A High Luminosity, High Energy Electron-Ion Collider: A New Experimental Quest to Study the Glue which Binds Us All

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**Perspective**

Quantum Chromodynamics (QCD) has been established for three decades now as the theory of the strong interaction, quantitatively validated, with a remarkable precision, by a host of experiments at high energies. The most important difference between QCD and QED is that gluons also interact with gluons. Unlike any other many-body system, the individual quark and gluon constituents making up a nucleon cannot be removed from the system and examined in isolation. One of the most profound discoveries in physics has been that the mass of atomic nuclei arises predominantly from the binding energy due to gluon exchange, with a large ‘sea’ of low mass gluons constantly fluctuating into quark-anti-quark pairs. This picture of the nucleon as being composed of an infinite number of highly relativistic (but low mass) spin-½ quarks exchanging spin-1 gluons is completely different from previous physical theories describing the structure of matter, e.g. atomic electrons or nucleon models of nuclei, where the binding energy is typically much smaller than the masses of the constituents. The study of the ‘sea’ in the nucleon and atomic nuclei in terms of the constituent gluons and quarks of QCD is a major frontier in nuclear physics, and one essential to obtaining a fundamental understanding of the mass of the visible matter in the universe. Simple questions related to the proton’s structure, such as how does the proton’s spin ½ originate from the dynamics of the quarks and gluons, demand new accelerators with highly-polarized beams at high energies.

At high energies, phases of quark-gluon matter allowed within QCD can be studied directly, and the study of the QCD phase diagram has evolved into a major thrust of nuclear physics at present at RHIC and soon beginning at the LHC. Experiments at RHIC using relativistic heavy ion beams have discovered a new hot, dense matter with the properties of a perfect fluid. The experiments are also consistent with the presence of maximally saturated gluon field strengths in the nuclear wavefunctions. As new phenomena in the QCD phase diagram are uncovered and explored, it is clear that measurements of the gluon distributions in heavy nuclei as well as the energy loss of fast quarks and gluons through nuclei will be essential for a rigorous and consistent understanding. Definitive data can only be obtained with a high energy lepton beam.

The future research program into the fundamental quark and gluon structure of matter will focus on three essential questions (adapted from [1]):

- What are the properties of the glue that binds matter into strongly interacting particles?
- What is the internal quark-gluon landscape of the proton?
- What are the properties of high density quark-gluon matter?

A sustained effort worldwide to determine the optimal experimental approach to address the above questions has resulted in the identification of a high luminosity, high energy electron-ion-collider (EIC) as the ideal accelerator [3-5]. In this document, we present a high level overview of the scientific case and the machine design for EIC in the context of the 2007 Long Range Planning exercise (for more detailed information on the EIC, see www.xxxx). EIC can provide the definitive answers to the above questions and allow a fundamental understanding of the glue which binds us all. EIC will be completely
complementary to the 12 GeV upgrade planned at Jefferson Lab which will focus on the study of the valence quark region.

Gluon distributions have been indirectly measured, through the explicit relationships in QCD between the glue and the ‘sea’ quarks, using high energy deep inelastic (DIS) lepton scattering at HERA [2]. DIS is the unique process which provides images of the structure of the proton, neutron or nucleus as a function of the quark or gluon momentum fraction (x) at a specific spatial resolution (Q^2). These images are displayed as structure functions and are interpreted rigorously in QCD. Lattice QCD can provide \textit{ab initio} QCD calculations of the moments of the structure functions.

![Figure 1. Quark and gluon distributions (valence quark u\textsubscript{V}(x), d\textsubscript{V}(x); sea quark S(x); gluon g(x)) at Q^2 = 10 GeV^2) as determined at HERA by the H1 and ZEUS experiments [2]. Note the dominance of the gluon and sea quark distributions below x ~ 0.1.](image)

The next generation lepton scattering facility to study the quark and gluon substructure of nucleons (both proton and neutron) and nuclei should have the following characteristics:

- A high energy, high luminosity electron/positron-ion collider with a luminosity of at least $10^{-3} \text{ cm}^{-2} \text{s}^{-1}$ and center-of-mass energies with a range from 20 to 100 GeV. A significant center-of-mass energy range is demanded to effectively use the evolution equations of QCD. Both positron and electron beams are desirable. The reference accelerator design assumes 5-10 GeV electron beams colliding with 25-250 GeV/c proton beams. In a fixed-target configuration, this corresponds to a lepton beam energy of several TeV. The time integrated luminosity determines the final statistical precision in an experiment. The HERA collider has delivered approximately 0.5 fb\textsuperscript{-1}, over about a decade. Hence, with an at least 100 times greater luminosity at EIC, it is reasonable to expect an integrated luminosity in excess of 50 fb\textsuperscript{-1}.
- polarized (~70%) electron, positron, proton and neutron beams. Both polarized nucleon beams are required to comprehensively study the spin structure of the nucleon, one of the central goals of hadron physics. In particular, this will allow a precision test of the Bjorken Sum Rule.
• nuclear beams from deuterium to uranium
A large range of nuclear beams is required to study the A dependence of nuclear observables. In particular, universal features of saturated gluon distributions are enhanced with nuclear size.
• suite of detectors
A central detector to measure DIS processes, both inclusive and with electro-produced hadrons, is essential. In addition, a number of special purpose detectors have been identified to measure specific processes, requiring complete nuclear final state detection.

