# SPIN STRUCTURE FUNCTIONS OF THE DEUTERON

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Over the past 20 years, an impressive data set on the inclusive spin structure functions $g_1(Q^2, x)$ and $g_2(Q^2, x)$ has been collected at many labs worldwide, on polarized proton, deuteron and $^3$He targets. The latter two targets are used to extract information on the neutron spin structure functions and their moments; however, nuclear corrections make the interpretation less straightforward (especially at low $Q^2$ and in the resonance region). The two different targets have different systematic uncertainties and advantages and disadvantages. In this paper, I present results on the deuteron from a recent experiment with CLAS at Jefferson Lab. I discuss some of the nuclear corrections and possible strategies for the extraction of neutron spin structure functions. Finally, I highlight some experimental strategies to learn more about structure function modifications in the nuclear medium.

## 1. Introduction

Spin structure functions of the nucleon have been measured with polarized lepton beams and polarized targets of protons, deuterons and $^3$He over many years. Typically, one measures the inclusive asymmetries $A_{||}$ and $A_{\perp}$ and extracts the virtual photon asymmetries $A_1$, $A_2$ and the spin structure functions $g_1$, $g_2$. In the deep inelastic (DIS) region, one can study these quantities as functions of the quark momentum fraction $x$ and the momentum transfer $Q^2$ to learn about the helicity-weighted momentum distribution of quarks in the nucleon and their pQCD evolution. The first moments of $g_1$ can be interpreted as the (charge-weighted) contributions of the quark helicities to the nucleon spin.

At low to medium $Q^2$, one enters the region of nucleon resonances, where the final state mass $W$ determines the contribution from different resonant and non-resonant transition amplitudes. The first moment of $g_1$ changes rapidly as $Q^2$ becomes small and the nucleon resonances (in particular the $\Delta$) begin to dominate. It approaches zero with a negative slope

at the photon point $Q^2 = 0$ where it is constrained by the Gerasimov-Drell-Hearn (GDH) sum rule [1]. Following the observation of duality in the unpolarized structure function $F_2$ [2], one can also study the spin structure functions as a function of the Nachtmann scaling variable $\xi = Q^2/M(q+\nu)$, which corresponds to the minimum light cone fraction of the struck quark. If duality holds, one would expect that even in the resonance region the average of $g_1(\xi, Q^2)$ approaches a universal scaling curve which equals the extrapolated DIS results.

For all these investigations, it is important to have available data from both proton and neutron targets. For example, the famous Bjorken sum rule [3] relates the difference between the first moments of $g_1$ for the proton and the neutron to the axial beta-decay constant $g_A$. On the other hand, the total contribution of quark helicities to the nucleon spin is most directly accessible in the *sum* of these two moments. The approach to the photon point should be studied both on the proton and the neutron since the GDH sum rule leads to independent predictions for both. Finally, only a comparison of proton and neutron data in the resonance region can yield the necessary information for the spin-isospin decomposition of both resonant and non-resonant transition amplitudes.

Unfortunately, free neutron targets of the necessary density do not exist. For that reason, information on the neutron has to be extracted from measurements on deuterium and $^3$He targets, each with their own set of systematic uncertainties and nuclear corrections. In the following, I present recent results from a measurement on deuterium in the resonance region (Section 2). I then discuss some of the necessary steps and difficulties extracting neutron spin structure functions from nuclear ones (Section 3). I conclude with an outlook on some experiments aiming to either study or to minimize nuclear effects on the extraction of structure functions (Section 4).

## 2. The EG1 experiment in CLAS

The EG1 experiment at Jefferson Lab is a comprehensive program to measure spin structure functions of the proton and the deuteron for a large range of $Q^2$ (from $Q^2 = 0.05$ GeV$^2$ to 4.5 GeV$^2$) and $W$ (in the resonance region and beyond, up to $W = 3$ GeV). We scatter the CEBAF polarized electron beam off longitudinally polarized cryogenic solid state targets of ammonia ($^{15}NH_3$) and deuterated ammonia ($^{15}ND_3$) and detect the scattered electrons with the CLAS detector in Jefferson Lab's Hall B.

