eRHIC: A Precision Tool for Studying Nuclear Structure

Thomas Burton

Brookhaven National Lab, Upton, NY 11973, USA

E-mail: `tpb@bnl.gov`

Abstract. eRHIC is a proposed electron-ion collider to be located at Brookhaven National Lab. This high-luminosity electron-hadron machine will provide unprecedented precision and versatility in studying features of QCD and the structure of nucleons and nuclei. We describe some key features of the eRHIC proposal, focusing on its potential for understanding the gluon structure of nuclei.

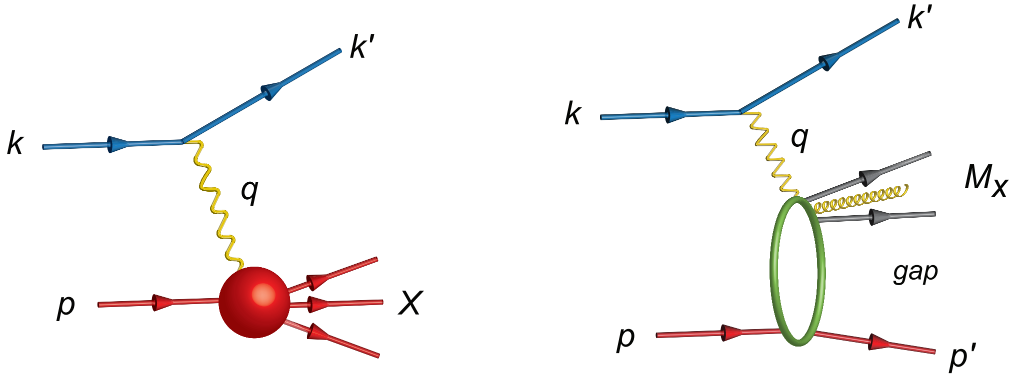
1. Introduction

eRHIC is proposed as a future electron-ion collider (EIC) to be located at Brookhaven National Lab. It would expand the existing RHIC collider complex with a polarised, high-intensity and variable-energy electron beam. This upgrade, providing capability for electron-proton and electron-nucleus collisions, would open up new frontiers in the precision study of QCD, nuclear structure and spin physics. eRHIC will utilise much of the existing RHIC infrastructure and investment, while incorporating novel new technologies, such as a pair of energy-recovery linacs to accelerate the electron beam. The upgraded facility will build on the successes of both the RHIC programme, and of the only previous electron-proton collider, HERA. The significantly higher luminosity of eRHIC (up to ~ 500 times that of HERA), coupled with its ability to run with a wide variety of ion species at variable beam energy will allow unparalleled precision and flexibility in studying the structure of nuclear matter.

2. Electron-hadron collisions

RHIC has operated as a highly successful hadron-hadron collider for over a decade now. One may therefore ask the question: why perform *electron*-hadron collisions? There are three key features of electron-hadron collisions that distinguish them from hadron-hadron collisions. Firstly, they eliminate “spectator” backgrounds that may interfere with signal. Secondly, they make it simple to distinguish initial- and final-state effects, as interactions between “beam” and “target” do not occur before the hard interaction as they do in hadron-hadron collisions. Thirdly, and perhaps most compellingly, they provide direct access to parton-level kinematics via deeply inelastic scattering (DIS).

DIS (figure 1(a)) involves the interaction of an electron with a quark inside a hadron via the exchange of a virtual photon. It is such a powerful process for understanding nuclear structure because of its direct, but experimentally simple, access to the photon-quark kinematics. Consider a DIS interaction, where an electron, of four-momentum k, interacts with a quark inside a



(a) DIS (b) Diffractive DIS

Figure 1. Schematic view of a DIS interaction between an electron (blue) and a nucleon or nucleus (red) via exchange of a virtual photon (yellow). In diffractive DIS (b) there is also an exchange of a colour-neutral state, such as a pair of gluons (green).

hadron, p, via the exchange of a virtual photon, q. All the information about the photon-quark interaction is encapsulated in a few invariant quantities:

$$Q^2 = -q^2 = -(k - k`)^2 \qquad x = \frac{Q^2}{2p \cdot q} \qquad y = \frac{q \cdot p}{k \cdot p}. \tag{1}$$

Q^2 is the squared momentum transfer in the interaction. The Bjorken variable, x, can be interpreted as the fraction of the proton's momentum carried by the struck parton. The variable y is a measure of the inelasiticity of the interaction. Significantly, all these quantities may be obtained simply by measuring the angle and energy of the scattered electron. They are also related to one-another and the squared centre-of-mass energy, s, of the collision via