Figure 2. The EIC $Q^2$ vs. x kinematic plane for a 10 GeV electron beam colliding with a 250 GeV proton beam. The four orders of magnitude reach in x and $Q^2$ for both polarized nucleon and nuclear beams will explore completely new aspects of hadron structure. EIC is completely complementary to the 12 GeV JLab capability, which studies the valence quark region at much higher luminosity.

EIC is the accelerator facility to explore QCD well beyond any existing frontiers, to allow for unprecedented studies of both the polarization of the glue in the nucleon and the role of quarks and gluons in nuclei. Understanding the physics of glue in detail will have direct and immediate consequences to the understanding of QCD in extreme conditions, and bring fundamental insight to the recent discoveries at RHIC, and to the explorations at much higher energies at LHC.

The science case for EIC was favorably reviewed in the U.S. 2001 Nuclear Physics Long Range Plan, with strong endorsement for R&D. NSAC in March 2003 declared that EIC science was ‘absolutely central to the future of Nuclear Physics.’ eRHIC was identified in November 2003 as a future priority in the DOE Office of Science 20 year plan. EIC is
a natural evolution for the U.S. QCD community in that it draws strength from both U.S.
nuclear physics flagship facilities, the electromagnetic physics community at JLab and
the hadronic physics community at BNL. EIC will maintain a leadership role for the
United States in the study of QCD and will be complementary to the next generation
facilities in Europe (LHC@CERN and FAIR@GSI) and Asia (J-PARC).

**Scientific Highlights**

The scientific case for EIC was presented in detail in a white paper at the 2001 Long
Range Plan [5], has evolved considerably through succeeding workshops and was most
recently described in [6]. EIC directly addresses questions central to the study of QCD.
Here a selected few of the highlights are picked to convey the importance and strength of
the EIC science case.

**Precision Study of the Gluon Distribution in the Nucleon**

Direct study of the glue is only possible at high energy. The established technique to
access glue is via DIS and to use the evolution equations of QCD to produce gluon
distributions as shown in Fig. 1 above. EIC can make precise measurements of the
unpolarized structure function $F_2$ as a function of $x$ and $Q^2$. This will allow precise
determination of the longitudinal DIS structure function $F_L$ of the proton, which is very
sensitive to the gluon distribution and presently does not appear to be well-understood at
low $x$ and $Q^2$. Fig. 3 shows projected uncertainties for determination of $F_L$ with EIC.

![Figure 3](image)

**Figure 3.** Projected uncertainties for determination of $F_L$ on the proton at EIC with
10 fb$^{-1}$ integrated luminosity. The projections are based on phenomenological fits to
data. The yellow band results from NLO extrapolation. Projected results from a possible
HERA run in 2007 are also shown.
The Spin Structure of the Nucleon

Few surprises encountered in the exploration of the structure of the nucleon have had a bigger impact on our understanding than the discovery that the quarks and anti-quarks together carry only about a quarter of the nucleon’s spin. This result, found by the EMC in the late eighties [7], came as a major surprise to most researchers in the field. To determine how the constituents of the proton, the fundamental quarks, anti-quarks and gluons of QCD, conspire to provide the spin-$\frac{1}{2}$ of the nucleon, presents the formidable challenge of understanding a complex composite system in nature and has by now developed into a world-wide quest central to nuclear physics. The proton spin sum-rule:

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

states that the proton spin is the sum of the quark and gluon intrinsic spin ($\Delta \Sigma, \Delta G$) and orbital angular momentum ($L_q, L_G$) contributions. Here the dependence of each contribution on the resolution scale $Q$, which is predicted by QCD, is ignored. EIC with its unique high luminosity, highly polarized electron and nucleon capability, and its extensive range in center-of-mass energy, $x$ and $Q^2$, will simultaneously access the quark, sea quark, and gluon contributions through DIS. EIC will build on the results of the important current or forthcoming experiments at RHIC [8], DESY, CERN and JLab, will extend DIS measurements well beyond the reach of existing accelerators and will provide definitive information on the various contributions to the proton spin, as well as answers to many other questions about spin phenomena in QCD. Scientific highlights and key measurements relating to the spin structure of the proton at EIC include:

**Precision studies of up, down, and strange quark and anti-quark polarizations in the nucleon**

An important early measurement at EIC would be of the spin-dependent structure function $g_1(x, Q^2)$ of the proton and neutron at values of Bjorken-$x$ down to $\sim 10^{-4}$. This would provide a crucial new verification of the present understanding that the quark and anti-quark spin contribution to the nucleon spin is small. It would make much more reliable the extrapolation of the structure functions to lower $x$ that is needed to extract $\Delta \Sigma$. In addition, it is important to remember that all (fixed-target) polarized-DIS measurements performed thus far have provided relatively little information on $g_1$ at $x<10^{-3}$. Where such information is available, $Q^2$ is usually rather small and just barely in the DIS regime, so that one has to worry about higher-twist contributions that might obscure the extraction of $\Delta \Sigma$. For these reasons, *EIC measurements at smaller $x$ than so far possible, and at similar $x$ as before, but with higher $Q^2$, should lead to an important consolidation of what we have learned so far, and would dramatically decrease the uncertainty in $\Delta \Sigma$.*

With precision measurements of $g_1(x, Q^2)$ on the proton and neutron to low $x$, another scientific highlight at EIC would be a precision test of the Bjorken sum rule [9],

$$\int_0^1 dx [g_1^p - g_1^n](x, Q^2) = 1/6 \ g_\Lambda \ [1 + O(\alpha_s) + O(1/Q^2)]$$

where $g_\Lambda$ is the neutron $\beta$-decay constant, and where the schematic terms on the right-hand-side indicate perturbative corrections in the strong coupling $\alpha_s$ and higher-twist contributions, respectively. The Bjorken sum rule is a rare example of a fundamental
relationship that is theoretically very well understood within QCD. The perturbative corrections are known through order $\alpha_s^3$, and we even have a relatively clear picture about the first higher-twist contributions. Thus, apart from being a remarkable relation between DIS structure functions and a low-energy hadronic quantity, the sum rule also offers unique tests of QCD dynamics, and of our ability to quantitatively describe these. This by itself warrants an experimental study, and it is anticipated that a 2% measurement of the sum rule would be possible at the EIC. At this level, one might actually start to see deviations from the sum rule due to isospin and charge symmetry violations. Relatively little is known about such effects so far, however, so that precision studies of the Bjorken integral also have the potential of providing genuinely new insights.

Beyond the inclusive $g_1$ structure function, EIC will provide information with unprecedented detail on the various individual spin-dependent quark and anti-quark densities, $\Delta u$, $\Delta d$, $\Delta s$, $\Delta \bar{u}$, $\Delta \bar{d}$, $\Delta \bar{s}$ in the nucleon. This would give us deeper insight into the question of why the total spin contribution by quarks and anti-quarks is so small. Do the anti-quarks all strongly spin “against” the proton, hereby counteracting the valence contribution and leading to the observed small total quark and anti-quark spin contribution? Or are anti-$u$ quarks positively polarized and anti-$d$ ones negatively, as one might expect on the basis of the Pauli principle? What role do strange quarks play? These, and other questions are also important for comparisons to models of nucleon structure, as well as to lattice calculations that are expected to become extremely powerful and precise on time-scales similar to those of an EIC. A number of fixed-target experiments have performed measurements that are sensitive to the individual polarizations of $u,d,s$ quarks and anti-quarks, but many of the results have remained inconclusive, and important questions have not yet been answered. Crucial information on the $\Delta u$, $\Delta \bar{u}$, $\Delta d$, $\Delta \bar{d}$ at relatively high momentum fractions $x$ will come from RHIC through its W-physics program, and from the 12-GeV upgrade at Jlab. At the EIC, there are two avenues for very precise measurements of the individual polarizations. One is semi-inclusive DIS (SIDIS), so far also employed in the fixed-target experiments. By detecting certain hadrons, $\pi^\pm$, $K^\pm$, in final-states in DIS, one may effectively “tag” on the various quark or anti-quark flavors in the proton. Figure 4 shows expectations for the precision with which the spin-dependent quark and anti-quark polarizations would be extracted from SIDIS measurements at EIC.

Further, EIC offers the possibility to carry out measurements of inclusive spin-dependent structure functions in which a $W$ or $Z$ boson, rather than a photon, is exchanged between the electron and the nucleon. Thanks to the nature of the Standard Model couplings, such exchanges violate parity and probe the spin-dependent quark and anti-quark distributions in different combinations than the purely electromagnetic scattering. Measurements of parity-violating structure functions would require the highest possible energies and ideally be performed using electrons as well as positrons. They would lead to probes at moderate to high Bjorken-$x$ that would be complementary to studies in the time-like regime at RHIC, or to the high-$x$ measurements at Jlab at much smaller $Q^2$. 
Figure 4. Left: projected precision of EIC measurements of $x(\Delta u - \Delta d)$, compared to the statistical accuracy of the corresponding HERMES measurements [10]. Right: same for $\Delta s(x)$ from spin-asymmetries for semi-inclusive $K^\pm$ measurements.