The data described here were taken with a 2.5 nA beam of 2.5 GeV

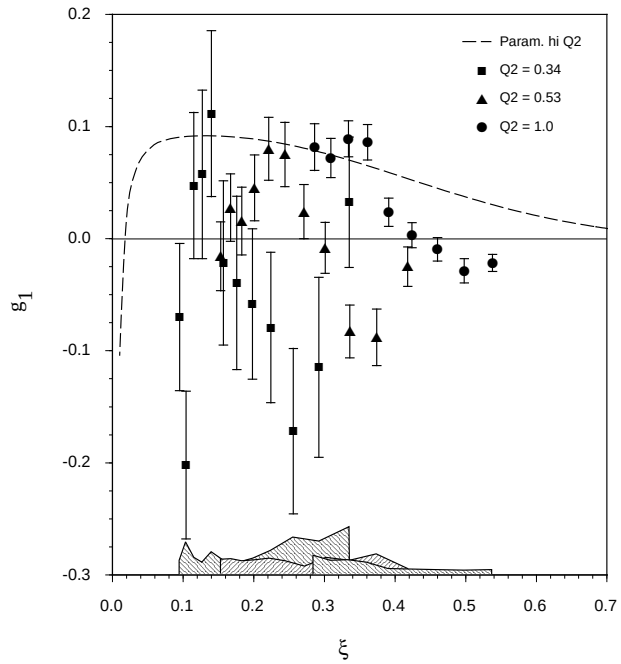


Figure 1. Data on the spin structure function $g_1^D(\xi, Q^2)$ from EG1 at three values of $Q^2$. Statistical errors are indicated with error bars and systematic errors with the shaded areas. The dashed line is a parametrization of the world's deep inelastic data, extrapolated to $Q^2 = 10$ GeV$^2$.

energy on a $^{15}ND_3$ target during the first run of EG1 in 1998. The average beam polarization was 71% and that of the target, 20%. The dilution due to events from the unpolarized target materials (mostly liquid $^4$He and $^{15}$N) was determined by comparing the count rate from the ammonia target with that from a Carbon target of equal thickness. The product of beam and target polarization was directly determined from the asymmetry in the region of the quasielastic peak (0.85 GeV $< W <$ 1 GeV), which can be calculated from the well-known nucleon form factors. We collected data for $Q^2 = 0.3 \ldots 1.2$ GeV$^2$ and $W \leq 2.0$ GeV.

Figure 1 shows our results for the spin structure function $g_1^D$ from these data, plotted against the Nachtmann variable $\xi$. While these data are close to the DIS limit at high $W$ (low $\xi$), one can see pronounced differences in the region of the $\Delta$ resonance (at the highest values of $\xi$), where $g_1^D$ becomes negative due to the dominance of the final state helicity 3/2. Overall, there is a clear trend to more negative values for the lower $Q^2$ bins.

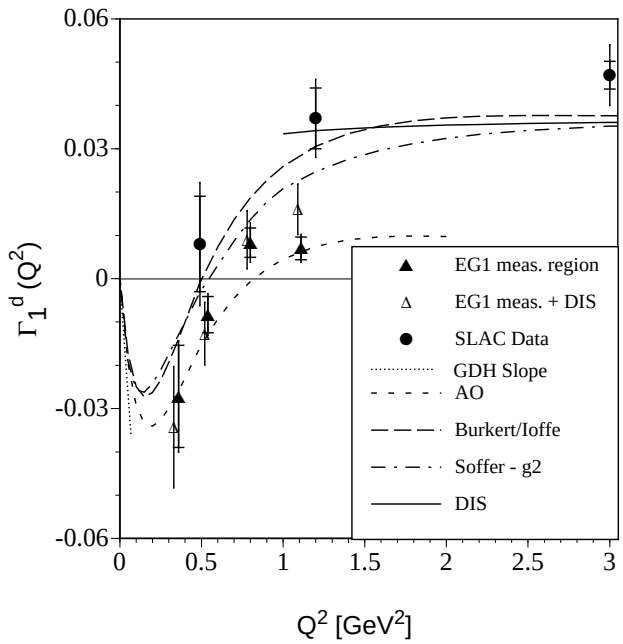


Figure 2. First moments of the spin structure function $g_1^D(x, Q^2)$ from EG1 as a function of $Q^2$. The solid triangles represent the integral over the measured region, with statistical errors indicated by the inner bars and total errors by the outer ones. The open triangles show the full integrals after adding the contribution from the unmeasured region using a parametrization of the world's DIS data, with combined statistical and systematical error bars. We also show the results from SLAC experiment E143 (circles) and several model predictions for the integral.

