Physics Opportunities with High Luminosity on Nuclear Targets

Probing In-Medium QCD Dynamics, Nuclear Modifications, and Hadron Tomography

Lamiaa El Fassi

Mississippi State University

November CLAS Collaboration Meeting

November 19, 2026









High-Luminosity Nuclear Target Frontier at CEBAF

Why high luminosity on nuclear targets?

- CW (100% duty factor) high-current beam with dense multi-foil (isotopic) target assemblies: several nuclei measured *simultaneously*, under identical conditions
- Ratios σ_A/σ_D: luminosity, acceptance and efficiencies largely cancel
- Compensates the steep fall of cross sections in rare exclusive, semi-inclusive, and spectator-tagged processes
- Reaches extreme valence kinematics ($x_B \to 1$, $x > 1$), high Q^2, and high spectator momenta ($k > k_F$)
- Enables fully multi-differential analyses instead of 1D projections

All four experimental halls have nuclear programs



Figure 1: CEBAF and its four experimental halls.

J. Arrington et al., Prog. Part. Nucl. Phys. **127**, 103985 (2022); P. A. Adderley et al., Phys. Rev. Accel. Beams **27**, 084802 (2024) (CEBAF 12 GeV).

Luminosity Reach and Nuclear Capabilities by Hall

Hall	Equipment	Luminosity ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Nuclear-target strengths
A	HRS, SBS (BigBite, SuperBigBite)	$\sim 10^{38}$–10^{39}	High-rate inclusive/DIS at large x; cryogenic ^{3}H/^{3}He; polarized ^{3}He; SRC and mirror-nuclei studies
B	CLAS12 + ALERT, BAND, polarized targets	$\sim 10^{35}$ (upgrade planned)	Large acceptance: exclusive & SIDIS final states, multi-foil solid targets (RG-D, RG-E), recoil tagging, polarized $NH_3/ND_3/^7$LiD
C	HMS, SHMS, NPS, LAD	$\sim 10^{38}$–10^{39}	Precision cross sections at high Q^2 and $x > 1$; isotope chains (e.g. ^{40,48}Ca); tagged DIS with backward protons (LAD)
D	GlueX, tagged photons	$\sim 10^{7}$–$10^{8}\,\gamma/\mathrm{s}$	Real-photon probe of nuclei: CT and SRC in photoproduction, J/ψ near threshold (gluons)

The halls are complementary: **large acceptance** (B) vs. **highest luminosity and precision** (A, C) vs. **real photons** (D)

V. D. Burkert et al. (CLAS12), Nucl. Instrum. Meth. A **959**, 163419 (2020); S. Adhikari et al. (GlueX), Nucl. Instrum. Meth. A **987**, 164807 (2021); Arrington et al., PPNP **127**, 103985 (2022)

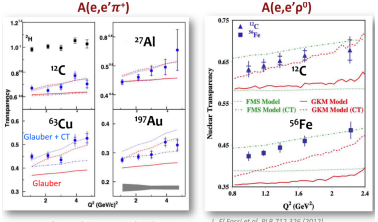
Color Transparency (CT) across Nuclear Targets

QCD mechanism & nuclear filtering:

- Hard exclusive reactions select small, point-like configurations (PLCs) with reduced FSI in cold nuclear matter
- Signature: transparency $T_A = \sigma_A/(A\,\sigma_N)$ rising with Q^2 (at fixed coherence length l_c)

Meson vs. Baryon sectors:

- **Mesons (π^+, ρ^0):** onset of CT observed, T_A rises with Q^2 (top)
- **Proton puzzle:** ^{12}C$(e,e'p)$ shows no rise of T_A up to $Q^2 \approx 14.2\,\mathrm{GeV}^2$ (bottom)
- **High-lumi reach:** isotopic scaling (^{4}He, C, Fe/Cu, Sn, Pb) to map $T_A \propto A^{\alpha-1}$; $\alpha \to 1$ signals CT



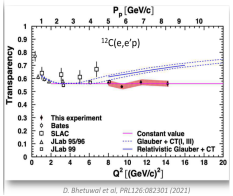


Figure 2: Top: CT onset for π^+ (Hall C) and ρ^0 (CLAS). Bottom: flat T_A for ^{12}C$(e,e'p)$ (Hall C)

S. J. Brodsky, A. H. Mueller, PLB **206**, 685 (1988); B. Clasie et al., PRL **99**, 242502 (2007); X. Qian et al., PRC **81**, 055209 (2010); L. El Fassi et al. (CLAS), PLB **712**, 326 (2012); D. Bhetuwal et al., PRL **126**, 082301 (2021); D. Dutta, K. Hafidi, M. Strikman, PPNP **69**, 1 (2013)

