Physics & Status of the Electron Ion Collider (EIC)

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Acknowledgement: Many EIC collaborators from whose talks these slides have been taken…

Outline

• Broad physics motivation
  – Understanding the fundamental structure of matter;
  – The role played by the “gluons” within nuclei and polarized protons

• Electron Ion Collider (EIC)
  – The collider options, layouts & staged realization
  – Possible measurements: some simulations studies

• Status of the EIC in the US

• Comment on the other e-N collider proposals being considered around the world

• Summary & Concluding remarks…
QCD and the Origin of Mass

- 99% of the proton’s mass/energy is due to the self-generating gluon field
  - Higgs mechanism has no role

- The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
  - Quarks contribute almost nothing.
Measurements of the Glue at HERA

Scaling violations of $F_2(x,Q^2)$
Linear DGLAP equations
Gluons: not well understood!

**Linear DGLAP @ low x:**
Rises with $Q^2$? Cross sections?
Small, even negative at low $Q^2$

**Nonlinear effects: Saturation!**
High gluon densities most easily accessed in nuclei
BK/JIMWLK propose:
Characteristic scale $Q_s(x,A)$
Color glass condensate!
e-A data at low $x$, also at low $Q^2$
How does e-A really help?

Nuclear Oomph Factor: \((Q_s^A)^2 \approx c \, Q_0^2 \left( \frac{A}{x} \right)^{1/3}\)  

Enhancement of \(Q_s\) with \(A\)

\[ \Rightarrow \text{non-linear QCD regime reached at significantly lower energy in } e+A \text{ than in } e+p \]

\[
\begin{align*}
s_{\text{HERA}} & \approx (330 \text{ GeV})^2 \\
s_{\text{EIC}} & \approx (63 \text{ GeV})^2 \\
\frac{s_{\text{EIC}}}{s_{\text{HERA}}} & \approx \frac{1}{27}
\end{align*}
\]

Instead of extending \(x\), \(Q\) reach we increase \(Q_s\)  

\[ Q^2 \sim sx: \text{EIC factor 27 behind} \]

\[(10+100 \text{ GeV})\]

\[
\begin{align*}
Q_s^2(\text{HERA}) &= Q_s^2(\text{EIC}) \rightarrow Q_0^2 \, x_{\text{HERA}}^{-1/3} &= c \, Q_0^2 \, A^{1/3} \, x_{\text{EIC}}^{-1/3} \\
x_{\text{EIC}} &= x_{\text{HERA}} \cdot c^3 A \\
c^3 A &= 0.5^3 \cdot 197 \approx 25
\end{align*}
\]
Gluon’s role in Nucleon Spin

Recent Analysis: $\Delta G(x) \ @ \ Q^2=10 \ GeV^2$

- Global analysis: DIS, SIDIS, RHIC-Spin
- Uncertainly on $\Delta G$ large at low $x$

Present

RHIC range

small-$x$

$0.001 \leq x \leq 0.05$

large-$x$

$0.05 \leq x \leq 0.2$

$\delta g \equiv \int_{0.05}^{0.2} \Delta g(x, 10 \ GeV^2) \ dx$
Status of the Nucleon Spin puzzle

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g \]

DIS fixed target Experiments
~0.23 +/- 0.03

DIS & RHIC Spin
Transverse Spin
GPDs, TMDs
~??
Not 0?

RHIC Spin
DIS experiments
~0.0 +/- (unknown)
0.02 < x < 0.3

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Fundamental Questions in QCD

• How do gluons contribute to the structure of the nucleon?
• What role do the gluons play in determining the spin structure of the nucleon?
• What is the spatial distribution of the gluons and sea quarks in the nucleon?
• How do the gluons contribute to the structure of the nuclei?
• What are the properties of high density gluon matter?
• How do fast quarks and gluons interact when they traverse through nuclear matter?

How do we get to the answers?