This is born out by the behavior of the first moment of $g_1$ (integrated over the Bjorken variable $x$), as shown in Fig. 2. The contribution from the resonance region alone (solid triangles) becomes negative below $Q^2 = 0.6$ GeV$^2$, following the prediction of the code "AO" (short–dashed line) which is a parametrization of unpolarized electroproduction data in the resonance region. After adding a model prediction for the unmeasured piece, the full integral follows approximately existing parametrizations (Burkert and Ioffe [4], dashed line and Soffer and Teryaev [5], dashed–dotted line) which connect the DIS limit (solid line) with the slope given by the GDH sum rule (dotted line).

The second part of the EG1 experiment has completed data taking in Spring of 2001, with vastly larger statistics and kinematic coverage. Data from this second run will be forthcoming shortly.

## 3. From Nuclei to Nucleons

Table 1. Nuclear properties affecting the extraction of nucleon spin structure functions from measurements on deuterium and $^3$He. The type of effect is listed in the first column, while some relevant quantities related to the likely magnitude of the effect are listed in the next two columns.

| Nuclear Effect | Deuterium | $^3$He |
|---|---|---|
| $0^{th}$ order approximation | d↑ ≈ p↑ + n↑ | $^3$He↑ ≈ n↑ |
| D–state, S'–state | $\mu_D = \mu_p + \mu_n - 0.022$ n.m. | $\mu_{^3He} = \mu_n - 0.214$ n.m. |
| Fermi Motion | $p_{RMS} = 0.13$ GeV/c | $p_{RMS} = 0.17$ GeV/c |
| Binding Effects | $E_{bound} - E_{free} \approx -10$ MeV | $E_{bound} - E_{free} \approx -20$ MeV |
| Tensor Polarization | $P_{zz} \approx 0.1$ | n.a. |
| EMC Effect<br>Final State Effects<br>Coherent Processes | Nuclear density ≈<br>0.06 Nucleons/fm$^3$ | Nuclear density ≈<br>0.09 Nucleons/fm$^3$ |
| Pre–existing Δ's | $P_{\Delta\Delta} < 0.5\%$ | $P_\Delta \approx 2\%$ ? |
| Pion excess (MEC) | 2% ? | 5% ? |
| Other exotic components | ? | ? |

While the existing data from the first run of EG1 are not sufficiently precise to warrant the extraction of neutron structure functions from the measured deuteron ones, it is timely to consider the necessary steps one needs to follow once the new data become available. Table 1 lists several nuclear effects that complicate the interpretation of nuclear structure functions in terms of nucleon ones.

In the DIS region and for the determination of integrals, it has been shown [6] that to a very good approximation, one needs to consider only the effect of small components of the nucleon wave function. In the case of deuterium, one can correct for the D-state by scaling with the "effective" polarization of both nucleons in deuterium, which is given by $(1 - 3/2P_D)$ ($P_D$ being the D–state probability). This is also born out by the rather good agreement of the world's data on the proton, deuteron and $^3$He among each other and with the Bjorken sum rule. However, in the resonance region one has to pay much more attention to the effects from "Fermi–smearing" and binding, which tend to wash out the resonance structure. One has to correct the measured structure function for this smearing before subtracting the contribution from the proton, requiring realistic wave functions of the nuclear target. Additional corrections may come from structure modifica-

