Hadron Polarimetry at an Electron-Ion Collider

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Requirements for an Electron-Ion Collider

- Physics observables
  - High beam polarizations: electrons & protons
- High EIC Luminosity $\rightarrow$ small systematics $\approx 1\%$
- Flexible bunch polarization orientation
- Polarimeter $\leftrightarrow$ polarization in collision
  - Bunch polarization profile in $x, y, z$
  - Polarization lifetime
  - Polarization per bunch
- First collider with polarized deuterium and $^3He$ beams
- Luminosity measurement depends on beam polarization
  - Need theory input
Polarized Protons at RHIC

- 120 bunches (106 ns spacing)
- $10^{11}$ protons per bunch
- Store $\approx$ 8 hours
Polarized Protons at RHIC

- Absolute beam polarization
- Polarization decay in store
- Transverse polarization profile
- Longitudinal polarization profile
- Polarization vector in experiment

- 120 bunches (106 ns spacing)
- $10^{11}$ protons per bunch
- Store $\approx$ 8 hours
Magnetic moment precession in magnetic fields:

- Thomas-BMT equation
- Lorentz force

\[ \frac{d\vec{P}}{dt} = -\left(\frac{e}{\gamma m}\right)\left[G\gamma\vec{B}_\perp + (1 + G)\vec{B}_\parallel\right] \times \vec{P} \]

\[ \frac{d\vec{v}}{dt} = -\left(\frac{e}{\gamma m}\right)\vec{B} \times \vec{v} \]

\[ G = 1.7928 \]
\[ \gamma = \frac{E}{m} \]
\[ \nu_{spin} \equiv G\gamma \]

- Imperfection resonances
  - \( \nu_{spin} = n \)
  - integer \( n \)
- Intrinsic resonances
  - \( \nu_{spin} = kP + \nu_y \)
  - integer \( k \)
  - superdiodicity \( P \)
  - vertical betatron tune \( \nu_y \)
Proton Polarimetry at RHIC

\[ A_N = \frac{d\sigma_{\text{left}} - d\sigma_{\text{right}}}{d\sigma_{\text{left}} + d\sigma_{\text{right}}} \]

\[ \varepsilon = A_N \cdot P = \frac{N_L - N_R}{N_L + N_R} \]

(*) perpendicular to polarization vector

\[ P_{\text{Beam}} = -\frac{\varepsilon_{\text{Beam}}}{\varepsilon_{\text{Target}}} P_{\text{Target}} \]
Elastic Proton Scattering

atomic hydrogen target
proton beam
100/250 GeV

Recoil proton from elastic scattering

Non-relativistic: $T_{\text{kin}} = \frac{1}{2}mv^2$

target width: $\sigma_T = 0.3$ cm
bunch length: $\sigma_B = 1.0$ ns

detector thickness

Si strip detectors
$\approx 75$ cm from interaction point
Polarization Decay and Bunch Profile

Experiments

\[ P = \frac{\int P(x, y, t) \cdot I_B(x, y, t) \cdot I_Y(x, y, t) \, dx \, dy \, dt}{\int I_B(x, y, t) \cdot I_Y(x, y, t) \, dx \, dy \, dt} \]

HJET Polarimeter

\[ P = \frac{\int P(x, y, t) \cdot I(x, y, t) \, dx \, dy \, dt}{\int I(x, y, t) \, dx \, dy \, dt} \]

Carbon Polarimeter

\[ P = P_{\text{max}} \cdot \left( \frac{I}{I_{\text{max}}} \right)^R \]

beam width

Polar. Decay dt, %/hour

Fill Id

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Polarization Decay and Bunch Profile

Experiments

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Carbon Polarimeter

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sweep

beam width

Fill Id

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Longitudinal Bunch Profile

Asymmetries in JHET

Bunch polarization in HJET

Longitudinal bunch profile: Time of flight difference from the elastic recoil
Significant and time dependent longitudinal bunch polarization profiles have been observed in 2017 data.
Elastic Recoil and Background

