eRHIC
A Precision Tool for Studying Nuclear Structure

Thomas Burton
On behalf of the EIC Science Task Force

SQM
18th July 2013
Introduction

- eRHIC and DIS overview
- Key eA measurements
- Detector concept
- Machine design
What is eRHIC?

Electron-Ion Collider (EIC) situated at BNL

Relativistic Heavy Ion Collider
+ Electron beam/linac

- Adds ep and eA capability to RHIC
- Utilises much current investment
- Builds on successes of both RHIC and HERA
Why eA collisions?

- RHIC is a successful hadronic machine
  - so why bother with electrons?

- Electrons give three advantages
  - **Clean**: no “spectator” background
  - **Clear**: distinguish initial/final-state effects
  - **Precise**: direct access to parton-level kinematics via deeply inelastic scattering
Kinematics entirely defined by scattered electron

- Kinematics **entirely defined** by scattered electron

\[ s = (p + k)^2 = 4 \cdot E_p \cdot E_e \]
\[ Q^2 = -q^2 = -(k - k')^2 \]
\[ x_B = \frac{Q^2}{2 \cdot p \cdot q} \]
\[ y = \frac{q \cdot p}{k \cdot p} \]

Deeply Inelastic Scattering
Overview

- eRHIC physics goals
  - impossible to give more than a taste here
  - eA
    - Saturation
    - Imaging
    - Nuclear PDFs
      - Hadronisation in strongly interacting medium
  - ep (not covered here)
    - nucleon imaging (impact parameter dependence)
    - unintegrated PDFs (pT-dependence)
    - spin sum rule (origin of spin-1/2 proton/neutron)

*Nuclear initial state:* vital to understanding nuclear collisions
Gluons at small x

- QCD interaction accounts for 99% of proton mass
  - c.f. 1% Higgs mass of quarks
- Gluon PDFs from DIS show explosive growth at small $x$
  - must be tamed at some point
- Non-linear evolution e.g. BK alternative to DGLAP, BFKL, account for gluon recombination
Gluons at small $x$

- QCD interaction accounts for 99% of proton mass
  - c.f. 1% Higgs mass of quarks
- Gluon PDFs from DIS show explosive growth at small $x$
  - must be tamed at some point
- Non-linear evolution e.g. BK alternative to DGLAP, BFKL, account for gluon recombination

"Saturation scale" at which phenomena manifest
An eA collider: why use nuclei?

Reaching predicted saturation scale in e-p needs **very low x**

→ *1-2 TeV machine*

But...

in a high-E collision gluon density scales ~ nuclear radius

Need even lower x than HERA accessed
Nuclear amplification

- Nuclear amplification of saturation scale

\[ Q_s^2(x) \sim A^{1/3} \left( \frac{1}{x} \right)^\lambda \sim \left( \frac{A}{x} \right)^{1/3} \]

- “Effective x” is much smaller in nuclei

→ Access saturation with ~100 GeV eA machine
eRHIC eA kinematics

- Access saturated regime
- Precise studies of nuclear structure

Extend reach far beyond existing data
Key measurements
Structure functions

\[ \sigma_r = F_2(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L(x, Q^2) \]

- precision nuclear PDFs
- indications of saturation/non-linearity

F\(_2\) sensitive to quarks
F\(_L\) sensitive to gluons
Separation requires variable energy

Systematics-dominated
large uncertainties on DGLAP predictions

Beam Energies  A/Ldt
5 on 50 GeV  2 fb\(^{-1}\)
5 on 75 GeV  4 fb\(^{-1}\)
5 on 100 GeV  4 fb\(^{-1}\)

Q\(^2\) = 2.7 GeV\(^2\), x = 10\(^{-3}\)
stat. errors enlarged (x 5)
sys. uncertainty bar to scale
Structure functions

\[ \sigma_r = F_2(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L(x, Q^2) \]

- precision nuclear PDFs
- indications of saturation/non-linearity

F\(_2\) sensitive to quarks
F\(_L\) sensitive to gluons
Separation requires variable energy