**Precision measurement of the spin-dependent gluon distribution at small $x$**

The integral of the spin-dependent gluon distribution over all $x$,

$$\int_0^1 dx \Delta g(x,Q^2) = \int_0^1 dx \left[ g^+(x,Q^2) - g^-(x,Q^2) \right]$$

gives the gluon spin contribution $\Delta G$ to the proton spin. It is the main goal of the spin program at RHIC to perform precise measurements of $\Delta g(x,Q^2)$ over a large range of gluon momentum fractions $x$, so that the spin contribution $\Delta G$ can be obtained from integration over $x$, assuming an extrapolation to $x$ below (or above) the measured region. HERMES [11] and COMPASS [12] use the photon-gluon fusion process to obtain information on $\Delta g$ at relatively large $x$. RHIC is expected to put quite precise constraints on $\Delta g$ all the way down to $x$ of about $10^{-2}$ from mid-rapidity high-$p_T$ pion, jet, and photon production in running at 200 and 500 GeV center-of-mass energies. Access to somewhat lower $x$ should become possible by performing measurements at very forward angles of the produced final states, where however the underlying theoretical calculation is perhaps slightly more challenging. Measurements of $\Delta g$ at $x$ well below $10^{-2}$ may turn out to be vital for reliably constraining the integral. As an example, a typical currently favored spin-dependent gluon distribution such as the GRSV “standard” one [13], receives about 30% of its integral from the region $x<10^{-2}$, at $Q^2=10$ GeV$^2$. With EIC, it will be possible to measure $\Delta g(x,Q^2)$ down to $x$ values of a few times $10^{-4}$, hereby dramatically reducing the extrapolation uncertainties on the integral. The main tool for performing such measurements would be scaling violations of the spin structure function $g_1$. Roughly speaking, the logarithmic derivative of $g_1$ in $Q^2$ is proportional to $\Delta g$, as shown by the DGLAP evolution equations. Depending on the size and behavior of $\Delta g$, the structure function $g_1$ may develop very dramatic scaling violations at small $x$, as shown in Fig.5.
Figure 5. Upper panel: projected EIC data as a function of $Q^2$ for different $x$ bins of the structure function $g_1(x,Q^2)$ in 150 x 7 GeV collisions, for 5 fb$^{-1}$ luminosity. We also show the currently available fixed-target data. Lower panel: Projected EIC data for the structure function $g_1(x,Q^2)$ as a function of $x$ for different $Q^2$ bins in 250 x 10 GeV collisions, for 0.4 fb$^{-1}$ luminosity (8 days at $10^{33}$ cm$^{-2}$s$^{-1}$, with 50% data taking efficiency). Error bars are statistical. A strongly positive $\Delta g$ is assumed [13].
Charm production is another channel that could provide precise information on $\Delta g$ at small to moderate $x$ at an EIC. Figure 6 shows projections for the statistical uncertainties on $\Delta g/g$ that would be expected. At higher $x$, measurements of $\Delta g$ at the EIC are possible in di-jet production, selecting the photon-gluon fusion process. This is very similar to what is currently done at HERMES and COMPASS. However, at much higher energies, the underlying theoretical interpretation is much cleaner. These measurements at EIC would be complementary to those currently underway at RHIC, which would provide an important test of our understanding of the probes used for measuring $\Delta g$.

**Figure 6.** Projected uncertainties in the determination of $\Delta g(x)/g(x)$ at EIC using the channel $D^0 \rightarrow K^-\pi^+$ in charm production. The integrated luminosity is 10 fb$^{-1}$ for the 10 GeV electron on 250 GeV proton measurement, and 2.5 fb$^{-1}$ for 5 GeV electrons on 50 GeV protons.

**Measurements of Generalized Parton Distributions and hard exclusive processes**

One of the most important recent theoretical breakthroughs was the realization that a certain wider class of parton distribution functions, the so-called generalized parton distributions (GPDs) can provide information on the total (spin plus orbital) angular momenta carried by quarks, anti-quarks, or gluons in the nucleon [14]. GPDs are
accessible experimentally in hard exclusive processes in lepton scattering, the classic example of which is “Deeply-Virtual Compton Scattering (DVCS)", $\gamma^* p \rightarrow \gamma p$, with a real photon produced in the final state. Hard exclusive processes require a non-vanishing momentum transfer $\Delta$ on the proton line. The importance of GPDs goes far beyond being a tool for accessing angular momentum, however. They are perhaps the most fundamental characterization of nucleon structure, because they interpolate in some sense between ordinary parton distributions and nucleon elastic form factors. In addition, they provide unique insights into the spatial structure of partons in the nucleon. A Fourier transform of a GPD in momentum transfer $\Delta$ probes the distribution of partons in the plane transverse to the proton direction, thus yielding a transverse profile of the proton [15]. Generalizations of this picture in terms of Wigner distributions of the nucleon provide insights into its three-dimensional spatial structure [16]. Measurements of GPDs are very challenging. GPDs depend on three separate kinematic variables, and it is generally hard to reliably identify the rare exclusive reactions that are of interest. It is of great help to have both electrons and positrons at one’s disposal, and also to have polarization of the lepton beams. With these available, one can define charge and beam spin asymmetries, which are in general very useful in dealing with the background by the Bethe-Heitler process. Measurements of hard exclusive processes have begun some time ago at DESY, CERN, and JLab. Determinations of valence quark GPDs are the flagship of the physics program at the 12-GeV upgrade at JLab. With EIC, it will be possible to extend the surveys of GPDs into a regime where sea quarks and gluons abound. Figure 7 shows projected uncertainties for measurement of the DVCS cross section at EIC.

