The Electron-Ion Collider
An electron attoscope

Berndt Mueller
BNL & Duke University

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Gluons are gauge bosons like photons [massless (?) and spin 1], but they carry the SU(3) color charge.

Gluons carry no electric or weak charge - they cannot directly interact with photons.

We know their coupling to quarks and self-coupling with moderate precision.
Gluons are weird particles

- Gluons, like quarks, never occur in isolation.
- So far, gluons have only been observed as short-lived, virtual quanta.
- States solely made of gluons ("glueballs") should exist, but have never been unambiguously identified.
- Free space without glue fields is unstable against the spontaneous formation of chromo-magnetic fields.
- We are constantly immersed in a gluon condensate, similar to the Higgs condensate: $\langle G^2 \rangle^{1/4} \approx 0.6$ GeV.
- The detailed structure of the gluon condensate and the mechanism by which it creates quark confinement is still unknown - many different models compete.
Gluon Ocean and Quark Sea

The Quark “Sea” derives from the Gluon “Ocean” by gluon splitting into a quark-antiquark pair: suppressed by factor $N_F \alpha_s/\pi$.

Clean separation of gluons and sea quarks from valence quarks requires experiments probing $x < 0.01$, or nucleon energies of order 100 GeV.

RHIC provides polarized protons up to 255 GeV and nuclei up to 100 GeV/nucleon.
Where are the gluons?

Proton Structure

Proton
Charge on the proton
\[ = 2(2/3) + (-1/3) = 1 \]

Neutron
Charge on a neutron
\[ = 2/3 + (-1/3-1/3) = 0 \]

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Where are the gluons?

Lattice simulation with artificially frozen quarks

D. Leinweber (Adelaide)
Where are the gluons?

- **Bag model:**
  - Field energy distribution is wider than the distribution of fast moving light quarks

- **Constituent quark model:**
  - Gluons and sea quarks “hide” inside massive quarks
  - Sea parton distribution similar to valence quark distribution

- **Lattice gauge theory:**
  - (with slow moving quarks)
  - Gluons are more concentrated than quarks
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Partons at $Q^2 \sim \text{few GeV}^2$

- Gluon saturation
- Sea partons (gluons and sea quarks)
- Confined valence quarks

$10^{-N}$ 0.001 0.01 0.1 1

Theoretically under control at weak coupling

EIC domain

Weakly or strongly coupled?

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Formalism

- Wigner distributions:

  - \[ W(x, b_T, k_T) \]

  - 5D: \( \int d^2 b_T \)
  - 3D: \( \int d^2 k_T \)
  - 1D: \( \int d^2 b_T \)

- EIC – 3D imaging of sea and gluons:
  - TMDs – confined motion in a nucleon (semi-inclusive DIS)
  - GPDs – Spatial imaging of quarks and gluons (exclusive DIS)
The quantum state of the proton is an amplitude distribution with phases among different configurations. Like a hologram versus a photograph. Different “angles of view” i.e. different observables weight the phases differently. There is not a single probabilistic picture of the proton, but many, depending on the observable and the frame of motion.

The 3-gluon vertex enters not only into the structure of the rest frame state, but also into the boost operator.

**Transverse Momentum Distributions** (TMDs) probe the parton transverse dynamics, while **Generalized Parton Distributions** (GPDs) remain collinear, but measure the transverse distribution of partons.

TMDs at large $k_T$ probe parton correlations. Large $k_T$ behavior is sensitive to short-range parton-parton correlations (similar to the high $p_T$ response in nuclei, which probes NN correlations).
The Electron-Ion Collider: An Attoscope for Gluons
EIC: A color dipole attoscope

Free color charges (quarks, gluons) do not exist, but color dipoles do! Virtual photons are a good source.

Two resolution scales:
- momentum $k$ (longitudinal)
- virtuality $Q$ (transverse)

$\Rightarrow$ More powerful than an optical microscope!

HERA was the 1st generation color dipole microscope.

Limited intensity and no polarization.

The EIC will be the 2nd generation color dipole microscope!
Proton mass and spin

- **Proton mass puzzle:**
  - Quarks carry ~1% of the proton’s mass
  - How does glue dynamics generate the energy for the nucleon mass?

- **Proton spin puzzle:**
  - Quarks carry only ~30% of the proton’s spin
  - How does quark and gluon dynamics generate the rest of the proton’s spin?

- **3D structure of nucleon:**
  - Color Confinement: 200 MeV (1 fm)
  - Asymptotic freedom: 2 GeV (1/10 fm)
  - $Q$ (GeV) Probing momentum

- How does the glue bind quarks and itself into a proton and nuclei?
- Can we scan the nucleon to reveal its 3D structure?
$\Delta g$ from $\pi^0$ and jets

$$S = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L$$

$$\Delta G = \int_0^1 \Delta g(x) dx$$

QCD global fit

$\int_{0.05}^{0.2} \Delta g(x) dx = 0.1 \pm 0.06$

$\int \Delta g(x,Q^2) dx$ in units of $\hbar$

$Q^2 = 10 \text{ GeV}^2$

~60% of the proton spin?
Gluon saturation at high energy
classical coherence from quantum fluctuations

With increasing energy more and more gluons are exposed until their wave functions “overlap”

Wee parton fluctuations dilated on strong interaction time scales

Gluon density saturates at a maximal value of $\sim 1/\alpha_s$ \( \Rightarrow \) gluon saturation

(Equivalent to perturbative unitarization of cross-section in rest frame of target)

\( 1/Q_s^2 \) Saturation scale \( Q_s \)

