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A U.S.-based Electron-Ion Collider

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Abstract.

An Electron-Ion Collider (EIC) in USA is currently discussed as a next-generation facility for high-energy nuclear physics. The main goal of the EIC is to study fundamental questions of Quantum Chromodynamics, which include the origin of the nucleon mass and spin and the three-dimensional structure of the nucleon in terms of quarks and gluons, the emergent properties of dense systems of gluons, and influence of nuclear matter on distributions of quarks and gluons and propagation of color charges through it. The EIC machine designs are aimed at achieving variable center of mass energies of $20-100$ GeV, upgradable to 150 GeV, high degree of polarization (70%) of beams of electrons, protons and light nuclei, high collision luminosity of 10^{33-34} cm^{-2}s^{-1}, and ion beams from deuteron to heaviest (Lead) nuclei. In this contribution, we present the current status of the EIC project, its physics program, and proposed designs of EIC realization.

1. EIC: goals, fundamental problems, and main parameters

An Electron-Ion Collider (EIC) in USA is the project of a new collider of polarized electrons and ions on the base of Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab (eRHIC) or CEBAF at Jefferson Lab (JLEIC). The main goals of the EIC include:

- To provide continuity of the U.S. high-energy nuclear physics program after 2025, when RHIC II and JLab at 12 GeV will have completed their programs, and to unite RHIC and JLab users around this project and to attract the international community to it

- To have a domestic facility to test new concepts and technologies in accelerator physics

- To answer a central question of nuclear physics on the nature of visible matter around us in terms of quarks and gluons of Quantum Chromodynamics.

In particular, the EIC will address the fundamental problems of the origin of the nucleon mass and spin, the emergent properties of dense systems of gluons, influence of nuclear matter on distributions of quarks and gluons, and the nature of hadronization and confinement [1, 2, 3]. In more detail, since current quarks of the QCD Lagrangian carry $\sim 10\%$ of the proton mass, there arises the question of the role of quark-anquark quantum fluctuations and gluons. Similarly, it has been established in polarized deep inelastic scattering (DIS) experiments that quarks carry about 30% of the proton spin. This has lead to the so-called proton spin crisis, whose resolution requires an understanding of the role of gluons and parton orbital motion. One facet of this

problem is the question of the three-dimensional quark and gluon distributions in coordinate and momentum spaces. Turning to nuclei, one expects to determine quark and gluon distributions in nuclei, which are rather poorly known at present, with the unprecedented accuracy and in a wide kinematic range. An important part of this program is the search for a new non-linear dynamics of the strong interactions at high energies, which is characterized by high gluon densities and emergence of a new dynamical scale referred to as the saturation scale. In addition, nuclei at the EIC will provide an arena to study propagation and interaction of fast color charges with nuclear matter, which will help to understand the nature of hadronization and confinement.

The cleanest way to study the microscopic structure of hadrons (proton, nuclei) is to use deep inelastic scattering (DIS), $e(k)p \to e'(k')X$, which can thought of as a "QCD microscope" with the photon virtuality $Q = \sqrt{-(k'-k)^2}$ providing the resolution scale $\sim 1/Q$ to probe partons with the longitudinal momentum fraction $x = Q^2/(2pq)$ ($q = k - k'$ is the momentum of the exchanged virtual photon and p is the proton momentum; similar expressions hold in the case of electron-nucleus scattering). DIS will be the main experimental tool at the EIC because it allows for a clean theoretical description and interpretation due to the point-like nature of the electron probe and the control over parton kinematics. In addition, one can also measure semi-inclusive and exclusive (elastic) final states in DIS, which are essential for studies of the three-dimensional (in momentum and coordinate space) parton structure.

The open physics questions mentioned above drive the designs and parameters of the EIC. The main characteristics of the EIC include the invariant collision energy, luminosity, polarization, and nuclear beams. In particular, the planned variable center of mass invariant energy will be in the range of $\sqrt{s_{eN}} = 20 - 100$ GeV, with a possibility to upgrade it up to $\sqrt{s_{eN}} \sim 150$ GeV. It opens wide coverage in Q^2 and x, which will encompass both the non-perturbative and perturbative regimes of the strong interaction as well as the transition from one regime to another. In the language of the parton picture of the nucleon and nuclei, the broad range in x will reveal their full structure going from the few-body valence quark regime to the many-body regime of sea quarks and gluons and further to the QCD radiation-dominated (gluon-dominated, possibly saturated) regime. The planned luminosity is $\mathcal{L} \sim 10^{33-34}$ cm^{-2}s^{-1}, which should be sufficient for precision measurements of not only inclusive DIS, but also semi-inclusive and exclusive DIS processes. The EIC spin program relies on achieving the high degree of polarization of beams of electrons, protons, and light nuclei – including the transverse polarization – which is projected to be at the level of 70%. This will be essential for measurements of polarized structure functions and parton distributions in polarized inclusive DIS, transverse-momentum dependent structure functions and parton distributions (TMDs) in semi-inclusive DIS, and generalized parton distributions (GPDs) in exclusive processes. Finally, acceleration of light (D, He-3) and heavy (U, Pb) nuclei will allow one for the first time to study nuclear DIS at a collider. It should enable one not only to determine nuclear parton distributions in a wide range of x from $x \approx 10^{-4}$ to $x \approx 1$, but also to search for possible saturation of the gluon distribution at very small x.

