STAR RESULTS FROM POLARIZED PROTON COLLISIONS AT RHIC

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Abstract

This talk reports on progress from the first two years of polarized proton collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). STAR is one of the two large experiments at RHIC. It features large acceptance spanning a broad range of rapidity. The long-term goals of the STAR spin program are to measure the gluon contribution to the proton's spin; determine the contribution of specific quark flavors to the spin of the proton through the study of spin observables for vector boson production, and to determine the transversity structure function. The study of polarized proton collisions at $\sqrt{s}=200$ and 500 GeV is expected to provide important insight into the spin structure of the proton, revealing the contributions to the spin sum rule either from gluons or from the orbital motion of the partons. Selected STAR results from the study of polarized proton collisions during the first two runs are presented.

1 Introduction

The parton model codifies our present understanding of the proton. Viewed in the Breit frame, the proton consists of collinear quarks and gluons each carrying a fraction of the proton’s momentum, given by Bjorken $x$. Global analyses of many spin-independent high-energy scattering observables (e.g., Ref. [1]) provide details of the Bjorken $x$ dependence of the quark and gluon densities. Global analyses of polarized deep inelastic scattering experiments demonstrate that the quarks alone cannot account for the proton’s spin (for a recent analysis, consult Ref. [2] and references therein). To satisfy the proton’s spin sum rule, either the gluons must be polarized or there must be significant contributions to the proton’s spin from the orbital motion of its constituents. If the latter, then the transverse momentum of the quarks and gluons cannot be ignored, as in the parton model. One of the goals of the RHIC spin program [3] is to determine whether gluons or parton orbital motion account for the part of the proton’s spin not carried by the quarks.

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is designed with the capability of accelerating and colliding high-energy beams of polarized protons. Measurements of polarization observables for the inclusive production of hadrons, hadronic jets, and photons in longitudinally polarized $p^+\bar{p}$ collisions at $\sqrt{s}=200$ and 500 GeV will address whether gluons contribute to the proton spin. More exclusive measurements, such as $\gamma+$jet final states, hold the promise of determining the Bjorken $x$ dependence of gluon polarization within the framework of leading-order pQCD [4]. The extensions to next-to-leading order that have already been made for inclusive observables are still needed for these more exclusive final states. Measurements of spin observables for $W^\pm$ and $Z^0$ production will allow a decomposition of the flavor dependence of quark and
antiquark contributions to the proton’s spin. The study of transversely polarized $p+p$ collisions at RHIC can provide information about quark transversity ($\delta q(x) = q^\uparrow(x) - q^\downarrow(x)$) and possibly some insights into orbital angular momentum of the partons. The physics goals of the two large experiments (PHENIX and STAR) at RHIC include the study of the proton’s spin structure via measurements of spin observables in polarized proton collisions.

The primary focus of the first three RHIC runs has been on the study of Au+Au collisions and d+Au collisions to search for evidence of the quark-gluon plasma. Portions of the last two RHIC runs have been committed to commissioning the accelerator for polarized proton collisions, and to conduct the first studies of of $\vec{p}+\vec{p}$ collisions at $\sqrt{s}=200$ GeV. Nine-week periods in RHIC run 2 (from December, 2001 to January, 2002) [5] and RHIC run 3 (from March, 2003 to May, 2003) were devoted to this purpose. In run 2, only vertically polarized beams were available, since spin rotator magnets had not yet been installed. In run 3, spin rotator magnets were in place at the STAR and PHENIX interaction regions and were commissioned to provide the first collisions of longitudinally polarized protons [6]. In run 2, an integrated luminosity of 0.3 pb$^{-1}$ with an average beam polarization of 15% was delivered to STAR. In run 3, 0.5 pb$^{-1}$ of vertically polarized proton collisions and 0.4 pb$^{-1}$ of longitudinally polarized proton collisions, with an average polarization of 25%, was delivered to STAR.

An important goal for run 2 was to identify processes that had sizeable analyzing powers and yields. Since the stable spin direction of RHIC is vertical, special magnets either side of the STAR (and PHENIX) interaction region (IR) are required to precess the spin to make longitudinal polarization at the IR and then back again after the IR. Local polarimeters are required to establish that vertical and radial polarization components of the colliding proton beams are small when the rotator magnets are excited. As described below, two such processes were identified in measurements at STAR. In run 3, a primary objective was to embark on measurements of $A_{LL}$ for mid-rapidity inclusive jet production, a process sensitive to gluon polarization. This talk reports on selected spin physics results from the STAR experiment during the first two years of polarized proton operations at RHIC.

