Nuclear dependence of the transverse-single-spin asymmetry for forward neutron production in polarized $p + A$ collisions at $\sqrt{s_{NN}} = 200$ GeV

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During 2015 the Relativistic Heavy Ion Collider (RHIC) provided collisions of transversely polarized protons with Au and Al nuclei for the first time, enabling the exploration of transverse single-spin asymmetries with heavy nuclei. Large single-spin asymmetries in very forward neutron production have been previously observed in transversely polarized $p+p$ collisions at RHIC, and the existing theoretical framework that was successful in describing the single-spin asymmetry in $p+p$ collisions predicts only a moderate atomic-mass-number ($A$) dependence. In contrast, the asymmetries observed at RHIC in $p+A$ collisions showed a surprisingly strong $A$ dependence in inclusive forward neutron production. The observed asymmetry in $p+Al$ collisions is much smaller, while the asymmetry in $p+Au$ collisions is a factor of three larger in absolute value and of opposite sign. The interplay of different neutron production mechanisms is discussed as a possible explanation of the observed $A$ dependence.

Understanding forward particle production in high energy hadron collisions is of great importance, because most of the energy goes in the forward direction, and therefore informs our understanding of overall particle production. This has particular importance in studies at colliders and of ultra-high energy cosmic rays, where the interpretation, including possibly beyond the standard model, requires estimation through modeling of forward particle production [1, 2]. Mechanisms for forward particle production are not well understood, as perturbative quantum chromodynamics (pQCD) is not applicable at small momentum transfers and diffractive production mechanisms are not well modeled. To better understand production mechanisms, measurement of the single spin asymmetry $A_N$, describing the azimuthal asymmetry of particle production relative to the spin direction of the transversely polarized beam or target provides crucial tests and deeper insight beyond just cross-section measurements. The spin degree of freedom has served as a strong discriminator between theoretical models. For example, the origin of the large asymmetries discovered in forward meson production in $p+p$ collisions from $\sqrt{s} = 4.9$–$19.4$ GeV [3–10] and later confirmed at $\sqrt{s} = 62.4$–$500$ GeV at the Relativistic Heavy Ion Collider (RHIC) [11–16] has been under intensive discussion for three decades and still remains an open question [17]. Despite substantial theoretical attempts to reproduce data in the pQCD regime using the conventional $2 \to 2$ parton scattering processes, the latest multiplicity dependent $A_N$ measurements from RHIC [18] indicate that a significant contribution to the asymmetry may be of a diffractive nature.

In this Letter, we report the first measurements in 2015 of $A_N$ for very forward neutron production in collisions between polarized protons and nuclei (Al and Au) at $\sqrt{s_{NN}} = 200$ GeV with the PHENIX detector [28]. The average beam polarization in $p+p$, $p+Al$, and $p+Au$ data samples was $0.515 \pm 0.002$, $0.59 \pm 0.02$, and $0.50 \pm 0.04$, respectively, with additional global uncertainty of 3% from the polarization normalization [29, 30].

The experimental setup using a zero-degree calorimeter (ZDC) [31] and a position-sensitive shower-maximum detector (SMD) is similar to the one used for $p+p$ data [32]. The ZDC comprises three modules located in series at $\pm 18$ m away from the collision point. The ZDC has an acceptance in the transverse plane of $10 \times 10$ cm$^2$, with a total of 5.1 nuclear interaction lengths (or 149 radiation lengths), and an energy resolution of $\sim 25$–$20$% for 50–100 GeV neutrons. The SMD comprises $x$-$y$ (horizontal-vertical) scintillator strip hodoscopes inserted between the first and second ZDC modules (approximately at the position of the maximum hadronic shower), and provides a position resolution of $\sim 1$ cm for 50–100 GeV neutrons. These detectors are located downstream of the RHIC DX beam splitting magnet, so that near beam-momentum charged particles from collisions are expected to be swept into the beam lines and out of the ZDC acceptance (see Fig. 1).

To accommodate asymmetric $p+A$ collisions of beams with different rigidity, the DX magnets were moved horizontally [33]. In this special setup for the present measurement, the proton beam was angled off axis by $\sim 2$ mrad relative to the nominal beam direction at the collision point, with a crossing angle with the Au (Al) beam of 2.0 mrad (1.1 mrad). Correspondingly, the ZDC was moved by 3.6 cm (2 mrad) to keep zero-degree neutrons at the ZDC center (see Fig. 1).