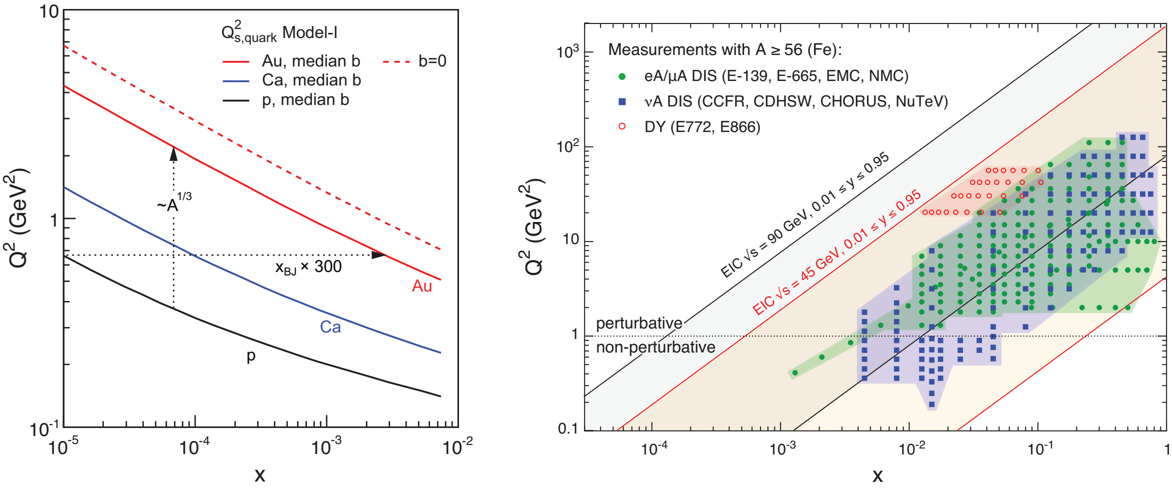
$$Q^2 = sxy. \tag{2}$$

The eRHIC physics programme is very diverse, spanning a wide variety of measurement using both electron-proton and electron-nucleus collisions. The goals and potential of the programme, and the details of the accelerator itself, are summarised in the EIC whitepaper document [1]. Here, we shall select just two topics of particular interest, in the electon-nucleus programme, to highlight the capabilities of eRHIC: gluon saturation and nuclear imaging.

3. Saturation

Quarks exist in nature only as tightly bound states. However, the overwhelming majority of the mass of these states, such a protons and neutrons, is provided not by the mass of the quarks themselves, but by the QCD interaction binding them. The partonic composition of the proton shows explosive growth in the gluon density as small values of the Bjorken parameter x. This growth cannot continue indefinitely, and so must be tamed at some sufficiently small x. Such taming can be accounted for by non-linear evolution equations. In addition to the splitting of gluons included in linear evolution schemes (such as DGLAP), non-linear evolution incorporate the re-merging of small-x gluons into larger-x gluons. As gluon density increases, recombination competes with splitting until the growth in gluon density is restrained. This is referred to as gluon *saturation*.

Results from HERA show no clear signature of saturation in e-p collisions for x down to $\sim 10^{-6}$. As can be seen from equation 2, access to low x (at a given Q^2 and y) requires high



(a) (b)

Figure 2. (a) Nuclear amplification of the saturation scale makes it accessible at larger x, and therefore lower energy. (b) eRHIC kinematics for e-A collisions compared to existing world data

centre-of-mass energy. While HERA reached $s \sim 300$ GeV, eRHIC will be a lower energy-machine. Theoretical predictions for the onset of saturation suggest an e-p machine with $s \sim$ 1-2 TeV would be required. How, then, can eRHIC investigate the onset of saturation at low x? The answer lies in using *nuclear* beams. In a high-energy collision, the electron probe sees a nucleus Lorentz-contracted into a disk. It therefore "sees" a higher gluon density. This results in a nuclear amplification of the saturation scale, Q_s^2, below which saturation manifests, approximately as follows:

