}{2}\left(\frac{4}{9}\Delta u_v(x,Q^2) + \frac{1}{9}\Delta d_v(x,Q^2)\right)$$
$$= \frac{1}{2}\left(\frac{4}{9}A_0(x,Q^2) + \frac{2}{9}A_1(x,Q^2)\right), \quad (2.16)$$
$$g_{1v}^{n}(x,Q^2) = \frac{1}{2}\left(\frac{1}{9}\Delta u_v(x,Q^2) + \frac{4}{9}\Delta d_v(x,Q^2)\right)$$
$$= \frac{1}{2}\left(\frac{1}{9}A_0(x,Q^2) + \frac{1}{3}A_1(x,Q^2)\right), \quad (2.17)$$

where A_I, $I = 0, 1$ denotes the contribution in which the valence quark is struck by the virtual photon and the remaining (spectator) valence quarks are in spin and isospin I configuration. The $A_I(x,Q^2)$ can be expressed by the valence quark distributions in the proton:

$$A_0(x,Q^2) = \Delta u_v(x,Q^2) - \frac{1}{2}\Delta d_v(x,Q^2), \quad (2.18)$$
$$A_1(x,Q^2) = \frac{3}{2}\Delta d_v(x,Q^2). \quad (2.19)$$

The Δ structure function is constructed assuming the universality of the functions $A_I(x,Q^2)$ in ground state baryons. Noting that the spectator valence quarks in the Δ isobar are always in spin-isospin 1 state, one writes:

$$g_{1v}^{\Delta^{++}}(x,Q^2) = \frac{4}{9}A_1(x,Q^2) = \frac{2}{3}\Delta d_v(x,Q^2), \quad (2.20)$$
$$g_{1v}^{\Delta^{+}}(x,Q^2) = \frac{1}{3}A_1(x,Q^2) = \frac{1}{2}\Delta d_v(x,Q^2), \quad (2.21)$$
$$g_{1v}^{\Delta^{0}}(x,Q^2) = \frac{2}{9}A_1(x,Q^2) = \frac{1}{3}\Delta d_v(x,Q^2), \quad (2.22)$$
$$g_{1v}^{\Delta^{-}}(x,Q^2) = \frac{1}{9}A_1(x,Q^2) = \frac{1}{6}\Delta d_v(x,Q^2). \quad (2.23)$$

In addition we assume that the sea quarks and gluons remain in the same shape in any of the Δ isobars and neglect Fermi motion effects for the Δ isobars in our analysis. Hence $f^{\Delta}(z)$ has the form:

$$f^{\Delta}(z) = \langle n_{\Delta}\rangle\, \delta\left(z - 1 + \langle z_{\pi}\rangle\right). \quad (2.24)$$

3.

To demonstrate nuclear effects on the spin-dependent structure functions g_1^p and g_1^n, we have chosen three recent parametrizations of free polarized parton distributions in the nucleon at the next-to-leading order in the $\overline{\rm MS}$ scheme: AAC [18] (called AAC-NLO-2), LSS [19] and TBK [20]. For completeness, we also give predictions of our model using leading-order parametrization [18] (called AAC-LO). Nuclear parameters required in the calculation are extracted from Ref. [12]. For ^{3}He and ^{3}H they take the values: $\langle n_\Delta \rangle = 0.02$, $\langle n_\pi \rangle = 0.05$, $\langle z_\pi \rangle = 0.038$, whereas for ^{7}Li: $\langle n_\Delta \rangle = 0.04$, $\langle n_\pi \rangle = 0.09$, $\langle z_\pi \rangle = 0.069$. The Fermi momentum $k_{\rm F}$ for ^{7}Li is 0.86 fm^{-1}. In Eq. (2.1) g_1^Δ stands for averaged over isospin spin-dependent Δ isobar structure function.

The results are presented at $Q_0^2 = 1$ GeV^2. The first moment of the spin-dependent structure function $g_1^\beta(x, Q^2)$ (where $\beta = p,\ p/A\ , n\ , n/A$) is defined as

$$\Gamma_1^\beta \left(Q^2\right) = \int\limits_0^1 dx\ g_1^\beta(x, Q^2), \tag{3.1}$$

and its values for free proton, free neutron and for proton and neutron in various nuclei are presented in all considered parametrizations in Table I.

