The importance of $e+A$ collisions at an Electron-Ion Collider

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Abstract. Despite decades of high-energy nuclear physics experiments, relatively little is known about the structure of nuclei outside of the valence region. In order to explore this region, nuclear Deep Inelastic Collisions are required. The proposal to build an electron accelerator at RHIC (to form eRHIC) will be able to answer some of these outstanding questions. This paper will outline a couple of measurements that could be made at the new accelerator.

1. Introduction
Results from Deep-Inelastic Scattering (DIS) $e+p$ at HERA on the momentum-structure of the proton in the longitudinal direction were quite striking - at small Bjorken-$x$ (the momentum fraction of the parton with respect to the hadron), the gluons were by far the most dominant parton, by over an order of magnitude [1]. In fact, linear-QCD “DGLAP” fits to the data showed that this increase showed no signs of abating. However, there is an upper bound on the total cross-section, where the hadron behaves as a “Black-disk”, which is given by: $\sigma_{\text{tot}} \leq 2\pi R^2$.

One way to achieve such attenuation is though gluon saturation. Gluons themselves are self-interacting. Linear QCD equations (such as DGLAP [2] and BFKL [3]) can describe the high-gluon contribution at low-$x$ via the splitting of high-$x$ gluons into smaller-$x$ gluons. To achieve the saturation required to tame the growth of the cross-section, low-$x$ gluons can be allowed to recombine into higher-$x$ gluons, a process described by non-linear QCD equations such as BK [4] and JIMWLK [5]. The scale at which this happens is called the saturation scale, $Q_s^2$ and is a function of both $x$ and $Q^2$, the negative square of the momentum transfer in the collision and is small - typically a few GeV$^2$ for $x < 10^{-4}$. Therefore the phase-space coverage at HERA does not cover the saturation region for protons.

2. The Structure of Nuclei
The universal nature of the saturation regime, described by the “Colour Glass Condensate” (CGC) effective field theory, means that it should also occur in nuclei [6]. Existing experiments on nuclear DIS are very sparse and predominantly probe the high-$x$ and small mass range, well away from the saturation regime. However, it is hoped that experiments at a new collider, eRHIC, will be able to study this regime. eRHIC will add an electron beam to the current RHIC hadron facility, allowing collisions for 5-30 GeV electrons with 100(250) GeV nuclei(protons) respectively [7]. Figure 1 shows the phase space coverage for $e+A$ and polarised $e+p$ collisions (where the gluonic contribution to the proton spin at small-$x$ will be studied) at eRHIC compared to existing measurements, as well as the saturation scale.

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One of the important phenomena in nuclei, which will allow for the study of a saturation regime at eRHIC is the “nuclear oomph factor”. That is, due to geometrical effects where a probe of a given wavelength will coherently probe all partons in the nucleus, the saturation scale in the nucleus is related to that in the proton by the nuclear radius, $A^{1/3}$:

$$ (Q_A^s)^2(x) \approx A^{1/3} \left( \frac{1}{x} \right)^{\lambda} \approx A^{1/3}(Q_p^s)^2(x) $$  

Therefore, at eRHIC, we will be able to study the nucleus in sufficient detail to answer the following questions:

(i) What is the role of strong gluon fields, parton saturation effects and collective gluon excitations in scattering off nuclei?

(ii) Can we experimentally find evidence for non-linear QCD evolution in high-energy scattering off nuclei?

(iii) What is the momentum and spatial distribution of gluons and sea quarks in nuclei?

(iv) Are there strong colour (quark and gluon density) fluctuations inside of a large nucleus? How does the nucleus respond to the propagation of a colour charge through it?

The following sections will describe two of the measurements which have been identified to answer some of these questions. For descriptions of other measurements, see elsewhere [8].

