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Search for Exotic Glue in Nuclei: Gluonic Transversity in Polarized DIS

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Although crucial to our understanding of nuclear structure, probes of gluonic components in the nucleus can be elusive, as gluons are accessed only indirectly in deep inelastic scattering. In 1989, Jaffe and Manohar identified a gluonic transveristy structure function $\Delta(x, Q^2)$ which is sensitive to exotic gluonic states in the nucleus, and is accessible via an inclusive measurement on a transversely polarized nucleus of spin greater than or equal to 1. We are developing an experiment to utilize Jefferson Lab's 12 GeV electron beam with a transversely polarized ^{14}N target to mount a first measurement of the Δ structure function. The Jefferson Lab experiment will probe Δ from from x of 0.3 to 0.05, but the vast kinematic reach of an electron-ion collider would allow a thorough probe of this quantity. We will discuss the impact of exciting new lattice QCD results on this quantity, our proposal to measure $\Delta(x, Q^2)$ at JLab, and what a measurement might look like at an EIC.

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1. Introduction

Despite the fundamental role the gluon fills in QCD, direct measures of gluonic states in the nucleus remain elusive. The gluon does not couple directly to the photon, and is probed only indirectly in electron scattering from hadrons. Jaffe and Manohar [1] describe a leading twist structure function which is sensitive to gluonic states—a "nuclear" gluon effect, free from contributions from any single nucleon. This structure function, $\Delta(x,Q^2)$, has been postulated to be observable in spin–1 (or greater) nuclei and is not sensitive to the contributions of bound nucleons or pions in the nucleus, as neither can contribute two units of helicity; likewise neither can any state with spin less than one contribute (see Figure 1). Unlike unpolarized and helicity gluon distributions, the double-helicity-flip structure function mixes with quark distributions only at higher twist, making it a clean measure of gluonic degrees of freedom. Ma *et al.* [2] call $\Delta(x,Q^2)$—labeled as $\hat{G}_T$ in their paper—the "most interesting" of the structure functions related to tensor polarization. Jaffe and Manohar emphasize the power of this structure function to illuminate the glue, calling a measurement of $\Delta(x,Q^2)$ "nuclear gluonometry."

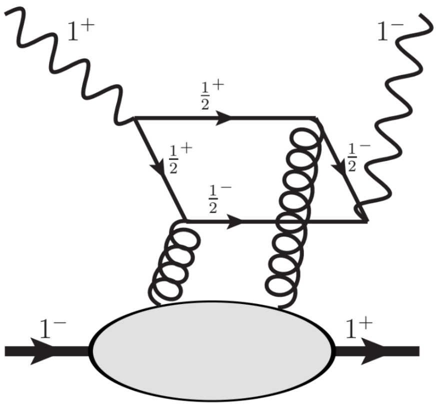

Figure 1: Example of leading DIS process sensitive to $\Delta(x,Q^2)$ [3].

While this nuclear glue effect was first proposed in 1989, recent lattice QCD results have generated new excitement for an experimental investigation. A 2016 lattice QCD study of the effect resolved a clear non-zero signal for the first moment of $\Delta(x,Q^2)$ on a spin–1 ϕ ($s\bar{s}$) meson [3]. This early proof of principle was reinforced the following year with a definitive signal for the exotic glue observable in a deuteron, albeit with an exaggerated pion mass, $m_\pi \sim 806$ MeV [4]. These results have exciting implications for the feasibility of an experimental measurement, and lattice QCD calculations to study the gluon transversity in the deuteron at lighter values of the pion mass (where statistical uncertainties become more challenging), including at the physical point [5], are underway. As a purely multi-nucleonic, or ensemble, glue effect in a nucleus, the Δ effect is expected to be enhanced in "compact" nuclei with deep bindings, which could result in the enhanced signal seen in the 800 MeV pion lattice calculation. This would be analogous to other known multi-nucleon effects in nuclei such as the EMC effect in the quark structure functions or the quenching of the axial charge of large nuclei. In addition to a Δ search on the deuteron—where theory predictions may be expected on a shorter timeframe—this implies that the experimental investigation of a heavier, spin≥1 target nucleus is crucial [6].