TABLE I

First moments $\Gamma_1^\beta \left(Q_0^2 = 1\ \text{GeV}^2\right)$.

	AAC (NLO)	AAC (LO)	LSS (NLO)	TBK (NLO)
Γ_1^p	0.129	0.144	0.129	0.113
$\Gamma_1^{p/^3\text{H}}$	0.110	0.123	0.109	0.095
$\Gamma_1^{p/^7\text{Li}}$	0.101	0.113	0.103	0.090
Γ_1^n	-0.054	-0.067	-0.050	-0.062
$\Gamma_1^{n/^3\text{He}}$	-0.057	-0.069	-0.053	-0.064

We expect our model to work for $0.1 \leq x \leq 1$, since at smaller x possible shadowing effects, not included in our calculations, may contribute significantly [21]. The question how the first moment of g_1 is modified can be answered only partially because of this limit of applicability of the model.

Defining

$$\Gamma^{\beta}_{1,\,y}\left(Q^2\right) = \int\limits_{y}^{1} dx\; g_1^{\beta}(x,Q^2), \tag{3.2}$$

in Table II we present quantities analogical to those of Table I, but integrated in the region $0.1 \leq x \leq 1$.

TABLE II

First moments $\Gamma^{\beta}_{1,\,0.1}\left(Q_0^2 = 1\ \mathrm{GeV}^2\right)$.

	AAC (NLO)	AAC (LO)	LSS (NLO)	TBK (NLO)
$\Gamma^{p}_{1,\,0.1}$	0.081	0.097	0.099	0.091
$\Gamma^{p/^3\mathrm{H}}_{1,\,0.1}$	0.067	0.080	0.082	0.075
$\Gamma^{p/^7\mathrm{Li}}_{1,\,0.1}$	0.063	0.076	0.078	0.071
$\Gamma^{n}_{1,\,0.1}$	-0.024	-0.022	-0.021	-0.020
$\Gamma^{n/^3\mathrm{He}}_{1,\,0.1}$	-0.026	-0.025	-0.024	-0.023

4.

We start the discussion from ^{3}He nucleus, since it is an ideal target to extract the neutron structure function $g_1^n(x,Q^2)$. We plotted the spin-dependent structure functions of neutron in ^{3}He and free neutron in three different NLO parametrizations in Fig. 1. From Table I and Table II one reads:

$$\frac{\Gamma_1^n}{\Gamma_1^{n/^3\mathrm{He}}} \approx \begin{cases} 0.96 & \text{for} \quad 0 \geq x \geq 1.0\,, \\ 0.89 & \text{for} \quad 0.1 \geq x \geq 1.0\,, \end{cases} \tag{4.1}$$

what means 11% decrease of the first moment of the spin-dependent structure function of neutron in ^{3}He due to nuclear effects in the range where our model gives predictions.

One should remember that in the experimental analyzes (like [7,8]) a correction for the spin depolarization described by Eq. (2.11) is often included. That is why it is interesting to see what are the corrections predicted by our model not only to the free neutron structure function $g_1^n(x,Q^2)$, but also to the function $\mathcal{P}_n g_1^n(x,Q^2) + 2\mathcal{P}_p g_1^p(x,Q^2)$. Therefore, in Fig. 2 we presented two ratios:

$$P_{\uparrow}^{^3\mathrm{He}}(x,Q^2) \;=\; \frac{g_1^{n/^3\mathrm{He}}(x,Q^2)}{\mathcal{P}_n g_1^n(x,Q^2) + 2\mathcal{P}_p g_1^p(x,Q^2)} \tag{4.2}$$

$$R_{\uparrow}^{^3\mathrm{He}}(x,Q^2) \;=\; \frac{g_1^{n/^3\mathrm{He}}(x,Q^2)}{g_1^n(x,Q^2)} \tag{4.3}$$

