Nuclear effects in extraction of $g_{1n}(x, Q^2)$ at small x

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Abstract: We consider nuclear structure uncertainties in extraction of $g_{1n}(x, Q^2)$ from inclusive $\vec{l}$-$\vec{D}(^3\vec{He})$ data at small x. Theoretical uncertainties in extraction of g_{1n} from $\vec{l}\vec{D}$ data are small as far as $g_{1n}(x, Q^2) \approx -g_{1p}(x, Q^2)$ at small x. In case of ^3He combination of effects of the spin depolarization, interaction with nonnucleonic degrees of freedom, and nuclear shadowing is likely to reduce $g_{1^3\mathrm{He}}(x \leq 0.05)$ by $\sim 15\%$ and significantly enhance $g_{1^3\mathrm{He}}$ at $x \sim 0.1$.

1 Introduction

Knowledge of g_{1n} at small x is crucial for learning whether currently observed experimentally regime of dominance of nonsinglet contribution to $g_{1N}(x, Q^2)$ would be followed by dominance of singlet contribution at $x \leq 10^{-3}$. Measurement of $g_{1n}(x, Q^2)$ involves use of polarized deuterium and ^{3}He targets. Hence one has to address two question: How large are nuclear effects for $g_{1A}(x, Q^2)$? What is theoretical uncertainty in evaluation of these effects? We focus here on the region of small x which is relevant for this workshop. In this kinematics three major effects are present: (i) spin depolarization due to presence of higher orbital states in nuclei, (ii) nonnucleonic degrees of freedom in nuclei, (iii) nuclear shadowing.

2 Spin depolarization and Fermi motion

In the many-nucleon approximation where non-nucleonic degrees of freedom in nuclei and nuclear shadowing are neglected the Fermi motion, and the relativistic spin rotation effects are small at $x \leq 0.5$ [1]. As a result, the static approximation expression for the deuteron

$$g_{1^2H}(x, Q^2) = (1 - \frac{3}{2}P_D)(g_{1p}(x, Q^2) + g_{1n}(x, Q^2)) \tag{1}$$

provides very good approximation for $x \leq 0.5$. Here $P_D = 6 \pm 1\%$ is the probability of the D-wave in the deuteron. Similarly, in the case of $A = 3$ target approximately 8% depolarization effect is present. It is due to depolarization of the neutron (which in the case of S-wave ^{3}He would be 100% polarized), and from a small proton polarization [2, 3, 4, 5].

3 Nonnucleonic degrees of freedom

The EMC effect has unambiguously demonstrated that nonnucleonic degrees of freedom are present in nuclei, though this effect does not allow to identify what particular nonnucleonic degrees of freedom are responsible for the effect. However the EMC effect is small for $0.05 < x < 0.3$, so naively one would expect that such effects are not important in extraction of g_{1n} at medium and small x. It is possible to check the relevance of nonnucleonic degrees of freedom by considering the ratio of the Bjorken sum rules for the $A = 3$ and $A = 1$ systems. The QCD corrections to the sum rule which are proportional to $\alpha_s^n(Q^2)$ cancel out and one obtains:

$$R = \frac{\int_0^1 [g_1^{^3He}(x, Q^2) - g_1^{^3H}(x, Q^2)]dx}{\int_0^1 [g_1^n(x, Q^2) - g_1^p(x, Q^2)]dx} = \frac{G_A(^3\mathrm{H})}{G_A(n)}, \tag{2}$$

independent of Q^2, where we have ignored the higher twist effects. Nonrelativistic expression for $R = P_S - \frac{1}{3}P_{S'} + \frac{1}{3}P_D = 1 - (0.0785 \pm 0.0060)$ is perfectly consistent with the standard nonrelativistic expression for $G_A(^3\mathrm{H})$. However both these relations contradict the data: $\frac{G_A(^3\mathrm{H})}{G_A(n)} = 1 - (0.0366 \pm 0.0030)$.

