Transverse Single Spin Asymmetry of Forward Neutron Production in p+A using Fixed Targets at STAR

RHICf Collaboration

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1 Motivation

1.1 Single Spin Asymmetry of Forward Neutron Production in p+p

The single spin asymmetry of very forward (almost zero degree) was first discovered[1] at RHIC in transversely polarized proton+proton collision at $\sqrt{s} = 200$ GeV. The magnitude of observed asymmetry of the neutron which has the energy fraction of incident proton $z = E_{\rm n}/E_{\rm p} \geq 0.4$ was several percent. This asymmetry was unexpectedly large. 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. However the predicted asymmetry within the OPE framework appeared to be very tiny and far underestimated the data[2]. The forward neutron asymmetry is formulated as

$$A_{\rm N} = \phi_{\rm flip}\phi_{\rm non-flip}\sin\delta \tag{1}$$

where $\phi_{\rm flip}$ ($\phi_{\rm non-flip}$) is spin flip (non-flip) amplitude between incident proton and out-going neutron, and δ is the relative phase between these two amplitudes. Although the OPE can contribute to both spin flip and non-flip amplitudes, resulting $A_{\rm N}$ is small due to the small relative phase. The several percent amplitude was produced only by introducing the interference between spin flip π exchange and spin non-flip a_1-Reggeon exchange which has large phase shift in between. Shown in Fig. 1 are observed forward neutron asymmetries in three different collision energies 64, 200, and 500GeV and plotted as a function of transverse momentum p_{T} of detected neutron. The data demonstrate the absolute amplitude of the asymmetries grow as a function of p_{T}. These data are well reproduced by the model calculations[2].

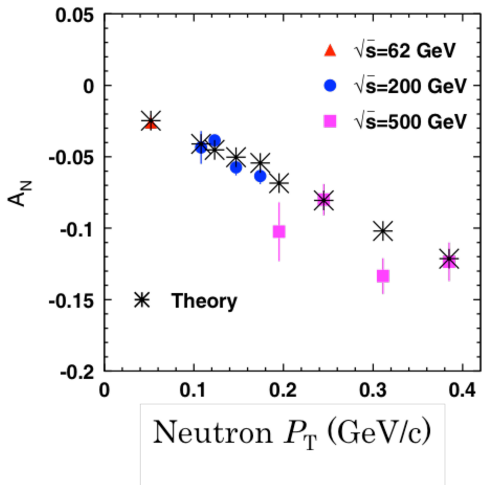

Figure 1: The forward neutron asymmetries observed in three different collision energies 64, 200, and 500GeV plotted as a function of transverse momentum p_{T}. The data points are well reproduced by the model calculations assumes the interference between π and a_1-Reggeon[2].

1.2 Run15 Forward Neutron Asymmetries in p+A

In Run15, the first attempt was made to collide the 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) of opponent particle of the transversely polarized proton, the forward (p-going side) neutron asymmetries were measured for p+Au and p+Al collisions. The same detector Zero-Degree-Counter (ZDC) was used to detect out-going neutrons as the p+p measurement before.

Fig.2 shows preliminary results of forward neutron A_{N} measurements in Run15. The red points are the results of forward neutron A_{N} inclusive measurements. Surprisingly, they show unexpectedly strong mass number (A) dependence while the existing π and a_1-Reggeon interference framework predicts quite minor evolution as growing A. The asymmetry even flips the sign from p+p to p+Au though, there is no known mechanism to flip the sign within the existing framework. Further more the existing framework predicts vanishing amplitude rather moderately as growing A, while p+Au data point shows factor of 3 larger than that of p+p in absolute amplitude.