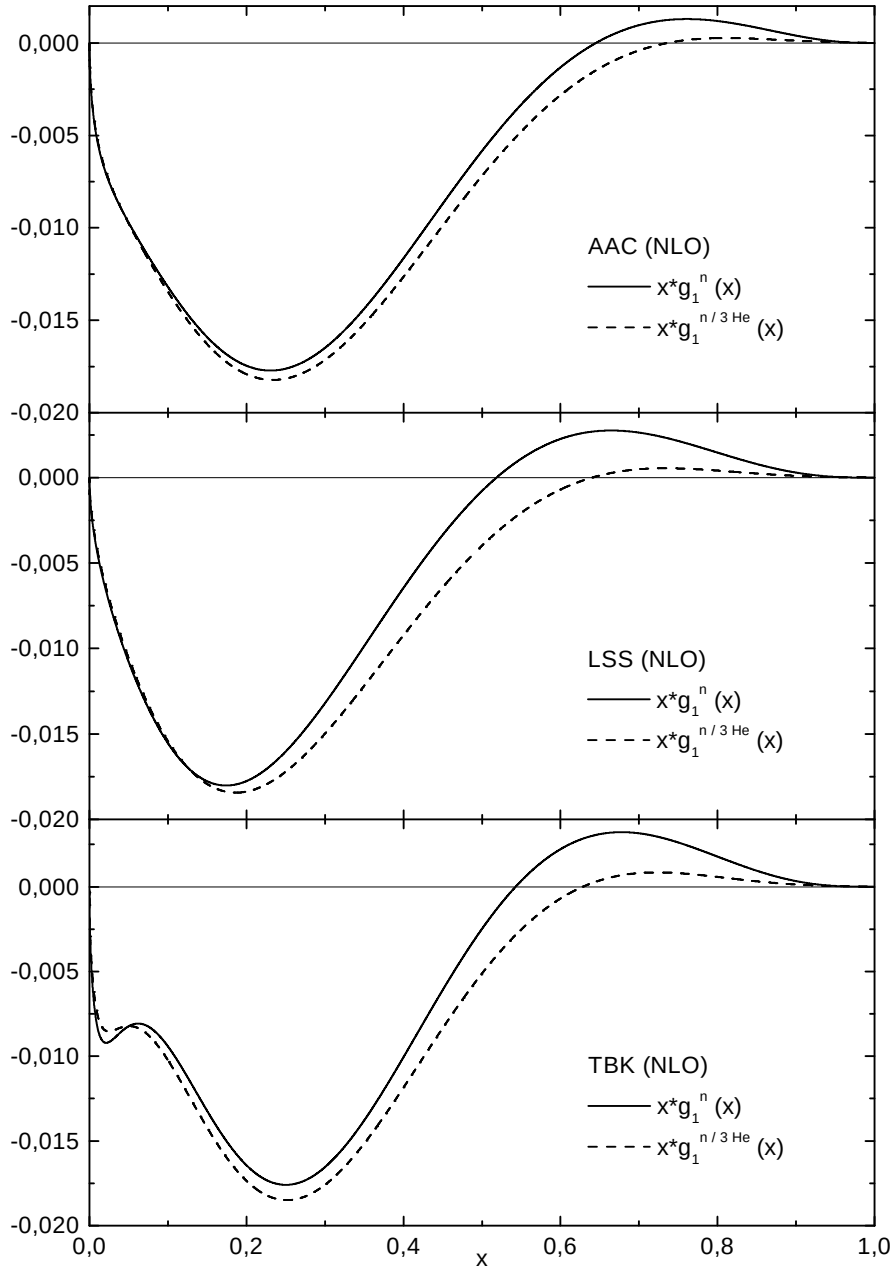


Fig. 1. The NLO neutron structure functions $xg_1^n(x)$, $xg_1^{n/^3\mathrm{He}}(x)$ at $Q_0^2 = 1\,\mathrm{GeV}^2$ in various parametrizations.

