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Single spin asymmetries of forward neutron production in polarized $p+p$ and p+A collisions at $\sqrt{s_{NN}} = 200$ GeV

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We studied single spin asymmetry (A_N) of forward neutron production in the PHENIX experiment using a transversely polarized proton beam. In 2015, we took data for p+A collisions for the first time with Au and Al beams at $\sqrt{s_{NN}} = 200$ GeV and observed a surprising A dependence. As a possible mechanism to explain the observed A dependence, we make a speculative discussion on the contribution of the electromagnetic interaction.

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1. Introduction

In high-energy hadron collisions, most energy goes into the forward region. However, particle production mechanisms in the forward region are not well understood as perturbative QCD is not applicable at small momentum transfers. In the case of neutron production in proton-proton collisions, production cross sections were discussed in terms of one pion exchange (OPE). For example, Nikolaev *et al.* [1] successfully explained the forward neutron data from the ISR experiment [2, 3] with a dominant OPE contribution plus small contributions from ρ, a_2 exchange and two-step processes.

We are interested in single-spin left-right asymmetry (A_N), which is sensitive to neutron production mechanism. Since A_N is caused by an interference between spin flip, which is dominant in OPE, and spin non-flip amplitudes, we can study minor spin non-flip amplitudes by looking at A_N. For example, if there is a mechanism that gives a spin non-flip amplitude as small as 10% of the spin-flip amplitude, it is hardly seen in the cross-section, which shows only a 1% effect, while A_N can be as large as an order of 10%, which is rather easy to measure.

A large A_N for very forward neutrons was first discovered at RHIC in transversely polarized proton+proton collisions at $\sqrt{s} = 200$ GeV [4, 5]. The magnitude of observed A_N was of order 10%, which was unexpectedly large. The predicted asymmetry with an OPE model was very small, and it was necessary to include a_1 Reggeon exchange in addition to OPE in order to explain the experimental data [6].

In this article, we report preliminary measurements of forward neutron A_N in collisions of transversely polarized protons with (unpolarized) nuclei (Al and Au) at $\sqrt{s_{NN}} = 200$ GeV with the PHENIX detector. Our interests are mass number (A) dependence of forward neutron A_N. Naively, the π and a_1-Reggeon exchange model predicts a rather small A dependence, while it could be quite different if there is another mechanism.

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2. Experimental Setup

In 2015, the first attempt was successfully made to collide transversely polarized protons with nuclei (Al and Au), in addition to $p+p$, in RHIC at $\sqrt{s_{NN}} = 200$ GeV. The experimental setup for very forward neutron measurements at the PHENIX experiment is in principle the same for $p+p$ collisions, as schematically shown in Figure 1.

Neutrons were measured by a Zero-Degree Calorimeter (ZDC) with a position-sensitive Shower-Max Detector (SMD) [7]. The ZDC is composed of copper-tungsten alloy absorbers with optical fibers and each module has 1.7 interaction length (λ_I). A photomultiplier collects Cherenkov lights via the optical fibers in each module. Three ZDCs are located in series (5.1 λ_I in total) at ± 1800 cm away from the collision point within the small acceptance, covering 10 cm in the trasverse plane. SMD consists of *x*-*y* scintillator strip hodoscopes and is inserted between the first and second ZDC modules at the position of maximum hadronic shower approximately. The *x*-coordinate (horizontal) is sampled by 7 scintillator strips of 15 mm width, while the *y*-coordinate (vertical) is sampled by 8 strips of 20 mm width, tilted by 45 degrees. These detectors are located downstream of the RHIC-DX magnet so that charged particles from collisions are expected to be bent away.

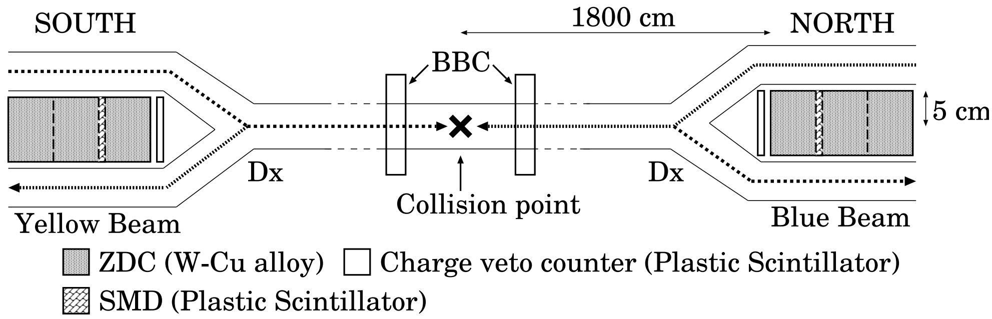

Figure 1: A plan view of the experimental setup at PHENIX (not to scale). Principle components for the leading neutron measurement are shown.