**Figure 7.** Left panel: projected uncertainties in the measurement of the DVCS unpolarized cross section as a function of invariant mass $W$ (GeV) in two measurements with EIC. The HE measurement has an integrated luminosity of 0.52 fb$^{-1}$ and is carried out with 10 GeV electron on 250 GeV proton. The LE measurement has an integrated luminosity of 0.18 fb$^{-1}$ and is carried out with 5 GeV electron on 50 GeV proton. Right panel: existing data from ZEUS and H1 for comparison.

**Orbital angular momentum and fragmentation**

Experimental constraint of the quark and gluon orbital angular momentum components to proton spin is a highly desirable goal for future programs. Recent work has focused on transverse-spin observables involving fragmentation. Very significant single-spin
asymmetries have been observed in lepton scattering in the HERMES experiment [17]. Some of these asymmetries provide new insights into nucleon structure, for example, in terms of so-called “Sivers” distributions that express correlations between the proton momentum, its spin, and the transverse momentum of a parton in the proton. Such correlations provide probes of orbital angular momenta of partons. Related correlations in fragmentation processes, known as “Collins effects”, allow new insights into hadronization and may also be used as tools to determine the elusive transversity distributions of the nucleon. Measurements at EIC would vastly enhance our understanding of all of these observables.

EIC will also provide the first measurement of the spin-dependent structure functions of the photon, possible by studying spin asymmetries in photo-production reactions [18]. These might offer unique insights into the spin structure of vector mesons like the $\rho$, which are not attainable in any other way we know of. An exciting question that one might possibly be able to address would be: does the $\rho$ show a similar “spin crisis” as the nucleon?

**What are the properties of high density partonic matter?**

Our current understanding of hadron structure indicates that the proton is overwhelmingly comprised of gluons for $x \leq 0.01$. In nuclei, the regime of $x < 0.01$ is *terra incognita*. EIC offers the unprecedented opportunity to map the fundamental structure of nuclei in this glue dominated kinematic region.

Simple arguments in QCD suggest that, at small $x$, the field strengths of gluon fields should be the maximum possible in nature, corresponding to a novel non-linear regime of the theory. The physics governing gluon interactions in this regime may be universal across hadrons and nuclei.

Further simple arguments indicate that this non-linear regime is reached at larger values of $x$ in heavy nuclei and its effects amplified by nuclear size. Studies of the properties of gluons and the accompanying sea quarks in this regime, across a wide range of nuclei, have the potential to fundamentally impact our understanding of QCD at high energies.

The possible impact of such studies can be better appreciated in the context of what we know. At larger $x$, and at large momentum transfers $Q$, the properties of quarks and gluons are well described by the linear evolution equations of perturbative QCD (pQCD). These predict, for fixed $Q$ and decreasing $x$, the density of gluons grows by hard (large $x$) partons successively shedding softer partons in a self-similar cascade. This bremsstrahlung picture is well confirmed in a wide kinematic range by the HERA experiments. However, at smaller $x$, when the density of gluons from the cascade becomes large, multi-gluon correlations appear causing softer gluons to recombine into harder ones. When these correlations become large, strong deviations from linear evolution must occur. Gluon saturation is a simple mechanism for nature to prevent the rapid growth of gluons from violating the “black disk” limit set by the unitarity of the theory.

What are the properties of QCD in this novel regime of gluon saturation? Theoretical predictions suggest that the properties of this saturated gluonic phase are controlled by a
dynamical, saturation scale $Q_s(x, A)$, which grows as $x$ gets smaller and the nuclear size $A$ gets larger. When this scale is much larger than the fundamental scale of the theory (~200 MeV), asymptotic freedom predicts that the QCD coupling constant in the gluon saturation regime is weak, thereby making systematic computations feasible. These suggest that the properties of saturated gluons may be described as a Color Glass Condensate (CGC) [19]. Data from HERA at small $x$ and RHIC in forward (small $x$) kinematics are consistent with saturation models albeit not conclusively so.

