

## Polarized light ions and spectator nucleon tagging at EIC

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An Electron–Ion Collider (EIC) with suitable forward detection capabilities would enable a unique experimental program of deep–inelastic scattering (DIS) from polarized light nuclei (deuterium  $^2\text{H}$ , helium  $^3\text{He}$ ) with spectator nucleon tagging. Such measurements promise significant advances in several key areas of nuclear physics and QCD: (a) neutron spin structure, by using polarized deuterium and eliminating nuclear effects through on-shell extrapolation in the spectator proton momentum; (b) quark/gluon structure of the bound nucleon at  $x > 0.1$  and the dynamical mechanisms acting on it, by measuring the spectator momentum dependence of nuclear structure functions; (c) coherent effects in QCD, by exploring shadowing in tagged DIS on deuterium at  $x \ll 0.1$ . The JLab MEIC design (CM energy  $\sqrt{s} = 15 - 50$  GeV/nucleon, luminosity  $\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ) provides polarized deuterium beams and excellent coverage and resolution for forward spectator tagging. We summarize the physics topics, the detector and beam requirements for spectator tagging, and on-going R&D efforts.

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The Electron–Ion Collider (EIC) proposed as a next-generation facility for nuclear physics would offer unprecedented capabilities for high–energy scattering on light nuclei (deuterium  $^2\text{H}$ , helium  $^3\text{He}$ , ...), including polarized beams. The medium–energy EIC designs presently developed feature center–of–mass energies in the range  $\sqrt{s} \sim 15\text{--}50$  GeV/nucleon at luminosities up to  $\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  [1]. Measurements of deep–inelastic scattering (DIS) and related processes on light nuclei in this kinematic region address several basic questions of nuclear physics:<sup>1</sup>

- A) *Neutron spin structure.* What are the spin structure functions of the neutron and their  $Q^2$  dependence? This information is essential for the flavor decomposition of the quark spin densities in the nucleon. It also impacts on the determination of the gluon spin density, as proton data alone are not sufficient to separate quarks and gluons. The isovector structure function  $g_{1p} - g_{1n}$  exhibits especially simple QCD evolution (insensitive to gluons), permits accurate separation of leading and higher–twist contributions, and is needed to test the Bjorken sum rule.
- B) *Bound nucleon structure.* What are the quark/gluon distributions of the bound nucleon at  $x > 0.1$ ? By what mechanisms are they modified in the nuclear medium? How does the modification depend on the nuclear configuration (off–shellness, strength of interaction)? Answering these questions will help to understand the QCD origin of the short–range  $NN$  interaction and the role of non-nucleonic degrees of freedom in nuclei.
- C) *Coherent scattering in QCD.* How does the quantum effect of coherence in high-energy scattering manifest itself in QCD? How does it influence the gluon and quark densities seen by a short–distance probe at  $x \ll 0.1$ ? Coherence results in shadowing, a basic prediction of QCD which can be observed experimentally. It also determines how rapidly the regime of high gluon densities (saturation) is approached at small  $x$ .

In trying to answer these questions on the basis of actual nuclear DIS data one faces considerable challenges. In the extraction of free neutron structure one must eliminate the effects of nuclear binding and final–state interactions, and accurately account for the neutron polarization in the nucleus. In the study of bound nucleon structure one needs to control the nuclear environment, which is compounded from different types of configurations that one would like to separate (mean field, short-range correlations). In the search for coherent effects one wants to identify unambiguous signatures of coherence and, ideally, separate contributions involving  $N = 2, 3, \dots$  nucleons. While all this can be accomplished partly with theoretical calculations, it is clear that more experimental control is needed in the analysis of nuclear DIS data. Two new experimental tools that become available with the EIC would greatly help one to address the challenges.

One essential tool are deuterium beams, especially polarized deuterium, as would be available for the first time with JLab MEIC, thanks to the figure–8 shape of the ion ring designed to compensate the effect of spin precession. The deuteron is the simplest nucleus ( $A = 2$ ); its wave function is known well up to large relative momenta  $\sim$  few 100 MeV, including the light-front wave function describing microscopic nuclear structure as probed in high-energy scattering processes [3]. The deuteron has spin 1 and is mostly in the  $L = 0$  configuration (S–wave), with a small admixture of

<sup>1</sup>For a general overview of the medium–energy EIC physics program, including proton beams, see e.g. Ref. [2].

$L = 2$  (D-wave), such that the proton and neutron are spin-polarized and their degree of polarization is known very well. Because there are only two nucleons the possibilities for final-state interactions are limited; in configurations where they can happen they can be estimated using theoretical models. Finally, at small  $x$  the deuteron allows one to study coherent effects exactly in the  $N = 2$  system, greatly simplifying the theoretical analysis.

