The First Transverse Single Spin Measurement in High Energy Polarized Proton-Nucleus Collision at the PHENIX experiment at RHIC

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Abstract. Large single spin asymmetries in very forward neutron production seen using the PHENIX zero-degree calorimeters are a long established feature of transversely polarized proton-proton collisions at RHIC. Neutron production near zero degrees is well described by the one-pion exchange framework. The absorptive correction to the OPE generates the asymmetry as a consequence of a phase shift between the spin flip and non-spin flip amplitudes. However, the amplitude predicted by the OPE is too small to explain the large observed asymmetries. A model introducing interference of pion and $\alpha_1$-Reggeon exchanges has been successful in reproducing the experimental data. During the RHIC experiment in year 2015, RHIC delivered polarized proton collisions with Au and Al nuclei for the first time, enabling the exploration of the mechanism of transverse single-spin asymmetries with nuclear collisions. The observed asymmetries showed surprisingly strong A-dependence in the inclusive forward neutron production, while the existing framework which was successful in p+p only predicts moderate A-dependence. Thus the observed data are absolutely unexpected and unpredicted. In this report, experimental and theoretical efforts are discussed to disentangle the observed A-dependence using somewhat semi-inclusive type measurements and Monte-Carlo study, respectively.

1. Single Spin Asymmetry of Forward Neutron Production in p+p
The single spin asymmetry of very forward (almost zero degree) was first discovered\cite{1} at RHIC in transversely polarized proton+proton collision at $\sqrt{s} = 200$ GeV. Neutrons were measured by a zero-degree calorimeter (ZDC)\cite{2} with a position-sensitive shower-maximum detector (SMD). One ZDC module is composed of Cu-W alloy absorbers with PMMA-based communication grade optical fibers and corresponds to 1.7 nuclear interaction lengths. A single photomultiplier collects Cherenkov light via optical fibers. Three ZDC modules are located in series (5.1 nuclear interaction lengths) at 1800 cm away from the collision point, covering 10 cm in the transverse plane.

The detector covers the pseudo-rapidity range of $6.8 \leq \eta \leq 8.8$ where the neutron emission angle with respect to the incident proton direction is limited to less than 2.2 mrad. Relatively large energy neutrons are selected in the analysis, i.e. the neutron energy cut was applied at the energy fraction of incident proton $x_F = E_n/E_p \geq 0.4$. The production mechanism of the such a neutron is driven by soft process and of which cross section is well described by one pion exchange (OPE) model. The corresponding four momentum transfer can be defined $0.02 \leq -t \leq 0.5$ (GeV/c)$^2$ at under the assumption of OPE.
The single spin asymmetries for such a forward neutron turned out to be large as shown in Fig. 1 plotted as a function of transverse momentum $p_T$ of detected neutron. The data points are measured at three different collision energies of 64, 200, and 500GeV, respectively. The data demonstrate the absolute amplitude of the asymmetries grow as a function of $p_T$. Although the OPE model was quite successful to reproduce the cross section data, the predicted asymmetry within the OPE framework appeared to be very tiny and far underestimates the data[3]. The forward neutron asymmetry is formulated as

$$A_N = \phi_{\text{flip}} \phi_{\text{non-flip}} \sin \delta$$ (1)

where $\phi_{\text{flip}}$ ($\phi_{\text{non-flip}}$) is spin flip (spin non-flip) amplitude between incident proton and outgoing neutron, and $\delta$ is the relative phase between these two amplitudes. Although the OPE can contribute to both spin flip and non-flip amplitudes, resulting $A_N$ is small due to the small relative phase. The decent amplitude can be generated only by introducing the interference between spin flip $\pi$ exchange and spin non-flip $a_1$-Reggeon exchange which has large phase shift in between[3]. So calculated $A_N$ are compared with data points in Fig. 1 and are in good agreement with data.

**Figure 1.** The forward neutron asymmetries observed p+p collision system at three different collision energies 64, 200, and 500GeV plotted as a function of transverse momentum $p_T$. The data points are well reproduced by the model calculations assumes the interference between $\pi$ and $a_1$-Reggeon[3].

2. **New Forward Neutron Asymmetries in p+A**

In year 2015, the first attempt was made to collide the transversely polarized proton and nucleus in RHIC at $\sqrt{s} = 200$ GeV. In order to explore the evolving origin of the asymmetry as a function of atomic mass number (A), the forward (p-going side) neutron asymmetries were measured for p+Au and p+Al collisions. Since the proton beam is unpolarized at LHC, the measurement is the high energy frontier of the polarized proton and nucleus collision. The existing polarized proton+nucleus experiments are carried out in one order of magnitude lower $\sqrt{s}$, for instance, at RHIC[5] and Fermi Lab.[4] using polarized proton beam and fixed nuclear targets.
The asymmetry analysis basically followed the same procedures and conditions as previous p+p measurements. The measurement in p+p collision system was repeated in year 2015 and resulting asymmetry was consistent with previous measurements. The ZDC acceptance was segmented into eight azimuthal bins and evaluated left-right raw asymmetries $\epsilon^{\text{raw}}_N$ defined by the Eqn. (2) in the each bin independently.

$$\epsilon^{\text{raw}}_N(\phi) = \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

where $N^+(\phi)$ and $N^-(\phi)$ are number of neutrons observed in the given azimuthal $\phi$ bin when protons are polarized up and down, respectively.

The observed $\phi$ dependent asymmetries normalized by the proton polarization $P$ are plotted in Fig. 3 as a function of $\phi$. The $\phi = 0$ is set by the polarization direction of the proton. The analyzing power $A_N$ is evaluated by fitting the data with a sine function:

$$\frac{\epsilon^{\text{exp}}_N(\phi)}{P} = A_N \sin(\phi - \phi_0)$$

where $\phi_0$ allows a deviation of the maximum asymmetry axis from vertical.