The properties of gluons in nuclear wavefunctions are vital to better understand the formation and thermalization of hot and dense gluonic matter produced when nuclei are smashed together at the high energies of RHIC and the future LHC collider. Initial conditions for hydrodynamic flow and bulk properties of RHIC’s perfect fluid are sensitive to the centrality and energy dependence of the saturation scale $Q_s$. Further, high energy cross-sections for hard processes are proportional to the product of the nuclear gluon distributions in the colliding nuclei. In Fig. 8b, model predictions differ by a factor of 3 for the nuclear gluon distributions at LHC energies: this corresponds to an order of magnitude range in cross-sections for semi-hard final states at the LHC.

How can we explore the glue dominated regime of nuclei with EIC? We can do so by addressing the following questions:

- What is the momentum distribution of gluons (and sea quarks) in nuclei?
- What is the space-time distribution of gluons (and sea quarks) in nuclei?
- How do fast probes interact with an extended gluonic medium?
- Do strong gluon fields enhance the role of color neutral degrees of freedom in scattering off nuclei?

We shall now discuss measurements with EIC that will address these questions.

**Momentum distributions of gluons and quarks in nuclei:**

The $x$ and $Q^2$ distributions of gluons and quarks in nuclei are extracted through the following channels. i) *Structure function measurements:* The fully inclusive structure functions $F_2$ and $F_L$ offer the most precise determination of parton (quark and gluon) distributions in nuclei. The former is sensitive to quark distributions; the latter to gluon distributions. Scaling violations of $F_2$ with $Q^2$ are also sensitive to gluon distributions. In Fig. 8a, we show projections from pQCD based models with differing amounts of shadowing and from a saturation (CGC) model for the normalized ratio of structure function compared to the statistical precision expected with 0.02 nucleus fb$^{-1}$ of data for 10 GeV electrons on 100 GeV gold nuclei. Fig. 8a suggests that data can distinguish between differing model predictions. In Fig. 8b, the ratio of gluon distributions extracted from the longitudinal structure is shown for 10 nucleon fb$^{-1}$ data for DIS on lead nuclei. At small $x$, to good approximation, $F_L^A / F_L^D \sim G_A / G_D$. Measurements of the charm structure functions $F_2^C$ and $F_L^C$ provide first data on nuclear charm quarks distributions at $x < 0.1$ - the high luminosities of EIC give estimates of $10^5$ charm pairs for 5 fb$^{-1}$ enabling precision charm studies [20]. Measurements at $x > 0.3$ are sensitive to the intrinsic charm component in nuclei which dominates conventional (photon-gluon fusion) charm production mechanisms in this kinematic regime [21].
Figure 8. a) Statistical uncertainties of the ratio of $F_2$ (representing the sum of the quark and anti-quark distributions) in gold nuclei to deuterium. b) The ratio of gluon distributions in lead relative to deuterium. $L_p = 10 \text{ fb}^{-1}$ is assumed in 8b. In 8a, nDS,EKS and FGS represent pQCD models with different shadowing; CGC is a saturation model prediction. In 8b, additional shadowing parametrizations are shown. Shaded region in 8b is the kinematic domain for semi-hard processes in AA collisions at the LHC.

ii) Semi-inclusive final states: Photon-gluon fusion results in semi-inclusive final states that are sensitive to the nuclear gluon distributions. Noteworthy examples are di-jets channels. In the latter case, the QCD Compton process also contributes. For further discussion in the context of eA studies, see [22]. iii) Exclusive final states: Measurements of elastic vector meson production $eA \rightarrow (\rho, \phi, J/\psi)A$ are extremely sensitive to the nuclear gluon density. The ratio of forward cross-sections in pQCD, for longitudinally polarized photons, is proportional to the ratio of gluon distributions squared [23] - the $Q^2$ dependence changes significantly in the non-linear regime from $1/Q^6$ to $1/Q^2$.

Space-time distribution of gluons and quarks:
In DIS, at small $x$, the virtual photon fluctuates into a quark anti-quark dipole which scatters coherently on the hadron or nucleus. Combined use of the dipole model for total cross-sections and differential cross-section for the elastic production of vector mesons enables one to estimate the differential cross-section for the dipole to scatter elastically.
Survival Probability

Figure 9. Survival probability versus impact parameter $b$ of a quark-antiquark pair of size $d=0.32$ fm scattering off a proton extracted from HERA data on elastic production of vector mesons. From [24] and [25].

