MEIC Physics

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Jlab Users Meeting
The Structure of the Proton

Naïve Quark Model: \[ \text{proton} = uud \text{(valence quarks)} \]
QCD: \[ \text{proton} = uud + uu + dd + ss + \ldots \]

The proton sea has a non-trivial structure: \( \bar{u} \neq \bar{d} \) and gluons are abundant

The proton is \textbf{far more} than just its up + up + down (valence) quark structure

Nuclear physicists are trying to answer how basic properties like \textit{mass, shape, and spin} come about from the flood of gluons, quark/anti-quark pairs, and a few ever-present quarks.
The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Scope of the project includes:
- Doubling the accelerator beam energy
- New experimental Hall and beam line
- Upgrades to existing Experimental Halls

New C100 cryomodules in Ilinac tunnel
EIC - probing the sea

- (“Medium-Energy”) MEIC@JLAB energy choices driven by: 
  access to sea quarks and gluons

- s=few 100- few 1000 GeV² allows access to gluons, shadowing

EIC aims to study the sea quark and gluon dominated matter
To cover the physics we need...

Q² \sim ysx

(x, Q²) phase space directly correlated with s (=4EₑEₚ):
- @ Q² = 1 lowest x scales like s⁻¹
- @ Q² = 10 lowest x scales as 10s⁻¹

Need for:
- variable energies
- polarized luminosity over full range of energies

Fixed target equivalent: s = 2 Eₑ Mₚ = 2 \times 1066 \times 0.938 = 2000 \text{ GeV}²
MEIC Accelerator Layout at JLab
Design allows for:

- **Simultaneous** use of two full acceptance detectors
- Longitudinal and **transverse** polarization of light ions
  - Proton, deuterium, $^3$He, etc.
- Longitudinally **polarized** leptons
  - Electrons and positrons
- Running fixed-target experiments in parallel with collider

**Reduced R&D challenges**
- Regular electron cooling
- Regular electron source
- No multi-pass Energy-Recovery Linac (ERL)
- No space-charge compensation

MEIC - a Figure-8 Ring-Ring Collider
MEIC Design Report

• Posted: arXiv:1209.0757
• Stable concept for 3 years

“...was impressed by the outstanding quality of the present MEIC design.”
“The report is an excellent integrated discussion of all aspects of the MEIC concept.” (JSA Science Council 08/29/12)

“world’s first polarized e-p collider and world’s first e-A collider”

Overall MEIC design features:
• Highly polarized (including D)
• Full acceptance & high luminosity
• Minimize technical risk and R&D

EPJA article by JLab theory on MEIC science case (arXiv:1110.1031; EPJ A48 (2012) 92)
Map the spin and spatial structure of quarks and gluons in nucleons

- How much spin is carried by gluons?
- Does orbital motion of sea quarks contribute to spin?
  - Generalized Parton Distribution (GPDs)
  - Transverse Momentum Distributions (TMDs)
- What do the partons reveal in transverse momentum and coordinate space

Discover the collective effects of gluons in atomic nuclei

- What is the distribution of glue in nuclei?
- Are there modifications as for quarks?
- Can we observe gluon saturation effects?

Understand the emergence of hadronic matter from color charge

- How do color charges evolve in space and time?
- How do partons propagate in nuclear matter?
- Can nuclei help reveal the dynamics of fragmentation?

Needs high luminosity and range of energies
Transverse Spatial Imaging of Sea quark and gluons

EIC: Gluon size from $J/\Psi$ and $\phi$ electroproduction ($Q^2 > 10$ GeV$^2$)

[Transverse distribution derived directly from t dependence]

Hints from HERA:

- Area (q + $\bar{q}$) > Area (g)
- Dynamical models predict difference: pion cloud, constituent quark picture

Are radii of quarks and gluons different at a given x? – DVCS and $J/\Psi$ production

- $Q^2 > 10$ GeV$^2$ for factorization
- Statistics hungry at high $Q^2$

Are strange and non-strange (light sea) quark sizes different at given x? - $\pi$ and K production

Full image of the proton can be obtained by mapping t-distributions for different processes.
Example: Transverse Spatial Distribution of Gluons from J/ψ

10 < Q^2 + M_{J/ψ}^2 < 15.8 GeV^2
Colliders allow straightforward detection of recoil baryons, making it (in principle) possible to map the $t$-distribution down to very low values of $-t$.

At very high proton energies, recoil baryons are all scattered at small angles.
- Moderate proton energies give the best resolution.

High luminosity at intermediate proton energies and excellent small-angle detection make the MEIC a perfect tool for imaging of the proton.
TMDs: Imaging the Transverse Momentum of the Quarks

- TMDs encode the 3D partonic picture in momentum space
- Only a small subset of the \((x,Q^2)\) landscape has been mapped here: terra incognita
  - Gray band: present “knowledge”
  - Purple band: EIC (2\(\sigma\))

An EIC with good luminosity & high transverse polarization is the optimal tool to study this!
If we do not understand proton spin from QCD, we do not understand QCD!

• It is more than the number $\frac{1}{2}$! It is the interplay between the intrinsic properties and interactions of quarks and gluons

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g$$

• $\Delta \Sigma \sim 0.25$ (world DIS)
• $\Delta G$ small (RHIC+DIS)
• $L_q$? $J_g$?