Statistical errors enlarged (×5)
Systematics-dominated

Large uncertainties on DGLAP predictions
**Diffraction**

- Colour-neutral exchange e.g. 2 gluons
- **Signature**: absence of activity in detector over wide rapidity
- **Measuring additional variable**: 4-momentum transfer $t = p - p'$
- **Ideal for studying gluons**:
  \[ \sigma \sim g(x, Q^2)^2 \]

**15% of HERA cross section 25-40% in eA!**
Diffraction

- Ideal tool for both
  - studying saturation
  - imaging gluons
- "**Coherent**": nucleus intact
- "**Incoherent**": nucleus breaks up (no diffraction pattern)
Diffraction: saturation

- **No saturation:**
  \[
  \frac{eA}{ep} \text{ ratio} \sim 1
  \]

- **Saturation:**
  enhances \( \sigma_{\text{diff}} \) in \( eA \) vs. \( ep \)

  - strong distinguishing power at eRHIC

---

**Graph:**
- **Q^2 = 5 GeV^2**
- **x = 3.3 \times 10^{-3}**
- **eAu stage-I**
- **\( \int L dt = 10 \text{ fb}^{-1}/A \)**

**Ratio of diffractive-to-total cross-section for eAu over that in ep**

**Legend:**
- saturation model
- non-saturation model (LTS)

**Statistical errors & system uncertainties enlarged (\times 10)**
Exclusive vector mesons

\[ e + A \rightarrow e' + A' + VM \]

- Measure t via **exclusive final state**
- Clear difference between **saturated** and **unsaturated**

Coherent events only
\[ \int L dt = 10 \text{ fb}^{-1}/A \]
\[ x < 0.01 \]
Experimental Cuts:
\[ |\eta(\text{e decay})| < 4 \]
\[ p(\text{e decay}) > 1 \text{ GeV/c} \]

\[ Q^2 (\text{GeV}^2) \]

\[ (1/A^{4/3}) \sigma(\text{eAu})/\sigma(\text{ep}) \]

Coherent events only
\[ \int L dt = 10 \text{ fb}^{-1}/A \]
\[ x < 0.01 \]
Experimental Cuts:
\[ |\eta(\text{K decay})| < 4 \]
\[ p(\text{K decay}) > 1 \text{ GeV/c} \]

\[ Q^2 (\text{GeV}^2) \]

\[ (1/A^{4/3}) \sigma(\text{eAu})/\sigma(\text{ep}) \]

*code.google.com/p/sartre-mc/*
Diffraction: imaging

- \( t \) is conjugate of impact parameter, \( b \)

\[
\frac{d\sigma}{dt} \overset{\text{Fourier Transform}}{\rightarrow} F(b)
\]

- gluon imaging
- Strict detector demands

\[
\int L dt = 10 \text{ fb}^{-1}/A \\
1 < Q^2 < 10 \text{ GeV}^2 \\
x < 0.01 \\
|\ln(K_{\text{decay}})| < 4 \\
p(K_{\text{decay}}) > 1 \text{ GeV/c} \\
\delta t/t = 5\%
\]

PRC 87 024913 (2013)
Diffraction: imaging

- $t$ is conjugate of impact parameter, $b$

\[ \frac{d\sigma}{dt} \overset{\text{Fourier Transform}}{\rightarrow} F(b) \]

- gluon imaging

- Strict detector demands

---

PRC 87 024913 (2013)
Diffraction: imaging

- $t$ is conjugate of impact parameter, $b$

$$d\sigma/dt \xrightarrow{\text{Fourier Transform}} F(b)$$

- gluon imaging

- Strict detector demands

$$\int L dt = 10 \text{ fb}^{-1}/A$$
$$1 < Q^2 < 10 \text{ GeV}^2$$
$$x < 0.01$$
$$|\eta(e_{\text{decay}})| < 4$$
$$p(e_{\text{decay}}) > 1 \text{ GeV}/c$$
$$\delta t/t = 5\%$$

Coherent - no saturation
Incoherent - no saturation
Coherent - saturation ($b_{\text{Sat}}$)
Incoherent - saturation ($b_{\text{Sat}}$)