Caveat: Weak coupling picture may not apply in the interesting range
\((x > 10^{-3}, Q^2 \sim \text{few GeV}^2)\)
Is the relevant component of the nuclear wave function that turns into a quark-gluon plasma when nuclei collide a weakly coupled color glass condensate? Or is it generated by the decoherence of strongly coupled gluon fields surrounding colliding valence quarks (see recent PHHENIX article, arXiv:1312.6676)? Or is something more akin to the 4-D shadow of a 5-D gravitational shock wave?
Hadronization and Confinement

How do hadrons emerge from a created quark or gluon?
Neutralization of color = hadronization

- Femtometer detector/scope:
  Nucleus, a laboratory for QCD

- Quark/gluon properties:
  Initial-condition for hadronization
    Semi-inclusive DIS

From the EIC White Paper

- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

Needs a probe to precisely control the initial condition!
Requirements: $\sqrt{s}$ and Polarization

- Need to reach low-\(x\) where gluons dominate ($\Delta G$, $\Delta \Sigma$ range!)
- Flexible energies (see also structure functions later)
- Need sufficient lever arm in $Q^2$ at fixed $x$ (evolution along $Q^2$ or $x$)
- Electrons and protons/light nuclei ($p$, He$^3$ or d) highly polarized (70%)
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Requirements: $\sqrt{s}$ and Beam Masses

- Saturation physics needs low-x reach and wide range of nuclei (A dependence) up to the heaviest A ($Q_s$ enhancement): $d \rightarrow U$
- Needs sufficient lever arm in $Q^2$ down to at least $x = 10^{-3}$ to verify non-linear evolution equations of CGC

$eA$, $\mu A$, $\nu A$ ($A \geq Fe$)
eRHIC: EIC @ BNL
**eRHIC: Electron Ion Collider at BNL**

Add an electron accelerator to the existing $2.5B RHIC including existing RHIC tunnel and cryo facility

80% polarized electrons: 6.6 – 21.2 GeV

Center-of-mass energy range: 30 – 145 GeV

Full electron polarization at all energies

Full proton and He-3 polarization with six Siberian snakes

Any polarization direction in electron-hadron collisions:

Luminosity: $10^{33} – 10^{34}$ cm$^{-2}$ s$^{-1}$

70% polarized protons 25 - 250 (275*) GeV

Light ions (d, Si, Cu)

Heavy ions (Au, U)

Pol. light ions (He-3)

10 - 100 (110*) GeV/u

17 - 167 (184*) GeV/u

* It is possible to increase RHIC ring energy by 10%
eRHIC – Polarized Electron-Ion
EIC Design

eRHIC ERL + FFAG ring design @ $10^{33}$/cm$^2$s
21.2 GeV $e^-$ + 255 GeV p or 100 GeV/u Au.

When completed, eRHIC will be the most advanced and energy efficient accelerator in the world.
Innovations and challenges of eRHIC

- High intensity (50mA) polarized electron source using multi-cathode gun (“Gatling Gun”)
- Energy Recovery Linac with 98% recovery efficiency (energy loss from synchrotron radiation)
- Up to 16 re-circulations of the electron beam through the same 1.32 GeV Linac
- Novel FFAG lattice allows 16 beam re-circulations using only two beam transport rings
- Permanent magnet technology is used for the FFAG beamline magnets eliminating the need for power supplies, power cables and cooling.
- Strong cooling of hadron beams gives high luminosity while minimizing electron beam current and synchrotron radiation loss.
eRHIC high-luminosity IR with $\beta^* = 5$ cm

- 10 mrad crossing angle and crab-crossing
- 90 degree lattice and beta-beat in adjacent arcs (ATS) to reach beta* of 5 cm with good dynamic aperture
- Combined function triplet with large aperture for forward collision products and with field-free passage for electron beam
- Only soft bends of electron beam within 60 m upstream of IP
Design goals match physics goals

Detector requirements:
- Good PID ($e/h$ and $\pi, K, p$)
- Wide acceptance to reach edges of kinematic range
- Ongoing generic EIC detector R&D program
Selected Measurements
PDFs: Impact on nuclear modification
Imaging quarks and gluons using Generalized Parton Distributions (GPD’s):
Imaging gluons

➢ Exclusive vector meson production:

\[
\frac{d\sigma}{dx_B dQ^2 dt}
\]

Fourier transform of the t-dependence

Spatial imaging of glue density

Resolution \(\sim 1/Q\) or \(1/M_Q\)

➢ Gluon imaging from simulation:

Only possible at the EIC: From the valence quark region
depth into the gluon / sea quark region
Solving the spin puzzle

➢ The EIC – the decisive measurement (in 1st year of running):

(Utilitying the wide \( Q^2, x \) range accessible at the EIC)

No other machine in the world can perform this measurement!

➢ Solution to the proton spin puzzle:

◊ **Precision measurement of \( \Delta G \) – extends to smaller \( x \) regime**

◊ **Orbital angular momentum – motion transverse to proton’s momentum**
Probing gluon saturation

➢ Strong suppression of di-hadron correlation in eA:

- This has never been measured in e+A (only in d+Au, where it is ambiguous)
- Correlation directly probes the saturated gluon distribution in a large nucleus
- Suppression of back-to-back hadron correlation
Exclusive vector meson production

Towards Imaging!
Why now?

A set of compelling physics questions has been formulated.

A set of measurements has been identified that can provide answers to many of the open questions about the gluon structure of the proton and of nuclei.

A powerful formalism has been developed over the past decade that connects measurable observables to rigorously defined properties of the QCD structure of nucleons and nuclei.

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