2 Cross sections and analyzing powers for large rapidity pion production

The E-704 experiment at Fermilab observed large analyzing powers ($A_N$) for pion production at large Feynman $x$ ($x_F > 0.3$) and moderate transverse momentum ($0.5 < p_T < 2.0$ GeV/c) using a tertiary polarized proton beam in a fixed target experiment with total energy in the center of mass equal to $\sqrt{s}=20$ GeV [7]. Similar behavior has been observed at even lower $\sqrt{s}$ values [8]. Large values of $A_N$ were unexpected because the chiral properties of QCD result in only very small analyzing powers for partonic scattering processes involving u and d quarks. Subsequent theoretical work suggested that large $A_N$ for particle production could arise via correlations between transverse momentum ($k_T$) and the spin in either distribution functions (the Sivers effect [9, 10]) or fragmentation functions (the Collins effect [11, 12]). It is also possible that explicit higher twist effects can give rise to large $A_N$ [13, 14, 15]. Models incorporating these effects were developed and their
parameters were adjusted to fit the E704 results. These models were subsequently extended to RHIC collision energies, leading to theoretical expectations of large analyzing powers for forward pion production in $p+p$ collisions at $\sqrt{s}=200$ GeV.

The invariant cross section for a given process is an important observable to help establish the dynamical origin of particle production. At low collision energies, it is generally believed that large rapidity particle production arises from soft processes collectively known as beam fragmentation. Next-to-leading order perturbative QCD calculations at $\sqrt{s} = 20$ GeV underestimate measured cross sections for pion production at large $x_F$ and small $p_T$ by nearly an order of magnitude [16]. Cross section measurements at $\sqrt{s}=200$ GeV can help to clarify the relevant dynamics for particles produced at large rapidity. This is particularly important to understand because of expectations that pion production at large rapidity and moderate transverse momentum is in the kinematic domain where gluon saturation effects in a heavy nucleus will be manifest [17].

A prototype Forward $\pi^0$ Detector was used for measurements of large $x_F$ $\pi^0$ production cross sections and analyzing powers in the first polarized proton collision run at RHIC. Details of the measurements are reported elsewhere [18]. The results for the invariant cross section measured are shown in Fig. 1. The data are compared with NLO pQCD calculations evaluated with the CTEQ6M parton distribution functions [1] and equal renormalization and factorization scales set to $p_T$. Two sets of fragmentation functions are used. The ratio of the computed cross sections from the two fragmentation functions are similar to what is observed at mid-rapidity [19]. The agreement between the NLO pQCD calculation and the data is comparable to what is observed at mid-rapidity. Even though the transverse momenta are small, the agreement suggests that particle production at large rapidity in $p+p$ collisions at $\sqrt{s}=200$ GeV is dominated by partonic scattering, rather than soft mechanisms presumed responsible for beam fragmentation.

In addition to agreeing with NLO pQCD, the measured neutral pion production cross sections at pseudorapidities $< \eta > = 3.3$ and 3.8 also agree with results from the PYTHIA Monte Carlo generator [20] (left panel of Fig. 2). This is a non-trivial result, since small angle particle production measurements are not available at $\sqrt{s}=200$ GeV, meaning that the PYTHIA simulation is a prediction, rather than resulting from tuning of its variables. Given that agreement, it is possible to establish the relative contributions from the multiple different subprocesses. For $x_F > 0.3$, most of the contributions come from initial states involving a large-$x$ quark and a low-$x$ gluon. Initial-state parton showers, where the large-$x$ quark splits into a quark+gluon, and the gluon subsequently undergoes a
hard interaction with a low-\(x\) gluon from the other proton, is responsible for a significant fraction of the forward pion yield (right panel of Fig. 2).