The Fourier transform of the vector meson cross-section, as a function of the momentum transfer $t$ along the proton line allows one to estimate the S-matrix for this amplitude. The optical theorem is then employed to extract the survival probability of small sized dipoles of size $d$ to propagate through the target at a given $b$ without interacting. In pQCD, this probability is close to 1. This should be contrasted with the survival probability in fig. 9 extracted from dipole models. The Munier et al. [24] curves correspond to results from the elastic production of $\rho^0$ mesons. HERA data for this process are limited and the curves result from differing extrapolations. The Rogers et al. [25] curve uses data on elastic $J/\psi$ production allowing reliable extrapolation to lower impact parameters; the agreement at large $b$ of these models is within 5%. At $b=0$, the survival probability of dipoles can be as low as 20% suggesting very strong gluon fields localized at the center of the proton. A systematic dilution of the interaction strength (color transparency) is seen for larger $b$. Similar analyses for large nuclei give the survival probability of small sized (0.3 fm) dipoles from 60% at $x=0.01$ to as low as 10% at $x=0.001$ [25].

Estimates of the quark saturation scale give $Q_s^{2\text{ (proton)}} \sim 0.6$ GeV$^2$ at $b=0$ and $x=10^{-4}$ [26]. Because strong gluon fields dilute rapidly with $b$ in the proton, the effective saturation scale for most processes is significantly smaller making saturation effects harder to isolate. In contrast, the $b$ profile of nuclei is more uniform. Further, the quark saturation scale in gold nuclei at $x=10^{-4}$ is $Q_s^{2\text{ (Au)}} \sim 2$ GeV$^2$; the gluon saturation scale (x color factor 9/4) is $\sim 4.5$ GeV$^2$ [26]. Therefore, in large nuclei at small $x$, EIC will uniquely and cleanly access a regime of semi-hard $Q_s > Q$.

Deeply Virtual Compton Scattering (DVCS) studies, discussed previously, also provide insight into the space-time structure of nuclei, particularly for $x>0.1$. Independent
motivation for such studies comes from preliminary RHIC data from PHENIX showing suppression of direct photons in central Au-Au collisions at large $p_T$.

**Scattering and hadronization of fast probes in an extended gluonic medium:**
The previous discussion pertains to small $x$ where the probe interacts coherently with the entire nucleus and strong gluon field effects are enhanced by nuclear size. At larger $x$, the probe is coherent over only part of the extended nuclear medium. Ratios of inclusive hadron distributions in nucleons and nuclei measure nuclear effects as a function of photon and hadron kinematics. The large energy span of EIC enables extensive studies [27] of the nature of parton energy loss and in medium fragmentation with collider kinematics. Novel measurements are the attenuation of charm and bottom quarks and the in-medium formation of $D$ and $B$ mesons. Such studies are especially compelling because recent RHIC results indicate that charm and likely bottom quarks are quenched in hot matter more than anticipated by radiative energy loss models.

**Role of color neutral degrees of freedom in scattering off nuclei:**
Diffractive interactions result when the lepton probe interacts with a color neutral vacuum excitation, which may be visualized as colorless combination of two or more gluons in the hadron or nucleus. At HERA, an unexpected discovery was that $\sim 15\%$ of the $e\, p$ cross-section is from diffractive final states-a striking result implying the proton at rest remains intact one seventh of the time when struck by a 25 TeV electron. Several saturation/CGC models of strong gluon fields in nuclei suggest that large nuclei are intact nearly 40% of the time-nearly saturating the quantum mechanical black disc limit of 50%. For a recent study, see [28]. Very significantly, even though the nuclei are intact, the diffractively produced final states are semi-hard with momenta $\sim Q_S^A$. Multi-gluon interactions are enhanced in large nuclei; can these be described in terms of universal quasi-particle degrees of freedom? Measurements of coherent diffractive scattering on nuclei are easier in the collider environment of EIC relative to fixed target experiments. They will provide definitive tests of strong gluon field dynamics in QCD. Preliminary studies indicate that such measurements are not statistics limited but will be strongly influenced by detector issues.

**Complementarity of pA and eA studies at small x:**
Forward deuteron-nucleus scattering at RHIC shows strong shadowing of inclusive pion distributions at small $x$ in nuclei. These are consistent with CGC predictions; albeit, other model explanations are not ruled out. Future deuteron-gold (proton-lead) measurements at RHIC (LHC) widely extend the scope of these studies and have significant discovery potential. They will be complementary to measurements at EIC. Precision measurements of the gluon distribution will be more challenging at a hadron collider. The fundamental physics questions driving complementary studies of pA and eA are about the universality of observables extracted with the respective hadronic and leptonic probes. Factorization theorems predicated on universality are proven only for a small class of inclusive observables. They fail dramatically for ep and pp diffractive final states [29]. Factorization is uncertain in the strong gluon field regime even for inclusive observables.
Unambiguous extraction of the properties of a novel strong field regime of QCD requires complementary probes.

Realization

Since the 2001 Long Range Plan, there has been significant progress in the design of both the EIC accelerator and the detectors required to carry out the experiments.

