# Physics opportunities with an Electron-Ion Collider

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**Abstract.**
I briefly present main science goals, basics of design, and key measurements at a planned Electron-Ion Collider.

## 1. Nucleon and nuclear structure in QCD and the EIC project

Understanding the internal structure of the nucleon and nuclei on the basis of the fundamental theory of strong interactions, Quantum Chromodynamics (QCD), is one of the central problems of nuclear physics today. The outstanding fundamental questions include (i) the dynamical origin of mass in the visible Universe, (ii) the behavior of matter at astrophysical densities and temperatures, and (iii) the nuclear structure and reactions from first principles. While decades of experiments at SLAC, CERN, Fermilab, DESY, and Jefferson Lab and advances in theory have thoroughly explored the internal structure of hadrons, several key questions remain open:

- What is the internal landscape of the nucleon? In particular, what role do sea quarks and gluons play in the nucleon structure? What is their polarization and how do they distribute in space (and in the longitudinal and transverse momentum)?
- What is the role of gluons and their self-interactions in nuclei? What is the density of gluons in nuclei and the role of gluon collective (non-linear) effects?
- What governs the transition (hadronization) of quarks and gluons in pions and nucleons? How does color charge of QCD interact with nuclear matter?

These major science questions define main goals and form the science case for a future Electron-Ion Collider (EIC), a polarized electron-polarized proton and electron-nucleus collider that has been embraced by the U.S. nuclear science community and which received an informal recommendation in 2007 DOE/NSF NSAC Long Range Plan [1].

## 2. Basic characteristics and designs of EIC

The design of an EIC is driven by its science goals. The basic requirements for a future EIC include:

- Lepton beam which provides a clean and well-understood probe,
- Range of c.m. energies from $s$=few 100 GeV$^2$ to $s$=few 1000 GeV$^2$; the energy should be variable and upgradeable:
  - electrons with energy up to $20-30$ GeV,
  - protons with energy up to $250-325$ GeV and ions with energy up to $100-130$ GeV/A,
- Polarized electron and proton beams (polarization $> 70\%$) including longitudinal and transverse polarization of the proton beam, polarized light nuclei, e.g., $^3$He,
- High luminosity of the order of $10^{34}$ cm$^{-2}$s$^{-1}$ ($>$ 100 times that of HERA),
- Range of nuclei, from deuterium to $^{208}$Pb.

From the start of the EIC project, there have been two competing designs of an EIC: ELIC at Jefferson Lab and eRHIC at Brookhaven National Laboratory (BNL), see figure 1. ELIC assumes a ring-ring design with the existing CEBAF as an injector; the hadron complex and accelerator ring need to be constructed; up to four interaction points are considered. The accelerator ring is envisioned to have the shape of the figure eight (for polarization transport) and to be realized in two stages: (i) an initial medium-energy option (MEIC) with a 1-km long ring providing $3-11$ GeV/c electrons on 60/95 GeV/c protons (the nuclear momentum scales as $Z/A$, where $Z$ is the charge and $A$ is the atomic mass number), (ii) followed by an upgrade (ELIC) to a larger 2.5-km ring with $3-11$ GeV/c electrons on 250 GeV/c protons. The aimed luminosity is $\sim 10^{34}$ cm$^{-2}$s$^{-1}$.