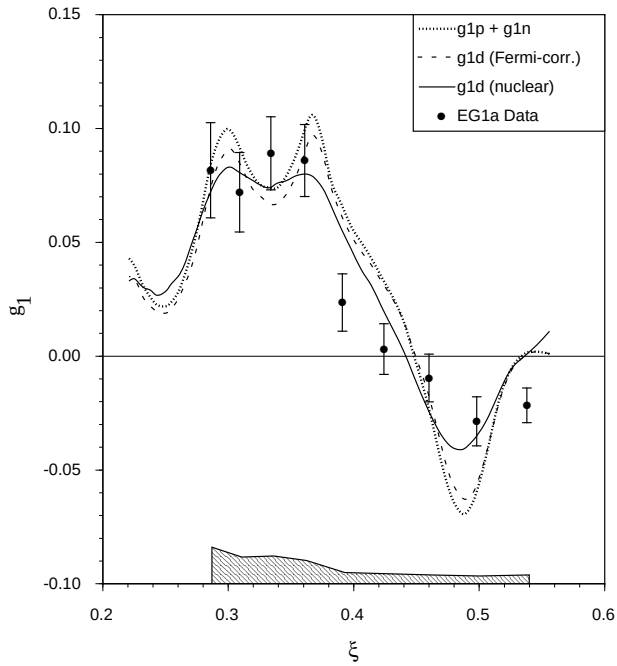


Figure 3. $Q^2 = 1.0$ GeV$^2$ data set from Fig. 1. The curves come from a parametrization of world data on protons, deuterons and $^3$He. The solid line indicates the prediction for deuterium, the dashed line shows the result after correcting for Fermi-smearing and binding effects, and the dotted line is the sum of proton and neutron spin structure functions. The main difference between the latter two curves is due to the D-state of deuterium which leads to an effective depolarization of both proton and neutron.

tions of the bound nucleon (like the EMC effect) and non-nucleonic degrees of freedom (mesons, deltas and possibly multi-quark correlations). Thanks to the very weak binding of the deuteron, these effects tend to be smaller here than in $^3$He or even heavier nuclei

At low $Q^2$, one has to also worry about deviations from the simple PWIA picture were the electron scatters from a "quasi–free" single nucleon. Fortunately, theoretical studies [7] show that above the free pion production threshold ($W = 1.08$ GeV), the *nuclear* structure functions are very close to the incoherent sum of the two *nucleon* ones in the case of the deuteron.

Figure 3 shows as an example the size of the various nuclear effects on the structure function $g_1^D$ at $Q^2 = 1.0$ GeV$^2$ from the first EG1 run. The main modification from the incoherent sum of free proton and neutron structure functions comes from the D–state depolarization (difference be-

tween dashed and dotted curve) and Fermi–smearing and binding (solid curve). A simple PWIA model using the Paris wave function for the deuteron and fully relativistic kinematics was used to calculate the nuclear structure function. Using a light-cone wave function instead leads to only slight changes. In addition to kinematic smearing, there are also changes due to the different electron kinematics in the rest frame of the nucleon in the initial state (leading to slightly different combinations of the structure functions $g_1$ and $g_2$). The D-state contribution also influences the momentum distribution along and perpendicular to the scattering electron direction since the deuteron is slightly tensor-polarized ($P_{zz} \approx 0.1$). Again, these changes are rather small.

## 4. Outlook

Extracting neutron spin structure functions from measurements on deuterium and $^3$He is becoming more demanding with the advent of high–precision data in the region of the nucleon resonance and at high $x$ or low $W$. Careful comparison between these two targets can help to confirm that model uncertainties are under control. Ideally one would like to have a more direct method of accessing neutron structure functions (polarized *and* unpolarized), with smaller theoretical uncertainties due to proton contributions and binding effects. A new program at Jefferson Lab by the "BoNuS" (BOund NUcleon Structure) collaboration aims to measure neutron structure functions by tagging scattering events on a nearly on–shell, slow–moving neutron via coincident detection of a slow proton in the backward hemisphere relative to the $\mathbf{q}$ vector. There are already data from the E6 experiment in CLAS which look for modifications of the neutron structure function when tagged by a *fast* backward–going proton. Similar programs for polarized targets would be highly desirable, but are technically much more challenging. Ultimately, both theoretical efforts to better understand the various nuclear modifications of bound nucleon structure functions and new experiments to test these models are needed.

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