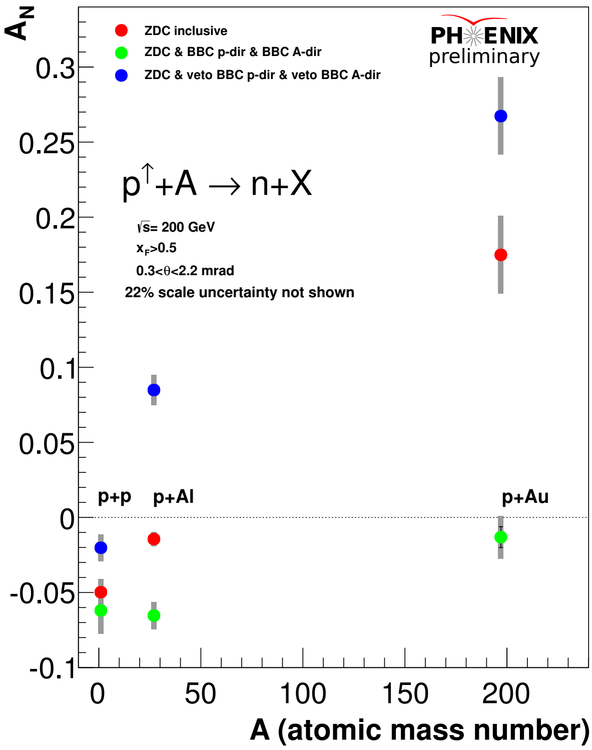

Figure 2: (Observed forward neutron AN in transversely polarized proton-nucleus collisions. Data points are A=1, A=27, and A=197 are results of p+p, p+Al, and p+Au, respectively. Red, Blue and Green data points are neutron inclusive, neutron + BBC veto, and BBC tagged events, respectively

More interestingly, another drastic dependence of $A_{\rm N}$ was observed in semi-inclusive measurements. In this measurements, another out-going charged particle was either tagged or vetoed within the acceptance of the beam-beam counter (BBC) in both North and South arms which covers $3.9 < |\eta| < 3.1$.

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.

1.3 Ultra-Peripheral Collision Effects

There is one possible effect which can be ignored in p+p collision but can play a rather significant role in p+A. Due to the smallness of the four momentum transfers of the reaction, i.e. $-t < 0.5(GeV/c)^2$, electro-magnetic (EM) interaction may play a role which becomes increasingly important in large atomic number nucleus. The electro-magnetic field of the nucleus becomes rich source of exchanging photons between the polarized proton. This is known as the ultra-peripheral collision (UPC) of hadron-hadron collider experiments. Unlike neither π nor a_1 hadronic exchange, there is no charge exchange at the collision vertex in UPC. The forward neutron in the final state can be produced via diagrams shown in Fig. 3

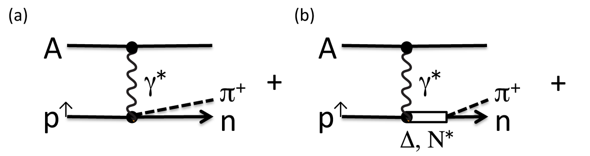

Figure 3: Feynman diagrams of UPC process to leave the high-z neutron in the final state to the proton going directions. (a) threshold photo pion production (b) Δ or N^* excitation and its decay into n+π^+ channel.

The description of A_{N} is thus extended from Eqn. (1) as follows including not only hadronic but also EM amplitudes:

$$\begin{aligned} A_{\mathrm{N}} &= \phi^{\mathrm{had}*}_{\mathrm{flip}}\phi^{\mathrm{had}}_{\mathrm{non-flip}}\sin\delta_1 + \phi^{\mathrm{EM}*}_{\mathrm{flip}}\phi^{\mathrm{had}}_{\mathrm{non-flip}}\sin\delta_2 \\ &+ \phi^{\mathrm{had}*}_{\mathrm{flip}}\phi^{\mathrm{EM}}_{\mathrm{non-flip}}\sin\delta_3 + \phi^{\mathrm{EM}*}_{\mathrm{flip}}\phi^{\mathrm{EM}}_{\mathrm{non-flip}}\sin\delta_4 \end{aligned} \tag{2}$$

where 'EM' stands for electromagnetic interactions, and 'had' stands for strong hadronic interaction, and from $\delta_1 \sim \delta_4$ 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 [3]. The increasing magnitude of $A_{\rm N}$ is consistent as a function of increasing atomic number Z because the number of exchanging virtual photon flux glows as well if EM effect has opposite sign of $A_{\rm N}$ of p+p.

