Disentangling transverse single spin asymmetries for forward neutrons in high-energy polarized-proton–nucleus collisions

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It is reported from the PHENIX experiment at BNL-RHIC that the transverse single spin asymmetry, denoted as A_{N}, for forward neutrons measured in transversely polarized-proton–nucleus (pA) collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ is far different from that in proton–proton (pp) collisions at $\sqrt{s} = 200\,\mathrm{GeV}$[1)] (see panel (b) of Fig. 1.)

In this report, I present an important but rather unknown mechanism: ultra-peripheral pA collisions (UPCs, also known as Primakoff effects). UPCs contribute to the measured A_{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 radius 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

$$\frac{d\sigma^4_{\mathrm{UPC}(pA\to\pi^+n)}}{dW\,db^2\,d\Omega_n} = \frac{d^3N_{\gamma^*}}{dW\,db^2}\frac{d\sigma_{\gamma^*p\to\pi^+n}(W)}{d\Omega_n}\overline{P_{\mathrm{had}}}(b), \qquad (1)$$

where $d^3N_{\gamma^*}/d\omega^{rest}_{\gamma^*}db^2$ is the double differential photon flux due to the fast-moving nucleus, W is the γ^*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 γ^*p center-of-mass frame, and $\overline{P_{\mathrm{had}}}(b)$ is the probability of having no hadronic interactions in pA collisions at a given b. Single neutron and pion productions from the γ^*p interaction are simulated following the differential cross sections predicted by the MAID 2007 model.[2)] The cross section of the $\gamma^*p \to \pi^+n$ interaction is approximated as

$$\frac{d\sigma_{\gamma^*p\to\pi^+n}}{d\Omega_\pi} \propto R_T^{00}\left(1+\cos\Phi\frac{R_T^{0y}}{R_T^{00}}\right), \qquad (2)$$

where R_T^{00} and R_T^{0y} are the response functions for pion photoproduction. A_{N} for forward neutrons in UPCs (hereafter $A_{\mathrm{N}}^{\mathrm{UPC}}$) inherits the target asymmetry $T(\pi-\Theta) \equiv R_T^{0y}/R_T^{00}$ in Eq. (2), which is ~ 0.7 at $W < 1.3\,\mathrm{GeV}$ and ~ -0.2 at $W > 1.3\,\mathrm{GeV}$ within the PHENIX detector 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 $A_{\mathrm{N}}^{\mathrm{UPC}} \sim 0.35$ for forward neutrons.

Figure 1 (a) shows the differential cross section in pAu collisions, $d\sigma/d\Phi$, as a function of Φ, for UPCs (dashed red line) and a one-pion exchange model (OPE) that represents hadronic interactions occuring at $b < R_p + R_A$ (solid black line). A_{N} originating in OPE well explains the PHENIX result in pp collisions but does not in pA collisions. In this study, the Glauber multiple scattering model is applied to OPE to account for nuclear effects. Here we find that UPCs have a positive and large $A_{\mathrm{N}}^{\mathrm{UPC}}$ compared with $A_{\mathrm{N}}^{\mathrm{OPE}} = -0.05$ of hadronic interactions.

In Fig. 1 (b), filled black circles indicate A_{N} inclusively measured by the PHENIX zero-degree calorimeter[1)]. These A_{N} values can be compared with open red circles that correspond to the sum of UPCs and OPE MC simulations, denoted as $A_{\mathrm{N}}^{\mathrm{UPC+OPE}}$ and calculated as

$$A_{\mathrm{N}}^{\mathrm{UPC+OPE}} = \frac{\sigma_{\mathrm{UPC}}A_{\mathrm{N}}^{\mathrm{UPC}} + \sigma_{\mathrm{OPE}}A_{\mathrm{N}}^{\mathrm{OPE}}}{\sigma_{\mathrm{UPC}} + \sigma_{\mathrm{OPE}}}, \qquad (3)$$

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}.

In the MC simulations discussed in this report, electromagnetic effects (UPCs) and hadronic effects (OPE) are taken into account independently. However, the interference between these two effects, called the Coulomb-nuclear interference, would have nonzero amplitudes in the very small momentum-transfer region. The imprementation of the Coulomb-nuclear interference will be a topic of future investigation.

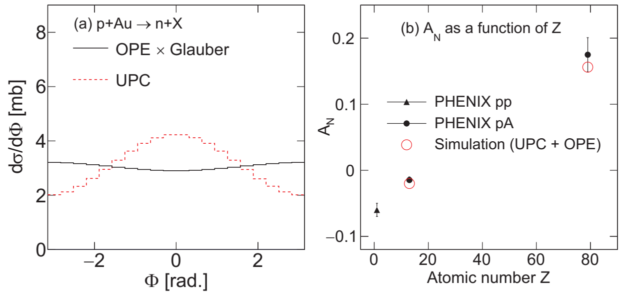

Fig. 1. Left: $d\sigma/d\Phi$ distributions for UPCs and OPE. Right: Comparison of A_{N} as a function of Z.

References

1) I. Nakagawa et al. (PHENIX Collaboration), J. Phys. Conf. Ser. **736**, 012017 (2016).
2) D. Drechsel, S. S. Kamalov, L. Tiator, Eur. Phys. J. A **34**, 64 (2007).

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