3. Inclusive Structure Functions

The reduced cross-section of a DIS collision can be written in terms of structure functions, as given by:

$$ \sigma_r(x, Q^2) = F_2(x, Q^2) - \frac{y}{Y^+} F_L(x, Q^2) $$  

where $F_2$ and $F_L$ represent the (anti)quark and gluon momentum distributions respectively, $y$ is a measure of the inelasticity of the collision and $Y^+ = 1+(1-y)^2$. Inelasticity is described in terms of $x$, $Q^2$ and $s$, the centre-of-mass energy via the relation: $y = \frac{Q^2}{s}$. In order to measure $F_L$ well, it is imperative to take data at a number of energies. As this didn’t happen at HERA, the gluon contribution was extracted via the scaling violation of a fit to the $F_2$ data.
In order to study how well eRHIC will be able to measure the $F_2$ and $F_L$ distributions for different nuclei, Monte-Carlo studies have been performed using the PYTHIA event generator and nuclear PDFs. For ease of viewing, Figure 2 plots the $F_2(F_L)$ for each nucleus divided by the $F_2(F_L)$ in a proton. Two theoretical curves are shown on the plot, rcBK is a non-linear QCD model [9] and EPS09 is a linear QCD model [10]. EPS09 performs a full error calculation and this is represented by the shaded grey band in each figure. The rcBK simulation does not perform a full error calculation, rather the width of the band comes from two different assumptions of the A dependence of the saturation scale. These figures show clearly that whilst the existing nuclear data outlined in Figure 1 can place some constraints on the quark ($F_2$) distributions, there are very few constraints on the gluons ($F_L$). Also shown on Figure 2 are the statistical and systematic errors obtained from the Monte-Carlo, scaled to a total cross-section of 10 fb$^{-1}$ for each nucleus, corresponding to 6 months running per species. The statistical uncertainties are enlarged so that they can be seen and are placed at unity.

### 4. Di-hadron Correlations

One of the important measurements to come from RHIC was the suppression of di-hadron correlations, back-to-back in azimuth, in central Au+Au collisions at mid-rapidity whilst at the same time, no suppression was observed in $p+p$ and $d+Au$ collisions [11]. Di-hadron correlations were used as a proxy for jets in high-multiplicity A+A collisions and the interpretation of this result was that high-momentum particles have their energy quenched as they pass through a de-confined medium. Further experiments went on to show that if these measurements were performed at forward rapidities, then suppression was observed already in the $d+Au$ collisions [12]. This is a striking result and has so far only been explained by models incorporating saturation effects [13]. This is one of the first pieces of evidence of saturation at small-$x$ in nuclei.

One of the disadvantages of $p(d)+A$ collisions is that there is no direct correlation between the rapidity and the $x$ of the collision. Therefore, it is important to also perform these measurements in $e+A$ collisions, where the $x$ can be measured precisely through a reconstruction of the scattered electron. Di-hadron correlations are important as they give information on not just the gluon distribution, but on multi-gluon correlations and theories predict that there will be a similar suppression of correlations in $e+A$ correlations as was observed in d+A correlations. This is presented in Figure 3 (a) which shows the suppression of the away-side correlation ($\Delta \phi=\pi$) for $e+p$, $e+Ca$ and $e+Au$ respectively, where the suppression level increases for larger nuclei [14].

Figure 3 (b) shows what can be achieved experimentally. Again, Monte-Carlo simulations, this time using PYTHIA along with DPMJET-III, were used to simulate 10 fb$^{-1}$ of saturation...
Figure 3. (a) The away-side di-hadron correlation for different nuclei from a saturation model. (b) the away-side di-hadron correlation for $e^+Au$ from a Monte Carlo model with and without saturation, including the estimated experimental uncertainties for 6 months running.

and non-saturation $e^+Au$ collisions respectively. The statistical and systematic uncertainties are shown on the plot and reveal that at eRHIC, it will be possible to differentiate between the two scenarios.

5. Conclusions
Studies with Monte-Carlo simulations have shown that by performing $e^+A$ collisions at eRHIC, with electron energies ranging from 5 to 30 GeV, we are able to answer some of the most important outstanding questions in nuclear physics, namely, to understand the spatial and momentum distributions (longitudinal and transverse) of quarks and gluons at low-$x$. In fact, due to the many assumptions that have to be made in interpreting hadron-hadron interactions, such a facility is the only place where these questions can be answered unambiguously.

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