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

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Outline

1. Introduction and Physics motivation
   • Large $A_N$ for forward neutrons discovered in pAu collisions
   • Can electromagnetic effects explain positive and large $A_N$?
2. Ultra-peripheral collisions (UPCs)
   • Do $\gamma^*p$ interactions have large $A_N$?
   • MC simulations of $\gamma^*p$ interactions
3. MC simulation results
   • UPCs vs. hadronic interactions
   • MC simulations vs. the PHENIX measurements
4. Summary and Future prospects
1. Introduction and Physics motivations

**Single spin asymmetry \( A_N \) for very forward neutrons in \( pp \)**

\( A_N \) in \( pp \) at the RHIC energies are well explained by an one-Reggeon exchange model with the interference between \( \pi \) (spin flip) and \( a_1 \) (nonflip).

Kopeliovich et al.
PRD. 84.114012 (2011)

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**Single spin asymmetry \( A_N \) for very forward neutrons in \( pA \)**

Can \( A_N \) in \( pA \) be successfully explained by the \( \pi \)-\( a_1 \) interference? or by other mechanisms?

→ understand forward neutron production in \( pA \)
1.1 Transversely polarized pA collisions

**Run15 pAl/pAu collisions**
Dedicated run for $A_N$ measurements
Average pol. $\sim 0.5$–0.6
(syst. uncertainty $\sim 3\%$)

- ZDC (Zero Degree Calorimeter): hadron calorimeter with a 10 x 10 cm$^2$ area ($\Delta E/E \sim 20$–$30\%$)
- SMD (Shower Max Detector): X-Y plastic scintillator hodoscope ($\Delta x, \Delta y \sim 1$ cm)
- Charge veto counter: plastic scintillator pad at front

18 m from IP, 10 cm x 10 cm ($E > 6$)

$\eta > 6.8$
1.2 *Inclusive* $A_N$ for forward neutrons

**Prediction before the measurement:**

weak $A$-dependence  
(Reggeon exc. and/or nuclear effects)

Surprisingly strong $A$-dependence  
→ what mechanisms do produce such strong $A$-dependence?  
→ *hint: how does $A_N$ behave with the other triggers?*
1.3 **BBC correlated** $A_N$ for forward neutrons

PHENIX, arXiv:1703.10941

$A_N$ as a function of atomic mass number $A$ for different nuclei (p, Al, Au).

- **ZDC inclusive**
- **ZDC$\otimes$BBC-tag**
- **ZDC$\otimes$BBC-veto**

$p^\uparrow + A \rightarrow n + X$ at $\sqrt{s_{NN}}=200$ GeV

$x_F > 0.5$, $0.3 < \theta < 2.2$ mrad

3% scale uncertainty not shown

Particle veto at lower rapidities: **BBC-VETO**

→ much stronger A-dependence

Particle hits at lower rapidities: **BBC-TAG**

→ weak A-dependence
1.3 **BBC correlated** $A_N$ for forward neutrons

**PHENIX, arXiv:1703.10941**

- **Particle veto at lower rapidities:** *BBC VETO*
  - Large $A_N$ when fewer underlying particles
  - Small $A_N$ when ample underlying particles
  - Do not only hadronic interactions but also electromagnetic interactions play a crucial role in pA?

- **Particle hits at lower rapidities:** *BBC HIT*
  - Much stronger A-dependence
  - Weak A-dependence

**Graph:**
- $p^{\uparrow} + A \rightarrow n + X$ at $\sqrt{s_{NN}} = 200$ GeV
- $x_F > 0.5$, $0.3 < \theta < 2.2$ mrad
- 3% scale uncertainty not shown

**Legend:**
- Red circle: ZDC inclusive
- Green square: ZDC$\otimes$BBC-tag
- Blue triangle: ZDC$\otimes$BBC-veto

**A (atomic mass number)**

**$A_N$**

- **p**
- **Al**
- **Au**
2. Ultra-peripheral collisions (UPCs)

**UPCs (aka Primakoff effects):**
- A collision of a proton with the EM field made by a relativistic nucleus when the impact parameter $b$ is larger than $R_A + R_p$
- Fewer underlying particles unlike in hadronic interactions → smaller activity at BBC

**UPC cross section**

$$\frac{d\sigma_{UPC}(p^+ A \rightarrow \pi^+ n)}{dW \, db^2 \, d\Omega_n} = \frac{d^3 N_{\gamma^*}}{dW \, db^2} \frac{d\sigma_{\gamma^* p^+ \rightarrow \pi^+ n (W)}}{d\Omega_n} \frac{P_{had}(b)}{}$$
2.1 Do $\gamma^*p$ interactions have large $A_N$?

