PROCEEDINGS OF SCIENCE

Disentangling transverse single spin asymmetries for very forward neutrons in polarized p-A collisions using ultra-peripheral collisions

Gaku Mitsuka[*†]
RIKEN
2-1 Hirosawa, Wako, Saitama 351-0198, Japan
E-mail: gaku.mitsuka@riken.jp

We discuss the transverse single spin asymmetries A_{N} for very forward neutrons measured by the PHENIX zero-degree calorimeters (ZDCs) in high-energy polarized proton–nucleus (pA) collisions at Relativistic Heavy Ion Collider (RHIC). The ZDCs cover the psudorapidity range of $6.8 < \eta < 8.8$ where the neutron emission angle with respect to the incident proton direction is limited to less than 2.2 mrad. First-ever pA data taken in the RHIC-2015 run exhibit positive and remarkably large $A_{\mathrm{N}} \sim 0.18$ only in pAu collisions whereas nearly zero A_{N} in pAl collisions. In this proceeding, to explain such A_{N} in pA collisions we present an important but rather unknown mechanism: ultra-peripheral pA collisions (UPCs, also known as Primakoff effects). UPCs lead to very large A_{N} of about 0.35 and have cross sections proportional to Z^2 of the nuclei. UPCs contribute to inclusively measured A_{N} modestly in pAl collisions and significantly in pAu collisions. We show that the Monte Carlo simulations incorporating both a one-pion exchange (OPE) and UPCs, where virtual photon–polarized proton interactions follow the MAID 2007 isobar model, successfully describe the PHENIX data in pAl and pAu collisions simultaneously.

25th International Workshop on Deep Inelastic Scattering and Related Topics
3-7 April 2017
University of Birmingham, Birmingham, UK

[*] Speaker.
[†] for the PHENIX Collaboration

PoS(DIS2017)240

1. Introduction

To understand high-energy hadronic interactions, one needs to investigate forward particle production in inelastic interactions since most of the incident energy is carried by the leading particles into the forward direction. Understanding forward particle production is of great importance as well from high-energy cosmic ray observation point of view. Extraction of the cosmic ray energy and composition from air shower measurements inevitably depends on models of forward particle production in the interaction with nuclei in the Earth's atmosphere [1]. To investigate particle production mechanisms, one can utilize the single spin asymmetry $A_{\rm N}$, namely the azimuthal asymmetry of particle production relative to the spin direction of the transversely polarized beam or target. The spin degree of freedom serves as a strong discriminator between theoretical models.

In this proceedings, we discuss the first measurements of $A_{\rm N}$ for very forward neutrons in pA collisions at $\sqrt{s_{\rm NN}} = 200\,{\rm GeV}$ recorded in 2015 with the PHENIX ZDC detector, and an explaination of these $A_{\rm N}$ by a OPE model and UPCs.

2. Experimental data taking conditions

In pp collisions 18 RHIC stores were used and 1 store was used in pAl and pAu collisions. The average beam polarization in pp, pAl, and pAu collisions was 0.515 ± 0.002, 0.59 ± 0.02 and 0.59 ± 0.04, respectively, with an additional global uncertainty of 3% from the polarization normalization.

A ZDC and a position-sensitive shower-maximum detector (SMD) are used for the experimental data taking for the study in this proceedings. The ZDC comprises three modules located in series at $\pm 18\,{\rm m}$ away from the collision point. One ZDC module is composed of Cu-W alloy absorbers with PMMA-based communication grade optical fibers. A single photomultiplier collects Čerenkov light via optical fibers. The ZDC has an acceptance in the transverse plane of $10 \times 10\,{\rm cm}^2$, with a total of 5.1 nuclear interaction lengths corresponding to 149 radiation lengths, and an energy resolution of $\sim 25-20\%$ for $50-100\,{\rm GeV}$ neutrons. The SMD comprises horizontal-vertical scintillator strip hodoscopes inserted between the first and second ZDC modules (equivalent to the position where a hadronic shower develops maximumly), and provides a position resolution of $\sim 1\,{\rm cm}$ for $50-100\,{\rm GeV}$ neutrons. The trajectories of charged particles produced at the collision point and directed towards the ZDC are deflected by the RHIC DX beam splitting magnet before reaching the ZDC itself.