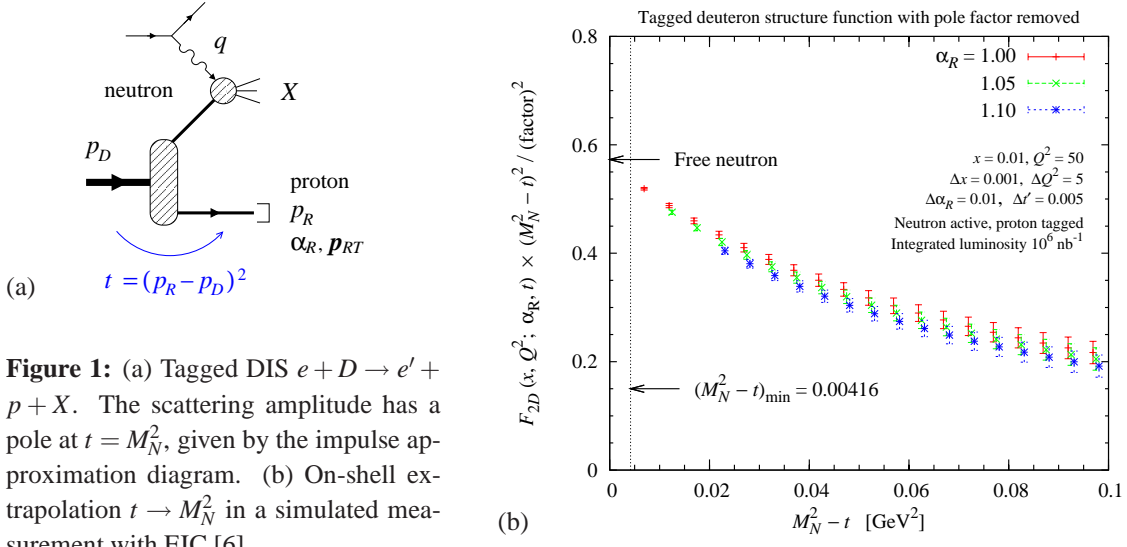
The other tool is the detection of spectator nucleons emerging from the high-energy scattering process (“spectator tagging”). In collider experiments the spectator nucleons carry fraction  $\sim 1/A$  of the ion beam momentum and can be detected with appropriate forward detectors (see below). The technique is uniquely suited to colliders: there is no target material absorbing low-momentum nucleons, and it can be used with polarized ion beams (longitudinal and transverse). Spectator tagging is especially powerful in scattering on deuterium. It allows one to positively identify the active nucleon (e.g., DIS on the  $n$  with a  $p$  spectator detected) and control its quantum state through measurement of the recoil momentum. Spectator tagging with unpolarized deuterium was explored in a pioneering fixed-target experiment at JLab with 6 GeV beam energy (CLAS BoNuS detector, covers recoil momenta  $p_R \gtrsim 70\text{MeV}$ ) [4] and will be studied further at 11 GeV.

Spectator tagging with polarized deuterium at EIC represents a unique combination that would qualitatively advance our understanding of nuclear effects in DIS and answer the fundamental nuclear physics questions listed above. It enables a theoretical analysis of nuclear DIS at a level of precision that is commensurate with the expected quality of the data. In this note we briefly summarize the physics impact, the detector and beam requirements, and on-going R&D efforts.

**Neutron structure.** Spectator tagging with deuterium provides a model-independent method for determining the DIS structure functions of the free neutron. One measures the conditional DIS cross section  $e + D \rightarrow e' + p + X$  (here  $D \equiv {}^2\text{H}$ ) as a function of the recoil proton momentum, described by the light-cone fraction  $\alpha_R \equiv 2(E_R + p_R^z)/(E_D + p_D^z)$  and the transverse momentum  $\mathbf{p}_{RT}$  (the components refer to a frame in which the deuteron and virtual photon momenta are collinear and define the  $z$ -direction). Another important variable is the invariant 4-momentum transfer between the deuteron and the recoil proton,  $t \equiv (p_R - p_D)^2$ . As a function of  $t$  the scattering amplitude has a pole at  $t = M_N^2$  (unphysical region) corresponding to nucleon exchange in the  $t$ -channel (see Fig. 1a). The residue at the pole is, up to a constant factor representing deuteron structure, given by the structure function of the free neutron, evaluated at the argument  $\tilde{x} = x/(2 - \alpha_R)$ . Nuclear binding and final-state interactions only affect the amplitude away from the pole, but not the residue at the pole [5].

