PRECISION SMALL SCATTERING ANGLE MEASUREMENTS OF PROTON–PROTON AND PROTON–NUCLEUS ANALYZING POWERS AT THE RHIC HYDROGEN JET POLARIMETER*

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

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1. Introduction

The Polarized Atomic Hydrogen Gas Jet Target (HJET) [1] is employed to measure the absolute vertical polarization of the high-energy (~ 100 GeV) proton beams at the Relativistic Heavy Ion Collider (RHIC). The jet polarization P_j is about 96% and is monitored with the 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 $T_{\rm R}$, and coordinate $z_{\rm R}$ (along the beam) in the detector discriminated by the strip width of 3.75 mm are determined. A detailed description of the measurements is given in Ref. [2].

The following kinematical relations are important for the data analysis:

$$t = -2m_pT_{\rm R}\,, \tag{1}$$

$$\frac{z_{\rm R}-z_{\rm jet}}{L} = \sqrt{\frac{T_{\rm R}}{2m_p}} \times \left[1+\frac{m_p}{E_{\rm beam}}\left(\frac{m_p}{M}+\frac{\Delta}{T_{\rm R}}\right)\right]\,, \tag{2}$$

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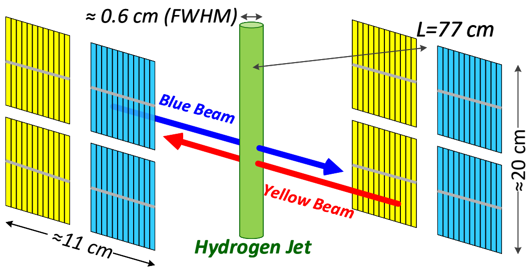

Fig. 1. A schematic view of the HJET recoil spectrometer.

where t is the momentum transfer squared, m_p is the proton mass, E_{beam} is the beam energy per nucleon, M is the beam particle mass, $\mathit{\Delta} = M_X - M$ with M_X being the effective scattered mass, and z_{jet} ($\langle z_{\mathrm{jet}} \rangle = 0$, $\langle z_{\mathrm{jet}}^2 \rangle^{1/2} \approx 2.5\,\mathrm{mm}$) 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 $0.0013 < -t < 0.018$ GeV^2 ($0.6 < T_{\mathrm{R}} < 10$ 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 ($\mathit{\Delta} = 0$). 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 $z_{\mathrm{R}}(T_{\mathrm{R}})$. Thus, the background can be accurately subtracted from the elastic data, which allows a low, $\sigma_P^{\mathrm{syst}}/P \lesssim 0.5\%$, systematic uncertainty in the beam polarization measurement.

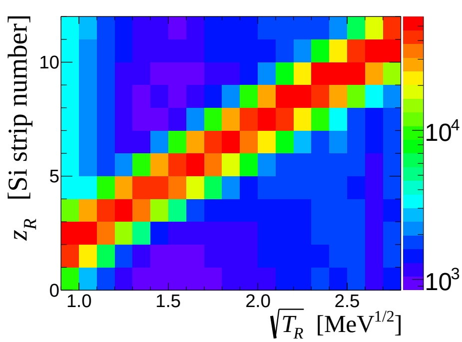

Fig. 2. Measured z_{R} *vs.* $\sqrt{T_{\mathrm{R}}}$ for the 100 GeV proton beam.

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

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}t\mathrm{d}\varphi} = \frac{\mathrm{d}\sigma}{2\pi\mathrm{d}t}\left[1+\left(A_N^jP_j + A_N^bP_b\right)\sin\varphi+\left(A_{NN}\sin^2\!\varphi+A_{\mathrm{SS}}\cos^2\!\varphi\right)P_bP_j\right]. \tag{3}$$

Since $\cos\varphi \approx 0$ at HJET, the measurements are insensitive to $A_{\mathrm{SS}}(t)$. For elastic polarized $p^\uparrow p^\uparrow$ scattering, $A_N^b = A_N^j = A_N(t)$ and the asymmetries, $a_N^{b,j}(T_\mathrm{R}) = A_N^{b,j}(t)P_{b,j}$, $a_{NN}(T_\mathrm{R}) = A_{NN}(t)P_bP_j$ 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. [3–5]. In a simplified form,

$$A_N(t) = \frac{\sqrt{-t}}{m_p}\,\frac{(\kappa_p - 2\,\mathrm{Im}\,r_5)\,t_\mathrm{c}/t - 2\,\mathrm{Re}\,r_5}{(t_\mathrm{c}/t)^2 - 2(\rho+\delta_\mathrm{C})\,t_\mathrm{c}/t + 1}\,, \tag{4}$$

where $\kappa_p = 1.792$ is the anomalous magnetic moment of a proton, $t_\mathrm{c} = -8\pi\alpha/\sigma_\mathrm{tot}$, σ_tot is the total pp cross section, ρ is the Re/Im amplitude ratio, $\delta_\mathrm{C} \approx \alpha\ln t_\mathrm{c}/t + 0.024$ 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.

