Physics with CEBAF at 12 GeV and Future Opportunities

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1.1 Scientific Highlights
1.1.1 Nucleon Spin and its 3D Structure and Tomography

Several decades of experiments on deep inelastic scattering (DIS) of electron or muon beams on nucleons have taught us about how quarks and gluons (collectively called partons) share the momentum of a fast-moving nucleon. They have not, however, resolved the question of how partons share the nucleon’s spin and build up other nucleon intrinsic properties, such as its mass and magnetic moment. The earlier studies were limited to providing the longitudinal momentum distribution of quarks and gluons, a one-dimensional view of nucleon structure. The EIC is designed to yield much greater insight into the nucleon structure (Fig. 1.1, from left to right), by facilitating multi-dimensional maps of the distributions of partons in space, momentum (including momentum components transverse to the nucleon momentum), spin, and flavor.

Figure 1.1: Evolution of our understanding of nucleon spin structure.
Left: In the 1980s, a nucleon’s spin was naively explained by the alignment of the spins of its constituent quarks.
Right: In the current picture, valence quarks, sea quarks and gluons, and their possible orbital motion are expected to contribute to overall nucleon spin.
Chapter 1
Overview: Science, Machine and Deliverables of the EIC

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Emergent Phenomena

Nuclear Femtography
Parton Distribution Functions (PDFs) of quarks and gluons used to illustrate the reach of CEBAF/EIC.

EIC/CEBAF Complementarity:

- CEBAF focus is on valence quark region with high luminosity
- Solenoidal Large Intensity Device (SoLID) will enhance capabilities
Kinematic Landscape for PDFs

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Higher CEBAF energies will allow an extension to lower $x_B$. 

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**Figure 1:** Kinematic regions of Deep Inelastic Scattering and the comparative reach of EIC and CEBAF, as well as other facilities compared with parton distributions from CJ15

Precision measurements in the valence quark region requiring high luminosity are clearly the purview of CEBAF, with the 24 GeV upgrade providing important overlap into the sea quark region where the EIC is designed to probe at low $x$. 

1.4.4. The Electron-Ion Collider (EIC) in China

The physicist community in China, together with international collaborators, proposed a polarized electron-ion collider at the High Intensity heavy-ion Accelerator Facility (HIAF), currently under construction in southern China. EIC@HIAF was proposed as an extension to HIAF in a phased approach. The first phase of the China EIC will include 3 to 5 GeV polarized electrons on 12 to 23 GeV polarized protons (and ions at about 12 GeV/nucleon), with luminosities of 1 to 2 $\times 10^{33}$ cm$^{-2}$s$^{-1}$. This facility with complementary kinematic reach to both Jefferson Lab and the US EIC will allow for the studies of one and three-dimensional nucleon structure, the QCD dynamics, and to advance the understanding of the strong nuclear force.

2. Electromagnetic Form Factors and Parton Distributions

With the advent of particle accelerator technology, high energy electron scattering became an indispensable tool for understanding the internal structure of nucleons. This is because the fundamental cross section separates into an electronic part (which is accurately determined from Quantum Electrodynamics) and a hadronic part which can be formulated in terms of structure functions of various kinematic quantities, and measured in electron scattering. For elastic scattering from the nucleon, the structure functions can be written in terms of form factors $G_E(q^2)$ and $G_M(q^2)$.
Fig. 6. The Wigner distributions yield a unified description of a nucleon in terms of the position and momenta of its constituents. The uncertainty principle precludes knowing both position and momentum simultaneously, but the three-dimensional Generalized Parton Distributions (GPDs) and Transverse Momentum-Dependent Distributions (TMDs) provide a powerful spatial and momentum tomography. The differential variables along the arrows indicate the variable integrated over to move from the upper to lower distributions.