2. EIC: key experiments

2.1. Gluon polarization

In QCD, the proton spin can be decomposed as a sum of the quark helicity $\Delta\Sigma$, the gluon helicity ΔG, and the quark and gluon orbital angular momenta L_q and L_g, respectively,

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g \,. \tag{1}$$

The quark polarization has been measured in polarized DIS on the proton and deuteron targets and it was found that $\Delta\Sigma \approx 30\%$, i.e., quarks carry only about 30% of the proton spin, which has lead to the so-called proton spin crisis, for a review, see, e.g. [4]. The measurements of the gluon

polarization, primarily as part of the RHIC spin program, showed that it is likely to be small [5], $\Delta G \approx 0$, but the existing experimental and theoretical uncertainties are very significant. At the EIC, using DIS of longitudinally-polarized electrons on the longitudinally-polarized proton, one will measure the polarized structure function $g_{1p}(x, Q^2)$ over an unprecedentedly wide range of x and Q^2, which will allow one to determine the polarized gluon distribution $\Delta g(x, Q^2)$ using scaling violations, $dg_{1p}(x, Q^2)/d\ln Q^2 \sim -\Delta g(x, Q^2)$. It is projected that such measurements will determine the gluon contribution to the proton spin, $\Delta G = \int dx \Delta g(x, Q^2)$, with very high precision [2].

2.2. Hard exclusive processes and generalized parton distributions

As follows from the preceding discussion, the quark and gluon orbital angular momenta provide an important contribution to the proton spin budget (1). It was one of the drivers behind the development of the theory and phenomenology of hard exclusive processes such as deeply virtual Compton scattering (DVCS) and exclusive photoproduction of mesons (DVEM) [6, 7]. The cross sections of these processes are expressed in terms of generalized parton distribution functions (GPDs), which are hybrids between usual parton distributions and elastic form factors. One of the appeals of GPDs is that their first Mellin moment gives the total quark and gluon angular momentum J [8, 9]. For instance, for a quark of flavor q,

$$J^q = \frac{1}{2} \int dx x \left[H^q(x, \xi = 0, t = 0) + E^q(x, \xi = 0, t = 0) \right] = \frac{1}{2} M_2^q + L^q, \qquad (2)$$

where H^q and E^q are leading-twist proton helicity-conserving and helicity-changing quark GPDs, respectively; M_2^q is the contribution of quark q to the momentum sum rule. Hence, measurements of DVCS and DVEM at the EIC and their analysis in terms of GPDs should bring new information on the parton orbital momentum and, hence, help to resolve the proton spin puzzle. Note that the composition used in Eq. (2), its gauge dependence and parton model interpretation is a topic of active research [10].

In general, the first moments of GPDs are related to form factors of the QCD energy-momentum tensor [9]. Hence, besides the proton spin, GPDs also encode information on the sheer forces [11] and the pressure [12] on partons in the nucleon. In the nuclear case, GPDs can also shed light on the presence of possible non-nucleon degrees of freedom in nuclei [13].

Another important property of GPDs is that they encode information on simultaneous longitudinal (momentum space) and transverse (coordinate space) distributions of partons in the nucleon [14, 15], which allows one to obtain a three-dimension picture of hadrons in QCD. In particular, for a transversely-polarized proton, the GPD E^q describes the distortion of the unpolarized quark distribution in the transverse plane. For a brief review of hard exclusive processes and GPDs, see [16].

2.3. Nuclear gluon distribution

The nuclear gluon distribution $g_A(x, Q^2)$ is the probability (at leading order) to find in a nucleus a gluon with the momentum fraction x at the resolution scale Q. Thanks to the QCD factorization theorem, it is a universal quantity, which describes the nuclear response in various hard processes with nuclei, e.g., those studied at RHIC and the LHC. Since $g_A(x, Q^2)$ and other nPDFs cannot be calculated from first principles of QCD, they are determined indirectly by performing global analyses of available data, most notably, on nuclear DIS on fixed nuclear targets. However, since the range of invariant energies and, hence, the range of x and Q^2, is rather limited and the gluon density is determined mostly indirectly via the scaling violations of the nuclear structure functions, the resulting nPDFs carry significant uncertainties, especially at low x [17, 18].