Spin = intrinsic (parton spin) + motion (orbital angular momentum)

• Two complementary approaches to resolve proton spin puzzle

Measure $\Delta g$ - Explore the “full” gluon and sea quark contribution
Measure TMD and GPDs - quantify the role of orbital motion
Helicity PDFs at an EIC

- Precision measurement of $\Delta g$:
  - stage I will greatly improve our understanding
  - stage II will further reduce uncertainty

![Graph showing current data and predictions for $Q^2 = 10 \text{ GeV}^2$](image1)

![Graph showing uncertainties on the x-shape of $\Delta g(x, Q^2)$](image2)
Gluons in nuclei

- HERA measured the longitudinal gluon distributions in the nucleon
  - $F_L$ and $dF_2/d\ln(Q^2)$

- Very little is known about gluons in nuclei

- EIC: access gluons through $F_L$ (needs variable energy) and $dF_2/d\ln(Q^2)$

- Knowledge of gluon PDF essential for quantitative studies of onset of saturation
Hadronization - parton propagation in matter

large $\nu$

$\gamma e \rightarrow h$ [production]$> R_A$

smaller $\nu$

$\gamma e \rightarrow h$ [production]$< R_A$

Accardi, Dupre

$\Delta p_T^2$ vs. $Q^2$

- $p_T$ broadening strongly constrains theory
- Large range in $\nu$ at a collider allows
  - Isolation of pQCD energy loss (large $\nu$)
  - Study of (pre)hadronization (smaller $\nu$)
- Heavy flavors: B, D mesons, $J/\Psi$ ...
- Jets above $s = 1000$ GeV$^2$
  - "real" pQCD, IR safe
Neutron Structure through Spectator Tagging

- In fixed target experiments, scattering on bound neutrons is complicated
  - Fermi motion, nuclear effects
  - Low-momentum spectators
  - No polarization

- The MEIC is designed to tag spectators, and all nuclear fragments
"If one could tag neutron, it typically leads to larger asymmetries"  Z. Kang

- MEIC will provide longitudinal and transverse polarization for $d$, $^3He$, and other light ions
- Polarized neutrons are important for probing $d$-quarks through SIDIS
- Measurements of exclusive reactions like DVCS also greatly benefit from polarized neutron "targets"
  - c.f. Hall A and B programs at JLab

**Spectator Tagging with Polarized Deuterium**

**Neutron Spin Observables - $y$**

**LDRD for polarized light nuclei at the EIC**
In general, e-p and e-A colliders have a large fraction of their science related to the detection of what happens to the ion beams... spectator quark or struck nucleus remnants will go in the forward (ion) direction → this drives the integrated detector/interaction region design

Central detector could be like “4th” ILC detector concept

Dual-solenoid allows for a compact, low mass detector
- Easy end-cap integration (line of sight) and good access
- Easy integration with small-angle detectors on outgoing ion side (right)

Hadron detection in three stages
- Endcap with 50 mrad crossing angle
- Small dipole covering angles to a few degrees
- Ultra-forward up to one degree, for particles passing the accelerator quads
Forward Hadron detection with crossing angle

Large crossing angle (50 mrad)
- Moves spot of poor resolution along solenoid axis into the periphery
- Minimizes shadow from electron FFQ
Ultra-forward Hadron detection requirements

- **Good acceptance for ion fragments (different rigidity from beam)**
  - Large downstream magnet apertures
  - Small downstream magnet gradients (realistic peak fields)
  - Roman pots not needed

- **Good acceptance for recoil baryons (rigidity similar to beam)**
  - Small beam size at second focus (to get close to the beam)
  - Large dispersion (to separate scattered particles from the beam)
  - Roman pots important

- **Good momentum and angular resolution**
  - Large dispersion (e.g., 60 mrad bending dipole)
  - Long, instrumented magnet-free drift space

- Sufficient separation between beam lines (~1m)
IR Optics for Ultra-Forward Particles

- Recoil baryon detection:
  - Small beam size (β function) and large dispersion at the secondary focal point give excellent resolution and great acceptance at small angles
  - Excellent t-coverage at all kinematics
Tracking of ultra-forward charged particles

- Design provides full acceptance for all nuclear fragments
  - Low gradient quads make possible the necessary large apertures
  - Can be achieved with realistic peak fields (gradient * aperture radius)
    - Easier with lower maximum energy – benefits from JLab two-ring staging
Ultra-forward detection concept

- Neutron detection in a 25 mrad cone **down to zero degrees**
- Excellent acceptance for **all ion fragments**
  - Recoil baryon acceptance
    - up to 99.5% of beam energy for **all angles**
    - down to 2-3 mrad for **all momenta**
  - Momentum resolution < $3 \times 10^{-4}$
    - 15 MeV resolution for 50 GeV deuteron beam
- 100 GeV maximum ion energy allows using large-aperture magnets with **achievable field strengths**
**Summary**

**EIC is the ultimate tool for studying sea quarks and gluons**

- An EIC is required to fully understand nucleon structure and the role of gluons in nuclei

**MEIC offers a fully integrated interaction region**

- Straightforward detection of recoil baryons, spectators, and target fragments
- Promising collaboration on central detector with HEP

**EIC is a maturing project**

- Designs ongoing at JLab and BNL
- Funds for joint detector R&D projects and accelerator R&D have been allocated
- Physics effort for polarized light nuclei and forward tagging ongoing