Precision small scattering angle measurements of proton-proton and proton-nucleus analyzing powers at the RHIC hydrogen jet polarimeter

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Received December 20, 2022

At RHIC, the hydrogen jet target polarimeter (HJET) is used to measure proton beam polarization with accuracy $\sigma_{\text{syst}}/P \lesssim 0.5\%$ by counting low energy (1–10 MeV) recoil protons in left-right symmetric detectors. The HJET performance also allowed us to precisely measure $p_p$ and $p_A$ (where $A$ is any ion stored at RHIC) analyzing powers in the CNI region. The results of the measurements are discussed.

1. Introduction

The Polarized Atomic Hydrogen Gas Jet Target (HJET) [1] is employed to measure absolute vertical polarization of the high energy ($\sim 100$ GeV) proton beams at the Relativistic Heavy Ion Collider (RHIC). The jet polarization is about $P_j \sim 96\%$ and is monitored with accuracy of about 0.1%.

The recoil protons from the RHIC beam scattering off the jet are counted in the left-right symmetric Si strip detectors depicted in Fig. 1. For each proton detected, time of flight (ToF), kinetic energy $T_R$, and coordinate $z_R$ (along the beam) in the detector discriminated by the strip width of 3.75 mm are determined. Detailed description of the measurements is given in Ref. [2].

* Presentied at “Diffraction and Low-x 2022”, Corigliano Calabro (Italy), September 24–30, 2022.
The following kinematical relations are important for the data analysis

\[ t = -2m_p T_R, \]

\[ \frac{z_R - z_{\text{jet}}}{L} = \sqrt{\frac{T_R}{2m_p}} \left[ 1 + \frac{m_p}{E_{\text{beam}}} \left( \frac{m_p}{M} + \frac{\Delta}{T_R} \right) \right], \]

where \( t \) is the momentum transfer squared, \( m_p \) is the proton mass, \( E_{\text{beam}} \) is the beam energy per nucleon, \( M \) is the beam particle mass, \( \Delta = M_X - M \) with \( M_X \) being the effective scattered mass, and \( z_{\text{jet}} \) (\( \langle z_{\text{jet}} \rangle = 0, \langle z_{\text{jet}}^2 \rangle^{1/2} \approx 2.5 \text{ mm} \)) is the coordinate of the scattering point.

The HJET detector geometry allows us to make measurements only in the Coulomb-nuclear interference (CNI) low momentum transfer range \( 0.0013 < -t < 0.018 \text{ GeV}^2 \) (0.6 < \( T_R < 10 \text{ MeV} \)), which is nearly independent of the beam particle mass and energy.

For recoil protons, measured ToF and \( T_R \) must be kinematically consistent. Considering the correlation shown in Fig. 2, one can easily identify the elastic events (\( \Delta = 0 \)). The background rate (as a function of \( T_R \)) can be interpolated [2], with a relative accuracy of about 3%, to the elastic values of \( z_R(T_R) \). Thus, the background can be accurately subtracted from the elastic data, which allows a low, \( \sigma_{\text{sys}}^P/P < 0.5\% \), systematic uncertainty in the beam polarization measurement.

2. Spin asymmetries measured with the HJET

For vertically polarized beam (\( b \)) and target (\( j \)), the recoil proton azimuthal angle distribution can be written as

\[
\frac{d^2\sigma}{dtd\varphi} = \frac{d\sigma}{2\pi dt} \left[ 1 + \left( A_N P_j + A_N^b P_b \right) \sin \varphi + \left( A_{NN} \sin^2 \varphi + A_{SS} \cos^2 \varphi \right) P_b P_j \right].
\]
Since \( \cos \varphi \approx 0 \) at HJET, the measurements are insensitive to \( A_{SS}(t) \). For elastic polarized \( p^+p^+ \) scattering, \( A_N^b = A_N^j = A_N(t) \) and the asymmetries, \( a_{b,j}^N(T_R) = a_{b,j}^N(t)P_bP_j \), \( a_{NN}^N(T_R) = A_{NN}(t)P_bP_j \) concurrently measured \[2\] using the same events allow one to determine \( P_b \), \( A_N(t) \), and \( A_{NN}(t) \).

Theoretical parametrization of the forward elastic proton-proton analyzing powers was developed in Refs. \[3, 4, 5\]. In a simplified form,

\[
A_N(t) = \frac{\sqrt{-t}}{m_p} \frac{(\kappa_p - 2\text{Im}r_5) t_c/t - 2\text{Re}r_5}{(t_c/t)^2 - 2(\rho + \delta_C) t_c/t + 1},
\]

(4)

where \( \kappa_p = 1.792 \) is the anomalous magnetic moment of a proton, \( t_c = -8\pi\alpha/\sigma_{\text{tot}} \), \( \sigma_{\text{tot}} \) is the total \( pp \) cross section, \( \rho \) is the \( \text{Re}/\text{Im} \) amplitude ratio, \( \delta_C \approx \alpha \ln t_c/t + 0.024 \) is the Coulomb phase, and \( |r_5| \sim 0.02 \) is the hadronic single spin-flip amplitude parameter. A more accurate expression discussed in \[6, 7\] includes small but essential corrections to meet the experimental precision achieved at HJET.