**Figure 2.** (Observed azimuthal angular modulations of the inclusive forward neutron production in p+p (left), p+Al (middle) and p+Au (right) collisions in year 2015.

Fig.3 shows preliminary results of forward neutron $A_N$ measurements in 2015. The red points are the results of forward neutron $A_N$ inclusive measurements. Surprisingly, they show unexpectedly strong mass number (A) dependence. The asymmetry even flips the sign from p+p, p+Al to p+Au. The p+Au data point shows magnificently large $A_N$ of about 0.18 which is three times larger than that of p+p in absolute amplitude. The existing $\pi$ and $a_1$-Reggeon interference framework predicts only moderate evolution as growing A and does not have any mechanism to flip the sign of $A_N$ in any p+A collision systems.

More interestingly, another drastic dependence of $A_N$ was observed in correlation measurements in addition to the inclusive neutron. In these measurements, another out-going
Figure 3. (Observed forward neutron $A^N_n$ in transversely polarized proton-nucleus collisions. Data points are $A=1$, $A=27$, and $A=197$ are results of $p+p$, $p+Al$, and $p+Au$, respectively. Red, Blue and Green data points are neutron inclusive, neutron + BBC veto, and BBC tagged events, respectively)

charged particle was either tagged or vetoed within the acceptance of the beam-beam counter (BBC) in both North and South arms which covers $3.1 \leq |\eta| \leq 3.9$. The BBCs cover such a limited acceptance, but the resulting asymmetries behaved remarkably contradicts. Once BBC hits (BBC tagging) are required in both arms (green data points), the drastic behavior of inclusive $A_N$ is vanished and no flipping sign was observed between $p+p$ and $p+Au$. On the contrary, the asymmetries are pushed even more positive for $p+Al$ and $p+Au$ data points once no hits in BBC are required (BBC vetoed) as represented by blue data points.

3. Ultra-Peripheral Collision Effects
It was pointed out the importance of the electro-magnetic (EM) interaction effect in the existing fixed target experiments [4] and [5], which were carried out in small $t$, one may need to consider the effect here, although it was ignored in $p+p$ data. Due to the smallness of the four momentum transfers of the present kinematics, i.e. $-t \leq 0.5 \ (GeV/c)^2$, the EM interaction may play a role which becomes increasingly important in large atomic number nucleus. The EM field of the nucleus becomes rich source of exchanging photons between the polarized proton. This is known as the ultra-peripheral collision (UPC) in heavy ion collider experiments. In the UPC process,
there is no charge exchange at the collision vertex unlike $\pi$ or $a_1$ meson exchange. The forward neutron in the final state then can be produced through the diagrams shown in Fig. 4.

![Feynman diagrams of UPC process to leave the high-z neutron in the final state to the proton going directions.](image)

Figure 4. Feynman diagrams of UPC process to leave the high-z neutron in the final state to the proton going directions. (a) threshold photo pion production (b) $\Delta$ or $N^*$ excitation and its decay into $n+\pi^+$ channel.

The description of $A_N$ is thus extended from Eqn. (1) to Eqn. 5, which includes not only hadronic but also EM amplitudes:

\[
A_N = \phi_{\text{had flip}}^\text{had} \sin \delta_1 + \phi_{\text{had non-flip}}^\text{had} \sin \delta_2 + \phi_{\text{EM flip}}^\text{EM} \sin \delta_3 + \phi_{\text{EM non-flip}}^\text{EM} \sin \delta_4
\]

where 'EM' and 'had' stand for electromagnetic and hadronic interactions, and $\delta_1 \sim \delta_4$ are relative phases, respectively. The second and the third terms are known as Coulomb nuclear interference (CNI), which is observed to cause $< 5\%$ asymmetry of elastic scattering in p + p, and p + C processes [5].

According to MC study [6], the neutron and its counterpart $\pi^+$ via UPC process is substantially boosted towards the proton beam direction and therefore the fragmenting $\pi^+$ are mostly emitted in even higher rapidity region than BBC. Only small fraction of $\pi^+$ are detected by BBC. Thus EM processes are suppressed in the BBC tagging events while enhanced in the BBC vetoed events. As a consequence, one may draw a hypothesis that the moderate $A_N$ evolution of the BBC tagging data is consistent with the prediction based on $\pi$ and $a_1$-Reggeon interference scenario because the data are dominated by the hadronic amplitude. Although it is not trivial to predicts the sign of the $A_N$ caused by EM amplitude, the observed growing feature of $A_N$ for BBC vetoed events makes sense if EM amplitude guides to opposite sign of hadronic interactions at least qualitatively. Nevertheless it is not known at all at this moment why EM should have opposite sign nor should have such a large amplitude or large relative phases between hadronic/EM spin-flip and spin-nonflip amplitudes to produce such the large asymmetries. It remains mystery.

4. Summary

We have observed surprisingly strong $A$-dependence in the forward neutron asymmetry in transversely polarized proton-nucleus collision at $\sqrt{s}=200\text{GeV}$ in PHENIX using ZDC detector. Such a drastic $A$-dependence in the forward neutron asymmetry $A_N$ is absolutely unexpected within the current framework although it was successful in reproducing the $A_N$ data in p+p. Another drastic dependence has been observed in the semi-inclusive measurements by requiring both North and South BBCs $3.1 < \mid \eta \mid < 3.9$ to be fired or not-fired in addition to forward neutron. The EM effect may play key role to disentangle these drastic behavior because 1) its amplitude grows as a function of atomic number Z, and 2) the fraction of EM process events are suppressed in BBC fired events while enhanced in BBC vetoed events. Further experimental dependency study is now underway by segmenting $p_T$ into multiple bins.
References

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