Hence we conclude that *the use of the convolution model, combined with the 3-nucleon description of $A = 3$ nucleon system, leads to a $\sim 4\%$ violation of the Bjorken sum rule for the scattering of the $A = 3$ systems.* This is consistent with the general expectation that noticeable nonnucleonic degrees of freedom should be present in the $A = 3$ systems. Inconsistency of the convolution models and three nucleon description of $A = 3$ system with the Bjorken sum rule was first pointed out in Ref.[6].

We observe that consistency of nonrelativistic results for the Bjorken sum rule and the G_A ratio can be used as a guide to identify what nonnucleonic effects are responsible for the discrepancy in eq.2 [7]. Current analyses of $G_A(^3H)$ indicate that the major nuclear correction to the impulse approximation calculation of $G_A(A = 3)$ is due to $\Delta \to N$ transitions. Thus a natural mechanism for resolving the discrepancy between the Bjorken sum rule for $A = 3$ and for $A = 1$ targets which is present in the impulse approximation, is the necessity to account for the nondiagonal transitions $\gamma^* N \to \gamma^* \Delta$. No theoretical investigations of this structure function have been done as yet. For the simple case of $g_{1n}^{n.s.}$ one can expect the same low x behavior for this structure function as for the diagonal transitions since Regge trajectories with rather close value of intercept couple in this case. Based on $SU(6)$ symmetry, for average $x \sim 0.2 \div 0.3$ we can expect a behavior similar to the diagonal nonsinglet matrix elements. Consequently, we estimate that the contribution of the $\gamma^* N \to \gamma^* \Delta$ transition to $g_{1,A=3}^{n.s.}$ leads to a change in the ratio $\frac{g_{1,A=3}^{n.s.}(x,Q^2)}{g_{1N}^{n.s.}(x,Q^2)}$ for $x \leq 0.5$ from 1-(0.0785 ± 0.0060) to $G_A(^3\mathrm{H})/G_A(n) = 1-(0.0366 \pm 0.0030)$. Moreover, treating the Δ-admixture as a perturbation we observe that main contribution to g_1 should originate in the ^{3}He case from the $n \to \Delta^0$ nondiagonal transition and in the ^{3}H case from the $p \to \Delta^+$ nondiagonal transition. In the $SU(6)$ limit, which seems reasonable at least for the valence quark contribution [1] $g_{1\ n \to \Delta^0}(x, Q^2)/g_{1n}(x, Q^2) = g_{1\ p \to \Delta^+}(x, Q^2)/g_{1p}(x, Q^2)$. Thus up to a small correction due to contribution of $g_{1p}(x, Q^2)$ combined effect of nucleon depolarization and nondiagonal contributions is approximately the same for $g_{1,^3He}(x, Q^2)/g_{1n}(x, Q^2)$ and for $g_{1,A=3}^{n.s.}(x, Q^2)/g_{1N}^{n.s.}(x, Q^2)$. We can write in this approximation

$$g_{1^3He}(x, Q^2) = \frac{G_A(^3H)}{G_A(n)} g_{1n}(x, Q^2) + 2p_p(g_{1p}(x, Q^2) + g_{1n}(x, Q^2)), \tag{3}$$

where $p_p \approx -2.8\%$ is polarization of a proton in ^{3}He. We neglect here contribution of $\Delta^+ \to p$ nondiagonal terms since they effectively result merely in the renormalization of p_p by a factor $\sim \frac{G_A(^3H)}{G_A(n)}$. Experimentally, $|g_{1p}(x, Q^2) + g_{1n}(x, Q^2)| \ll |g_{1n}(x, Q^2)|$, $|g_{1n}(x, Q^2)|$ for $x \leq 0.1$ and hence the last term for these x is a very small correction. In the sea region g_{1N} and $g_{1N \to \Delta}$ may have different x dependence. This leads to $\leq 4\%$ theoretical uncertainty in extraction of $g_{1n}(x \leq 0.05)$

Overall, the uncertainties in extraction of g_{1n} from this source due to poor knowledge of x dependence of nondiagonal matrix elements is likely to be of the order 4% for small x. For the deuteron case this effect is much smaller since nonnucleonic degrees of freedom are significantly smaller and also ΔN admixture is forbidden.