EIC Accelerator Design

There are two complementary concepts to realize EIC:
- to construct an electron beam (either ring or linac) to collide with the existing RHIC ion complex. This is known as eRHIC
- to construct an ion complex to collide with the upgraded CEBAF accelerator. This is known as ELIC.

eRHIC

The principal EIC accelerator design effort has focused on utilization of the existing RHIC ion complex (so-called eRHIC) and is summarized in a comprehensive document, the Zero Order Design Report (ZDR) [31]. The ZDR has been reviewed by the standing accelerator Technical Advisory Committee at BNL. The ZDR contains an eRHIC ring-ring design which meets the scientific specifications, utilizes existing accelerator technology and can achieve a luminosity of $5 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$. With some extrapolation beyond demonstrated capabilities a luminosity of $10^{33} \text{ cm}^{-2} \text{s}^{-1}$ is expected. It is particularly important to carry out the necessary R&D to increase the number of bunches in RHIC. The ring-ring design includes the capability to produce polarized positrons at 10 GeV. The cost of the eRHIC ring-ring design has been carefully estimated and is the basis for planning by both BNL and DOE.

The ZDR also describes a concept to realize higher luminosities of $\sim 5 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ eRHIC using a linear accelerated beam of polarized electrons with intensity up to 300 mA. The 10 GeV linear accelerator must be designed so that the beam energy can be recovered. The high intensity polarized electron current and energy recovery capability require significant R&D effort. The linac-ring concept cannot provide positron beams but this could be provided with an additional positron ring.

ELIC

Accelerator physicists at Jefferson Lab are pursuing an Electron-Light Ion Collider, ELIC, which uses the CEBAF linear accelerator and requires the construction of a 30 to 150 GeV ion storage ring. This represents a more ambitious design concept to realize a luminosity of up to $8 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$, using much higher collision frequencies and crab-crossing of colliding beams. A detailed summary of this design effort, and associated R&D requirements, is given in the ELIC ZDR [32]. In this concept, the booster rings,
electron collider ring, and ion collider ring are designed as a “figure 8”, a design directly aimed at spin physics opportunities. This ring-ring design could be substituted by a linac-ring design using CEBAF as a one-pass energy recovering linac, should future R&D warrant this.

**EIC Detector Design**

EIC will require the design and construction of a new optimized detector building upon the high-energy experience gained from the H1 and ZEUS detectors operated at the HERA collider at DESY. In view of the different physics objectives, EIC must have detection of full hadron final states incorporated into the detector design. To optimally benefit from the higher luminosity, details of the design will be closely coupled to the design of the interaction region, and thus to the machine development work in general.

The following minimal requirements on a future EIC detector can be made:

- Measure precisely the energy and angle of the scattered electron (kinematics of the DIS reaction)
- Measure the hadronic final state (kinematics of DIS reaction, jet studies, flavor tagging, fragmentation studies, precision vertex detection and particle ID system for heavy flavor physics, and K/π separation)
- Missing transverse energy measurement (Events involving neutrinos in the final state, electro-weak physics)

In addition to those demands on a central detector, the following forward and rear detector systems are crucial:

- Zero-degree photon detector to control radiative corrections and measure Bremsstrahlung photons for luminosity measurements (absolute and relative with respect to different ep spin combinations)
- Tag electrons under small angles (<1°) to study the non-perturbative and perturbative QCD transition region
- Tagging of forward particles (Diffraction and nuclear fragments)

Optimizing all of the above requirements is a challenging task. Two detector concepts have been considered so far. One, which focuses on the rear/forward acceptance and thus on low-x / high-x physics, which emerges out of the HERA-III detector studies [33,34]. This detector concept, applicable at lower luminosities only, is based on a compact system of tracking and central electromagnetic calorimetry inside a magnetic dipole field and calorimetric end-walls outside. Forward produced charged particles are bent into the detector volume which extends the rapidity coverage compared to existing detectors.

The second design effort focuses on a wide acceptance detector system similar to the current HERA collider experiments H1 and ZEUS to allow for the maximum possible Q^2 range. The physics program demands high luminosity and thus focusing machine elements in a ring-ring configuration have to be as close as possible to the interaction region while preserving good central detector acceptance. The hermetic inner and outer tracking system including the electromagnetic section of a barrel calorimeter is
surrounded by an axial magnetic field. The forward calorimeter is subdivided into hadronic and electromagnetic sections. A fairly compact configuration is demanded.

Conclusion

EIC has developed over a decade from workshops and meetings within the international nuclear physics community into the next generation QCD machine in the U.S. beyond the present JLab and RHIC programs. The scientific focus is to explore the glue and sea quarks, the main contributors to the mass of the visible universe. A sound accelerator design which can reach a luminosity of $10^{33} \text{cm}^{-2}\text{s}^{-1}$ is in place and concepts which have the possibility of significantly increased luminosity are being developed. EIC will maintain U.S. leadership in QCD and is complementary to planned facilities in Europe and Asia. With existing high energy lepton scattering programs either terminated or scheduled for phaseout in the near future, it is essential that EIC be placed on a trajectory such that realization can get underway by 2012.

References