Polarized $\gamma^*p$ cross sections

\[
\frac{d\sigma_{\gamma^*p \to \pi+n}}{d\Omega_\pi} = \frac{|q|}{\omega_{\gamma^*}} \left( R_T^{00} + P_y R_T^{0y} \right)
\]

Equivalent to $A_N$

\[
= \frac{|q|}{\omega_{\gamma^*}} R_T^{00} (1 + P_2 \cos \phi_T T(\theta_\pi))
\]

$T(\theta_\pi)$ is decomposed into multipoles:

\[ T(\theta_\pi) \equiv \frac{R_T^{0y}}{R_T^{00}} \propto \text{Im} \{ E^*_{0+} (E_{1+} - M_{1+}) \}
\]

Interference between $E_{0+}$ and $M_{1+}$ leads to large $T(\theta_\pi)$ in the $\Delta(1232)$ region

MC simulations of the polarized $\gamma^*p$ interactions are developed for testing $T(\theta_\pi)$, i.e. $A_N$ in pA collisions.
2.2 MC simulations for $\gamma^*p$ interactions

- MC simulations based on the MAID2007 model (Drechsel et al. EPJ A 34, 69 (2007)) are performed for $R_{T00}$ and $T(\theta_\pi)$.
- $T(\theta_\pi) \sim 0.8$ at $\Delta(1232)$, $\sim -0.5$ at $N(1680) \rightarrow$ large $A_N$!!

$\gamma^*p$ center-of-mass system

- transversely polarized proton along 2-axis
- Numerical data from MAID 2007 ($Q^2 = 0, \theta_\pi = 90$ degree)

$R_{T00}$

$R_{T00}^{0}/R_{T00} = T(\theta_\pi)$

[Diagram showing $\gamma^*p$ interactions with Au beam and ZDC]
2.2 MC simulations for γ*p interactions

- MC simulations based on the MAID2007 model (Drechsel et al. EPJ A 34, 69 (2007)) are performed for $R_{T00}^0$ and $T(\theta_\pi)$.
- $T(\theta_\pi) \sim 0.8$ at $\Delta(1232)$, $\sim 0.5$ at $N(1680) \rightarrow$ large $A_N$!!

**γ*p center-of-mass system**

- transversely polarized proton along 2-axis
- Au beam (γ*)
- neutron
- $\pi^+$
- scattering plane
- reaction plane
- $\gamma^*$
- $k$
- $q$
- $x$
- $2$
- $1$
- $\phi_\pi$
- $\theta_\pi$
- $p$
- proton
- $\pi^+$
- $\phi_\pi$
- $\theta_\pi$
- reaction plane
- ZDC
- proton beam
- $\theta_\pi$
- $\pi^+$
- $W$ (GeV)
- $R_{T00}^\gamma/R_{T00}^0 = T(\theta_\pi)$
- Solid curves indicate the ZDC acceptance.
- $T(\theta_\pi)$ with the weight of $\gamma^*$ flux = $A_N$
3.1 UPCs vs. hadronic interactions

- Neutron cross section in pAu UPCs ($\propto Z^2$) is comparable with hadronic interactions, while $\sigma_{\text{UPC}} \sim \sigma_{\text{HAD}} \times 0.1$ in pAl.
- UPC-induced $A_N$ is positive and large in both pAl and pAu.