Color Transparency: High-Luminosity Opportunities by Hall

High luminosity compensates the steep fall of exclusive cross sections with Q^2 and allows fine binning in (Q^2, l_c, t) on several targets at once, separating CT from coherence-length effects

- **Hall C:** highest-Q^2 $(e, e'p)$ and $(e, e'\pi^+)$ on C, Cu, Au with HMS/SHMS; heavier targets and higher Q^2 test whether the proton onset is delayed
- **Hall B (CLAS12):** ρ^0 CT at fixed l_c on LD_2, C, Cu, Sn (RG-D, 2023) up to $Q^2 \approx 5$–6 GeV^2; same data give A-scaling with one setup; baryon channels (Δ, quasi-elastic p) in large acceptance
- **Hall D:** CT in hard exclusive photoproduction on D, ^{4}He, C (SRC/CT run), a complementary real-photon probe

Hall C CT: E12-06-107; CLAS12 RG-D: E12-06-106 (CT with ρ^0)

In-Medium Hadronization with Nuclear Targets

Nuclei as calibrated spatial analyzers:

- Hard scattering inside nuclei of increasing radius ($R_A \propto A^{1/3}$) maps hadron-formation timescales
- Struck (di)quark propagates through cold matter, radiating gluons (energy loss dE/dx)
- Transport coefficient $\hat{q}$ from p_T-broadening: $\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_A - \langle p_T^2\rangle_D$
- Hadron attenuation: multiplicity ratio $R_A^h = \dfrac{(N_h/N_e)_A}{(N_h/N_e)_D}$

Timescales:

- **Production time (τ_p):** parton propagation until color neutralization into a pre-hadron
- **Formation time (τ_f):** pre-hadron evolves into the final hadron h

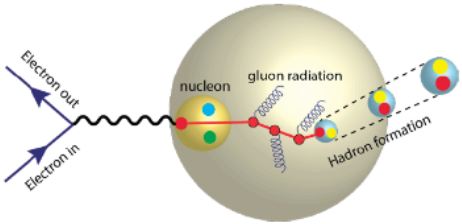


Figure 3: Space-time picture of DIS on a nucleus: gluon radiation by the struck (di)quark, pre-hadron, and hadron formation

A. Accardi et al., Riv. Nuovo Cim. **32**, 439 (2009); A. Airapetian et al. (HERMES), NPB **780**, 1 (2007); S. Moran et al. (CLAS), PRC **105**, 015201 (2022); T. Chetry et al. (CLAS), PLB **849**, 138451 (2024)

Hadronization: High-Luminosity Opportunities by Hall

High luminosity enables fully multi-dimensional binning in $(\nu, z, Q^2, p_T^2, \phi_h)$, separating energy loss from absorption, and provides the statistics for rare species ($K^{\pm}$, ϕ, Λ, di-hadrons) and heavy targets (Sn, Pb)

- **Hall B (CLAS12):** RG-E dual target (LD_2 + C, Al, Cu, Sn, Pb): $\pi^{\pm}$, $K^{\pm}$, p, ϕ, Λ, di-hadrons in 4–5D bins; RG-D nuclear TMDs (LD_2, C, Cu, Sn)
- **Hall B:** meson vs. baryon (and current vs. target fragmentation) $\Rightarrow$ (di)quark propagation and diquark correlations
- **Halls A/C:** precision multiplicity ratios at fixed kinematics and high z as cross-checks of acceptance-dominated systematics

CLAS12 RG-E: E12-06-117 (Quark propagation and hadron formation); RG-D: E12-06-106 / nuclear-TMDs program

EMC–SRC connection:

- EMC slope $|dR_{\mathrm{EMC}}/dx|$ correlates linearly with the SRC pair density $a_2(A/d)$ from ^{3}He to ^{208}Pb
- CLAS (Nature 2019): simultaneous DIS and SRC on C, Al, Fe, Pb; after accounting for SRC pairs, the modification is universal

Local density vs. Mean field:

- Strong evidence that quark modification is driven by high-momentum, highly correlated nucleon pairs
- **Isotopic comparisons** (^{40}Ca vs. ^{48}Ca): isospin dependence (np vs. pp pairs)
- **Spectator tagging:** tests directly whether the modification is localized in nucleons within SRC pairs

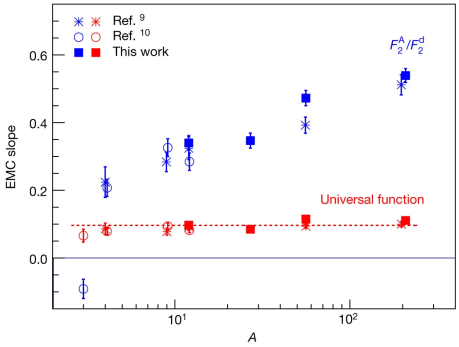


Figure 4: EMC slopes vs. A (blue); after correcting for SRC-pair abundance the modification becomes A-independent (red, universal function)