The data was collected with triggers employing the ZDC and beam-beam counters (BBCs) [34]. Only the north ZDC detector, facing the incoming polarized proton beam was used in this analysis. Two BBC counters are located at $\pm 144$ cm from the nominal collision point along the beam pipe and are designed to detect charged particles in the pseudorapidity range of $\pm (3.0$–$3.9)$ with full azimuthal coverage. The ZDC inclusive trigger required the energy deposited in the ZDC to be
greater than 15 GeV. The ZDC⊗BBC-tag trigger in addition required at least one hit in each of the BBCs, and ZDC⊗BBC-veto trigger required no hits in both BBCs. The latter two sets represent mutually exclusive but not complete subsets of the ZDC inclusive triggered data.

As described in detail in Ref. [32], event selection and neutron identification cuts include: (1) a total ZDC energy cut of 40–120 GeV; (2) at least two SMD strips fired (above threshold) in both x and y directions, and a nonzero (above threshold) energy in the second ZDC module (to reject photons); and (3) an acceptance cut of 0.5 < r < 4.0 cm for the reconstructed radial distance r from the determined beam center (to reduce the impact of the position resolution and edge effects in the asymmetry measurements).

The raw asymmetry (ε_N(φ)) is calculated using the square-root formula [32] for each azimuthal angle (φ) bin. The polarization normalized A_N^fit is then extracted from the fit to a sine function

$$\epsilon_N(\phi) = P A_N^{fit} \sin(\phi - \phi_0),$$

where P is the proton beam polarization and φ_0 is the polarization direction in the transverse plane.

The contribution of charged hadron background from hard scattering processes, distributed nearly uniformly over the ZDC acceptance, was estimated using PYTHIA6 [35] with a GEANT3 [36] detector simulation. However, from previous studies where a charge veto counter was installed in front of the ZDC to measure the charged hadron background, it was found that simulation underestimates the proton background by a factor of ~2 [32]. Therefore the hard scattering background contribution from simulation was scaled by a factor of two with an uncertainty equal to the size of the increase. In p+p collisions this background fraction resulted in 6±3%, 3±1.5% and 12±6% in ZDC, ZDC⊗BBC-veto and ZDC⊗BBC-tag triggered samples, respectively. In p+A collisions due to increased neutron signal from electromagnetic (EM) processes (to be discussed later), the relative background contributions are expected to be smaller. Therefore the measured asymmetries in p+A collisions were not corrected for background, but one side systematic uncertainties (in the direction of asymmetry dilution) equal to background fraction plus 1σ uncertainty in the p+p case, i.e. 9%, 4.5% and 18% were conservatively assigned in ZDC, ZDC⊗BBC-veto and ZDC⊗BBC-tag triggered samples, respectively.

From the considerations above, only the p+p asymme-

FIG. 1. ZDC location and beam orbits of proton (blue) beam and heavy-ion (yellow) beam in the special stores used for this analysis; the z-axis shows the nominal beam direction, and the dashed line represents the zero-degree neutron trajectory. DX and D0 are the RHIC beam bending dipole magnets.

FIG. 2. A_N^{fit} fit of ZDC inclusive samples.
tries were corrected for backgrounds according to
\[ A_N^S = \frac{A_N^S \cdot r_{eff} \cdot A_B^B}{1 - r_{eff}} \]
where \( A_N^S \) and \( A_B^B \) stand for signal and background asymmetries, and \( r_{eff} \) is the “effective” background fraction in the reconstructed neutron sample. The parameter \( r_{eff} \) accounts for the dilution of the background effect in \( A_N^S \) in the case when the background contributes preferably on one side of the detector (as from elastic or diffractive protons). The background asymmetry \( A_N^B \) was evaluated from the comparison of asymmetries with and without the charge veto cut from the 2008 data when the charge veto counter was available. The asymmetries \( A_N^B \) were found to be consistent with zero within statistical uncertainties. Asymmetries were corrected for backgrounds according to
\[ A_N = A_N^S \cdot r_{eff} \cdot A_B^B \]
where \( A_N \) is the fully corrected transverse single spin asymmetry calculated as
\[ A_N = \frac{N(\phi) - N(\phi^*)}{N(\phi) + N(\phi^*)} \]

Besides charged hadrons, the other background sources are photons and \( K^0 \) mesons. From PYTHIA6 simulation their contribution after the analysis cuts was evaluated to be below 3% in all collision systems and triggers, and was neglected in the asymmetry results.