Data (2017)

- p+p at \( \sqrt{s} = 21.6 \) GeV
- PYTHIA 6.4.28, Tune 320
  - QCD 2 \( \rightarrow \) 2
  - Elastic
  - Diffractive
- Prompt background
  - pions / photons up to a few GeV
  - Kinematic correlation lost

Toy simulation

- Bunch length 1 ns

- Planned test with veto detector for charged pions
- Significant background also at low energies
- Problematic for much reduced bunch spacing
Carbon polarimeters (high rate)

- Reduced bunch spacing requires rejection and understanding of background
- Potential background asymmetry or dilution
- Loss of increased asymmetry at lower energies, $A_N(-t)$
Polarimetry with Forward Neutrons

- Early RHIC measurement $p^\uparrow + p \rightarrow n + X$
  - Forward neutrons in Zero Degree Calorimeter (ZDC)

- Significant asymmetry, $A_N \approx 8\%$
  - Interference of $\pi^+$ (spin-flip) and $a_1^+$ (spin-nonflip) exchanges (Kopeliovich et al.)

- Now a tool for local polarimetry in experiments
  - Tune spin rotators for azimuthal asymmetry $\rightarrow 0$
Nuclear Dependence of Forward Neutrons

- Surprise in $p + Al$ and $p + Au$ collisions
- Very large asymmetry (with opposite sign)
- Select low multiplicity with beam-beam counters
- Ultra-peripheral collision extension to $\pi/\alpha_1$ model

![Diagram of nuclear dependence](attachment:diagram.png)

**PHENIX, PRL 120, 022001 (2018)**

- $p^+ + A \rightarrow n + X$ at $\sqrt{s_{NN}} = 200$ GeV
- $x_T > 0.5$, $0.3 < \theta < 2.2$ mrad

3% scale uncertainty not shown

![Graph showing neutron asymmetry](attachment:graph.png)
Nuclear Dependence of Forward Neutrons

- Surprise in $p + Al$ and $p + Au$ collisions
- Very large asymmetry (with opposite sign)
- Select low multiplicity with beam-beam counters
- Ultra-peripheral collision extension to $\pi/\alpha_1$ model
- Photon flux from STARlight
- $\gamma + p^\uparrow \rightarrow n + \pi^+$ from MAID

G. Mitsuka, PRC 95 (2017) 044908

FIG. 2. Target asymmetry $T(\theta_{\pi})$ of the $\gamma^* p^\uparrow \rightarrow \pi^+ n$ interaction as function of $W$. In the detector reference frame, the curves correspond to the rapidity of produced neutrons $\eta = 6.8$ and 8.0.
- Surprise in $p + Al$ and $p + Au$ collisions
- Very large asymmetry (with opposite sign)
- Select low multiplicity with beam-beam counters
- Ultra Peripheral collision extension to $\pi/\alpha_1$ model
- Photon flux from STARlight
- $\gamma + p^\uparrow \rightarrow n + \pi^+$ from MAID
- Excellent agreement with data

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Nuclear Dependence of Forward Neutrons

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- $\gamma + p \uparrow \rightarrow n + \pi^+$ from MAID
- Potential candidate for fast polarimetry with fixed target ($Au$)
- Neutron multiplicity for azimuthal asymmetry
- Target effect on beam

Private communication (G. Mitsuka → W. Schmidke) for fixed target kinematics
Outlook

- Proton polarimetry at RHIC is well established
- Combination of absolute normalization with fast measurements
  - Time dependent polarization decay
  - Transverse and longitudinal bunch profiles
- High luminosity (short bunch spacing) is challenging
  - Bunch by bunch polarization measurement
  - Improvements in detector performance and read-out needed
- Potential new concept for fast polarimeters (high energy neutrons)
- Also required
  - Local polarimetry at IP
  - Light ion beam polarimetry
- Be prepared for surprises!

https://groups.google.com/a/eicug.org/forum/#!forum/eicug-polarimetry