A forward scintillation counter, covering 10×12 cm^2, is installed in front of the ZDC to further remove charged particle backgrounds.

Neutron position was reconstructed by the energy deposit in SMD scintillators with the centeroid method. The position resolutions were estimated by a simulation to be around 1 cm for the neutron energy at 100 GeV. The reliability of the position measurement was checked by comparing hadron shower shapes of the real and simulation data. Then, based on the obtained position and neutron energy (E_n), p_T was calculated as $p_T = E_n \sin\theta_n \sim E_n r/d$, where θ_n is the reaction angle, r is the distance from the beam center to the hit position at ZDC, and $d = 1800$ cm is the distance from the collision point to the ZDC. The single-spin asymmetry, A_N, was calculated using the square-root-formula. Smearing due to finite position resolution and finite acceptance was corrected for using simulations. More details about the setup and analysis procedures can be found in the previous paper for $p+p$ collisions [5].

3. Results and Discussions

Figure 2 shows the preliminary result for inclusive neutrons. The result shows surprising A dependence: A_N for p-Au is about 3 times larger in amplitude and the sign even flips, though there is no known mechanism to flip the sign within the existing framework.

Another interesting result is obtained for events with out-going charged particles within the acceptance of Beam-Beam Counters (BBCs, see also Fig. 1) which covers $3.1 < |\eta| < 3.9$ being either tagged or vetoed (Fig. 3). The results are drastically different from that for inclusive neutrons; when BBC hits are required (BBC tagging) in both arms (green data points), the drastic behavior of inclusive A_N is vanished and no sign change is observed between $p+p$ and p+Au. On the contrary, the asymmetries are pushed even more upward for p+Al and p+Au when BBC-veto is required (blue data points).

The BBC tagged/vetoed results give a hint for the mechanism of such a significant A dependence. Namely, large positive A_N is seen only when BBCs have no hits, implying that the reacting proton and nuclei are not badly broken. Diffractive processes have such a feature, but simple diffractive processes are common to $p+p$ and p+A, and so it is difficult to explain the observed A dependence.

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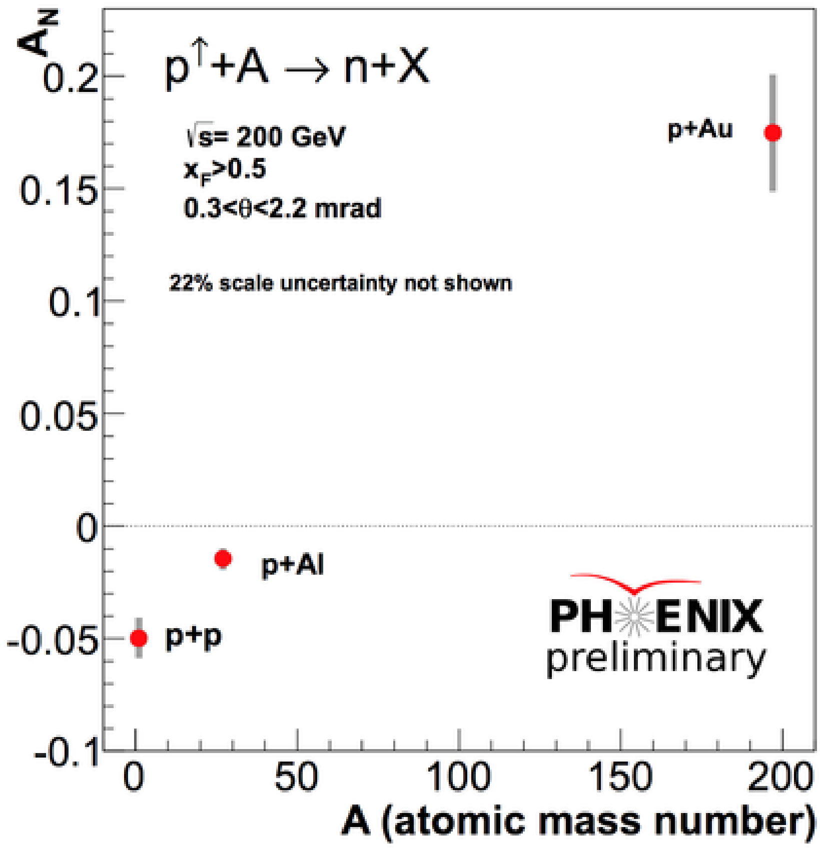

Figure 2: Preliminary result for A_N of inclusive neutron.