Precise imaging of the sea-quarks and gluons in the nucleon

Need to explore a new QCD frontier: of strong color fields in nuclei

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Electron Ion Collider

A high energy, high luminosity polarized electron-proton and electron-ion collider will enable us to explore some of the most fundamental and universal aspects of QCD

Parameters of the Electron Ion Collider

- **New kinematic region**
- **$E_e = 10$ GeV ($\sim 5-20$ GeV variable)**
- **$E_p = 250$ GeV ($\sim 50-250$ GeV)**
- **$E_A = 100$ GeV**
- **$\sqrt{s_{ep}} = 30-100$ GeV**
- **Kinematic reach of EIC:**
  - $X = 10^{-4} \rightarrow 0.7$ ($Q^2 > 1$ GeV$^2$)
  - $Q^2 = 0 \rightarrow 10^4$ GeV$^2$
- **Polarization of e,p and light ion beams at least $\sim 70\%$ or better**
- **Heavy ions of ALL species**
- **Machine Luminosities envisioned**
  - $L(ep) \sim 10^{33-34}$ cm$^{-2}$ sec$^{-1}$
- **Integrated Luminosity goal:**
  - 50 fb$^{-1}$ in 10 years
  - possible with $10^{33}$ cm$^{-2}$ sec$^{-1}$
ERL-based eRHIC Design (Circa 2008)

- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- Full polarization transparency at all energies for the electron beam;
- Ability to take full advantage of transverse cooling of the hadron beams;
- Possible options to include polarized positrons: compact storage ring

Can reach $L \sim 10^{33-34} \text{ cm}^{-2} \text{ sec}^{-1}$

**A staged approach with significantly reduced initial cost possible**
Staged EIC=eRHIC@BNL

~2.8 GeV presently seems possible
What would it take to increase the e-beam energy to 4 GeV?
20 (10 & 30) GeV e x 250 (325) GeV p eRHIC with ERL inside RHIC tunnel

2 x 200 m SRF linac
10-12.5 MeV/m
4-5 GeV per pass

5 (6) vertically separated passes
ELIC @ Jefferson Laboratory: Conceptual Design (circa 2008)

3-9 GeV electrons
3-9 GeV positrons

30-225 GeV protons
15-100 GeV/n ions

Electron Cooling
Snake
Snake

prebooster

Most ambitious: \( L_{\text{max}} \sim \text{few x } 10^{34} \text{ cm}^{-2} \text{ sec}^{-1} \)

Green-field design of ion complex directly aimed at full exploitation of science program.

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Scientific Frontiers Open to EIC

- Nucleon Spin structure
  - Polarized quark and gluon distributions
    - Longitudinal spin structure (Low x critical)
    - Transverse spin structure (wide $Q^2$ arm critical)
  - Correlations between partons
    - Exclusive processes --> Generalized Parton Distributions
  - Precision measurements of QCD and of EW parameters in SM

- Un-polarized Nucleon Structure
  - Understanding confinement with low $x$/low$Q^2$ measurements
  - Un-polarized quark and gluon distributions

- Nuclear Structure, role of partons in nuclei
  - Confinement in nuclei through comparison e-p/e-A scattering

- Hadronization in nucleons and nuclei & effect of nuclear media
  - How do knocked off partons evolve in to colorless hadrons

- Partonic matter under extreme conditions
  - For various $A$, compare e-p/e-A

Polarized Beams
- low
- Lumi
- high

Proton & Nuclear Beams
Based on experience and lessons learnt from HERA:
(Conventional HERA like detector by B. Surrow & a forward detector concept by A. Caldwell)
World Data on $F_2^p$

Region of existing $g_1^p$ data makes it possible!
ΔG from Di-Jets and Charm

ΔG (x, 20 GeV²)

eRHIC Di-Jet DATA 4 fb⁻¹ (One run)

ΔG from scaling violations > x_min ~ 10⁻⁴ at eRHIC

Projected data on Δg/g with an EIC, via γ + p → D⁰ + X

Silicon VTX tracker needed
Parity Violation Studies
(studied ELIC 150 x 7 GeV, D-e scattering)

Measurement of Weinberg angle at a different scale

$E_6$ Z’ Based Extensions  RPV SUSY Extensions  Leptoquarks

Due to finite $Y$

$$\left. \frac{\delta \sin^2 \theta_W}{\sin^2 \theta_W} \right|_{Y=0.46} \approx \frac{1}{2} \left( \frac{\delta A_d}{A_d} \right)$$

$A_d \approx 2.9 \times 10^{-4}$

Assumed $10^{35}$ /cm$^2$/s, 10 weeks & 100% machine and detector efficiency
Sub 0.5% polarimetry

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Preliminary e-A simulations

Simulations to demonstrate the quality of EIC measurements

Assume:
L = 3.8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \quad (100 \text{x Hera})
T = 10 \text{ weeks}
duty cycle: 50%
L \sim 1/A \text{ (approx)}
\dot{L}dt = 11 \text{ fb}^{-1}

F_{L} \sim \alpha_{s} G(x, Q^{2}) \text{ requires } \sqrt{s} \text{ scan, } Q^{2}/xs = y

Plots above:
\dot{L}dt = 4/A \text{ fb}^{-1} \quad (10+100) \text{ GeV}
= 4/A \text{ fb}^{-1} \quad (10+50) \text{ GeV}
= 2/A \text{ fb}^{-1} \quad (5+50) \text{ GeV}
statistical error only
“An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. In support of this new direction:

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.”