The data was collected with triggers employing the ZDC and beam-beam counters (BBCs). Only the ZDC facing the incoming polarized proton beam was used in this analysis. Two BBCs, for detecting charged particles in the pseudorapidity range of $\pm(3.0-3.9)$ with full azimuthal coverage, are located at $\pm 144\,{\rm cm}$ from the collision point along the beam pipe. The *ZDC inclusive trigger* is issued when the energy deposited in the ZDC is greater than $15\,{\rm GeV}$. The *ZDC*$\otimes$*BBC-tag trigger* additionally requires at least one hit in each of the BBCs, and *ZDC*$\otimes$*BBC-veto trigger* requires no hits in both the BBCs.

The following event selections and neutron identification cuts are used in the analysis: (1) a total ZDC energy cut of $40-120\,{\rm GeV}$; (2) at least two SMD strips fired in both the horizontal and vertical directions, and a nonzero energy in the second ZDC module (to reject a photon-induced electromagnetic shower); and (3) an acceptance cut of $0.5 < r < 4.0$ cm for the reconstructed radial distance r from the determined beam center to avoid the impact of the position resolution in the asymmetry measurements. More details on the data taking conditions and event selections are found in Ref. [3].

3. Results

Figure 1 summarizes the measured $A_{\rm N}$ for very forward neutrons in pp, pAl and pAu collisions, for ZDC inclusive (filled red circles), ZDC⊗BBC-tag (filled green squares) and ZDC⊗BBC-veto (filled blue triangles) data samples. The presented asymmetries $A_{\rm N} \sim -0.05$ in pp collisions are consistent with our previous publication [2]. Larger systematic uncertainties in this analysis compared with the previous ones are understood by the substantial background contribution (a charged veto suppressed the background contribution in the previous study [2]), and variations due to uncertainty of the beam position on the ZDC plane.

From Fig. 1, $A_{\rm N}$ for inclusive neutrons strongly depends on A and accordingly Z. The observed asymmetry in pAl collisions is much smaller ~ -0.02, while the asymmetry in pAu collisions is positive and a factor three larger in absolute value than in pp collisions. The asymmetries measured with the ZDC⊗BBC-tag trigger indicate the reduced A-dependence and approaching $A_{\rm N} = 0$ at large A with its sign staying negative. In contrast, the asymmetries measured with the ZDC⊗BBC-veto trigger show the strongest A-dependence.

The requirement (or veto) of hits in the BBCs should enhance (or suppress) the events with the activity near the detected neutron.

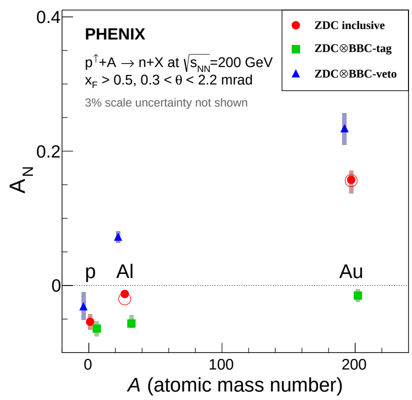

Figure 1: Transverse single-spin asymmetry $A_{\rm N}$ for very forward neutrons (PHENIX Preliminary).