High and variable energies at the EIC will allow one to accurately measure the nuclear structure functions $F_{2A}(x, Q^2)$ and $F_L^A(x, Q^2)$ in a very wide range of x and Q^2. For the first time,

taking advantage of the variable energy, the longitudinal nuclear structure function $F_L^A(x, Q^2)$ will be measured, which is directly sensitive to $g_A(x, Q^2)$

$$
\begin{aligned}
F_L^A(x, Q^2) &= \frac{2\alpha_s(Q^2)}{\pi} \int_x^1 \frac{dy}{y} \left(\frac{x}{y}\right)^2 \sum_q e_q^2 \\
&\times \left[\left(1 - \frac{x}{y}\right) y g_A(y, Q^2) + \frac{2}{3} \left(q_A(y, Q^2) + \bar{q}_A(y, Q^2) \right) \right],
\end{aligned}
\tag{3}
$$

where α_s is the strong coupling constant. Also, the charmed nuclear structure function, which is also directly sensitive to the nuclear gluon distribution, is planned to be measured [19].

Note that before the EIC, new constraints on $g_A(x, Q^2)$ at small $x \approx 10^{-3}$ can be obtained by analyzing the data on coherent photoproduction J/ψ on nuclei in Pb-Pb ultreperipheral collisions (UPCs) at the LHC [20].

2.4. Gluon saturation

As the collisions energy increases (x decreases), the gluon density increases due to gluon radiation. At some point, one also needs to take into account gluon recombination; the two processes compensate each other and there arises a new dynamical saturation scale Q_s:

$$
Q_s^2 \sim \frac{\alpha_s x g_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3} \frac{1}{x^{0.3}},
\tag{4}
$$

where R_A is the effective nuclear radius. The nuclear enhancement of Q_s is a kew factor for the EIC since it allows one to look for signs of the gluon saturation in the perturbative regime, when Q_s^2 is of the order of a few GeV^2.

The regime of gluon saturation at small x was theoretically predicted in the color glass condensate (CGC) framework [21]. Despite many successful phenomenological applications of this framework at RHIC and the LHC, there is no convincing and compelling evidence of the onset of this new regime of low-x QCD. At the EIC, it is proposed to look for saturation by studying the combination of inclusive, diffractive, and exclusive DIS since the saturation effects can be easily mimicked when each process is considered by itself, for details, see [2].

3. EIC: realization, status, organization

Very briefly, at the moment of writing this contribution, there are two competing designs of the EIC. The BNL-based EIC called eRHIC places an emphasis on the collision energy and envisions collisions of $5 - 10$ GeV electrons (upgradable to $20 - 30$ GeV) with $50 - 250$ GeV protons and nuclei. The design requires building an electron system in the form of energy recovering linacs and recirculating electron rings, which will be placed in the existing RHIC tunnel. The JLab-based EIC called JLEIC focuses on high luminosity. It envisions collisions of $3 - 11$ GeV electrons with $10 - 100$ GeV protons and nuclei. This design requires a new ion complex. For details and further information, see [2].

The EIC project enjoys a broad support of the U.S. nuclear physics community. In the 2007 National Science Advisory Committee (NSAC) Long Range Plan, it received a recommendation to develop a conception design of the accelerator and detector guided by the physics program. These studies culminated in a ten-week program at the Institute for Nuclear Theory, Seattle, USA [1], which later led to the EIC White Paper [2]. This effort resulted in an even stronger support for the EIC by the 2015 NSAC Long Range Plan, which gave a high-energy and high-luminosity polarized EIC the highest priority. Recently, the assessment of the EIC by National Academies of Sciences, Engineering, and Medicine also wholeheartedly endorsed the project [**?**].

The work towards an EIC is carried out at BNL and JLabin form of the respective working groups. Also, recently the international EIC User Group was formed, which now has more that 800 scientists from more than 170 institutes and universities.

4. Summary

In summary, high-energy and high-luminosity polarized EIC is viewed as a key facility to study fundamental questions of QCD. The main aim of the EIC physics program is to understand the microscopic nature of the visible matter in the language of quarks and gluons of QCD. In particular, it is planned to study the spin and three-dimensional structure of the proton, the role of nuclear matter in the distribution of quarks and gluons, propagation of color charges (hadronization), and a possible onset of a new regime of high-density saturated gluonic matter. The EIC has full support of the U.S. nuclear physics community. Next steps is to obtain CD0 (Mission Need statement, expected in 2018) and CD1 (design choice and site selection, expected in 2019).

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