Past studies of deep inelastic electron scattering offered us merely a one-dimensional view of nucleon structure where we learned about the motion of partons parallel to the direction of travel of the nucleon. Their longitudinal momentum distribution is then described by parton distribution functions (PDFs). The nucleon was viewed as a collection of fast moving quarks, antiquarks and gluons, whose transverse momenta were not resolved. While simple and elegant, such a description is unable to address one of the key questions in our understanding of the nucleon, namely how its spin is apportioned between the spin of its constituents and their orbital angular momentum. To understand this requires a three-dimensional description.

Are representations using GPDs and TMDs driven by the overwhelming need to go beyond the one-dimensional picture of the nucleon structure [34]. Even at large Bjorken \( x \), where most of the longitudinal momentum is carried by valence quarks, seemingly puzzling results from a first generation of worldwide exclusive and semi-inclusive deep inelastic lepton scattering experiments require a GPD and TMD description for their interpretation. Thus these representations provide us with a unified view, demonstrating both the importance of this new phenomenology, and the limitation of our previous studies of nucleon structure.

Knowledge from inclusive, semi-inclusive and exclusive electron scattering using the 12 GeV CEBAF upgrade will provide information on the transverse position and transverse momentum of quarks for a fixed slice of their longitudinal momentum leading to a three-dimensional imaging of the nucleon both in position and momentum. This upgrade offers for the first time the tools to unravel the nucleon valence quark structure by mapping the spatial position and momentum distribution of the quarks with sufficient precision to propel our knowledge and understanding of the basic building blocks of nuclear matter to a level unprecedentedly.

The ultimate (and lofty!) goal is to extract \( W(x, k_\perp, r_\perp) \) experimentally and compare to theory.

Program of experimentation:
- Ongoing measurements of PDFs and Form Factors
- A start on determining the Generalized Parton Distributions
- Planning for measurements of the Transverse Momentum Distributions

Phenomenology/Theory
- Lots of model-building
- Fundamental theory calculations are currently underway
Deeply Virtual Compton Scattering

\[ t = (P' - P)^2 \]

\[ e', e, \gamma, x + \xi, x - \xi, P, P' \]

+ Bethe-Heitler

Compton Form Factors (CFF) derived from asymmetries with polarized beam, compared to convolution integrals of GPDs.

Previous data [19]
This work
KM15

\[ \langle \Phi \rangle \]

\[ \sigma \]

\[ \text{Previous data [19]} \]

\[ \text{This work} \]

\[ \text{KM15} \]
Timelike Compton Scattering

PRL 127(2021)262501
First Measurement of Timelike Compton Scattering (CLAS12)

Measured asymmetries arising from interference with Bethe-Heitler, compared to model calculations from Vanderhaeghen-Guichon-Guidal (VGG) model and Goloskokov-Kroll (GK).

Nuclear Femtography

\[
\gamma(q) \rightarrow e^+(k') + e^-(k) \quad \text{GPD}
\]
\[
x + \xi \quad P(p) \quad x - \xi \quad P'(p')
\]

\[
\text{Forward angular bin: } \theta \in [50^\circ, 80^\circ], \phi \in [-40^\circ, 40^\circ]
\]
Double DVCS

EPJA 57(2021)240

\[ e^+p \rightarrow e^+p\mu^+\mu^- \]

Note: Positron beams

- Access GPDs away from \( x=\pm \xi \)
- Cross section \( \times 100 \) smaller than for DVCS
- Requires large acceptance, high luminosity detector with superb muon detection
- Two Letters of Intent submitted to PAC (SoLID & CLAS12)
Transverse Momentum Dist

Semi Inclusive Deep Inelastic Scattering (SIDIS) at 12 GeV with SoLID

World vs. SoLID baseline (systematic uncertainty included)

Transversity

\[ x h_1(x) \]

\[ x \]

\[ \int \]

\[ g_T \]

Tensor charge

Jim Napolitano

2022 JLUO Meeting
**Exclusive Photoproduction**

E12-20-008 and E12-21-005

\[ \gamma n \rightarrow \pi^- p \]