[1] Note that the SMC semi-inclusive data indicate that the sea contribution to g_1 is small down to $x \sim 0.01$.

4 Nuclear shadowing effects

At small x, when the coherence length $l = \frac{1}{2m_N x}$ far exceeds the nucleus radius, the virtual photon converts to a quark-gluon configuration h well before the target. In the case of nucleon targets this leads to diffraction in deep inelastic scattering which has recently been observed at HERA. For the nuclear targets this leads to the shadowing phenomenon which is well established experimentally, for review and references see report of Group 8.

The phenomenon of shadowing reflects the presence of quark-gluon configurations in γ^* which can interact with cross sections comparable to that of hadrons. A quantitative description of nuclear shadowing phenomenon in deep inelastic scattering was developed in the color screening models, where γ^* converts to a quark-gluon state h which interacts with the nuclear target via multiple color singlet exchanges. The effect of shadowing is determined in these models primarily by the value of the ratio $\sigma_{eff} = \frac{\langle\sigma^2\rangle}{\langle\sigma\rangle}$, where averaging is taken over different strengths of interaction, that is, over different quark-gluon configurations involved in the transition $\gamma^* \rightarrow$ "*hadron state*". Numerical analyses of nuclear shadowing for $A \geq 12$ give $\sigma_{eff} \sim 17\ mb$. Similar number follows from the estimate based on the generalization of the optical theorem to the diffractive processes $\sigma_{eff} = \frac{16\pi \frac{d\sigma(\gamma^*+p\rightarrow X+p)}{dt}_{|t=0}}{\sigma_{tot}(\gamma^*+p)}$. As soon as this parameter is fixed all color singlet models give very similar results for $x \ll \frac{1}{4m_N R_A}$ especially for light nuclei.

It follows from the formulae of the eikonal-type approximation that for the case of cross sections which constitute a small fraction of the total cross section, the shadowing effects should be larger. Several examples include shadowing in the parity violating $\vec{p}A$ scattering [8] and shadowing for valence quarks [9]. The same is true for shadowing of g_{1A} [7]. For light nuclei like ^{2}H and ^{3}He the screening effect for g_{1A} is ≈ 2 larger than for F_{2A}. Numerically, we find the reduction effect due to shadowing is $g_{1^3He}(x,Q^2)/g_{1n}(x,Q^2) \sim 0.90$, and $g_{1^2H}(x,Q^2)/(g_{1p}(x,Q^2)+g_{1n}(x,Q^2)) \sim 0.96$, with spin depolarization effects and nonnucleonic degrees of freedom effects entering multiplicatively. This estimate probably has 50% uncertainty due to due to uncertainties in the value of the real part of the spin dependent amplitude, and spin dependent diffraction, etc. The Bjorken sum rule indicates that shadowing effects generate an enhancement of $g_{1A}(x,Q^2)$ at $x \sim 0.1$. Overall one expects significant modifications of $g_{1,A=3}$ for $x \leq 0.15$, see Fig.1.

To summarize, at small x nuclear corrections lead to

$$\frac{g_{1^3He}(x,Q^2)}{g_{1n}(x,Q^2)} \sim 0.87 \pm 0.07; \quad \frac{g_{1^2H}(x,Q^2)}{g_{1p}(x,Q^2)+g_{1n}(x,Q^2)} \sim 0.86 \pm 0.04, \tag{4}$$

