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March 17, 2006
Physics Summarized from


White Paper on Electron Ion Collider at BNL
BNL Report Number 68933-02/07-Rev
Edited by S. Davis, A. Deshpande, R. Milner, R. Venugopalan

The Zero\textsuperscript{th} Design Report (ZDR) of eRHIC at BNL
Ed. M. Farkhondeh(MIT-Bates) & V. Ptitsyn(BNL)

The Contributors
40-50 Accelerator Physicists from BNL, MIT, BINP, DESY & Jlab
100-120 High Energy & Nuclear Physicists
**SPIN SURPRISES...**

- Stern & Gerlach (1921) Space quantization associated with direction
- Goudsmit & Ulhenbeck (1926): Atomic fine structure & electron spin magnetic moment
- Stern (1933) Proton anomalous magnetic moment $2.79 \mu_N$
- Kusch (1947) Electron anomalous magnetic moment $1.00119\mu_0$
- Prescott et al., Yale-SLAC Collaboration (1978), EW interference in polarized e-d DIS, parity non-conservation in EW physics

- **European Muon Collaboration (1988/9)** Longitudinal Double Spin Measurements led to the **Spin Crisis/Puzzle**
  - Series of SLAC, CERN and DESY fixed target experiments


- Recent Jlab experiments explore the proton shape and orbital angular momentum
Low x or High $Q^2$ Surprises

- Elastic e-p scattering at SLAC (1950s) $\rightarrow Q^2 \approx 1 \text{GeV}^2$ $\rightarrow$ Finite size of the proton

- Inelastic e-p scattering at SLAC (1960s) $\rightarrow Q^2 > 1 \text{GeV}^2$ $\rightarrow$ Parton structure of the proton

- Inelastic mu-p scattering off p/d/N at CERN (1980s)
  - $Q^2 > 1 \text{GeV}^2$
  - Unpolarized EMC effect, nuclear shadowing?

- Inelastic e-p scattering at HERA/DESY (1990s) $\rightarrow Q^2 > 1 \text{GeV}^2$
  $\rightarrow$ Unexpected rise of $F_2$ at low $x$
  $\rightarrow$ Diffraction in e-p
  $\rightarrow$ Saturation(??)
Deep Inelastic Scattering

- Observe scattered electron [1] inclusive measurement
- **Exclusive measurements put demanding requirement on detectors, interaction region and their integration**

\[ Q^2 = -q^2 = sxy \]
\[ x = \frac{Q^2}{2p \cdot q} \]
\[ y = \frac{p \cdot q}{p \cdot l} \]
\[ s = 4E_e E_p \]
\[ W = (q + p)^2 \]
Large amount of polarized DIS data since 1998… but not in NEW kinematic region!
Why Collider In Future?

- Polarized DIS in past only in fixed target mode
- Collider geometry --> distinct advantages (HERA Experience)
  - Higher Center of Mass energies reachable
  - Better angular resolution between beam and target fragments
    - Better separation of electromagnetic probe
    - Recognition of rapidity gap events (diffractive physics at HERA)
    - Better measurement of nuclear fragments
- Tricky issues: integration of interaction region and detector
The Proposal

eRHIC at BNL

A high energy, high intensity polarized electron/positron beam facility at BNL to colliding with the existing heavy ion and polarized proton beam would significantly enhance RHIC’s ability to probe fundamental and universal aspects of QCD.
**eRHIC vs. Other DIS Facilities**

- **New kinematic region**
- $E_e = 10$ GeV ($\sim 5$-$12$ GeV variable)
- $E_p = 250$ GeV ($\sim 50$-$250$ GeV variable)
- $E_A = 100$ GeV
- $\sqrt{S_{ep}} = 30$-$100$ GeV
- Kinematic reach of eRHIC:
  - $X = 10^{-4} \rightarrow 0.7$ ($Q^2 > 1$ 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 at RHIC
  - High gluonic densities
- **Luminosity Goal:**
  - $L(ep) \sim 10^{33-34}$ cm$^{-2}$ sec$^{-1}$
CM vs. Luminosity

- eRHIC
  - Variable beam energy
  - P-U ion beams
  - Light ion polarization
  - Huge luminosity
Scientific Frontiers
Open to eRHIC

- Nucleon structure, role of quarks and gluons in the nucleons
  - Un-polarized quark and gluon distributions, confinement in nucleons
  - Polarized quark and gluon distributions \(\text{(LOWEST POSSIBLE X)}\)
  - Correlations between partons
    - Exclusive processes--> Generalized Parton Distributions
    - Understanding confinement with low \(x/\text{low}Q^2\) measurements