To extract the free neutron structure function one measures the tagged cross section over a range of  $t$ , removes the pole factor  $1/(t - M_N^2)^2$ , and extrapolates to  $t \rightarrow M_N^2$  [5]. The pole in  $t$  is extremely close to the physical region (the distance is proportional to the deuteron binding energy,  $\varepsilon_D M_D$ ) so that the extrapolation can be performed with great accuracy. The method is analogous to the Chew-Low extrapolation used to extract pion structure from  $\pi N$  scattering data. Figure 1b shows a simulated on-shell extrapolation with MEIC pseudodata ( $s_{eD} = 1000\text{GeV}^2$ , integrated luminosity  $10^6\text{nb}^{-1}$ ) [6]. One sees that the extrapolation is very smooth. Comparison of the data at different recoil light-cone fraction  $\alpha_R$  allows one to test universality of the nucleon pole. Critical to the success of the method is the ability to measure the recoil momentum with complete coverage down to  $p_{RT} = 0$  and resolution  $\Delta p_{RT} \lesssim 20\text{MeV}$  and  $\Delta\alpha_R \lesssim 10^{-3}$  (see below).

Spectator tagging with on-shell extrapolation can be used for precision measurements of  $F_{2n}$

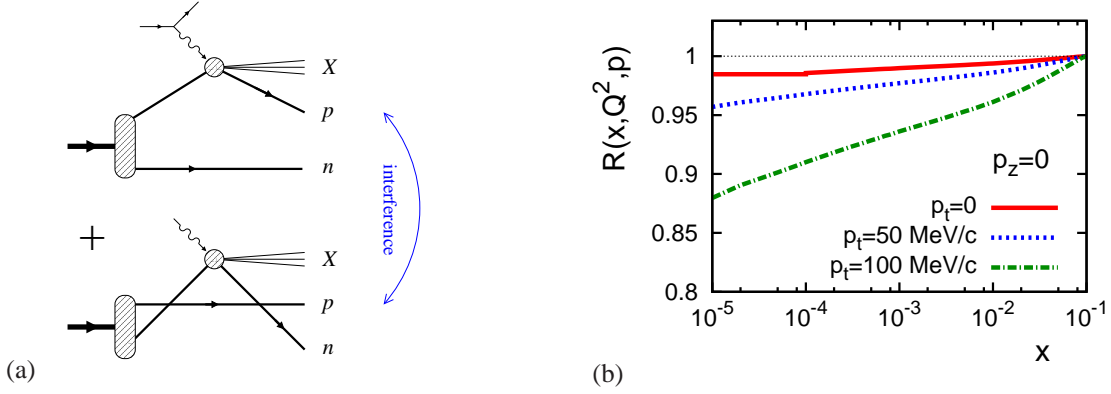


**Figure 1:** (a) Tagged DIS  $e + D \rightarrow e' + p + X$ . The scattering amplitude has a pole at  $t = M_N^2$ , given by the impulse approximation diagram. (b) On-shell extrapolation  $t \rightarrow M_N^2$  in a simulated measurement with EIC [6].

(and, indirectly, the difference  $F_{2p} - F_{2n}$ ), which determine the flavor structure of the nucleon sea and validate models of nuclear effects. Even more importantly, it can be used to extract the neutron spin structure function  $g_{1n}$  from measurements with polarized deuterium beams. It represents the cleanest and most model-independent method to determine the neutron spin structure. The impact of neutron data on the flavor decomposition of the quark spin and the determination of the gluon polarization has been discussed in the literature. The method can also be extended to semi-inclusive DIS on the neutron (flavor decomposition of transverse momentum distributions and spin-orbit effects) and exclusive final states (generalized parton distributions).

**Bound nucleon structure.** Spectator tagging with polarized deuterium also offers a unique method for studying the modification of the nucleon’s quark/gluon structure in the nucleus. Measurements of ratios of inclusive nuclear structure functions at  $x > 0.25$  show a distinctive nuclear dependence (“EMC effect”), whose origin has been the subject of much theoretical speculation. Spectator tagging would allow one to study the nuclear modification as a function of the recoil nucleon momentum, extending the measurements of Fig. 1b over a broad range of momentum transfers up to  $t - M_N^2 \sim -0.5 \text{ GeV}^2$ . In this way one could directly reveal the connection between the nuclear modification and short-range  $NN$  correlations, resolving a basic question in the interpretation. By combining spectator proton tagging in DIS on deuterium with conventional flavor tagging (semi-inclusive DIS) one could in addition determine whether the (polarized)  $u$  and  $d$  quarks in the neutron are modified in the same way. Finally, because of the wide kinematic coverage in  $Q^2$  one could map out the  $Q^2$  evolution of the nuclear structure functions at  $x > 0.1$  and separate the modification of quark and gluon distributions. Altogether, these measurements would enable a new level of understanding of the modification of the nucleon’s partonic structure in nuclei. This program relies essentially on the high luminosity of the EIC, as the tagged deuteron cross sections decrease very fast when increasing the spectator momentum.