Concurrent with the cross section measurements, the analyzing power for neutral pion production at \(< \eta > = 3.8\) was measured for \(\vec{p} + \vec{p}\) collisions at \(\sqrt{s} = \text{200 GeV}\) in RHIC run 2 (Fig. 3). At \(< \eta > = 3.3\), the cross section is an order of magnitude smaller for the same \(x_F\), hence the statistics for the \(A_N\) measurement were insufficient. As for the E704 data, the analyzing power is found to be an increasing function of energy, proportional to Feynman \(x\). Unlike the situation for E704, the concurrently measured cross section is found to be in agreement with NLO pQCD. In Fig. 3, the \(A_N\) measurements are compared to model calculations incorporating spin-correlated \(k_T\) effects in the distribution function (Sivers effect) [10], a non-zero transversity distribution and spin-correlated \(k_T\) effects in the fragmentation function (Collins effect) [12], and higher-twist effects [14, 15]. All of these models fit the E-704 data [7] and were predictions made by extrapolation from the lower \(\sqrt{s}\) to RHIC energies, evaluated at a fixed \(p_T\) of 1.5 GeV/c.

The magnitude of the analyzing power has two uncertainties, both related to knowledge of the beam polarization. At the RHIC injection energy of 24.3 GeV knowledge of the beam polarization is presently limited by calibration experiments to \(\pm 30\%\) [26]. Relative determinations of the polarization of the RHIC beams rely on the measurement of the azimuthal distribution of recoil carbon ions emerging near 90° scattering angles from a ultra-thin ribbon target inserted into the RHIC beam. The kinematics correspond to proton-carbon elastic scattering at small momentum transfer (0.006 < |\(t\)| < 0.030 (GeV/c)^2). The analyzing power for this reaction arises from the interference of the calculable Coulomb amplitude and the unknown strong interaction amplitude; hence, polarimetry in RHIC is based on Coulomb Nuclear Interference (CNI). Dependence on the proton beam momentum is, at present, inferred from calculation [23] to be small. This is consistent with the observation that the measured asymmetry (\(\epsilon_{CNI} = P_{\text{beam}} \times A_N^{CNI}\))
was nearly the same at injection energy and at 100 GeV for many fills. Since the beam acceleration process is unlikely to increase the beam polarization ($P_{\text{beam}}$), this suggests that $A_N^{\text{CNI}}$ at 100 GeV is no smaller than at the injection energy. So, the data in Fig. 3 assumes that the $A_N$ for the CNI polarimeter at proton beam energy of 100 GeV is the same as measured values at lower energy [24]. Measurements of $\vec{p} + \vec{p}$ elastic scattering using a polarized gas jet target are expected to provide a 10% determination of the beam polarization in RHIC run 4 [25].

The precision of the measurements of forward $\pi^0$ production in $\vec{p} + \vec{p}$ collisions at $\sqrt{s}=200$ GeV is, at present, insufficient to discriminate the various models. Nonetheless, it can be concluded that large analyzing powers persist to high collision energies as anticipated by these models. Furthermore, the particle production appears to be dominated by partonic scattering, as evidenced by the agreement of the cross section with NLO pQCD calculations. It is interesting to note that all of the models were adjusted to fit the E-704 data, but have different $x_F$ dependences at $\sqrt{s} = 200$ GeV. Hence, higher precision measurements may lead to an improved understanding of the dynamics responsible for these spin effects.

More direct measurements, such as correlation of the spin effects with the Collins angle or correlation of the spin effects with a fully reconstructed forward jet, are expected to provide a more definitive method of establishing the dynamical origins of the large analyzing power. To that end, STAR developed and partially installed a Forward $\pi^0$ Detector prior to the start of RHIC run 3, as shown in Fig. 4. Significant data samples were obtained triggering STAR by large energy deposition in the FPD. Those samples will allow study of particle correlations in $\vec{p} + \vec{p}$ and $d + Au$ reactions at $\sqrt{s_{NN}}=200$ GeV. Furthermore, at the RHIC design luminosity, the analyzing power for forward neutral pion production can be employed as a local polarimeter for tuning and monitoring the spin rotator magnets.

## 3 Analyzing Powers for Large Rapidity Charged Particle Production

The STAR beam-beam counters (BBC) are scintillator annuli that span the pseudorapidity interval $2.2 < |\eta| < 5.0$. The annuli are mounted on each poletip of the STAR magnet and are separated by a distance along the beam equal to 7.4 m. Each annulus is tiled by optically isolated hexagonal elements, as shown in Fig. 5. Large tiles cover the smaller $\eta$ range and small tiles the larger $\eta$ range. Two rings of regular hexagonal cells, whose
size is defined by an inscribed circle of diameter 9.6 cm, provide azimuthally symmetric coverage for the interval $3.4 < |\eta| < 5.0$. These small tiles serve as a minimum bias trigger for $p + p$ collisions, a luminosity monitor and a local polarimeter, as described below.