with errors reflecting our guess of the theoretical uncertainties involved in calculating discussed nuclear effects. Smaller error in the deuteron case reflects smaller shadowing effects and suppression of nonnucleonic degrees of freedom due to smaller energy binding and zero isospin which forbids $N\Delta$ states. Hence in the discussed x-range ^{2}H targets may have certain advantages in terms of theoretical uncertainties. Besides, in the first approximation, experimentally $g_{1p}(x,Q^2) \approx -g_{1n}(x,Q^2)$ for $x \sim 10^{-2}$ in which case shadowing does not affect the extraction of g_{1n} from the g_{1d} data and does not lead to noticeable enhancement effects at $x \sim 0.1$. If, on the other hand, at very small $x \sim 10^{-3}$ g_{1n} and g_{1p} become comparable, theoretical uncertainty in extraction of g_{1n} would be $\sim 8\%$. Experimental error is usually larger in the deuteron case since one has to combine experimental measurements of g_{1d} and g_{1p}.

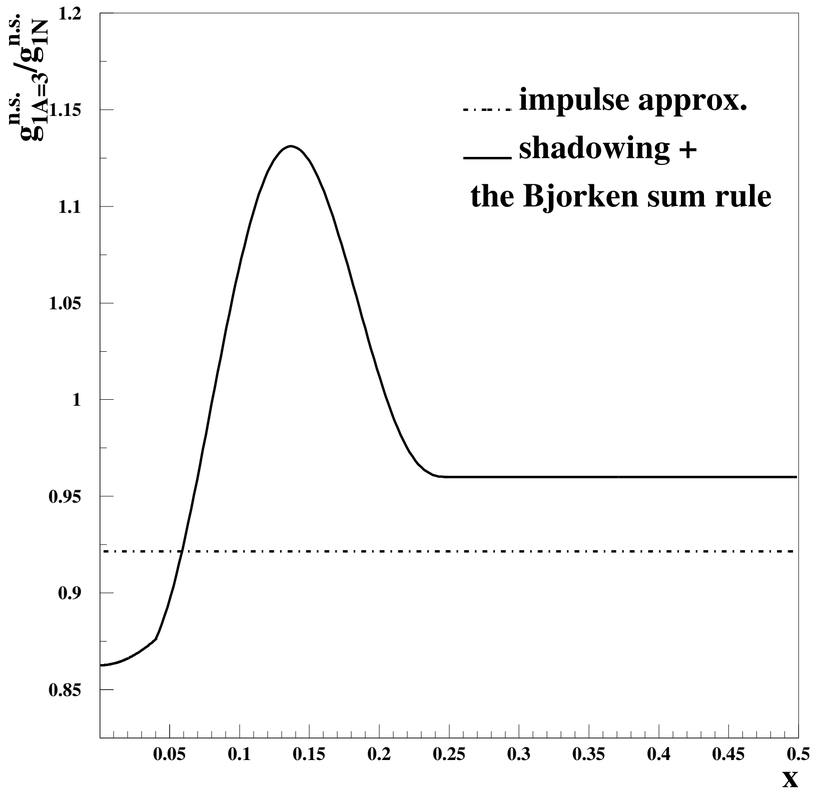

Figure 1: $g^{n.s.}_{1A=3}/g^{n.s.}_{1N}$ as a function of x. Dash-dotted curve is nonrelativistic calculation of Refs.[2-5]. The solid curve is result of calculation [7] which includes nuclear shadowing, spin depolarization, $\Delta \to N$ nondiagonal contributions, and the Bjorken sum rule constraint.

Note also existence of specific nuclear effect for the scattering off the polarized deuteron, which is analog of the Germond and Wilkin effect [10] for $\pi\vec{d}$ total cross sections: due to the presence of D-wave in the deuteron, the cross section of shadowing for scattering off deuteron with helicities $\lambda_d = \pm 1$ and $\lambda_d = 0$ differs leading to approximately 1% difference of the cross sections of unpolarized electron scattering off the deuteron in different helicity states for $x \leq 10^{-2}$ [11]. Experimental study of this effect would check the basic ideas about mechanism of nuclear shadowing. Unfortunately, the effect is quite small making its measurement nearly impossible.

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