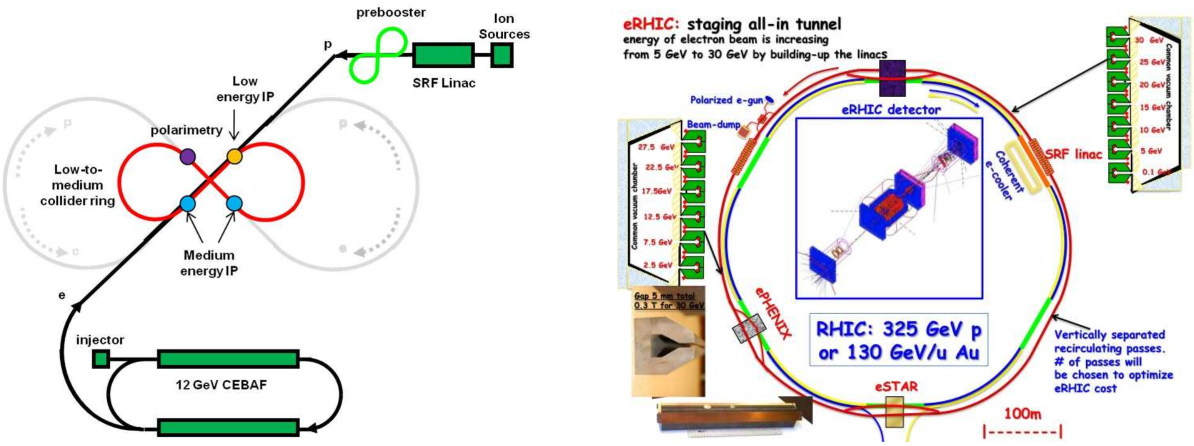

**Figure 1.** Two competing designs of an EIC: (left) ELIC at Jefferson Lab, (right) eRHIC at BNL.

The eRHIC at BNL assumes a linac-ring design with the existing RHIC complex; energy-recovering linacs for electrons need to be built and they can be placed in the existing RHIC tunnel. The project is also envisioned to take place in two stages: (i) an initial medium-energy stage (MeRHIC) with 5 GeV/c electrons on $250-325$ GeV/c protons, (ii) followed by un upgrade (eRHIC) to $20-30$ GeV/c electrons on $250-325$ GeV/c protons. The aimed luminosity is $\sim 10^{33,34}$ cm$^{-2}$s$^{-1}$; it is also discussed to re-use the existing RHIC detectors (ePHENIX and eSTAR).

During 2010-2011 the Jefferson Lab and BNL EIC designs have significantly converged: the aimed c.m. energies and luminosities are now rather similar; both designs assume staging (energy upgrade). At the same time, the designs are different in technological challenges and cost. For detailed and up-to-date information on the EIC accelerator designs, see [2].

## 3. Key measurements at an EIC

The nucleon/nucleus in QCD is a many-body system whose wave function consists of an infinite number of configurations containing valence and sea quarks and gluons. The high-energy and high-luminosity EIC will study the sea quark and gluon structure of the nucleon/nuclei as well as their propagation in nuclear matter. Some key measurements at the EIC are summarized below.

**Mapping the spin and spatial structure of quarks and gluons in the nucleon.**

One of the key measurements at the EIC is the measurement of the gluon helicity distribution $\Delta g(x,Q^2)$. Measurements of the polarized structure function $g_1$ in a wide range in Bjorken $x$ and $Q^2$ will dramatically extend the available data set and will enable one to extract $\Delta g(x,Q^2)$ using global QCD fits down to $x \approx 10^{-4}$ at stage-1 (medium-energy EIC) and down to $x \approx 3 \times 10^{-5}$ at stage-2 (full-energy EIC). Additional constraints on $\Delta g(x,Q^2)$ can be obtained from the measurements of charm and jet production in polarized DIS. It will significantly reduce the present uncertainty associated with the first moment $\int_0^1 dx \Delta g(x,Q^2)$ (which is expected to be determined with 10% accuracy) and, thus, with the gluon contribution to the nucleon spin sum rule.

While the polarization of valence quarks is known fairly well and will be further constrained by the measurements at Jefferson Lab at 12 GeV, the polarization and flavor dependence (asymmetry) of sea quarks is poorly known. One example is polarized strange quark distributions $\Delta s(x)$ and $\Delta \bar{s}(x)$: while the available data prefers small and positive $\Delta s(x)$ and $\Delta \bar{s}(x)$, the first moment of $\Delta s(x)$ is negative and sizable due to the constraints from hyperon decays. The flavor dependence of polarized parton distributions (PDFs) will be studied at an EIC using the combination of inclusive and semi-inclusive polarized DIS. In the latter, the quark flavor will be "tagged" by selecting $\pi^{\pm}$ and $K^{\pm}$ produced from its fragmentation. The kinematic coverage and detection capabilities of a discussed future detector for an EIC (good particle ID in a wide kinematic range) are uniquely suited for such measurements. In addition to semi-inclusive DIS, flavor decomposition of polarized PDFs can be performed in charged-current ($W^+$ and $W^-$) inclusive polarized DIS; these measurements do not require the knowledge of fragmentation functions.