- \(q\)
- \(q' = q - \Delta\)
- \(k_j = k_j - \frac{\Delta}{2}\)
- \(k'_j = k_j + \frac{\Delta}{2}\)
- \(p = p - \frac{\Delta}{2}\)
- \(p' = p + \frac{\Delta}{2}\)

**GPD-Based Theory Predictions**

- Above resonance region and at sufficiently large \(s, -t, -u \gg \Lambda^2\) QCD GPD treatment should work
- Leading order treatment describes real Compton scattering quite well for chosen kinematics
- However calculations including twist-2 amplitudes underestimate CLAS \(\pi^0\) cross-sections by >2 orders of magnitude
- Twist-2 treatment within GPD framework not sufficient


Handbag mechanism: one q from ingoing and one q from outgoing nucleon participate in hard process only. Others are spectators.


- Recent calculations by Kroll et al. found that inclusion of twist-3 contributions are dominant factor in agreement with cross-section

B, c, d are twist-3 Fock components for DA GPDs
Several experiments in progress or planned in the near future, pushing the limits of $Q^2$ with highest possible precision.

Electric form factor measurements rely on polarization observables to extract the ratio of electric to magnetic.
Search for a Strange $G_{M,E}$

Parity violating elastic electron scattering from the proton using a coincidence counting approach.

One issue is potential contributions from the proton axial vector form factor, but these seem to be under control.

Measurements go towards a flavor separation of elastic form factors.

See “Jefferson Lab Hall C: Precision Physics at the Luminosity Frontier”, The Hall C Futures Working Group
The Proton Charge Radius


- Pohl 2010 (μH spect.)
- Antognini 2013 (μH spect.)
- Beyer 2017 (H spect.)
- CODATA-2018
- Bezginov 2019 (H spect.)
- PRad 2019 (ep scatt.)
- PRad-II projection
- Grinin 2020 (H spect.)
- Bernauer 2010 (ep scatt.)
- Zhan 2011 (ep scatt.)
- CODATA-2014
- Fleurbaey 2018 (H spect.)

Proton charge radius $r_p$ [fm]
A narrow range of models are consistent with a “thick” skin in $^{208}$Pb and a “thin” skin in $^{48}$Ca.
Neutron Star Merger GW170817


LIGO - Virgo

Fermi/GBM

INTEGRAL/SPI-ACS

counts/s (arb. scale)

t-tc (s)

DLT40 -20.5 d

Swope +10.9 h

PRL 119(2017)161101

Primary mass $m_1$ 1.36–1.60 $M_\odot$

Secondary mass $m_2$ 1.17–1.36 $M_\odot$

Astrophysics!

Jim Napolitano

2022 JLUO Meeting
Primary goal for GlueX: Resonant (?) P-wave in $\gamma p \rightarrow \eta\pi N$

Excellent data quality, continuing analysis for unambiguous extraction of P-wave
Photoproduction of J/ψ

- Searching for evidence of photoproduction of pentaquark state
- Connection to proton mass radius: Phys Rev D 104(2021)054015
Search for New Particles

Heavy photons: APEX and HPS

Note: Contours are projections
Precision Electroweak Physics

Precise measurements of parity violation with polarized electrons.

**MOLLER**
\[ \vec{e} e \rightarrow e e \]

**SoLID**
\[ \vec{e} q \] couplings using Deep Inelastic Scattering
An Exciting Future for CEBAF

The “12 GeV Era” continues to produce groundbreaking new measurements over a wide range of topics in fundamental Nuclear Physics. New facilities, including upgrades to CEBAF, show the promise of a long and productive future that will be complementary to eventual measurements from the Electron Ion Collider.

Talks follow this one on Positron Beams, the CEBAF Energy Upgrade, and the “J-FUTURE” workshop series.

Consider attending the High Energy Workshop Series 2022 organized by JLUO
- Hadron Spectroscopy with a CEBAF Energy Upgrade
- The Next Generation of 3D Imaging
- Science at Mid-x: Anti-shadowing and the Role of the Sea
- J/ψ and Beyond
- Physics Beyond the Standard Model