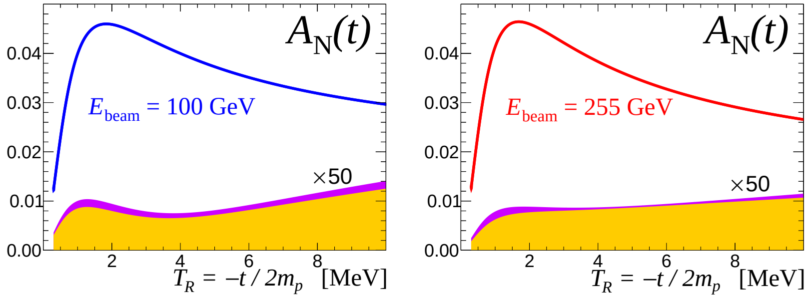

Fig. 3. Single spin-flip elastic pp $A_N(t)$. Filled areas show experimental uncertainties scaled by a factor of 50. Violet is for stat+syst and orange is for syst only.

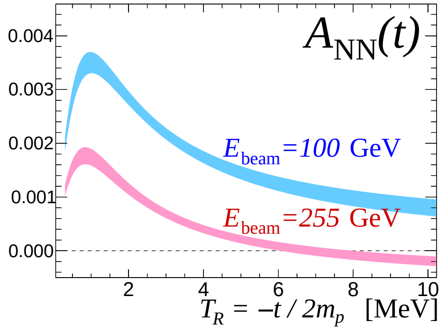

Fig. 4. Double spin-flip forward elastic pp analyzing power $A_{NN}(t)$.

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 $\mathrm{Re}\, r_5 = \mathrm{Re}\, r_5^{[8]} + (3.1_{\mathrm{abs}} + 0.8_{r_p}) \times 10^{-3}$ due to the absorption [7] and updated value of the proton charge radius $r_p = 0.841$ fm [9].

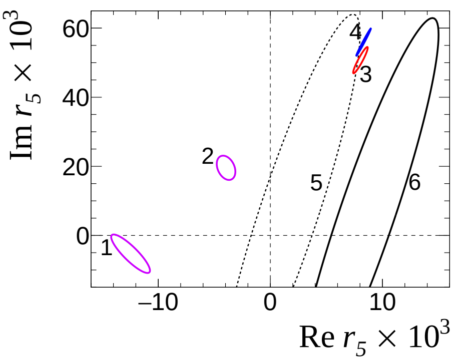

Fig. 5. Experimental 1-sigma contours (stat+syst) for r_5. The HJET results are marked “1” ($\sqrt{s} = 13.76$ GeV) and “2” (21.92 GeV). The Regge fit extrapolations to 200 GeV are “3” for Froissaron and “4” for simple pole Pomeron. “5” and “6” are the STAR value (200 GeV) [12] before and after applying (in this analysis) the absorption and r_p-related corrections.

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

$$\sigma_{\mathrm{tot}}(s)\, r_5(s) = f_5^+ R^+(s) + f_5^- R^-(s) + f_5^P P(s)\,, \tag{5}$$

where couplings $f_5^{\pm,P}$ are free parameters in the fit and Reggeon pole $R^\pm(s)$ and Pomeron $P(s)$ (in the Froissaron approximation) are functions found in a fit [11] $\sigma_{\mathrm{tot}}(s)\,[i + \rho(s)] = R^+(s) + R^-(s) + P(s)$ of the unpolarized pp data.

The r_5 fit result, $f_5^P = 0.054 \pm 0.002_{\mathrm{stat}} \pm 0.003_{\mathrm{syst}}$, 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 $\chi^2 = 2.2 \to 0.7\,(\text{n.d.f.} = 1)$. Although consistency with the STAR value of r_5 dis-improves, the discrepancy is not critically significant, $\chi^2/\text{n.d.f.} = 4.8/3$ (which is statistically equivalent to about 1.8 standard deviations).