A more detailed information about the nucleon structure can in principle be obtained from hard exclusive processes (exclusive electroproduction of a real photon or a vector or pseudoscalar meson) which access generalized parton distributions (GPDs). GPDs provide the distributions and correlations of partons both in the longitudinal light-cone fraction(s) and transverse coordinate (impact parameter). Therefore, it is often said that GPDs provide the spatial, three-dimensional snapshot of the nucleon. Additionally, GPDs quantify the fundamental decomposition of the nucleon spin in terms of the quark and gluon helicities and orbital moments (Ji's spin sum rule). Various deep exclusive processes access different flavor and spin combinations of GPDs: production of a real photon or deeply virtual Compton scattering (DVCS) and production of light vector mesons ($\rho$, $\omega$, $\phi$) probe unpolarized sea quark and gluon GPDs, production of $J/\psi$ probes the unpolarized gluon GPD, production of pseudoscalar mesons ($\pi$, $K$) probes the non-strange and strange polarized GPDs. Such measurements require differential measurements of low-rate exclusive processes which will be possible at an EIC due to its high luminosity; the possibility to longitudinally and transversely polarize the proton beam will help to disentangle different kinds of GPDs.

In parallel to the nucleon imaging program, deep exclusive processes with nuclei (DVCS, $J/\psi$ production) will access impact parameter dependence of nuclear PDFs and will obtain the spatial image of nuclear shadowing of sea quarks and gluon in nuclei. This information is essential for perturbative calculations for $pA$ scattering at RHIC and the LHC.

Other relevant EIC measurements include PDFs at large $x$ and a program of measurements of transverse momentum dependent distributions (TMDs) in semi-inclusive DIS.

**The gluon structure of nuclei.**

One of manifestations of the role of QCD in nuclear physics is the nuclear modifications of structure functions and parton distributions. The pattern of the deviations of the nuclear structure function $F_{2A}(x,Q^2)$ from the sum of the nucleon structure functions $AF_{2N}(x,Q^2)$ has been established in fixed-target experiments and looks as follows: suppression for small $x < 0.05$ (nuclear shadowing), slight enhancement for $0.05 < x < 0.2$ (antishadowing), suppression for $0.2 < x < 0.8$ (EMC effect), and rapid enhancement for $x > 0.8$ (Fermi motion). This trend of nuclear modifications translates into a similar pattern of modifications of quark and gluon distributions in nuclei when these are extracted using global QCD fits. However, in the small $x$ region, the gluon PDF in nuclei is essentially unconstrained by such fits and sea quark PDFs are poorly constrained. At an EIC, one will accurately determine the gluon PDF in a range of nuclei down to $x = 10^{-3}$ and the sea quark PDFs down to approximately $5 \times 10^{-4}$ due to: (i) a wide $x - Q^2$ range probing deep in the shadowing region (the collider kinematics will allow one to simultaneously have small $x$ and sufficiently large range in $Q^2$ such that the gluon distribution can be reliably determined from scaling violations), (ii) direct access to gluons via the longitudinal structure function $F_L^A(x,Q^2)$ (via the measurements at different beam energies), (iii) complimentary measurements of charmed structure functions $F_{2A}^{(c)}(x,Q^2)$ and $F_L^{A(c)}(x,Q^2)$, (iv) measurements of light-quark and heavy-quark jets in DIS.

At very small $x$, the gluon density rapidly increases and one expects an onset of a new high-gluon density (non-linear) regime of the strong interactions. Such a scenario is realized in the framework of the Color Glass Condensate (CGC) formalism, where the regime of high parton densities is characterized by a new dynamical scale $Q_s^2$. While even the full-energy EIC will not be capable to look for saturation effects with the proton beam, the hope to achieve the saturation regime at the EIC rests on the nuclear enhancement of $Q_s^2 \sim A^{1/3}$ (one needs to have $Q_s^2 \geq 1$ GeV$^2$ for the validity of the parton picture). It is impossible to unambiguously establish the presence of parton saturation in one kind of experiment since saturation effects can be masked, e.g., by a suitable adjustment of the input parton densities. Therefore, at the EIC, one considers a host of different measurements aimed at a search of the non-linear regime of high-gluon density in nuclei including inclusive, diffractive and exclusive DIS.