Mass dependence may come from processes involving the electro-magnetic (EM) interaction. Especially γ^* exchange and Reggeon exchange can interfere, and such intereference may give a positive A_N. Since γ^* exchange amplitude is proportional to Z, this process can give the observed large A dependence. Also, since the EM interaction is important mostly at low p_T, most of the charged particles produced by the EM process (ultraperipheral collision) do not hit BBC, and hence this hypothesis gives a consistent behavior with the BBC-tagged/vetoed data. (Here, it should be noted that such γ^* exchange cannot interfere with charged pion (and other charged Reggeon) exchange, which is dominant for forward neutron production in $p+p$ collision.)

In order to further study the hypothesis, we are trying to obtain the production cross section, especially in small p_T region. If γ^* exchange gives a significant contribution, an enhancement of production cross section due to ultraperipheral collisions, whose cross section is proportional to Z^2, must be observed in small p_T region. Also, the p_T dependence of A_N is important. On the theoretical side, it should be studied whether γ^*-Reggeon exchange intereference can indeed produce positive A_N. In addition, since other mechanisms are still possible, such ideas are very much welcome.

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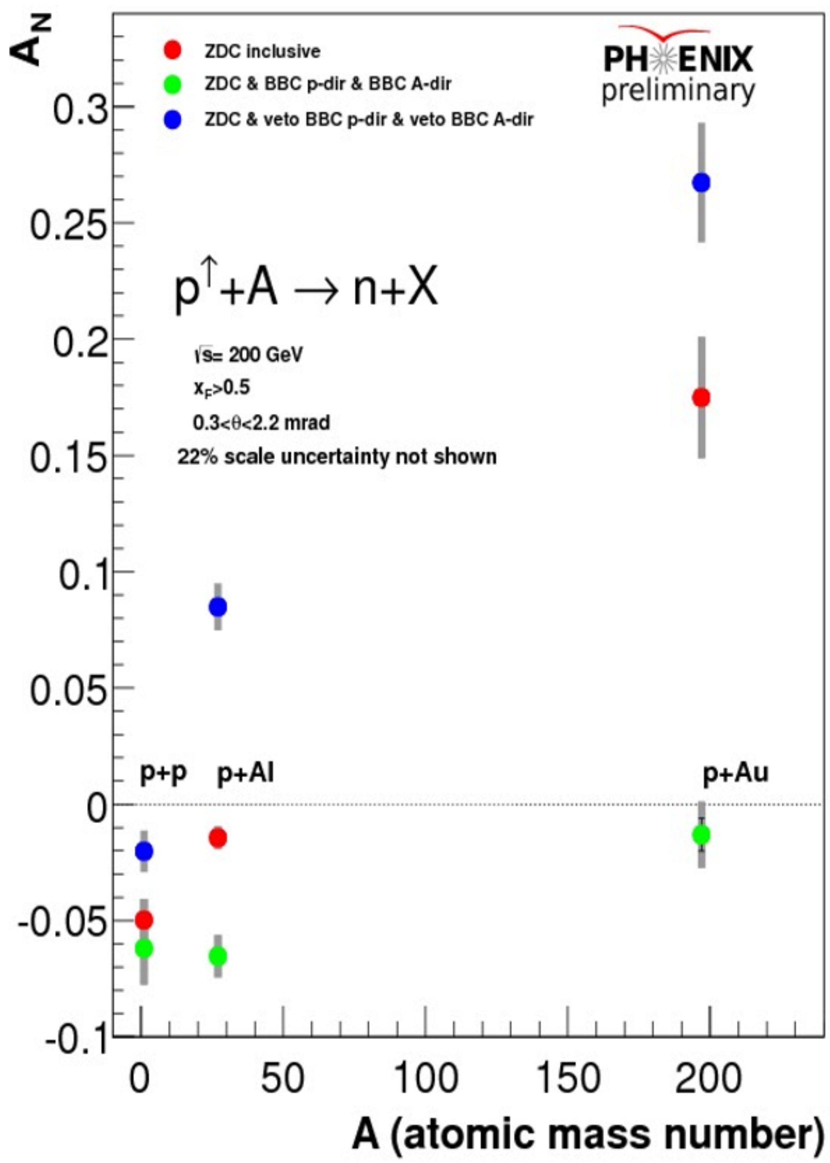

Figure 3: Preliminary result for A_N of neutrons with BBC tagging (green) or vetoing (blue). A_N of inclusive neutron are shown in red.

4. Summary

We have observed surprisingly strong A dependence in the A_N of forward neutron production in proton-nucleus collisions at $\sqrt{s_{NN}} = 200$ GeV. Such a drastic A dependence was not expected, but BBC tagged or vetoed data may give a hint to elucidate the mechanism for the A dependence. We have a hypothesis that electro-magnetic effects may play a key role bacause the amplitude is proportional to Z and the electro-magnetic processes are suppressed in BBC tagged events while it is enhanced in BBC vetoed events.

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