J. J. Aubert et al. (EMC), PLB **123**, 275 (1983); L. B. Weinstein et al., PRL **106**, 052301 (2011); O. Hen et al., Rev. Mod. Phys. **89**, 045002 (2017); B. Schmookler et al. (CLAS), Nature **566**, 354 (2019)

SRC/EMC: High-Luminosity Opportunities by Hall

High luminosity reaches the tiny cross sections at $x \to 1$ and $x > 1$, makes coincidence tagging with slow recoils feasible, and gives the statistics for percent-level isotope comparisons across many nuclei

- **Hall C:** EMC ratios on light and medium nuclei including ^{40,48}Ca (XEM2); SRC via $x > 1$ scaling; LAD tagged DIS $d(e, e' p_s)X$ at high spectator momentum
- **Hall A:** ^{3}H/^{3}He mirror nuclei (MARATHON, tritium SRC): isospin of SRC and F_2^n/F_2^p at large x
- **Hall B (CLAS12):** BAND tagged DIS $d(e, e' n_s)X$; ALERT tagged DIS on ^{2}H/^{4}He; RG-M SRC in nuclei; RG-G polarized EMC (next slide)
- **Hall D:** SRC pairs probed with real photons (SRC/CT run)

Hall C: E12-10-008 (XEM2), E12-06-105, E12-11-107 (LAD); Hall A: D. Abrams et al. (MARATHON), PRL **128**, 132003 (2022); S. Li et al., Nature **609**, 41 (2022); BAND: T. Denniston et al. (CLAS), PRL **133**, 152502 (2024); ALERT: E12-17-012

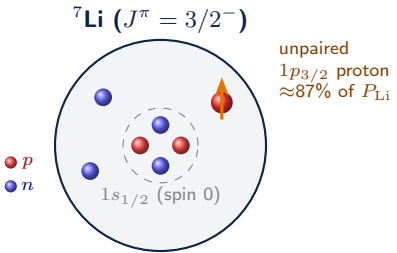
The Polarized EMC Effect: CLAS12 Run Group G

Is the nucleon's spin structure modified in the medium?

- Nuclear modification of the spin structure function $g_1(x, Q^2)$: never measured
- **Discriminating:** SRC picture ⇒ small effect; mean-field models (Cloët–Bentz–Thomas) ⇒ comparable to or larger than unpolarized

E12-14-001 (Hall B, CLAS12 RG-G):

- Polarized ^{7}LiD alternated with NH_3 (free-proton reference); 11 GeV
- ^{7}Li ≈ polarized proton in a nucleus: ≈87% of its polarization on the unpaired $1p_{3/2}$ proton
- Ratio of ^{7}Li to free-proton g_1 vs. x in Q^2 bins; 55 PAC days, rated A$^-$ (PAC-48)
- **Luminosity-limited:** beam heating and depolarization cap polarized targets ($\sim 10^{35}$); higher rate capability = direct precision gain



$$R_{\rm pol}(x) \approx \frac{g_1^{^7\rm Li}(x)}{P_p\, g_1^{p}(x)}$$

$\neq 1$ ⇒ spin-dependent EMC effect

JLab E12-14-001, "The EMC Effect in Spin Structure Functions" (S. Kuhn, W. Brooks, L. El Fassi et al.); CLAS12 RG-G update to PAC (2024); I. C. Cloët, W. Bentz, A. W. Thomas, PRL **95**, 052302 (2005); V. Guzey, M. Strikman, PRC **61**, 014002 (1999)

Tomography of bound nucleons & nuclei:

- Generalized Parton Distributions (GPDs) correlate longitudinal momentum x with transverse position $b_\perp$
- Probe the nuclear energy-momentum tensor: gravitational form factors, internal pressure and shear forces

Coherent vs. Incoherent nuclear DVCS:

- **Coherent** ($eA \to e'A\gamma$): nucleus stays intact; 3D matter and pressure distribution of the nucleus
- **Incoherent** ($eA \to e'N'\gamma X$): in-medium modification of bound-nucleon GPDs ("generalized EMC effect")

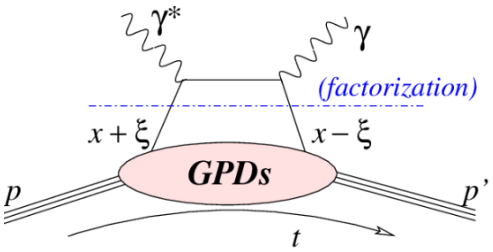


Figure 5: DVCS handbag diagram: the hard $\gamma^*\gamma$ subprocess factorizes from the GPDs of the target (nucleus or bound nucleon)