Turning to the medium and large $x$ region, $0.05 < x < 0.8$, one notes that the quark PDFs in nuclei in this region have been rather thoroughly investigated in fixed-target experiments and will be further studied at Jefferson Lab at 12 GeV. At the same time, the behavior of the gluon PDF in this region is poorly constrained. Using the same probes and methods as in the studies of nuclear shadowing in the gluon channel (see above), one will be able to study antishadowing and the EMC effect in the gluon channel at the EIC.

Other relevant EIC measurements include tagged structure functions of light nuclei (D, $^3$He) and studies of medium modifications of bound nucleons.

**Emergence of hadronic matter from quarks and gluons.**

The transition of colored partons to colorless hadrons—hadronization—still lacks an understanding from the first principles in QCD: there compete several mechanisms (parton energy loss, prehadron re-interactions inside the nuclear medium, etc.) involving several time scales. To disentangle these mechanisms, probably the best experimental tool is DIS with nuclei. At an EIC, the combination of high energy and high luminosity will bring the studies of hadronization to a qualitatively new level. Indeed, the large $Q^2$ range will permit measurements in the fully perturbative regime with enough leverage to determine nuclear modifications of the fragmentation functions; the high luminosity will permit for multidimensional binning necessary for separating the many competing mechanisms and detecting rare processes. The large $\nu \approx 10 - 1000$ GeV range will allow one to isolate in-medium parton propagation effects (large $\nu$) and cleanly extract color neutralization and hadron formation times (small $\nu$). For the first time, one will also be able to study hadronization of open charm and open bottom mesons and in-medium propagation of heavy mesons; these studies are crucial for understanding of quark-gluon plasma at RHIC. Also, within a collider environment, one would be able to separate target from current fragmentation adding a new dimension to hadronization studies.

The second aspect of hadronization studies at an EIC is the possibility to use colored probes to study the gluon distribution in nuclei. In addition, for the first time one will be able to to measure jets and their substructure in $eA$ collisions.

## 4. The EIC project status and timeline

After the informal recommendation by NSAC Long Range Plan in 2007 [1], the EIC collaboration was formed. Now the collaboration includes more than 100 scientists from about 20 institutions. The EIC collaboration functions as follows: the activities are coordinated by the EIC Steering Committee; the status and progress are reported at semi-annual collaboration meetings; regular reviews of physics and updates on the accelerator designs take place and are overseen by the International EIC Advisory Committee. For more information, see [3, 4].

Also, a series of Jefferson Lab Users workshops on EIC was held in 2010 [5, 6, 7] and the EIC science was discussed at 2010 Institute for Nuclear Theory program INT 10-03 in Seattle [8].

Now the EIC Collaboration and EIC enthusiasts are working towards a full recommendation by the NSAC LRP in 2013.

[1] 2007 DOE/NSF NSAC Long-Range Plan, `http://science.energy.gov/np/nsac`

[2] Y. Zhang, *Progress in MEIC and ELIC Design and Development*, and V. Litvinenko, *Progress in eRHIC Design and Development*, talks at EIC Advisory Committee meeting, Jefferson Lab, April 10, 2011, `http://conferences.jlab.org/eic2011/program.html`.

[3] `http://www.jlab.org/meic`

[4] `http://www.eic.bnl.gov`

[5] `http://www.physics.rutgers.edu.np/2010rueic-home.html`

[6] `http://michael.tunl.duke.edu/workshop`; M. Anselmino *et al.*, Eur. Phys. J. A **47** (2011) 35 [arXiv:1101.4199 [hep-ex]].

[7] `http://www.phy.anl.gov/mep/EIC-NUC2010`

[8] `http://www.int.washington.edu/PROGRAMS/10-3`.