**Coherent scattering in QCD.** In DIS at  $x \ll 0.1$  the longitudinal extent of the interaction becomes much larger than the typical internucleon distances in nuclei, so that the high-energy



**Figure 2:** (a) Shadowing in tagged DIS on deuterium. Diffractive scattering on the  $p$  and  $n$  causes interference between the two amplitudes. (b) Theoretical prediction for the shadowing ratio  $R = F_{2D}/(F_{2p} + F_{2n})$  as a function of  $x$  and the recoil proton transverse momentum [7].

probe can interact coherently with all the nucleons lined up along its path, giving rise to distinctive phenomena such as shadowing. Attempts to observe these phenomena experimentally have so far relied mostly on inclusive DIS from heavy nuclei. In DIS on light nuclei with spectator tagging coherence manifests itself in novel ways and can be studied with much better experimental control.

At  $x \ll 0.1$  there is a significant probability for DIS on the nucleon to produce a diffractive final state, where the nucleon remains intact and recoils with a momentum transfer  $\sim$  few 100 MeV (see Ref. [8] for a discussion of the HERA results). In DIS on deuterium such diffractive scattering can happen on the proton or the neutron, causing quantum-mechanical interference between the two amplitudes with the same final state (see Fig. 2a). In inclusive DIS,  $e + D \rightarrow e' + X$ , the interference gives rise to leading-twist nuclear shadowing and can be calculated as an integral over the deuteron wave function [7]. In tagged DIS,  $e + D \rightarrow e' + p + X$  (or double-tagged DIS,  $e + D \rightarrow e' + p + n + X$ ), the interference effect can be observed directly as a function of the recoil momentum (see Fig. 2b), especially at larger transverse momenta  $p_{RT} \sim 100$  MeV, where it can be as large as 10-20%. Such measurements would enable detailed tests of the theoretical description of coherence and shadowing at small  $x$ . Besides its intrinsic interest this would benefit the extraction of parton densities from nuclear DIS data and the phenomenology of the black-disk regime (unitarity limit) at small  $x$ , as shadowing influences quantitatively how rapidly this regime is approached in nuclei. The diffractive parton densities needed as input to the shadowing calculations can be measured in  $ep$  scattering with EIC in the same kinematics.

An attractive feature of the deuteron is that one can study coherence strictly in the  $N = 2$  system and does not have to deal with multiple scattering from  $N > 2$  nucleons. By going from  ${}^2\text{H}$  to  ${}^3\text{He}$  one can then switch on the  $N = 3$  term in the multiple scattering series. This stepwise approach represents an interesting complement to coherence studies with heavier nuclei.<sup>2</sup>

**Detector and beam requirements.** Spectator tagging with EIC requires integrated forward detectors with (a) complete coverage for protons with low recoil momenta relative to beam momentum per nucleon:  $p_{RT} < 200$  MeV,  $p_{R\parallel}/p(\text{beam}) \sim 0.8 - 1.2$ ; (b) sufficient recoil momentum

<sup>2</sup>Another observable potentially sensitive to coherence is the deuteron's tensor-polarized structure function  $b_1$ , which is absent in scattering from a single free nucleon [3].

resolution:  $\Delta p_{RT} \lesssim 20 \text{ MeV}$ ,  $\Delta p_L/p_L \sim 10^{-4}$ ; (c) ideally, also neutron detection with reasonable angular and position resolution. The MEIC interaction region and forward detection system have been designed specifically for this purpose and provide fully sufficient capabilities for the physics program outlined here [9]. Spectator tagging also requires that the intrinsic momentum spread in the ion beam be sufficiently small to allow for accurate reconstruction of the actual recoil momentum at the interaction vertex. Simulations show that with the MEIC beam parameters the “smearing” of the kinematic variables is very moderate and does not substantially affect the physics analysis (in  $t$  the uncertainty is of the order  $\sim 0.005 \text{ GeV}^2$  — the bin size in Fig. 1b) [6].

An R&D program is under way at JLab to develop simulation tools for spectator tagging with EIC (cross section models, event generators) and demonstrate the feasibility of such measurements [6]. The tools are being made available to users and can be applied to a variety of processes of interest. Information about available resources may be obtained from the authors.

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