- Meson Structure:
  - Goldstone bosons and play a fundamental role in QCD

- 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 DIS at eRHIC

- Spin structure functions $g_1(p,n)$ at low $x$, high precision
  -- $g_1(p-n)$: Bjorken Spin sum rule 1-2% accuracy
- Polarized gluon distribution function $\Delta G(x,Q^2)^*$
  -- at least three different experimental methods
- Precision measurement of $\alpha_s(Q2)$ from $g_1$ scaling violations
- Spin structure of the photon from photo-production
- Electroweak s. f. $g_5$ via virtual $W^{+/−}$ production* (heavy quarks)
- Deeply Virtual Compton Scattering (DVCS), exclusive VM production
  >> Generalized Parton Distributions (GPDs)
- Transversity: Single and Double Spin Measurements*
- Drell-Hern-Gerasimov spin sum rule test at high $\nu$
- Flavor separation of PDFs through semi-inclusive DIS
- Target/Current fragmentation studies
- … and many more ….

*Also being pursued at RHIC Spin Now.

[1] --> inclusive, [2]--> semi-inclusive
[3] --> exclusive measurements
A Detector for eRHIC
A $4\pi$ Detector

- Scattered electrons to measure kinematics of DIS
- Scattered electrons at small (~zero degrees) to tag photo production
- Central hadronic final state for kinematics, jet measurements, quark flavor tagging, fragmentation studies, particle ID
- Central hard photon and particle/vector detection (DVCS)
- ~Zero angle photon measurement to control radiative corrections and in e-A physics to tag nuclear de-excitations
- Missing $E_T$ for neutrino final states ($W$ decays)
- Forward tagging for 1) nuclear fragments, 2) diffractive physics

- Lot of experience from HERA... use it!
  - What was good about HERA detectors?
  - What was bad? How/What can we improve?

- eRHIC will provide: 1) Variable beam energies 2) different hadronic species, some of them polarization, 3) high luminosity
Detector: HERA like... + PID

(Not to scale)

A Hera like Detector with dedicated PID:
>> Time of flight
>> Aerogel Ckov

AND

Forward detectors including
Roman Pots etc…
Integrated in to the beam Elements!
Low x Proton Spin Structure

Fixed target experiments
1989 – 1999 Data

$g_1^p$

$Q^2 = 1 \text{ GeV}^2$

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

Studies included statistical error & detector smearing to confirm that asymmetries are measurable. No present or future approved experiment will be able to make this measurement.

⇒ Bjorken Sumrule $\int_0^1 dx (g_1^p - g_1^n)(x, Q^2) \sim 1$-$2\%$ precision at eRHIC
Spin Structure of Neutron at Low x

- With polarized He
- ~ 2 weeks of data at EIC
- Compared with SMC(past) & possible HERA data
- If combined with $g_1$ of proton results in Bjorken sum rule test of better than 1-2% within a couple of months of running

Helium beams can be stored & manipulated in RHIC with existing magnets
Intense enough He beams & polarimetry need to be developed.
Both efforts are starting now at BNL
**BJ SUM RULE & DETERMINATION OF $\alpha_s$**

$\alpha_s(M_Z)$ has been determined from Bj spin sum rule by many groups:

4. .......

Values range from 0.114-119 with uncertainties:
- +/- 0.004 (experimental)
- +/- 0.010 (theory/ low x extrapolation)

**Particle Data Book (2002), Extended version:**

“Theoretically, this sum rule is better for determining $\alpha_s$ because perturbative QCD result is known to higher order ($\mathcal{O}(\alpha_s^4)$), and these terms are important at low $Q^2$…….. **Should data at lower x become available**, so that the low x extrapolation is more tightly constrained, the **Bj sum rule method could give the best determination of $\alpha_s$**.”
$\Delta G$: Fits of $g_1(x, Q^2) + \text{Di-Jets}$

Constrain better the shape and the first moment

$\Delta G$ determined from the Scaling violations of $g_1$

$\text{SMC Published 1998: First Moment of } \Delta G(x)$

$$\int \Delta G(x) dx = 1.0 \pm 1.0 \text{ (stat)} \pm 0.4 \text{ (exp.syst)} \pm 1.4 \text{ (theory)}$$

-- one week eRHIC reduces statistical & theory errors by $\sim 5$

-- low $x (\sim 10^{-4})$ –> strong coupling, functional form at low $-x$, renorm. & fact. scales