### 3. Forward elastic proton-proton analyzing powers

During the RHIC Runs in 2015 and 2017 with beam energies of 100 and 255 GeV, respectively, the forward elastic proton-proton \( A_N(t) \) (Fig. 3) and \( A_{NN}(t) \) (Fig. 4) were precisely measured \[8\] at HJET.

The hadronic single spin-flip amplitude \( (r_5) \), was clearly isolated as shown in Fig. 5. Here, compared to the published \[8\] results, we applied a correction \( \text{Re}r_5 = \text{Re}r_5^8 + (3.1_{\text{abs}} + 0.8_{\text{rp}}) \times 10^{-3} \) due to the absorption \[7\] and updated value of the proton charge radius \( r_p = 0.841 \text{ fm} \) \[9\].

To find the spin-flip amplitude dependence on the center of mass energy squared, \( s = 2m_p(m_b + E_{\text{beam}}) \), the following parametrization was used

\[
\sigma_{\text{tot}}(s) r_5(s) = f_5^+ R^+(s) + f_5^- R^-(s) + f_5^P P(s),
\]

(5)
where couplings $f_5^{\pm}$ are free parameters in the fit and Reggeon pole $R^\pm(s)$ and Pomeron $P(s)$ (in Froissaron approximation) are functions found in a fit [11] $\sigma_{\text{tot}}(s) = R^+(s) + R^-(s) + P(s)$ of the unpolarized pp data. The $r_5$ fit result, $f_5^P = 0.054 \pm 0.002_{\text{stat}} \pm 0.003_{\text{syst}}$, suggests non-vanishing hadronic spin-flip amplitude at very high energies. The extrapolation of the HJET values of $r_5$ to $\sqrt{s} = 200$ GeV can be compared with the STAR measurement [12]. The correction applied to $r_5$ improves the agreement of the HJET results with the parametrisation in Eq. (5), since $\chi^2 = 2.2 \rightarrow 0.7$ (ndf=1). Although consistency with STAR value of $r_5$ dis-improves, the discrepancy is not critically significant, $\chi^2/\text{ndf} = 4.8/3$ (which is statistically equivalent to about 1.8 standard deviations).

For the $A_{\text{NN}}(t)$, the hadronic double spin-flip amplitude ($r_2$) is also non-zero and the Regge fit gives $f_2^P = -0.0020 \pm 0.0002$ [8].

### 4. Inelastic proton-proton scattering

With the HJET detectors, the inelastic events $p_{ib} p_j \rightarrow (\pi X)_{ib} p_j$ can be separated (due to relatively large $\Delta \geq m_\pi$) from the elastic ones and the inelastic analyzing powers for the beam $A_N^b(t, \Delta)$ and target $A_N^t(t, \Delta)$ spins can be evaluated.
Preliminary results for the 255 GeV proton beam are shown in Fig. 6. Only bins with event rate (after background subtraction) \( R > 0.4\% \) relative to the elastic maximum were analyzed. The inelastic events (\( R \) up to 5\%) are well identified in the upper left corner of the histograms.

One can see that \( A_N^{pA} < A_N^{elastic} < A_N^b \). The inelastic analyzing power grows with decreasing of \( \Delta \). For \( A_N^{b}(t,\Delta) \), values of about 20\% are observed in the data.

For the 100 GeV beam (Fig. 7), the detected inelastic rate is much lower, \( R \lesssim 0.5\% \). Nonetheless, results for the analyzing powers are, qualitatively, about the same as for 255 GeV. A 100 GeV beam spin inelastic analyzing power up to 35\% was observed.

5. Elastic proton-nucleus analyzing power

Since 2015, HJET was routinely operated in RHIC Heavy Ion Runs. It was found that HJET performance in an ion beam is as good as in a proton one. Consequently, the proton-nucleus analyzing power \( A_N^{pA}(t) \) can be
The study has been performed for six ions $^2H (d), {^{16}}O, {^{27}}Al, {^{96}}Zr, {^{96}}Ru, and {^{197}}Au$. Also, the energy scans were done for Au and $d$.

Some preliminary results for normalized, $A_{N}^{\text{norm}}(t) = A_{N}^{pA}(t)/A_{N}^{pp}(t)$, analyzing powers are shown in Fig. 8. Systematic uncertainties in the measurements were not considered. The beam nucleus breakup fraction in the elastic data is expected to be small, $\lesssim 1\%$ [10].

For 100 GeV/nucleon Au beam, the experimental data were compared with theoretical predictions in Ref. [13]. It was found that absorption corrections are very important for calculation of $A_{N}^{pAu}(t)$. However, not all essential discrepancies between the data and theory were eliminated.

6. Summary

The HJET, which was designed to measure absolute proton beam polarization at RHIC, can also be considered as a standalone fixed target experiment to precisely measure proton-proton and proton-nucleus analyzing powers in the CNI region.

The measurements of elastic $pp$ $A_{N}(t)$ and $A_{NN}(t)$ resulted in finding non-zero single and double spin Pomeron couplings.

Preliminary results for inelastic $pp$ $A_{N}^{b}(t, \Delta)$ and $A_{N}^{j}(t, \Delta)$ for 100 and 255 GeV, and elastic $pA$ analyzing powers, in wide range of $1 < A < 200$ (for $E_{\text{beam}} = 100$ GeV) and $3.8 < E_{\text{beam}} < 100$ GeV (for Au), were obtained. However, to properly understand these measurements, an appropriate theoretical description of these analyzing powers is needed.

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