Expected $X_F$ and $\Phi$ distributions for forward neutrons in pAu

(a) pAu $\rightarrow$ nX ($\eta > 6.8$)
- OPE $\times$ Glauber
- UPC

(OPE is based on Kopeliovich et al. arXiv:1702.07708)

(b) pAu $\rightarrow$ nX ($\eta > 6.8$, $z > 0.4$)

Positive and large $A_N$ in UPCs

Negative and small $A_N$ in hadronic interactions
3.2 MC sim. vs. the PHENIX measurements

- PHENIX measurements are well explained by the sum of UPCs and hadronic interactions.
- BBC-veto can be reasonably understood by the enhanced UPC fraction.

The subtraction of UPCs (sys.~10%) from the PHENIX measurements enables discussions on
- nuclear effects
- Coulomb-Nuclear Interference

PHENIX, arXiv:1703.10941
GM, arXiv:1702.03834
4. Summary and Future prospects

• Large $A_N$ for forward neutrons in polarized $pAu$ collisions and its $A$-dependence are discovered by PHENIX.

• To compared with the PHENIX data, we developed the MC simulations involving UPCs and hadronic interactions in polarized $pA$ collisions.

• UPCs has large $A_N$ and the cross section is proportional to $Z^2$.

• Simulation results well explain the PHENIX inclusive measurements.
  → Large $A_N$ in $pAu$ collisions originates in UPCs.

• **Future prospects**: $p_T$- and $X_F$-dependent $A_N$ is under analysis
  - detailed understanding in UPCs  → reduction of UPC sys. errors.
  - UPC subtracted $A_N$ in $pA$ enables (almost) model-independent discussion on hadronic contribution to $A_N$. 


Backup
UPC formalism

The UPC cross section is factorized as

\[
\frac{d\sigma_{\text{UPC}(p^\dagger A \to \pi^+ n)}}{dW \, db^2 \, d\Omega_n} = \frac{d^3 N_{\gamma^*}}{dW \, db^2} \frac{d\sigma_{\gamma^* p^\dagger \to \pi^+ n}(W)}{d\Omega_n} P_{\text{had}}(b)
\]

- photon flux (\(N\)): quasi-real photons produced by a relativistic nucleus
- \(\sigma_{\gamma^* p \to x}\): inclusive cross sections of \(\gamma + p\) interactions
- \(P_{\text{had}}\): a probability not having a p+A hadronic interaction.

- \(P_{\text{had}}\) is calculated by using a Glauber MC simulation.
- UPCs occur only if the impact parameter \(b\) is larger than the sum of radii \(R_p\) and \(R_A\).
- \(P_{\text{had}}(b)\) distribution is important not only for the cross section but also for the energy distribution.
Virtual photon flux

The number of virtual photons per energy and $b$ is formulated by the Weizsacker-Williams approximation or QED (Phys. Rep 364 359 ‘02, NPA 442 739 ‘85, etc…):

$$
\frac{d^3 N_{\gamma^*}}{d\omega_{\gamma^*} \, db^2} = \frac{Z^2 \alpha}{\pi^2} \frac{x^2}{\omega_{\gamma^*} b^2} \left( K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x) \right)
$$

where $x = \omega_{\gamma^*} b / \gamma$ and $\omega_{\gamma^*}$ is the virtual photon energy in the proton rest frame. Note that the virtual photon flux depends on the charge of photon source as $Z^2$.

- From the virtual photon flux, we see that low-energy photons dominate UPCs.

$$\sqrt{s} = 200 \text{ GeV}$$

Phenomenological parameter: $Q^2 < \frac{1}{R^2}$. So, $Q^2 < 10^{-3} \text{ GeV}^2$
Only 1π channel is simulated in this study. It is hard to simulate neutron momenta in 2π channels (future study?).
UPC cross sections as a function of $W$

![Graph showing UPC cross sections as a function of $W$]

\[
\frac{d\sigma_{\text{UPC}}(p^A \rightarrow n^+)}{dW\,db^2\,d\Omega_n} = \frac{d^3 N_{\gamma^*}}{dW\,db^2} \frac{d\sigma_{\gamma^* p^A \rightarrow n^+ n}(W)}{d\Omega_n} P_{\text{had}}(b)
\]

- 2π channels are anyway subdominant in UPCs.
- Table I and II show the total cross sections in UPCs and hadronic interactions.