The measured asymmetries are affected by detector resolutions and other detector systematic effects (e.g. edge effects), as well as by the uncertainty in the shape of the neutron production cross section vs \( p_T \) and \( x_F \), and the assumption for the shape of \( A_N(p_T) \) within the \( p_T \) range sampled in this analysis. These effects were studied in detail with a GEANT3 Monte Carlo simulation. The fully corrected transverse single spin asymmetry \( A_N \) was calculated as \( A_N = A_N^S / C_\phi \) where the correction factor \( C_\phi \) was calculated in the simulation as the ratio of the measured asymmetry to the average input asymmetry over the neutron sample collected with experimental cuts used in the analysis. The biggest variation in \( C_\phi \) comes from the position resolution uncertainty and the assumption for \( A_N(p_T) \). The position resolution in the simulation was varied by changing noise and thresholds in the SMD channels, as well as by introducing a cross talk effect, similar to [32]. An overall value of 3% was assigned to the \( C_\phi \) uncertainty. For the shape of \( A_N(p_T) \), it was modeled as \( A_N(p_T) = \text{const} \) (as was assumed in [32]) and \( A_N(p_T) \propto p_T \) (which is supported by theory [26]).

The difference of 3% was included in the \( C_\phi \) uncertainty. The final correction factor applied to the measured asymmetries is \( C_\phi = 0.855 \pm 0.036 \).

The analyzed data correspond to the neutron sampled \( p_T \) in the range smaller than 0.25 GeV/c peaked at about 0.1 GeV/c, which is affected by detector resolutions. Due to the varying contribution of different processes to neutron production, the sampled \( p_T \) distribution may vary in different collision systems and in different triggered data. Figure 3 shows the differences in the radial distributions, which is related to the neutron production cross section \( d\sigma/dp_T \) by \( p_T \propto r \) [32]. From a comparison with simulation assuming different slope parameter, \( b \), in the parameterization \( d\sigma/dp_T \sim e^{-b \cdot p_T} \), the data were found to be consistent with \( b = 4 \) (GeV/c)^{-1} for all collision systems in ZDC\textcircled{B}BBC-tag triggered data, and \( b = 4 \), 6 and 8 (GeV/c)^{-1} in \( p+p \), \( p+Al \) and \( p+Au \) collisions, respectively, in ZDC\textcircled{B}BBC-veto triggered sample, with uncertainty \( \sigma_b = 1 \) (GeV/c)^{-1} reflecting its sensitivity to SMD gain calibration and thresholds. These variations lead to a difference in the average \( p_T \) sampled in different collision systems and triggers by as much as 10%.

Figure 4 and Table I summarize the results for \( A_N \) in forward neutron production in \( p+p \), \( p+Al \) and \( p+Au \) collisions, for ZDC inclusive, ZDC\textcircled{B}BBC-tag and ZDC\textcircled{B}BBC-veto samples. In addition to the beam polarization, background, and smearing correction \( (C_\phi) \) discussed above, the other sources of systematic uncertainties are the ZDC and SMD gain calibrations (including SMD threshold variation) and location of the beam center on the SMD plane.

From Fig. 4, the \( A \) dependence of \( A_N \) for inclusive neutrons is strong. Compared to the \( A_N \) of \( p+p \) collisions, the observed asymmetry in \( p+Al \) collisions is much smaller, while the asymmetry in \( p+Au \) collisions is a factor of three larger in absolute value and of opposite sign. This behavior is unexpected because the theoretical framework using \( \pi \) and \( a_1 \)-Reggeon interference can only predict a moderate nuclear dependence, and there is no known mechanism to flip the sign of \( A_N \) within this framework [27].

The asymmetries requiring BBC hits are remarkably different. Once BBC hits are required (ZDC\textcircled{B}BBC-tag), the drastic behavior of the inclusive \( A_N \) vanishes and its sign stays negative, approaching \( A_N = 0 \) at large \( A \). In contrast, the strong \( A \) dependence is amplified once no hits in the BBC are required (ZDC\textcircled{B}BBC-veto). While the BBCs cover a limited acceptance, the requirement (or veto) of hits in the BBC should place constraints on the activity near the detected neutron and thus the corresponding production mechanism.
TABLE I. \(A_N\) for forward neutron production in \(p+p\), \(p+Al\), and \(p+Au\) collisions, for ZDC inclusive, ZDC\&BBC-tag, and ZDC\&BBC-veto samples.