4. Discussions

Comparisons among these new results in pp, pAl, and pAu collisions raise the following question: what mechanisms do produce such a large $A_{\rm N}$ in only pAu collisions and smaller or close to zero $A_{\rm N}$ in other collisions? One attempt is a OPE model considering the interference of pion exchange (spin flip) and a_1-Reggeon exchange (spin nonflip) [4]. The OPE model well explains

$A_{\rm N}$ in pp collisions [2] and can be extended to pA collisions by taking into account strong nuclear absorption correction as well as nuclear breakup. However, according to the recent theoretical study [5], the predicted $A_{\rm N}$ by the extended OPE model is far smaller than the PHENIX data in pAu collisions and stays its sign negative.

Here we present important but rather unknown effects of UPCs. UPCs contribute to the measured $A_{\rm N}$ modestly in pAl collisions and significantly in pAu collisions. UPCs occur when the impact parameter b is larger than the sum of the radii of each colliding particle, namely $b > R_p + R_A$ (R_p and R_A are the radii of the proton and nucleus, respectively). In UPCs, virtual photons (γ^*) emitted from the relativistic nucleus interact with the polarized protons and then produce the neutrons and other particles.

The differential cross section for single pion and neutron production, dominant among many other channels, in UPCs is given by

$$\frac{d\sigma^4_{{\rm UPC}(p{\rm A}\to\pi^+n)}}{dW\,db^2\,d\Omega_n} = \frac{d^3N_{\gamma^*}}{dW\,db^2}\frac{d\sigma_{\gamma^*p\to\pi^+n}(W)}{d\Omega_n}\overline{P_{\rm had}}(b), \tag{4.1}$$

where $d^3N_{\gamma^*}/dW\,db^2$ is the double differential photon flux due to the fast-moving nucleus, W is the $\gamma^* p$ center-of-mass energy, $d\Omega_n = \sin\Theta\, d\Theta\, d\Phi$ with the neutron scattering polar angle Θ and azimuthal angle Φ in the $\gamma^* p$ center-of-mass frame, and $\overline{P_{\rm had}}(b)$ is the probability of having no hadronic interactions in pA collisions at a given b. Single neutron and pion productions from the $\gamma^* p$ interaction are simulated following the differential cross sections predicted by the MAID 2007 model [6]. The cross section of the $\gamma^* p \to \pi^+ n$ interaction is approximated as

$$\frac{d\sigma_{\gamma^*p\to\pi^+n}}{d\Omega_\pi} \propto R_T^{00}\left(1 + \cos\Phi\frac{R_T^{0y}}{R_T^{00}}\right), \tag{4.2}$$

where R_T^{00} and R_T^{0y} are the response functions for pion photoproduction. $A_{\rm N}$ for forward neutrons in UPCs (hereafter $A_{\rm N}^{\rm UPC}$) inherits the target asymmetry $T(\pi - \Theta) \equiv R_T^{0y}/R_T^{00}$ in Eq. (4.2), which is ~ 0.7 at $W < 1.3\,{\rm GeV}$ and ~ -0.2 at $W > 1.3\,{\rm GeV}$ within the ZDC acceptance. Owing to the virtual photon flux leading to low-energy photons and the pion photoproduction cross section via a $\Delta(1232)$ resonance, UPCs accordingly provide $A_{\rm N}^{\rm UPC} \sim 0.35$ for forward neutrons.

Figure 2 (a) shows the differential cross sections in pAu collisions as a function of the Feynman-x, namely, $d\sigma/dx_{\rm F}$, for UPCs (dashed red line) and OPE (solid black line). UPCs dominate in $d\sigma/dx_{\rm F}$ at $x_{\rm F} > 0.6$ and have a sharp peak around $x_{\rm F} = 0.95$. Detailed discussion for the other features is found in Ref. [7].

Figure 2 (b) shows the differential cross section in pAu collisions, $d\sigma/d\Phi$, as a function of Φ, for UPCs (dashed red line) and OPE (solid black line). Here we find that UPCs have a positive and large $A_{\rm N}^{\rm UPC}$ compared with $A_{\rm N}^{\rm OPE} = -0.05$ of hadronic interactions. Those for pAl collisions are presented in the panels (c) and (d).