2. Jefferson Lab Measurement

A collaboration from JLab, MIT, UVa and ORNL is pursing a measurement of $\Delta(x,Q^2)$ at Jefferson Lab via inclusive deep-inelastic scattering of the CEBAF 12 GeV electron beam on a transversely polarized, spin-1 nuclear target [7]. For a spin–1 target polarized at angle θ_m from the z-axis and electron incident from $-z$, we can express the differential cross section for the target spin in the $\hat{m}$ direction $\lambda_m = (1,0,-1)$ as:

$$\frac{d\sigma}{dx\,dy\,d\phi}(\lambda_m) = \frac{2y\alpha^2}{Q^2}\left(F_1 + \frac{2}{3}a_m b_1 + \frac{1-y}{xy^2}\left(F_2 + \frac{2}{3}a_m b_2\right) - \frac{1-y}{y^2}b_m \sin^2\theta_m \Delta(x,Q^2)\cos(2\phi)\right),$$

where

$$a_m = \frac{1}{4}b_m(3\cos^2\theta_m - 1) \quad \text{and} \quad b_m = 3|\lambda_m| - 2$$

for scattered electron angle θ, azimuthal angle ϕ with respect to the place of the incident electron and target spin, and tensor structure functions b_1 and b_2. Averaging over polarization, where $b_+ + b_- + b_0 = 0$, we see no dependence on Δ. Since the differential cross section depends only on the absolute value of the target helicity λ_m, Δ also cancels out of the usual vector polarization difference $(N_+ - N_0) + (N_0 - N_-) = N_+ - N_-$. If we instead consider the portion sensitive to *tensor polarization*: $(N_+ - N_0) - (N_0 - N_-) = N_+ + N_- - 2N_0 \Rightarrow \Delta\sigma$, where $b_+ + b_- - 2b_0 = 6$, we have

$$\frac{d\Delta\sigma}{dx\,dy\,d\phi} = \frac{2y\alpha^2}{Q^2}\left((3\cos^2\theta_m - 1)(b_1 + \frac{1-y}{xy^2}b_2) - 6\frac{1-y}{y^2}\sin^2\theta_m \Delta(x,Q^2)\cos(2\phi)\right).$$

A difference between polarized and unpolarized cross sections—so that $N_+ - \bar{N} = N_+ - \frac{1}{3}(N_+ + N_- + N_0) = \frac{1}{3}(N_+ - N_0) \Rightarrow \hat{\sigma}$—gives a similar expression with different coefficients.

This presents 3 ways to approach a measurement of Δ. We could form a tensor asymmetry which would be made from yields with target polarized in the $m = -1,0,1$ substates N_-, N_0, and N_+ and tensor alignment P_{zz}. Here measurements at each target helicity state are separated in time, making the measurement sensitive to systematic drifts in detectors efficiencies, luminosity, etc. over time. We could also form a difference between polarized and unpolarized cross sections, giving a back door of sorts, allowing a measure of a tensor observable without needing a highly tensor aligned target. Finally, we could leverage the $\cos(2\phi)$ term to measure $\Delta(x,Q^2)$ through ϕ dependence in the cross section. Fixing the target polarization and observing scattering with a wide ϕ coverage would allow direct extraction of $\Delta(x,Q^2)$.

At Jefferson Lab, these approaches offer a couple feasible options. Looking at the first two approaches, we see from the previous equation that $\Delta(x,Q^2)$ would be overwhelmed by the presumably large contributions from tensor structure functions b_1 and b_2, unless we choose the target helicity angle such that $(3\cos^2\theta_m - 1) = 0$, where $\theta_m = 54.7°$. This means a polarized target oriented with a specific non-zero transverse component is actually preferable to a truly transverse target. The two halls which currently permit a transverse target, A and C, offer essentially no ϕ

acceptance, ruling out the third approach without the advent of detector systems which give greater acceptance in ϕ in Halls A or C, (such as SoLID [8]), or a transverse polarized target in Hall B (as is planned by HDice [9]).

2.1 Polarized Target Considerations

The largest challenge facing a measurement of $\Delta(x,Q^2)$ is a suitable polarized target. The existing dynamically nuclear polarized (DNP) solid targets at Jefferson Lab present a path to such a target, with development. The workhorse target materials of JLab's solid polarized target program, ammonia ($^{14}NH_3$), lithium hydride (^{6}LiH), and their deuterated counterparts, offer robust performance at high degrees of proton polarization in CEBAF's electron beam. With some development, the spin–1 ^{2}D,^{6}Li, and ^{14}N nuclei in these materials may offer tenable target candidates. While the heavier species may offer a larger signal and better chance of discovery of this truly nuclear effect, the deuteron offers comparison to the first available lattice QCD studies on moments of Δ in physical nuclei.