<table>
<thead>
<tr>
<th>UPCs</th>
<th>Hadronic interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p^A$Al</td>
<td>$p^A$Au</td>
</tr>
<tr>
<td>0.7 mb (2.2 mb)</td>
<td>19.6 mb (41.7 mb)</td>
</tr>
</tbody>
</table>

| $p^A$Au $\rightarrow nX$ ($\eta > 6.9$ and $z > 0.4$) | $p^A$Au $\rightarrow \pi^+ \pi^0 n$ |
|---------|---------|----------------|
| $< 1.1\text{ GeV}$ | $1.1$–$2.0\text{ GeV}$ | $> 2.0\text{ GeV}$ | $1.25$–$2.0\text{ GeV}$ |
| 0.6 mb | 27.4 mb | 1.8 mb | 6.2 mb |

**TABLE I.** Cross sections for neutron production in ultraperipheral collisions and hadronic interactions at $\sqrt{s_{\text{NN}}}$ = 200 GeV. Cross sections in parentheses are calculated without $\eta$ and $z$ limits.

**TABLE II.** Cross sections in ultraperipheral $p$Au collisions at $\sqrt{s_{\text{NN}}}$ = 200 GeV.
Target asymmetry as a function of $W$

Osaka-Argonne

z axis: $T(\theta)$

MAID 2007
**Hadronic interactions (one-π exchange)**

\[
\begin{align*}
N & \ 
\pi & \ 
q & \ 
p & \uparrow \\
X & \ 
\frac{d\sigma_{pp\to nX}}{dz dp_T^2} & = & \frac{S^2}{8} \left( \frac{\alpha'_\pi}{8} \right)^2 \frac{t}{|G_{\pi+pn}^2(t)|^2} \\
 & \times & (1-z)^{1-2\alpha_\pi(t)} \sigma_{\pi+pn}^{tot}(M_X^2), \\
 & = & \frac{d\sigma_{p\uparrow A\to nX}}{dz dp_T^2} \left( 1 + \cos \Phi A_{N\pi\pi}(pA) \right) \\
 & = & \frac{d\sigma_{pp\to nX}}{dz dp_T^2} A^{0.42} \left( 1 + \cos \Phi A_{N\pi\pi}(pA) \right)
\end{align*}
\]

- Kopeliovich et al. propose an interference between π and \(a_1\)-Reggeon leading to negative asymmetry in p-p and p-A.
- In this study, due to a technical difficulty, I omit an implementation of the interference. Alternatively, I apply \((1+\cos\Phi A)\) to the differential cross section of unpolarized proton and then effectively obtain the differential cross section of polarized proton.
- The coupling \(G_{\pi+pn}\) is chosen so that the calculated \(d\sigma/dz\) gives the best-fit to the PHENIX result.
Hadron distributions are observed in experiments with the absorption of a pion from p+p collisions. The single-spin asymmetry on a nuclear target due to the reaction $pA \rightarrow nX$ is related to the parameter $A_N$. The factor $A_{N}^{pA \rightarrow nX}$ depends on how the measurements were motivated in detail in [14, 18, 19], discussed in the context of the second Weinberg sum rule, where the spectral functions coupling was evaluated in [14], based on PCAC and the results of our calculations, presented in figure 4, reproduce either both BBCs fired, or only one of them in the nuclear direction, respectively [20–22]. An analysis of neutrons produced on nuclear targets is a very weak factor $A_{N}^{pA \rightarrow nX}$.

$A_{N}^{pA \rightarrow nX} = A_{N}^{pp \rightarrow nX} \times \frac{R_{1}}{R_{2}} R_{3}$

The parameter-free calculations of Kopeliovich et al. arXiv:1702.07708 agree well with the PHENIX data [15, 16]. The trajectory of the trajectory $A_{N}$ in accordance with (12) and (14) is determined by Eqs. (4) - (6) and (17) $(17)$.$\left.<\frac{dE_{\pi}^{2}}{dt}\right>_{\pi A} = 0$ $(17)$.