Now we turn to Fig. 1. Filled red circles indicate $A_{\rm N}$ inclusively measured by the ZDC. These $A_{\rm N}$ values can be compared with open red circles that correspond to the sum of UPCs and OPE MC simulations, denoted as $A_{\rm N}^{\rm UPC+OPE}$ and calculated as

$$A_{\rm N}^{\rm UPC+OPE} = \frac{\sigma_{\rm UPC}A_{\rm N}^{\rm UPC} + \sigma_{\rm OPE}A_{\rm N}^{\rm OPE}}{\sigma_{\rm UPC} + \sigma_{\rm OPE}}, \tag{4.3}$$

where σ_{UPC} and σ_{OPE} are the cross sections of UPCs and OPE, respectively. In pAu collisions, since $\sigma_{\mathrm{UPC}} \simeq \sigma_{\mathrm{OPE}}$, we obtain $A_{\mathrm{N}}^{\mathrm{UPC+OPE}} = 0.16$, which is consistent with the PHENIX result. Consistency between our simulation result $A_{\mathrm{N}}^{\mathrm{UPC+OPE}} = -0.02$ and the PHENIX data is also found in pAl collisions, where σ_{UPC} is 8 % of σ_{OPE}.

For the other triggers, the requirement (or veto) of hits in the BBCs effectively reduces the σ_{UPC} (or σ_{OPE}), and thus results in small (or large) A_{N}.

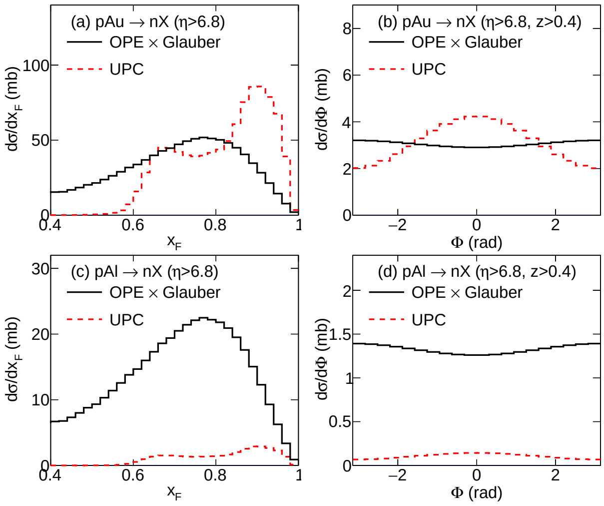

Figure 2: Differential cross sections of UPCs and hadronic interactions as a function of x_{F} and Φ [7].

5. Conclusions

We presented the transverse single spin asymmetries A_{N} for very forward neutrons measured by the PHENIX ZDC in high-energy pA collisions at RHIC. First-ever pA data taken in the RHIC-2015 run exhibited positive and remarkably large $A_{\mathrm{N}} \sim 0.18$ only in pAu collisions whereas nearly zero A_{N} in pAl collisions. The ZDC inclusive data in pAl and pAu collisions were successfully described by the mixture of the OPE and UPCs. The data taken with the BBC-related triggers can be also qualitatively understood by such mixture but effectively modified cross sections of each interaction.

References

[1] O. Adriani et al. (LHCf Collaboration), Phys. Rev. D **94**, 032007 (2016).

[2] A. Adare et al. (PHENIX Collaboration), Phys. Rev. D **88**, 032006 (2013).

[3] C. Aidala et al. (PHENIX Collaboration), arXiv:1703.10941.

[4] B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt, Phys. Rev. D **84**, 114012 (2011).

[5] B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt, AIP Conf. Proc. 1819, 050002 (2017).

[6] D. Drechsel, S. S. Kamalov, and L. Tiator, Eur. Phys. J. A **34**, 64 (2007).

[7] G. Mitsuka, Phys. Rev. C **95**, 044908 (2017).