While ^{14}N in ammonia offers perhaps the most attractive target material candidate for discovery, development is required to produce an appropriate, dynamically-polarized nitrogen target. At equal spin temperature, the polarization of the spin–½ hydrogen P_p and spin–1 nitrogen P_N in $^{14}NH_3$ are related as

$$P_N = \frac{4\tanh((\omega_N/\omega_p)\,\mathrm{arctanh}(P_p))}{3+\tanh^2((\omega_N/\omega_p)\,\mathrm{arctanh}(P_p))}, \tag{2.1}$$

where ω_N and ω_p are the ^{14}N and proton Larmor frequencies. Even achieving excellent proton polarization of 95% will give only 17% vector polarization in nitrogen, and just 2% tensor alignment.

Much in the same way that proton polarization is enhanced using the high polarization of electrons in DNP, the polarization of nitrogen in $^{14}NH_3$ or lithium in LiH may be enhanced using the high polarization of proton spins from DNP. Significant polarization in nitrogen has been achieved by the SMC collaboration using cross-relaxation between the different spin species [10]. Nitrogen polarization of 40% was reached by altering the magnetic field to bring the proton and nitrogen spin reservoirs into thermal contact. While frequently moving the magnetic field to allow nitrogen polarization enhancement would be untenable in an electron scattering application, RF irradiation of the sample can accomplish the same effect. The direct enhancement of spin–1 deuteron polarization in deuterated propanediol-D6 $C_3D_6(OH)_2$ using dynamically polarized protons has been demonstrated [11] by bringing the proton and deuteron spin systems into thermal contact using RF irradiation.

The continuous NMR methods used during DNP will need further development to accomodate a polarized nitrogen target, as well. The degree of polarization and alignment of a population of spin–1 nuclei can be measured through the two absorption peaks of nitrogen which result from quadrupole broadening by taking a ratio of the peak heights. However, even at 2.5 T these absorption peaks are nearly 2.4 MHz apart and not accessible by one frequency sweep of a standard NMR Q-meter. The SMC collaboration overcame this obstacle by measuring the low frequency peak at one field setting, then raising the field to measure the high frequency peak [10]. This would be very disruptive to experimental running, and to our knowledge has never been done at 5 T. By adopting varactor diodes as variable capacitors in the NMR circuit, we hope to adaptively tune the

NMR circuit to access both peaks. This method, demonstrated in 1982 [12], will undergo careful investigation to assess any change it will bring to systematic errors of the measurement of Δ.

3. Gluonometry at the EIC

A $\Delta(x,Q^2)$ search at JLab may prove to be the start of a wider nuclear gluonometry program, continuing the study of Δ beyond the practical kinematic reach of a fixed target. As plans for the proposed Electron–Ion Collider coalesce—a facility primarily aimed at understanding the glue [13]—the search for gluonic transversity could become a key focus.

In an EIC, the polarized ion source will be the crucial enabling technology, but maintaining the polarization during acceleration will be a key difficulty. Deuteron ion sources can provide 1 μA of flux at 100% polarization via optical pumping or atomic beam source, however he most attractive species readily available for an ion source would be alkalis. Highly polarized sources of ^{6}Li and ^{23}Na were produced at Heidelberg using sextupole Stern–Gerlach and optical pumping [14]. However, depolarizing resonances make the deuteron, and species of similar g-factor like ^{6}Li. very difficult to keep polarized in a ring. The figure-8 design of the JLab EIC would allow for easier spin manipulation of more species.

4. Outlook

Progress toward a measurement $\Delta(x,Q^2)$ at Jefferson Lab is moving steadily. Initial Monte Carlo studies for a $\Delta(x,Q^2)$ search in Hall C with an unpolarized electron beam and transversely polarized target indicate a first exploration at $0.04 < x < 0.33$ and $0.7 < Q^2 < 3.8\,\mathrm{GeV}^2$ appears feasible using the standard Hall C detectors. JLab's program advisory committee (PAC) responded to this collaboration's letter of intent with encouragement [15], acknowledging the challenges such an effort faces. The current focus of effort is the development of polarized target methods to enable the measurement, as lattice QCD work to estimate the size of the effect in physical nuclei continues. Initial investigation into an EIC-based measurement of Δ has begun, with preliminary work with the JLEIC detector geometry underway.

Acknowledgments

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