According to MC study [4], the neutron and its counter part π^+ via UPC process is substantially boosted towards the proton beam direction and therefore the fragmenting π^+ are mostly emitted in even higher rapidity region than BBC. Only small fraction of π^+ 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 moderate $A_{\rm N}$ evolution of the BBC tagging data points are consistent with the prediction based on π and a_1-Reggeon interference because the data are dominated by the hadronic amplitude with quenched EM process. Then the EM process should introduces the opposite sign in $A_{\rm N}$ from hadronic amplitude and leads to positive $A_{\rm N}$ in p+A for BBC votoed events. 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 large asymmetries. It remain mystery.

To summarize what we have observed in Run15:

- Drastic A-dependence in the forward neutron asymmetry $A_{\rm N}$ which is absolutely unexpected within the current framework which reproduces the $A_{\rm N}$ in p+p data well.
- Another drastic dependence has been observed in the semi-inclusive measurements by requiring both North and South BBCs $3.9 < |\eta| < 3.1$ 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 glows as a function of atomic number Z, and 2) the fraction of EM process events are suppressed in BBC fired events (blue data) while enhanced in BBC vetoed events (green data).

2 Run17 Proposal

In order to study further on this observable, new measurements of forward neutron asymmetry is to be proposed at STAR experiment in Run17 at the beam energy of 255 GeV using fixed targets. There is pre-existing fixed Au-target at STAR. In order to study A-dependent A_{N} further, two more additional fixed targets are to be implemented. Although the center-of-mass energy becomes lower, i.e. as low as $\sqrt{s} = 22$ GeV compared to existing Run15 measurements $\sqrt{s} = 200$ GeV, running this experiment at STAR in Run17 has following advantages:

1. Large kinematic coverage of the transverse momentum p_{T} of forward neutron using RHICf detector with better p_{T} resolution.

2. Large acceptance coverage for semi-inclusive measurements using full STAR detector.

3. Due to sufficient rates from the fixed target, the entire measurements can be done in 1day and do not sacrifice much approved STAR collider program.

Each items above are to be discussed in following subsections.

2.1 Large kinematic coverage

The RHICf detector is expected to provide about factor of $5 \sim 10$ (depending on neutron energy) better p_{T}-resolution than the existing ZDC detector. The detector also provides access to which extends the existing coverage from $0.022 < p_{\mathrm{T}} < 0.178$ GeV/c observed at GeV (Run15) up to ~ 1 GeV/c. The substantial extension of the pT coverage is also owing to lowered CM energy. In order to make use of the kinematic reach up to $p_{\mathrm{T}} \sim 1$ GeV/c, radial polarization is necessary. With the vertical polarization, the p_{T} range will be limited up to 0.3 GeV/c. It is known that the reaction mechanism of forward neutron has been demonstrated to have strong p_{T} dependence as shown in Fig. 1 .The p_{T} dependence of the forward neutron asymmetries observed in p+p collisions at three different energies. Thus extending the measurements at large p_{T} coverage is important. Shown in Fig. 4 are p_{T} dependence of existing data (open symbols). New Run15 data for p+Al and p+Al are plotted at the average p_{T} of 0.1. The proposed data points are plotted with solid symbols with projected statistical errors. The goal of statistical precision of each measurement is 1%. The estimated beam time will be discussed later.