Di-Jet at eRHIC: constraints shape mid $x$
Parity Violating Structure Function $g_5$

\[
\frac{d^2\sigma}{dx dQ^2} \sim \{a [F_1 - \lambda b F_3] + \delta [a g_5 - \lambda^2 b g_1]\} \frac{1}{(Q^2 + M_W^2)^2}
\]

where
\[
a = 2(y^2 - 2y + 2); \quad b = y(2 - y); \quad \lambda = \pm 1 \text{ for } e^\pm
\]
\[
\delta = \pm 1 \text{ for } \uparrow\downarrow \text{ and } \uparrow\uparrow \text{ spin orientations}
\]

- Experimental signature is a huge asymmetry in detector (neutrino)
- Unique measurement
- Unpolarized $xF_3$ measurements at HERA in progress
- Will access heavy quark distribution in polarized DIS

\[
A_{cc}^{W^+} = \frac{-2b g_1 + a g_5}{a F_1 - b F_3} \quad A_{cc}^{W^-} = \frac{+2b g_1 + a g_5}{a F_1 + b F_3}
\]

For eRHIC kinematics $a \gg b$

$\Rightarrow g_5$ dominates $\rightarrow$ Extract $g_5$

\[
g_{W^-}^5 = \Delta u + \Delta c - \Delta \bar{d} - \Delta \bar{s}
\]
\[
g_{W^+}^5 = \Delta d + \Delta s - \Delta \bar{u} - \Delta \bar{c}
\]

Need electron and positron beams in eRHIC
Measurement Accuracy PV $g_5$ at eRHIC

Assumes:
1. Input GS Pol. PDfs
2. $x_F$ measured by then
3. 4 fb$^{-1}$ luminosity

Positrons & Electrons in eRHIC $\Rightarrow g_5(\pm)$

$>>$ reason for keeping the option of positrons in eRHIC
DVCS/Vector Meson Production

- Hard Exclusive DIS process
- \(\gamma\) (default) but also vector mesons possible
- Remove a parton & put another back in!
  \(\Rightarrow\) Microsurgery of Baryons!

- Claim: Possible access to skewed or off forward PDFs?
  Polarized structure: Access to quark orbital angular momentum?

\[
\int x dx [H(x, t, \xi) + E(x, t, \xi)] = 2J_{quark} = \Sigma + 2L_q
\]

On going theoretical debate… experimental effort just beginning…
Roman Pots for eRHIC

For Deeply Virtual Compton Scattering:
- Central tracker
  (for scattered e’)
- Central and forward EMCal
  (for scattered e’ and γ)
- Roman Pots a la PP2PP@RHIC
  (for scattered p)

Generate DVCS events with Frankfurt et al. PRD58 (1998)
Interest in eRHIC from HERA

- Latest from HERA-III: probably no prospects for any Physics beyond 2007
- Physics of strong interaction, main motivation for HERA-III
  - Understanding the radiation processes in QCD at small and large distances:
    - Small distance scales: explores parton splitting (DGLAP, BFKL, CCFM…)
    - Large distance scales: transition from pQCD to non-pQCD regime
- Needs specially designed detector to look in to very forward directions, unprecedented so far at HERA

- Early indications are that eRHIC energies would be sufficient to study this physics… if a specially designed detector is installed in eRHIC

- Effort led by A. Caldwell from Munich MPI
Investigate this region

Large effects are expected in Forward jet cross sections at high rapidities (also for forward particle production (strange, charm, …))

A. Caldwell et al.
A new detector to study strong interaction physics

A. Caldwell et al.

Hadronic Calorimeter

Si tracking stations

EM Calorimeter

Compact – fits in dipole magnet with inner radius of 80 cm.
Long - $|z| \leq 5$ m
Low x Detector studies for eRHIC

2x14 Si tracking stations

A. Caldwell et al.
Highlights of e-A Physics at eRHIC

- Study of e-A physics in Collider mode for the first time
- QCD in a different environment

- Clarify & reinforce physics studied so far in fixed target e-A & $\mu$-A experiments including target fragmentation
  
  QCD in: $x > [1/(2m_N R_N)] \sim 0.1$ (high x)
  QCD in: $[1/(2m_N R_A)] < x < [1/(2m_N R_N)] \sim 0.1$ (medium x)
  Quark/Gluon shadowing
  Nuclear medium dependence of hadronization

- .... And extend in to a very low x region to explore:
  saturation effects or high density partonic matter also called the Color Glass Condensate (CGC)
  QCD in: $x < [1/(2m_N R_A)] \sim 0.01$ (low x)

Already hints of exciting physics in this from: HERA, RHIC d-A; if true, eRHIC will do a precision measurements in this regime
DIS in Nuclei is Different!

Regions of:
- Fermi smearing
- EMC effect
- Enhancement
- Shadowing
- Saturation?

