Measuring proton beam polarization and analyzing power with pp and pC elastic scattering at RHIC

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for the RHIC Spin Group

September 24, 2011
Accelerator Complex at Brookhaven Lab

- Relativistic Heavy Ion Collider (RHIC) is a superconducting synchrotron
  - In successful operation since 2000
  - Provides polarized high energy proton beams
  - Covers wide range of energies 24 GeV to 250 GeV
  - Also unpolarized heavy ion beams Au-Au, d-Au, Cu-Cu
- Alternatig Gradient Synchrotron (AGS)
  - Serves as injector for RHIC
  - Three nobel prizes since 1960
Physics Objectives and Motivation

- Two operational detectors STAR and PHENIX
- Measure transverse and longitudinal spin asymmetries
- Aim to understand gluon polarization in the proton spin structure

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_z + \Delta g
\]

- Heavy ion program: Studies of quark-gluon plasma

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Requirements on RHIC Polarimeters

- Non-destructive polarization measurement
- Elastic scattering of a fixed target
- Maximum asymmetry/analyzing power $\Rightarrow$
  $\Rightarrow$ Small momentum transfer $-t$ (region of Coulomb nuclear interference (CNI))

- Low energy of recoil products $\Rightarrow$
  $\Rightarrow$ the detectors are in vacuum + no material in front

- The polarimeters should operate over a wide range of beam energies from injection at 24 to 250 GeV

- Beam polarization profile

- Polarization lifetime or decay during a fill

- **The physics program requires precision polarimetry $< 5\%$**
Measuring Beam Polarization

- The kinematics of elastic scattering is fully defined by the energy of recoil products.
- The momentum transfer \( t = (p_{\text{in}} - p_{\text{out}})^2 = -2ME_{\text{kin}} \)

In absence of hadronic spin-flip amplitude analyzing power \( A_N \) is exactly calculable from QED.

- In the experiment we measure asymmetry \( \varepsilon \)

\[
\varepsilon = \frac{N_L - N_R}{N_L + N_R}, \quad \varepsilon = \frac{\sqrt{N_L^{\uparrow}N_R^{\downarrow}} - \sqrt{N_L^{\downarrow}N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow}N_R^{\downarrow}} + \sqrt{N_L^{\downarrow}N_R^{\uparrow}}}
\]

- Measured polarization \( P = \varepsilon / A_N(t) \), where \( A_N(t) \) is the analyzing power.

Model predictions
RHIC and AGS Polarimeters

- 120 buckets spaced by 114 ns
- Collisions with all spin combinations available: ↑↑, ↑↓, ↓↑, ↓↓
• **Hydrogen jet (H-jet) polarimeter**
  - Provides the *average* absolute polarization over the fill ($\sim 8$ hours)

• **Two p-Carbon polarimeters in each ring**
  - About four 60-second measurements per fill
  - Bunch and fill polarization for the experiments
  - Vertical and horizontal beam polarization profile
  - Polarization decay in fill

• AGS polarimeter is similar to RHIC p-Carbon polarimeter

• STAR and PHENIX local polarimeters monitor spin direction at collision regions
• The polarized jet target is vertical
• Target polarization cycles ↑ /0/ ↓
every 500/50/500 seconds
H-Jet Polarimeter: Event Kinematics

- The beam and the target are both protons:

\[ P = \frac{\varepsilon}{A_N(t)}, \quad P_{\text{beam}} = -\frac{\varepsilon_{\text{beam}}}{\varepsilon_{\text{target}}} \times P_{\text{target}} \]

- No need to know \( A_N \)!
- \( P_{\text{target}} \) is measured by a Breit-Rabi polarimeter
- After correction for molecular contamination in the hydrogen jet \( P_{\text{target}} \approx 92 \pm 2\% \)

- Both beams separated by \( \sim 4 \text{ mm} \) intersect the hydrogen jet target
- Elastic events are easily identified from non-relativistic equation

\[ t_{\text{TOF}} = L \sqrt{\frac{m_p}{2E_{\text{kin}}}} \]

and recoil angle \( \Theta \)

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• Two polarimeters in each ring
• The readout system is multiplexed between the two pairs
• Each polarimeter employs six vertical and six horizontal ultra thin carbon targets
• Typical target size is 2.5 cm × 5 – 10 µm × 25 nm
• Targets are made by vacuum evaporation-condensation onto glass substrate
• Two stepping motors are used to move the assembly and to rotate the targets into the beam
p-Carbon Polarimeters: Detector Calibration

- Detectors calibrated with $\alpha$ source ($^{241}\text{Am}$, 5.5 MeV)
- The $\alpha$'s do not probe the surface of the detector where the carbon ions stop
  Unacounted energy losses $\Rightarrow$ “effective dead-layer”

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Calibration parameters the **time offset** $t_0$ and the **effective dead layer thickness** $x_{DL}$ extracted from the non-relativistic equation:

$$E_{\text{meas}} + E_{\text{loss}} = \frac{M_C}{2} \times \frac{L^2}{(t_{\text{meas}} + t_0)^2},$$

where $E_{\text{loss}} = E_{\text{loss}}(E_{\text{meas}}, x_{DL})$ is an energy loss parameterization for carbon.
# Overview of RHIC Polarimeters