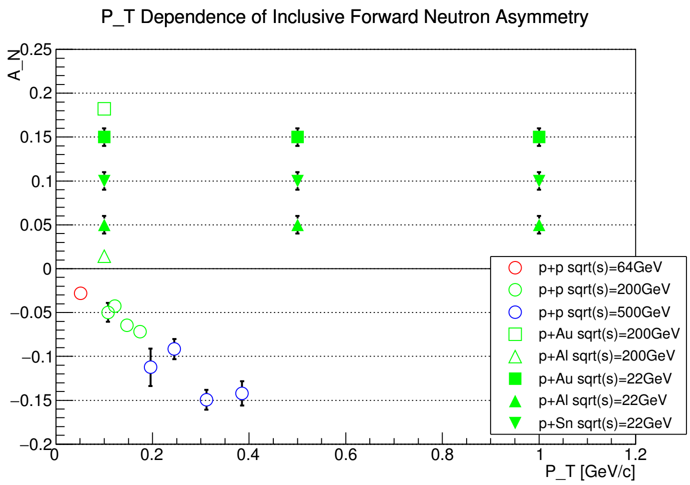

Figure 4: p_{T} dependence of existing data (open symbols). New Run15 data for p+Al and p+Al are plotted at the average p_{T} of 0.1. The proposed data points are plotted at arbitrary A_{N} by solid symbols with projected statistical errors.

2.2 Large Acceptance for Semi-Inclusive

The BBC acceptance is only limited to $3.1 < |\eta| < 3.9$, and one can imagine more pure sample of EM enhanced/ suppressed can be obtained if we have larger coverage of the coincidence particles with forward neutron. Given the fact that we observed large $A_{\mathrm{N}} \sim 30\%$ in BBC vetoed events, it is very interesting to explore how large asymmetry can possibly glows by the semi-inclusive measurements with better purity. In addition to the large acceptance coverage of STAR, the access to larger pT coverage also will lead to larger A_{N}.

2.3 Fixed Target

The fixed target was first installed to the beam pipe at 2.05m downstream to the west side of the nominal interaction point of STAR before Run14 and it was kept throughout the physics data taking in Run14. As a consequence, the effect of the additional material is proved to be negligible effect to the regular physics data taking. It is further confirmed during Run15 as well. Shown in Fig. 6 are the existing gold foil target and its support structure

Table 1: Atomic numbers and masses of Al, Sn and Au targets

	Al	Sn	Au
A	27	118	197
Z	13	50	79

(top-left) and proposed three nuclear targets implemented on the top, right and bottom of the beam pipe. Left side of the beam pipe is remained open on purpose in order to study the backgrounds such as the effect from the beam pipe scattering (bottom-left). Depending on the purpose of measurements, beam position is shifted towards the relevant position with respect to the center of the beam pipe. The beam is kept at the center of the beam pipe during the usual collider experiments (right-top), while the beam is shifted towards the target of interest while the fixed target experiment is executed. The thickness is 4% radiation length for each target. The target is to be implemented at 1.7cm away from the center of the beam pipe. This is more than 50σ away for the beam size of the typical collider mode tune.

The choice of three nuclear targets will be Al, Au and Sn, and their atomic numbers and masses are summarized in Table 1.

2.4 Run Plan

The estimated beam time is 24 hours including contingency. The break down of the beam time estimate is summarized in Table 2. The estimate for the condition change is estimated rather conservatively. Since the beams are not in collider mode and the fixed targets are bombard by the beam halo, the beam loss over the course of time is expected to be moderate. Thus all measurements can be done within 1 or 2 RHIC stores.

The estimated time to accumulate $< 1\%$ is limited by the DAQ band width, i.e 1kHz for the fixed target experiment. The neutron rates were achieved $\sim$ 5kHz in Run15 p+A measurement in collider mode at $\sqrt{s} = 200$ GeV. In fixed target mode, the beam position with respect to the target will be steered to give the neutron rates around 1kHz. 1 hour data taking at 1kHz provides total 3.6M events. In Run15, the 3.6M events lead to $\Delta A_{\mathrm{N}} \sim 0.0026$ which is factor of 4 smaller than the goal $\Delta A_{\mathrm{N}} \sim 0.01$. This leaves factor of 16 contingency in statistics.