| Systematic error: | Inclusive | \(p+p\) | BBC Tag | BBC Veto | Inclusive | \(p+Al\) | BBC Tag | BBC Veto | Inclusive | \(p+Au\) | BBC Tag | BBC Veto |
|-------------------|-----------|---------|---------|---------|-----------|---------|---------|---------|-----------|---------|---------|---------|
| Background        | ±0.0069   | ±0.0091 | ±0.0170 | +0.0012 | +0.0102  | -0.0036 | -0.0145 | +0.0027 | -0.0115   | ±0.0044 | ±0.0097 | ±0.0084 |
| Smearing          | ±0.0023   | ±0.0027 | ±0.0013 | +0.0005 | +0.0024  | +0.0031 | +0.0066 | +0.0036 | +0.0099   | ±0.0042 | ±0.0039 | ±0.0084 |
| Beam pos.         | ±0.0086   | ±0.0062 | ±0.0097 | ±0.0040 | ±0.0038  | ±0.0060 | ±0.0023 | ±0.0036 | +0.0084   | ±0.0013 | ±0.0097 | ±0.0024 |
| Polarization      | ±0.0004   | ±0.0005 | ±0.0007 | ±0.0005 | ±0.0022  | ±0.0028 | ±0.0112 | ±0.0012 | +0.0016   | ±0.0019 | ±0.0097 | ±0.0024 |
| Calibration       | ±0.0027   | ±0.0010 | ±0.0067 | ±0.0012 | ±0.0042  | ±0.0042 | ±0.0042 | ±0.0085 | ±0.0002   | ±0.0020 | ±0.0094 | ±0.0249 |
| Total systematic  | ±0.0116   | ±0.0114 | ±0.0208 | -0.0043 | -0.0065  | -0.0091 | -0.0201 | -0.0094 | -0.0249   | ±0.0044 | ±0.0097 | ±0.0249 |

According to a Monte-Carlo study [45], the neutron and its associated \(\pi^+\) produced through this process are substantially boosted towards the proton beam direction, so that only a small fraction of pions would be detected by the BBC. Thus, a large fraction of EM processes are expected to be suppressed in the ZDC\&BBC-tag events while enhanced in the ZDC\&BBC-veto events. Here, it is noted that the importance of EM processes in \(p+A\) collisions is also hinted at in the present data: the ratio between reconstructed neutrons in ZDC\&BBC-veto and ZDC\&BBC-tag samples increases from smaller than 0.5 in \(p+p\) to \(\sim 1\) (\(\sim 5\)) in \(p+Al\) (\(p+Au\)) collisions. In addition, a faster drop of the neutron production cross section with \(p_T\) in \(p+A\) collisions in ZDC\&BBC-veto triggered data discussed in Fig. 3b is consistent with increasing role of EM processes that have softer \(p_T\) distribution than hadronic processes.

Similarly in the asymmetry measurements, contributions of different production mechanisms may be suppressed or enhanced by different event selection triggers. Hence, while the result for the ZDC\&BBC-tag sample may be explained by the conventional pion and \(a_1\)–Reggeon interference mechanism [27], that for the ZDC\&BBC-veto triggered sample could be explained by contributions from interference with EM amplitudes which are expected to be enhanced in that dataset. However, the strengths of these interference contributions are not known, and there could be other mechanisms, such as diffractive scattering, which is also expected to be enhanced by a ZDC\&BBC-veto trigger. Therefore, further studies are needed to fully understand the present results.

In summary, we observe an unexpectedly strong \(A\) dependence in \(A_N\) of inclusive forward neutron production in polarized \(p+A\) collisions at \(\sqrt{s_{NN}} = 200\) GeV. Furthermore, a distinctly different behavior of \(A_N\) was observed in two oppositely trigger-enhanced data sets. These surprising behaviors could be explained by a contribution of EM interactions, which may be sizable for heavy nuclei. Further studies of the production mechanisms including EM contributions and diffractive scattering would have an impact not only to hadron physics, but also to cosmic-ray science, where measurements of high-energy cosmic rays depend on models of forward particle production.

![FIG. 4](image-url) Forward neutron \(A_N\) in \(p+A\) collisions for \(A = 1\) (\(p\)), 27 (\(Al\)) and 197 (\(Au\)), for ZDC inclusive, ZDC\&BBC-tag and ZDC\&BBC-veto triggered samples; color bars are systematic uncertainties, statistical uncertainties are smaller than the marker size. Data points are shifted horizontally for better visibility.

One possibility to explain the present results is a contribution from EM interactions, which have been demonstrated to be important for reactions with small momentum transfer, e.g., in ultra-peripheral heavy ion collision at RHIC [37–40] and Large Hadron Collider [41–44], including forward neutron production in \(p+A\) collisions [45], and polarization observables in fixed target experiments [46, 47]. Although it was ignored in the interpretation for the \(p+p\) data [27], EM interactions become increasingly important for large atomic number (\(Z\)) nuclei, as the EM field of the nucleus is a rich source of virtual photons, increasing as \(Z^2\). Forward neutrons in the final state can be produced through nonresonant photo-\(\pi^+\) production and neutron decay channel from photo-nucleon excitation processes, such as the \(\Delta\) resonance.
production in the interactions with nuclei in the air.

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