Each BBC phototube provides a summed charge proportional to energy deposition and, for the small tiles, a time of arrival signal. The energy deposition is dominated by the energy loss of high energy charged particles through the 1-cm thickness of plastic scintillator. Collisions between the beams are discriminated from single beam backgrounds using the timing signals. A minimum bias trigger for $p + p$ collisions is derived by requiring at least one hit on both sides of STAR with valid timing. The rate of these events has been calibrated as a luminosity monitor. Measurements of the trigger rate as the two beams are scanned relative to each other determine the beam size. Combining that information with an independent measurement of the number of ions in each ring determines the luminosity [27]. Knowledge of the luminosity then allows a determination of the total cross section observed by the BBC. This cross section is measured to be $26.1 \pm 0.2 \text{(stat.)} \pm 1.8 \text{(syst.)}$ mb [28], corresponding to $87 \pm 8\%$ of the inelastic, non-singly diffractive cross section. This measurement is consistent with simulations based on PYTHIA [20] and GEANT [21].

The simulations provide a good description of the overall detector response, the multiplicity of hits from $p+p$ collisions and the azimuthal and radial distributions of the hits recorded in the minimum bias configuration. The energy deposited on one side of STAR corresponds to, on average, five charged particles passing through the BBC small tile annulus for each $p+p$ collision.

By correlating the azimuthal topology of hits in the BBC with vertical beam polarization, a significant analyzing power is observed for forward particle production at positive $\eta$ (relative to the polarized proton beam). Backward particle production, relative to the polarized proton beam, is observed to have no analyzing power. The azimuthal angle to
associate with a given event is based on the topology of hits. As indicated in Fig. 5, the BBC annulus is divided into quadrants for the analysis. To analyze the vertical component of polarization, the following spin asymmetry ($\epsilon$) is formed:

$$\epsilon = P_{\text{beam}} \times A_N = \frac{\sqrt{(L \cdot R)_\uparrow \times (R \cdot L)_\downarrow} - \sqrt{(L \cdot R)_\downarrow \times (R \cdot L)_\uparrow}}{\sqrt{(L \cdot R)_\uparrow \times (R \cdot L)_\downarrow} + \sqrt{(L \cdot R)_\downarrow \times (R \cdot L)_\uparrow}}.$$  \hspace{1cm} (1)

Based on Fig. 5, Boolean expressions for the symbols are $L=(5+6+14+15+16)$ and $R=(2+3+9+10+11)$, where the numbers refer to a given phototube producing a sufficient pulse to exceed the discriminator threshold for the event. The symbols $\overline{R}(\overline{L})$ refer to the condition of no hits in the corresponding phototubes, imposed to avoid ambiguities in the azimuthal angle to assign to the event. In Eqn. 1, $\uparrow (\downarrow)$ refer to the direction of the polarization of the particular bunch crossing. As described elsewhere [3, 5], polarized proton operation in RHIC involves an injection pattern of bunches with different polarization directions. A similar analysis is applied to the top/bottom quadrants of the BBC.

For purely vertical polarization, these spin dependent asymmetries must be zero. Spin asymmetries from the top/bottom quadrants measure radial polarization components of the beams at the interaction region.

A scaler system [22], that counts at the RHIC bunch-crossing frequency (9.35 MHz), facilitates high-statistics measurements of spin asymmetries with the BBC. During run-3, more than $1 \times 10^{10}$ BBC minimum bias events were recorded by the scaler system with transverse polarization, and a comparable number of events were recorded with longitudinal polarization. Each scaler board has 24 input bits that serve as a memory address to a counter. Seven of the bits are reserved for the identification of the bunch crossing. RHIC can have up to 120 bunch crossings separated by 107 ns. On the scaler board, one bit is reserved for the minimum bias trigger, and the other 16 are driven by the discriminator outputs that establish if individual phototubes of the BBC are above threshold (Fig. 5). The resulting data are analyzed using Eqn. 1, with the spin direction determined from the polarization pattern used to inject beam bunches into RHIC, as identified by the bunch crossing number.