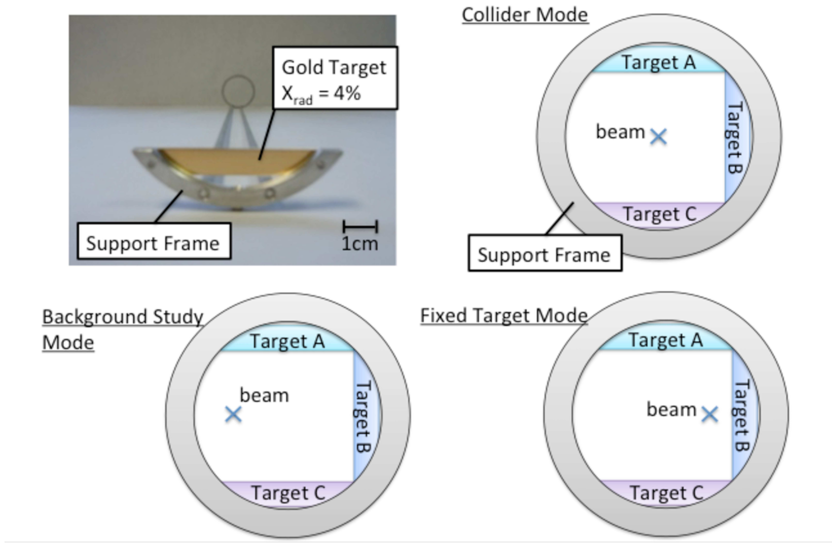

Figure 5: The existing gold foil target and its support structure. Other figures are proposed three nuclear targets implemented on the top, right and bottom of the beam pipe. Depending on the purpose of measurements, beam position is shifted to the relevant position with respect to the center of the beam pipe.

The proton beam should be radially polarized. With out radial polarization, p_{T} range will be limited up to 0.5 GeV/c.

References

[1] A. Adare et al.: Phys. Rev. D 88, 032006 (2013).

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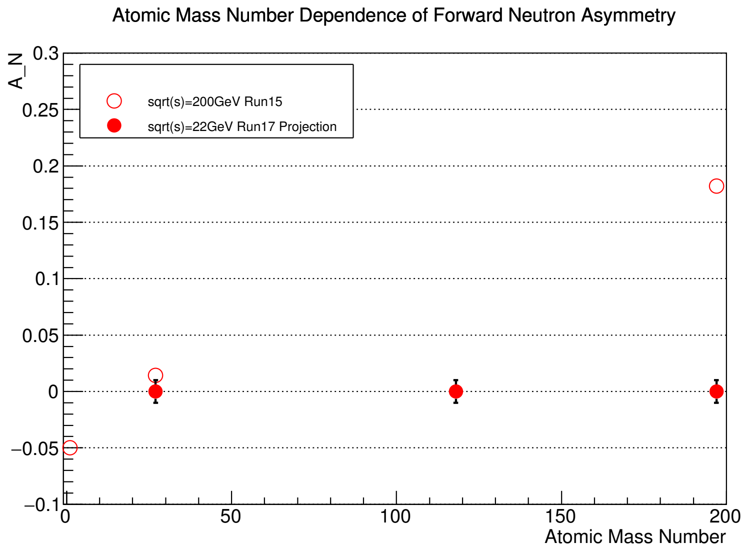

Figure 6: Run15 inclusive measurements of A-Dependence (open circles) and proposed measurements with three fixed nuclear targets.

Table 2: Estimated time for physics data taking, experimental condition changes and contingency.

Physics Data	1 h $\times$ 3 targets $\times$ 3 RHICf positions	9 h
Empty Target	1 h $\times$ 3 RHICf positions	3 h
Beam Position Change	0.5h $\times$ 4 target positions	2 h
RHICf Position Change	0.5h $\times$ 3 targets $\times$ 3 RHICf positions	4.5h
Contingency	30%	5.5h
Total		24 h