PRC 87 024913 (2013)
Diffraction: imaging

- $t$ is conjugate of impact parameter, $b$

$$\frac{d\sigma}{dt} \xrightarrow{\text{Fourier Transform}} F(b)$$

- gluon imaging

- Strict detector demands

![Graph showing $F(b)$ vs. $b$ and $F(b)/F(b)$ vs. $b$](image)

PRC 87 024913 (2013)
Detector and machine
Detector concept

- Largely hermetic
  - needed e.g. to detect rapidity gap

ZDC: breakup neutrons give ~100% efficiency to detect incoherent eA

To Roman pots, ZDCs
Detector concept

- Largely hermetic
  - needed e.g. to detect rapidity gap

Geant simulations under way

ZDC: breakup neutrons give ~100% efficiency to detect incoherent eA

To Roman pots, ZDCs
● **4 goals** of machine design:

1. Variable beams **species**
2. Variable beam **energies**
3. High **luminosity** $\sim 10^{34}$
4. $e^-$ **polarisation** $\sim 80\%$

● Maximise use of existing infrastructure and investment
eRHIC

- Re-use of existing infrastructure
- Two linacs
  - multiple passes
- Stageable energy
  - add RF cavities
- New high-intensity polarised e⁻ source

Electron & Existing beams
Conclusions

• eRHIC: ep/A collider at BNL
• Rich programme of eA (and ep physics)

Further reading

‣ arXiv:1212.1701
‣ arXiv:1108.1713
‣ wiki.bnl.gov/eic/index.php/Main_Page
Dihadron correlations

- “Semi-inclusive” DIS
- Multiple gluon re-scattering, emission in saturation framework washes out correlation
- Ratio = 1 in absence of collective nuclear effects
- Shaded: uncertainties in knowledge of saturation scale
- ep baseline needed, but cancels various uncertainties
DIS with polarised beams

Measure quark/gluon helicity

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ \int \Delta g(x,Q^2) \, dx \]

\[ \int \Delta \Sigma(x,Q^2) \, dx \]
Fourier transform

Measure more minima

Better measure of $b$-dependence
Fourier transform

Measure more minima

Better measure of b-dependence
Fourier transform

Measure more minima

Better measure of \( b \)-dependence
Fourier transform

Measure more minima

Better measure of b-dependence
Fourier transform

Measure more minima

Better measure of $b$-dependence
Fourier transform

Measure more minima

Better measure of b-dependence

![Graph showing Fourier transform and measures of minima and b-dependence.](image)
Fourier transform

Measure more minima

Better measure of $b$-dependence
Fourier transform

Measure more minima

Better measure of b-dependence
**SIDIS**

**Semi-Inclusive**
**Deeply Inelastic**
**Scattering**

Measure the electron + a single hadron  
\[ (z, p_T) \]

**DIS**  
\[ x, Q^2 \]  
**semi-inclusive**  
\[ z, p_T \]  
\[ \phi \]  
\[ \text{Multi-dimensional} \]
• Gives additional hadron information
  ▶ extract “transverse-momentum-dependent distributions”: TMDs

1) Spin-dependence: see deformation of parton distribution e.g. Sivers function

Alexei Prokudin
• Gives additional hadron information

- extract “transverse-momentum-dependent distributions”: TMDs

2) Identify hadrons: decompose flavour dependence
**J/psi production**

**Fourier transform**

- Tiny statistical errors in < 1 year running
- Fine binning in \((x, Q^2, t)\)

\[
\gamma^* + p \rightarrow J/\psi + p
\]

\[
\int L dt = 10 \text{ fb}^{-1}
\]

20 GeV on 250 GeV

\[
0.0016 < x_V < 0.0025
\]

15.8 GeV^2 < Q^2 + M_{J/\psi}^2 < 25.1 GeV^2
Nucleon tomography

Generalised Parton Distributions $\rightarrow$ b-dependence
Nucleon tomography

Generalised Parton Distributions $\rightarrow$ b-dependence

Spin dependence
Nucleon tomography

Generalised Parton Distributions $\rightarrow$ b-dependence

Spin dependence

PET brain image