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<th><strong>H-jet Polarimeter</strong></th>
<th><strong>p-Carbon Polarimeters</strong></th>
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<tbody>
<tr>
<td><strong>Target</strong></td>
<td>Polarized atomic hydrogen gas jet target</td>
<td>Ultra thin carbon ribbon</td>
</tr>
<tr>
<td><strong>Calibration</strong></td>
<td>Self-calibrating due to known target polarization</td>
<td>Normalized to the H-jet due to unknown $A_N$</td>
</tr>
<tr>
<td><strong>Event Rate</strong></td>
<td>$\sim 20$ Hz</td>
<td>$\sim 2$ MHz</td>
</tr>
<tr>
<td></td>
<td>Stat. uncertainty $\sim 8%$ in 6–8 hour fill</td>
<td>Stat. uncertainty $\sim 2%$ per measurement</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>Continuous throughout a fill</td>
<td>Few minutes every few hours</td>
</tr>
<tr>
<td><strong>Role</strong></td>
<td>• Average beam polarization</td>
<td>• Fast online feedback</td>
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<tr>
<td></td>
<td>• Absolute normalization for p-Carbon polarimeters</td>
<td>• Beam polarization profiles</td>
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<td>• Bunch by bunch polarization</td>
</tr>
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<td></td>
<td></td>
<td>• Fill by fill polarization for the experiments</td>
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</tbody>
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Fill Polarization: H-Jet Polarimeter

Blue beam $\langle P \rangle \approx 48\%$

Yellow beam $\langle P \rangle \approx 48\%$
Fill Polarization: p-Carbon Polarimeters

Blue-1

\[ \chi^2 / \text{n.d.f.} = 1843 / 133 \]
\[ \text{Prob} = 0 \]
\[ p_0 = 48 \pm 0.1 \]

Blue-2

\[ \chi^2 / \text{n.d.f.} = 2202 / 96 \]
\[ \text{Prob} = 0 \]
\[ p_0 = 46.93 \pm 0.12 \]
Systematics: Polarimeter-1 vs Polarimeter-2

Fill-by-fill $\frac{\Delta P}{P} \sim 3\%$

χ² / ndf 483.2 / 96
Prob 0
p0 1.012 ± 0.004

Fill-by-fill $\frac{\Delta P}{P} \sim 3\%$

χ² / ndf 414.7 / 72
Prob 0
p0 0.9801 ± 0.0034
We check normalization factors to a fixed $A_N$ for different targets.

Thicker targets are more susceptible to orientation.

Normalization for thicker targets is consistent with larger energy losses.
Polarization in Beam Collisions

\[ \langle P \rangle = \frac{\int P(x, y) I(x, y) \, dx \, dy}{\int I(x, y) \, dx \, dy} \]

\[ \langle P \rangle_{\text{coll}} = \frac{\int P(x, y) I^{(B)}(x, y) I^{(Y)}(x, y) \, dx \, dy}{\int I^{(B)}(x, y) I^{(Y)}(x, y) \, dx \, dy} \]

\[ \langle P \rangle_{\text{sweep}} = \langle P \rangle \]
Precise target position is not necessary if the beam is assumed to have a gaussian profile:

\[ I(x) = I_{\text{max}} e^{-\frac{x^2}{2\sigma_I^2}}, \quad P(x) = P_{\text{max}} e^{-\frac{x^2}{2\sigma_P^2}} \]

\( x \) can be either time or distance.

The intensity and polarization can be related as:

\[ \frac{P}{P_{\text{max}}} = \left( \frac{I}{I_{\text{max}}} \right)^R \quad \text{with} \quad R = \frac{\sigma_I^2}{\sigma_P^2} \]
Beam Polarization Profile

- Average polarization can be defined as:

\[
\langle P \rangle = \frac{P_{\text{max}}}{\sqrt{1 + R}}
\]

- Another source of systematic uncertainty comes from the profile measurements \( \langle P \rangle \) vs \( \langle P \rangle_{\text{sweep}} \)

- Fill-by-fill \( \frac{\Delta P}{P} \sim 3\% \)

- Assuming gaussian profiles polarization in collisions is:

\[
\langle P \rangle_{\text{coll}} = \langle P \rangle \frac{\sqrt{1 + R_h} \sqrt{1 + R_v}}{\sqrt{1 + \frac{1}{2}R_h} \sqrt{1 + \frac{1}{2}R_v}}
\]

- Results published online at

Analyzing Power $A_N$

- Good agreement between this and previous year!

HJet@RHIC
$p = 100$ GeV/c
PRD79(09)094014

Preliminary
H-Jet data @ $p = 250$ GeV:
2009 (red)
2011 (black)
Summary

- The *pp* and *pC* elastic scattering in CNI region is well suit for polarimetry in wide beam energy range
- RHIC polarimeters are non-destructive, unique, and compliment each other

- **Polarimeters performed well in 2011 run**
  - Measured beam polarization
  - Measured polarization profiles and beam polarization for the experiments
  - Estimated fill-by-fill systematic uncertainties

- **Future plans and outlook:**
  - Finalize global systematic uncertainties
  - Consider a different geometry for carbon targets as an alternative to ribbon
  - Calculate the analyzing power $A_N$ for *pC*
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