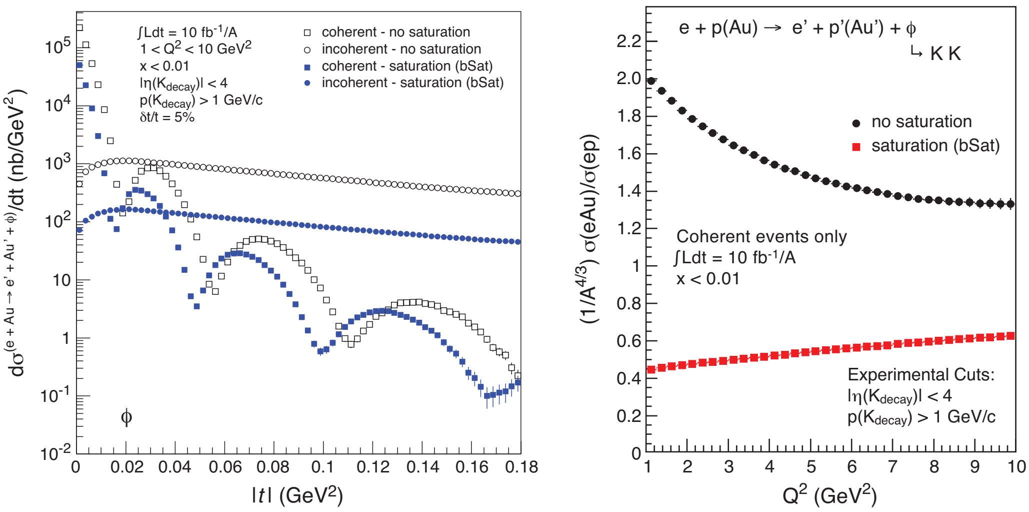
$$Q_s^2(x) \sim \left(\frac{A}{x}\right)^{1/3}, \tag{3}$$

for a nucleus of mass A. This increases the x below which saturation appears by a factor of several hundred (see figure 2(a)). Thus, saturation is accessible at an e-A machine with $s \sim 100$ GeV, as opposed to a TeV-scale e-p machine.

In addition, eRHIC will possess the ability to run at different energies, allowing a very wide span of x and Q^2 to be mapped out. This will allow the saturated and usaturated regimes, and the onset of saturation, to be studied in great detail (figure 2(b)).

3.1. Diffractive collisions

Of particular interest in saturation studies are *diffractive* interactions, shown in figure 1(b). These interactions differ from a simple DIS interaction by the exchange of a colour-neutral object, such as a pair of gluons, with the scattered nucleus either remaining intact, or subsequently breaking up due to excitation. Diffractive collisions are ideal for studying gluons because their cross section increases approximately as the *square* of the gluon density. The collisions have a clear experimental signature, whereby a hadronic final state is produced with a large angular separation, often referred to as a *rapidity gap*, from the scattered nucleus. A particularly clean channel for study is *exclusive vector meson production*, where the hadronic final state is a single vector meson like a ϕ or J/ψ. The cross section has two components; coherent, in which the scattered nucleus remains intact; and incoherent, in which the nucleus breaks apart. Simulated differential cross sections for exclusive diffractive production of ϕ mesons at eRHIC are shown



(a) (b)

Figure 3. (a) Simulated differential cross sections with respect to t for $e + Au \rightarrow e' + Au' + \phi$ [2]. Solid points show results with a saturation model, while hollow points show results with a non-saturation model. (b) The coherent cross section ratio between e-A and e-p collisions is highly sensitive to the presence of saturation.

in 3(a).

Diffractive collisions are characterised by an additional kinematic variable, t, the four-momentum transferred to the nucleon or nucleus in the scattering. The shape of the coherent differential cross section with respect to t displays a shape similar to a classical diffraction pattern. By detecting neutrons emitted close to the beam as a signature of nuclear breakup, it will be possible to disentangle the coherent and incoherent contributions.

Figure 3(b) shows the utility of diffractive collisions in studying saturation, as the cross section is strongly sensitive to the presence of saturation. The predictions when saturation effects are included differ significantly from the non-saturation prediction, and it is well within the eRHIC precision to separate them.

4. Nuclear Imaging

In addition to their use in understanding saturation, diffractive interactions have great potential for imaging nuclei. Parton distribution functions (PDFs) yield a 1-dimensional view of the nucleus: they give a picture only in terms of x. The momentum transfer t involved in a diffractive collisions is the conjugate variable of the impact parameter, b, of the interaction. Consequently, a Fourier transform of the coherent differential cross-section, $d\sigma/dt$, yields the distribution of partons in impact parameter space. Therefore, one is able to form a "3-dimensional" view of the nucleus: simultaneously in x and in transverse spatial profile, b. Given the sensitivity of diffractive interactions to gluons, this would allow the gluon density of the nucleus to be imaged in exquisite detail. Furthermore, the incoherent cross section is related to the "lumpiness" of the initial gluon density, providing information about fluctuations and "hot-spots" in the nuclear gluon distribution.

References

[1] Accardi A, Albacete J, Anselmino M, Armesto N, Aschenauer E *et al.* 2012 (*Preprint* `1212.1701`)
[2] Toll T and Ullrich T 2013 *Phys. Rev. C* **87** 024913