X. Ji, PRL **78**, 610 (1997); M. Burkardt, PRD **62**, 071503 (2000); M. V. Polyakov, PLB **555**, 57 (2003); V. D. Burkert, L. Elouadrhiri, F. X. Girod, Nature **557**, 396 (2018); M. Hattawy et al. (CLAS), PRL **119**, 202004 (2017); **123**, 032502 (2019)

Tomography: High-Luminosity Opportunities by Hall

High luminosity with recoil detection makes the small nuclear DVCS cross sections accessible over a wide $|t|$ range, with the fine (t, Q^2, x_B) binning needed to separate coherent from incoherent scattering

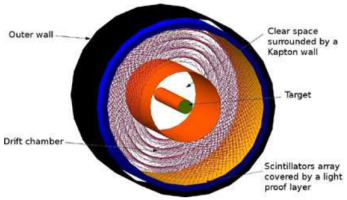
- **Hall B (CLAS12 + ALERT):** coherent DVCS on ^{4}He (single GPD H_A), incoherent DVCS on bound protons/neutrons, and coherent ϕ production; neutron DVCS on deuterium (RG-B)
- **Halls A/C:** high-precision DVCS cross sections at $\gtrsim 10^{37}$ (HRS, NPS calorimeter in Hall C) on hydrogen and deuterium as the free-nucleon baseline
- **Halls C/D:** J/ψ photoproduction near threshold $\Rightarrow$ gluonic gravitational form factors (mass radius); extension to nuclei probes gluons in the medium

ALERT: E12-17-012 ("Partonic structure of light nuclei"); B. Duran et al., Nature **615**, 813 (2023) (J/ψ-007, Hall C); S. Adhikari et al. (GlueX), PRC **108**, 025201 (2023)

Nuclear Target Spectator Tagging: ALERT, BAND, and LAD

- **Luminosity advantage:** $\sim 10^{35}$ (CLAS12) to $\gtrsim 10^{37}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Hall C) enables coincidence measurements with low-energy and backward nuclear spectators.
- **Physics coverage:** from soft recoils (tagged DIS, nuclear GPDs) to high-momentum backward nucleons ($k > k_F$) from SRC pairs

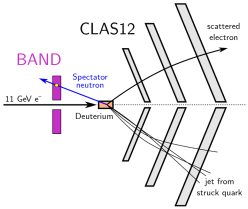
ALERT (Hall B)



Low-energy recoil tracker

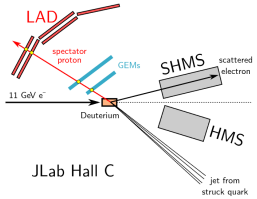
(p, ^{2}H, ^{3}H, ^{3}He, ^{4}He)

BAND (Hall B)



Backward neutron detector, $d(e, e' n_s)X$

LAD (Hall C)



Large-acceptance backward proton detector

ALERT: E12-17-012 and related proposals; BAND: T. Denniston et al. (CLAS), PRL **133**, 152502 (2024); LAD: E12-11-107

Summary & Outlook: Nuclear High-Luminosity Program

- **The intensity frontier on nuclear targets:**
  - High-luminosity running turns nuclei into femtometer-scale laboratories for non-perturbative QCD
  - Multi-differential precision in $(x_B, Q^2, z, p_T^2, \phi_h, t)$ is needed to decouple competing in-medium effects
  - Complementary halls: large acceptance (B), highest luminosity (A, C), real photons (D)
- **Resolving in-medium confinement & structure:**
  - Map the onset and boundaries of color transparency across extended isotopic target chains
  - Separate partonic energy loss and $\hat{q}$ from pre-hadron and final-hadron formation
  - Pin down the origin of the EMC effect by tagging SRC recoil spectators (ALERT, BAND, LAD)
  - First measurement of the **polarized EMC effect** with polarized ^{7}LiD (CLAS12 RG-G)
- **Comprehensive 3D tomography:**
  - Disentangle coherent whole-nucleus tomography from bound-nucleon structure; partonic pressure and shear inside nuclei
  - Provide the foundational nuclear data for the Electron-Ion Collider (EIC) and a future 22 GeV CEBAF
- **Outlook – energy extension:** a 22 GeV CEBAF reaches proton knockout at $Q^2 \approx 20$–$25\,\mathrm{GeV}^2$ (baryon CT onset), moves hadronization outside the nucleus to separate τ_p and τ_f, and widens the Q^2, x_B lever arm for nuclear GPDs; the EIC extends to low x and gluons

A. Accardi et al., "Strong interaction physics at the luminosity frontier with 22 GeV electrons at Jefferson Lab", Eur. Phys. J. A **60**, 173 (2024); EIC Yellow Report, Nucl. Phys. A **1026**, 122447 (2022)