EIC Working Group Structures

Steering Committee
• Abhay Deshpande, Stony Brook (Co-Chair/Contact person)
• Rolf Ent, Jlab
• Charles Hyde, ODU/UBP, France
• Peter Jacobs, LBL
• Richard Milner, MIT (Co-Chair/Contact person)
• Thomas Ulrich, BNL
• Raju Venugopalan, BNL
• Antje Bruell, Jlab
• Werner Vogelsang, BNL

International Advisory Committee
(appointed by BNL + Jlab Directors)
• Jochen Bartels (DESY)
• Allen Caldwell (MPI, Munich)
• Albert De Roeck (CERN)
• Walter Henning (ANL)
• Dave Hertzog (UIUC)
• Xiangdong Ji (U. Maryland)
• Robert Klanner (U. Hamburg)
• Alfred Mueller (Columbia)
• Katsunobu Oide (KEK)
• Naohito Saito (KEK)
• Uli Wienands (SLAC)

Working Groups and Convenors
• ep Physics
  • Antje Bruell, JLAB
  • Ernst Sichtermann, LBL
  • Werner Vogelsang, BNL
  • Christian Weiss, JLAB
• eA Physics
  • Vadim Guzey, JLAB
  • Dave Morrison, BNL
  • Thomas Ulrich, BNL
  • Raju Venugopalan, BNL
• Detector
  • Elke Aschenauer, JLAB
  • Edward Kinney, Colorado
  • Bernd Surrow, MIT
• Electron Beam Polarimetry
  • Wolfgang Lorenzon, Michigan

Next Meeting December 11-13, 2008
at Lawrence Berkeley Laboratory
-Details on EIC webpage:
- http://web.mit.edu/eicc

First meeting Spring-09

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A Long Term (Evolving) Strategic View for RHIC

2008

2010

2015

2020

RHIC physics runs

RHIC II physics runs

Detector Upgrades: $35M

EBIS: $20M

Luminosity upgrade: $10M

stoch. cooling of ion beams

RHIC-II science by-passing RHIC-II project

eRHIC: ~$750M [FY07$]

Furthe luminosity upgrades (pp, low-E)

LHC HI starts

EIC = Electron-Ion Collider; eRHIC = BNL realization by adding e beam to RHIC

Legend:

--- R&D

Construction

Multiple small projects

CD0: DOE Critical Decision, mission need

RHIC, RHIC-II, LHC-HI and EIC science share a common theme...
Other e-N colliders…

- **LHeC at CERN** (Caldwell’s talk today)
- **(MANUEL @ FAIR) --> Very preliminary**

  MAinz concept for NUcleon ELeCtron ion collider @ GSI/Fair (D. von Harrach)

  - Parameters: CM between COMPASS and HERMES; \( s=100 \) and 200 GeV\(^2\); Luminosity \(~ 10^{33}\) cm\(^{-2}\) sec\(^{-1}\)
  - Physics: dedicated study of hadronic structure & strong interactions
  - Realization: add polarized e injector to PAX using COSY as an e-storage ring at 3 GeV/c & fill HESR with polarized protons at 15 GeV
  - Open questions: can lumi be reached? Can polarization of \~80\% for both beams be achieved?
Conclusions & Summary

- QCD physics case for a future e-N collider is strong and continues to be refined: Of broad interest is a study of gluons in nuclei and precision study of polarized nucleons
  - With appropriate modifications of the collider parameters, a new paradigm of physics: precision tests of SM may be possible.
- Many international and national laboratories interested in pursuing the option: BNL, Jlab, CERN and FAIR
- Staged realization of the project is under active consideration for the US-based EIC project (BNL has preliminary ideas, Jlab may also propose soon)
- US milestone in future: 2012 Long range planning process for the Nuclear Physics community

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