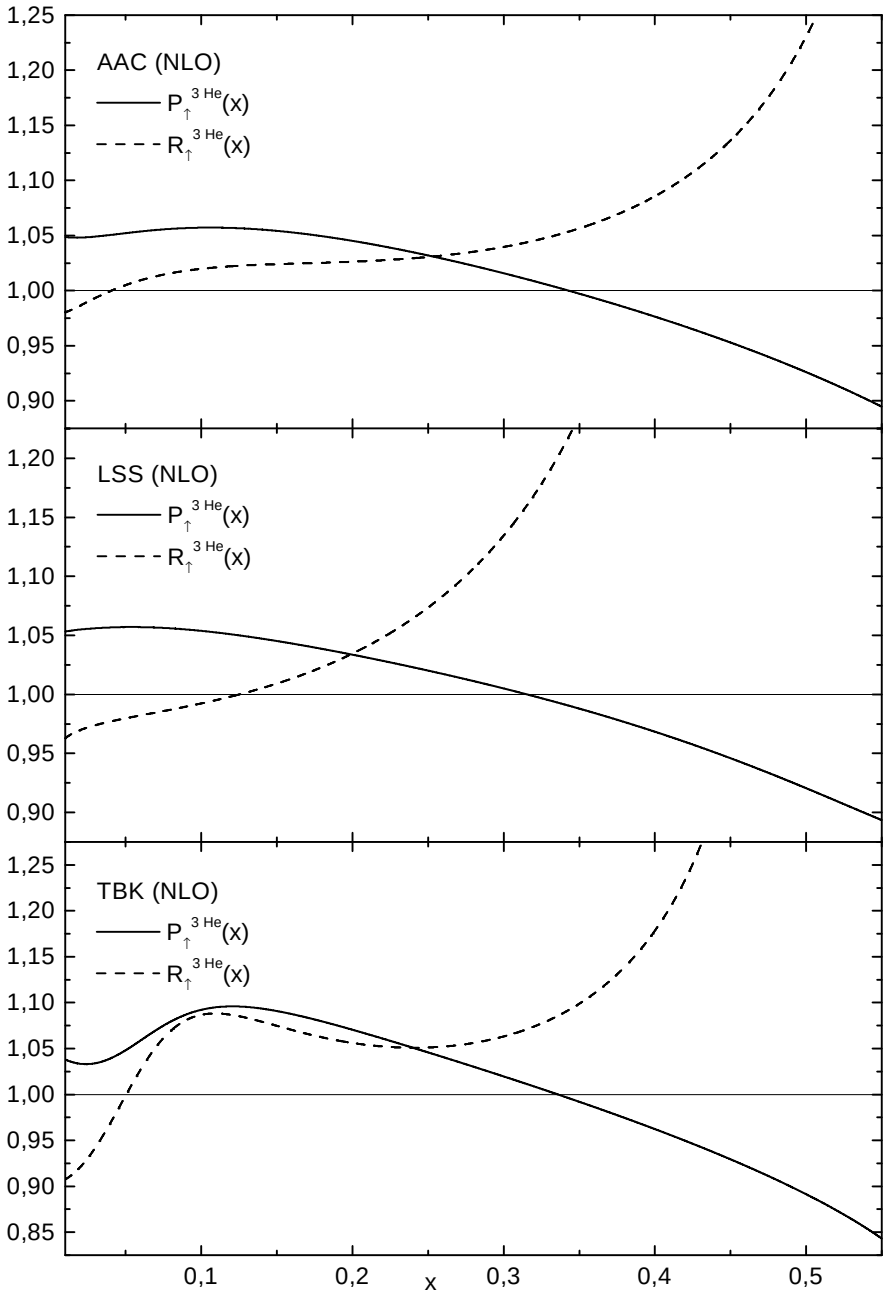


Fig. 2. The ratios $P_{\uparrow}^{^3\mathrm{He}}(x)$ and $R_{\uparrow}^{^3\mathrm{He}}(x)$ at $Q_0^2 = 1$ GeV^2 in various NLO parametrizations.

in various NLO parametrizations. The ratio $P_{\uparrow}^{^3\mathrm{He}}(x,Q^2)$ measures the influence only of the Δ isobars, excess pions and Fermi motion on the spin-dependent structure function of neutron in ^{3}He. If these effects were not important, $P_{\uparrow}^{^3\mathrm{He}}(x,Q^2)$ would be equal to unity. The ratio $R_{\uparrow}^{^3\mathrm{He}}(x,Q^2)$ describes all nuclear effects, including the spin depolarization in ^{3}He. We do not present $P_{\uparrow}^{^3\mathrm{He}}(x,Q^2)$ and $R_{\uparrow}^{^3\mathrm{He}}(x,Q^2)$ in the whole x region because the neutron structure function crosses zero.