Regions of shadowing and saturation mostly around $Q^2 \sim 1$ GeV$^2$

An e-A collision at eRHIC can be at significantly higher $Q^2$
The Saturation Region…

- As parton densities grow, standard pQCD break down.
- Even though coupling is weak, physics may be non-perturbative due to high field strengths generated by large number of partons.
- A new state of matter???

An e-A collider/detector experiment with high luminosity and capability to have different species of nuclei in the same detector would be ideal… \( \Rightarrow \) Low \( x \) --> Need the eRHIC at BNL
Signatures of Novel Small $x$ Physics (I)

Inclusive measurements:

Structure functions $F_2(x,Q^2)$, $dF_2/d\ln Q^2$, $dF_2/d\ln x$
- $dF_2/d\ln Q^2$ at fixed $x$ at high $Q^2$ is the gluon distribution
  $>>$ CGC vs. conventional pQCD predict very different
- Quark shadowing ($F_2^A/A*F_2^N$) in fixed target experiments observed
- Gluon shadowing ($G^A/A*G^N$) indirect evidence only… pQCD at NLO
- Gluon measurements using semi-inclusive… *di-jet final states*
- eRHIC collider-detector ideal

Longitudinal structure function $F_L = F_2 - 2xF_1$
- Provide independent gluon distribution measurement
- Needs *variable electron beam (sqrt(s)) energy* → Possible at eRHIC
Signatures of Novel Small x Physics (II)

DIFRACTION at eRHIC:

**Shadowing and diffraction:**
- Measurements of diffractive structure functions $F_2^D$ and $F_2^L$ as functions of $(x,Q^2,t,x_{\text{pomeron}})$ --> Examine relation with shadowing (Gribov)
  >> Will need good acceptance/tracking in” forward/backward” acceptance regions

**Hard Diffraction**
  \[ e + A \rightarrow e' + \gamma^* + A \rightarrow e' + X + A; \quad M_X^2 \gg \Lambda_{QCD}^2 \]
- Large rapidity gap between current and target fragmentation region. At HERA 7-10% cross section diffractive.
  In e-A at eRHIC, diffractive processes may contribute 30-40% to the total cross section.
  >> Also good acceptance/tracking in “forward & backward” regions

**Coherent & Inclusive vector meson production:**
- For light vector mesons diff. Cross section. = 0.5 (inclusive)
  Heavy vector mesons this decreases…finally reaching $1/\ln Q^2$
  eRHIC will measure for different nuclei, $\rho,\omega,\phi,J/\psi,Y$ cross sections
Statistical Precision at eRHIC for e-A

- High precision at eRHIC shown statistical errors for 1 pb⁻¹/A
- Recall: eRHIC will ~85 pb⁻¹ per day
- NMC data \( R = \frac{F_2(Sn)}{F_2(D)} \)
- eRHIC’s \( Q^2 \) range between 1 and 10 GeV²
- Will explore the interesting low \( x \) region!
**eRHIC Status**

- 2001 LRP: NSAC enthusiastically supported R&D and stated its would be the next major for nuclear physics (after 12 GeV Jlab upgrade)
- 2003 NSAC subcommittee’s high recommendation
  - Level 1 for physics, and level 2 for readiness
- **2003 One of the 28 “must-do” projects in the next 20 yrs of the DoE list**
  - What can be done with minimal R&D and shortest time scale?
    - **eRHIC:** Ring-Ring design (presently: “main design line”)
    - Identify parameters for enhanced machine parameters with identified R&D topics toward significant luminosity enhancement
    - **eRHIC:** Ring-Ring design enhancement
    - **eRHIC:** Linac-Ring design
  - Includes a preliminary but realistic Cost Estimates
  - RHIC Machine Advisory Committee: Reviewed June 2005
  - RHIC Physics Advisory Committee Review next week March, 2006
- **NSAC Long Rang Planning 2006/7, needs to bless this project**
- **BNL upon encouragement from DOE is now:**
  - Exploring what it will take to get CD0 2008/9….CD3 2011/12
  - Environmental impact review began last month
Concluding Thoughts

- E-RHIC promises to be a truly next generation collider experiment
  - Detector ideas dictated by the physics are developing
  - Over the next couple of years come up with a “conceptual design”
    - Many technical challenges, but none deemed unsolvable
    - Critical issues of integration of detector + interaction region being looked in to now
      - Experience at HERA helps on accelerator/IR design as well as detector ideas

- To fully realize these ideas:
  - Need keep on a fast path towards realization
  - Critical for the present DIS/Spin NON-RHIC experiments to have something tangible to proceed in a realistic time scale
  - Next Step 1: NSAC 2006/7 long range plan approval

- The more people show interest, the better the chances for a quick realization of this project.

http://www.bnl.gov/eic