For the $A_{NN}(t)$, 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 $p_b\,p_j \to (\pi X)_b\,p_j$ 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 $A_N^j(t, \Delta)$ 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.

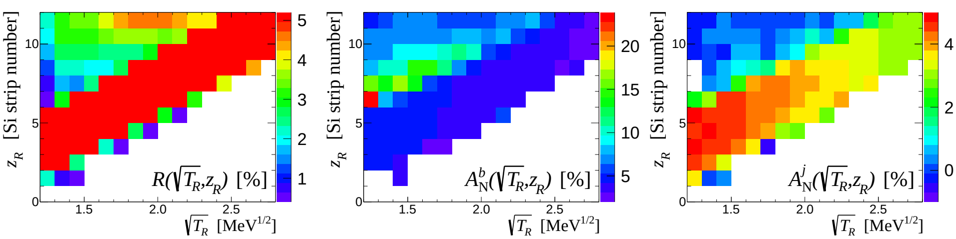

Fig. 6. Shown are elastic and inelastic events for the 255 GeV proton beam, left to right, normalized event rate $R(\sqrt{T_{\mathrm{R}}}, z_{\mathrm{R}}) = N_{\mathrm{bin}}(\sqrt{T_{\mathrm{R}}}, z_{\mathrm{R}})/N_{\mathrm{max}}^{\mathrm{el}}$, and the beam $A_N^b(t, \Delta)$ and target $A_N^j(t, \Delta)$ analyzing powers. A cutoff of $R > 0.4\%$ was used.

One can see that $A_N^j < A_N^{\mathrm{elastic}} < A_N^b$. The inelastic analyzing power grows with decreasing of Δ. 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.

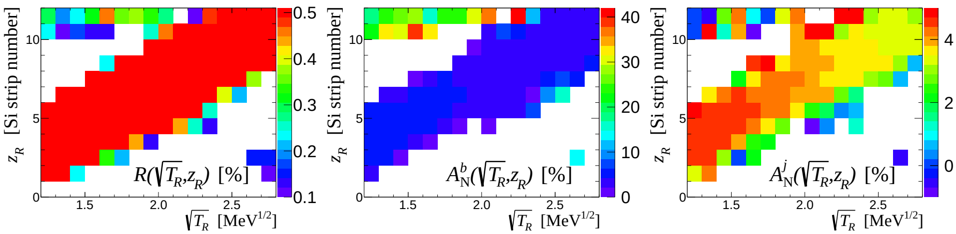

Fig. 7. The same as Fig. 6, but for the 100 GeV proton beam and $R > 0.1\%$ cutoff.

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 precisely measured. The study has been performed for six ions [^{2}H (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, $A_N^{\rm norm}(t) = A_N^{pA}(t)/A_N^{pp}(t)$, 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].

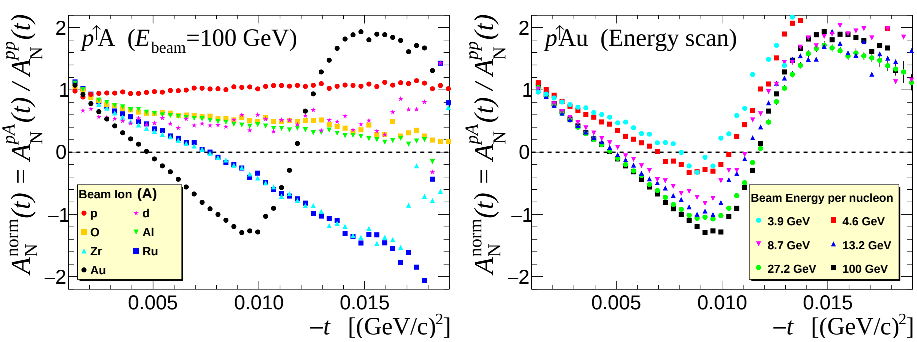

Fig. 8. The dependence of the proton–nucleus elastic $A_N^{pA}(t)$ on the beam ion (left) and the beam energy (right). The measured analyzing powers are normalized by the pp one calculated for $E_{\rm beam} = 100$ GeV and no hadronic single spin-flip, $r_5 = 0$.

For the 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 the calculation of $A_N^{p{\rm Au}}(t)$. 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 $A_N^b(t,\varDelta)$ and $A_N^j(t,\varDelta)$ for 100 and 255 GeV, and elastic pA analyzing powers, in the wide range of $1 < A < 200$ (for $E_{\mathrm{beam}} = 100$ GeV) and $3.8 < E_{\mathrm{beam}} < 100$ 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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