The corrections to the proton structure function $g_1^p(x,Q^2)$ are studied in ^{3}H and ^{7}Li (we also mention results for ^{19}F). The ^{7}Li nucleus is our best example not only for the effect which is very pronounced, but also because this nucleus seems to be a realistic polarized target. The ^{3}H is calculated to check the Bjorken sum rule [22] for system with $A=3$. The spin-dependent structure functions for free proton, proton in ^{3}H and proton in ^{7}Li are shown in Fig. 3 in NLO AAC parametrization. We do not plot them in the remaining parametrizations, since there is a very small parametrization-dependence in our predictions for $g_1^{p/A}$.

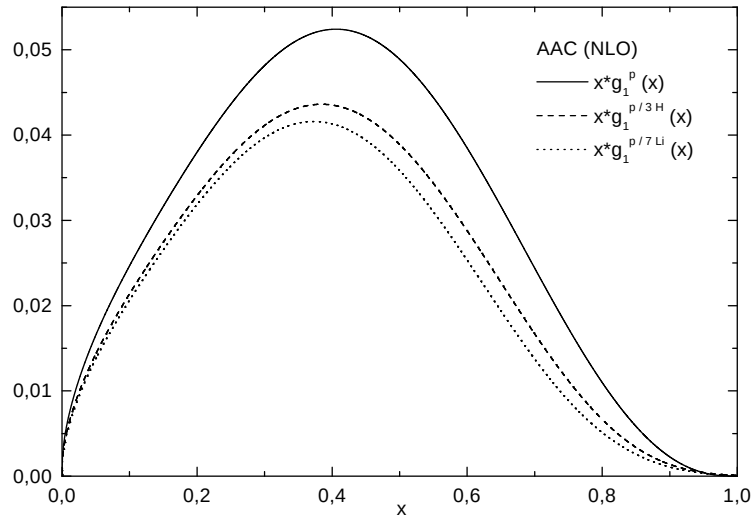


Fig. 3. The NLO proton structure functions $xg_1^p(x)$, $xg_1^{p/^3\mathrm{H}}(x)$ and $xg_1^{p/^7\mathrm{Li}}(x)$ at $Q_0^2=1$ GeV^2 in AAC parametrization.

In Fig. 4 ratios:

$$R_{\uparrow}^{^3\mathrm{H}}(x,Q^2)=\frac{g_1^{p/^3\mathrm{H}}(x,Q^2)}{g_1^p(x,Q^2)} \tag{4.4}$$

and

$$R_{\uparrow}^{^7\mathrm{Li}}(x,Q^2)=\frac{g_1^{p/^7\mathrm{Li}}(x,Q^2)}{g_1^p(x,Q^2)} \tag{4.5}$$