**Figure 5.** The STAR beam-beam counter as seen looking towards the interaction point from outside of the STAR magnet. The large tiles are exactly four times the size as the small tiles. For spin-dependent analyses, the small-tile annulus is divided into nearly equal quadrants, as indicated.
Figure 6. (a) The closed symbols are the raw single spin asymmetries ($P_{\text{beam}} \times A_N$) for charged hadrons produced in the pseudorapidity interval $3.4 < \eta < 5.0$ from polarized proton collisions at $\sqrt{s} = 200$ GeV, shown as a function of time. The time dependence results from variations in the beam polarization. The open symbols are the raw single spin asymmetries measured by the RHIC CNI polarimeter. The dashed line indicates when the STAR spin rotator magnets were turned on. This results in longitudinal polarization at the STAR interaction region, thereby making the spin asymmetry at STAR zero, while the CNI polarimeter results demonstrate the beam remains polarized. (b) Results from top/bottom spin asymmetries from the BBC as a function of time. This demonstrates that the spin rotator magnets stably produce longitudinal polarization at the STAR interaction region.

The magnitude of the analyzing power observed with the BBC for $\vec{p} + \vec{p}$ collisions at $\sqrt{s} = 200$ GeV is approximately half that observed by the CNI polarimeter ($A_N^{\text{CNI}} = 0.013 \pm 0.004$ [26]), as determined by correlations of the spin dependent asymmetry from the BBC with results from the CNI polarimeter from measurements conducted at regular intervals through a RHIC store [21]. The analyzing power is found to have a strong pseudorapidity dependence. When hits are required on only the inner ring of small tiles ($3.9 < \eta < 5.0$), the analyzing power is found to be nonzero. When hits are required on the outer ring of small tiles ($3.4 < \eta < 3.9$), and no hits are present on the inner ring, the analyzing power is found to be zero.

The dynamical origin of the spin effects observed with the BBC is presently unknown. They may be related to the E704 results [7], since, based on simulations, $\pi^\pm$ mesons produced at large Feynman $x$ are expected to be part of the charged particle flux responsible for the hits observed in the BBC, but $x_F$ cannot be measured by this detector. Furthermore, at the largest pseudorapidities, more $\pi^+$ are expected to be produced than $\pi^-$ because of the proton’s valence quark structure. But proving this from the BBC data alone is not possible, because neither the particle’s energy, its charge sign, nor its identity are determined in the measurements. Measurement of the $x_F$ dependence of $A_N$ for charged pions would be of interest and is naturally suited to the Brahm$\text{N}$ spectrometer [29], likely restricted to scattering angles that are larger than those from the BBC.

Even though the dynamics responsible for the spin effects observed with the BBC are not known, the non-zero analyzing power coupled with the rate capabilities of the scaler boards provides for a local polarimeter that has very good statistical figure of merit. At a
luminosity of $5 \times 10^{30}\text{cm}^{-2}\text{sec}^{-1}$ and beam polarization equal to 25%, the direction of the polarization vector for each beam can be established to $10^\circ$ with a statistical accuracy of 3 standard deviations within 30 minutes. This capability proved useful in confirming that the STAR spin rotator magnets were properly tuned to provide longitudinal polarization at the STAR interaction region. Furthermore, this local polarimeter provides a continuous monitor of transverse polarization components, as shown in Fig. 6 during operation with longitudinally polarized beams.

4 Summary of present status and future plans

The first collisions of spin polarized proton beams at $\sqrt{s}=200$ GeV have occurred at RHIC. The STAR experiment has established that the large analyzing powers observed for neutral pion production at $\sqrt{s} = 20$ GeV persist to the higher collision energy. The cross section for large rapidity neutral pion production is found to be in agreement with NLO pQCD calculations, and also leading-order pQCD, supplemented by the parton shower model [20]. In addition, a non-zero analyzing power was observed for inclusive charged particle production in the pseudorapidity interval $3.4 < \eta < 5.0$. This analyzing power has provided STAR with a high figure-of-merit local polarimeter, sensitive to transverse polarization components in the colliding proton beams.

In RHIC run 3, STAR acquired the first data for mid-rapidity jet production with both colliding beams longitudinally polarized. Analysis of this data is underway. In the near-term future, the plan is to acquire a significantly larger inclusive jet data sample, with improved beam polarization. In the longer term, larger luminosity and improved polarization will permit the start of spin observables for direct photon measurements at $\sqrt{s}=200$ GeV. Further runs with transverse polarization are also under consideration.

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