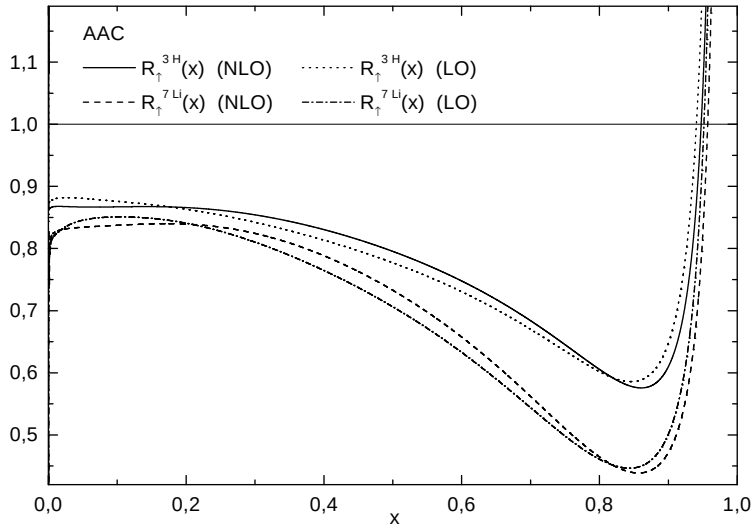


Fig. 4. The ratios $R_{\uparrow}^{^3\mathrm{H}}(x)$ and $R_{\uparrow}^{^7\mathrm{Li}}$ calculated using NLO and LO AAC parametrization at $Q_0^2 = 1$ GeV^2.

are shown in both NLO and LO AAC parametrization. As compared to ^{3}He richer content of non-nucleonic objects makes the nuclear effect deeper for ^{7}Li. The resulting corrections to the first moments presented in Table I and Table II are also considerably larger

$$\frac{\Gamma_1^{p/^7\mathrm{Li}}}{\Gamma_1^p} \approx \begin{cases} 0.79 \\ 0.78 \end{cases} \quad \text{for} \quad \begin{matrix} 0 \geq x \geq 1 \\ 0.1 \geq x \geq 1\,. \end{matrix} \tag{4.6}$$

Having calculated the nuclear effects for both proton in ^{3}H and neutron in ^{3}He we are able to check the Bjorken sum rule for system with $A = 3$. The numbers presented in Table I and Table II show that

$$\frac{\Gamma_1^{p/^3\mathrm{H}} - \Gamma_1^{n/^3\mathrm{He}}}{\Gamma_1^p - \Gamma_1^n} \approx \begin{cases} 0.91 \\ 0.88 \end{cases} \quad \text{for} \quad \begin{matrix} 0 \geq x \geq 1 \\ 0.1 \geq x \geq 1\,, \end{matrix} \tag{4.7}$$

what means 12% reduction in the region where our model is applicable.

The results for proton in ^{19}F are very similar to those of ^{7}Li due to the saturation of nuclear parameters $\langle n_\Delta \rangle$, $\langle n_\pi \rangle$ and $\langle z_\pi \rangle$. This nucleus, less realistic as a polarized target, is interesting because of possible application in the hunt for neutralino as a dark matter candidate [23].

One can certainly improve the model presented above. It would be interesting to include shadowing effects and extend the model to low x region ($x < 0.1$). Another improvement would be the inclusion of interference

terms resulting from N–Δ transitions. Although it is possible to construct the N–Δ spin dependent structure function in analogy to the Δ, we are unable to extract the density $f^{N-\Delta}(z)$ in the nucleus from the nuclear matter calculation, we are basing on [12]. Approach which attributes all nuclear effects (except depolarization Eqs. (2.11), (2.12)) to the interference term [24] is conceptually different from ours: the absolute normalization of this term is there a free parameter.

To summarize, we recall the idea how the nucleon spin-dependent structure functions get modified due to nuclear environment. The model we have used to present the effect has not been chosen by accident. Among other advantages it can be extended from unpolarized to polarized version without new, fundamental assumptions. Whereas the case of ^{3}He serves only as a warning what size of corrections should one expect when extracting the neutron structure function from polarized ^{3}He target experiments (our predictions for neutron in ^{3}He are within experimental error bars), the ^{7}Li nucleus seems to be more promising. With present experimental techniques one may seriously think of deep inelastic polarized lepton-polarized ^{7}Li scattering or polarized hadron-polarized ^{7}Li scattering with direct photon or muon pair production. In all cases the modification due to nuclear effects should be measurable. The expected results are interesting for both the nuclear structure and QCD studies. One should keep in mind that what is usually measured in deep inelastic scattering is the asymmetry:

$$A_1(x,Q^2) \simeq \frac{g_1(x,Q^2)}{F_1(x,Q^2)}, \tag{4.8}$$

where F_1 is the unpolarized structure function. Since the nuclear effect is similar on both the numerator and denominator, one may be misled by the fact that the asymmetry itself shows no significant change as compared to the free nucleon case.

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