Single transverse-spin asymmetry of very forward neutron production in polarized $p + p$ collisions at PHENIX

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Abstract. The cross section and $x_F$ dependence of $A_N$ of very forward neutron production in polarized $p + p$ collisions at $\sqrt{s} = 200$ GeV were measured in the PHENIX experiment at RHIC. The measured cross sections were consistent with the $x_F$ scaling claimed by the ISR experiment which measured neutron production in $p + p$ collisions at $\sqrt{s}$ from 30.6 to 62.7 GeV. These cross sections for large $x_F$ neutron production, as well as those in $e + p$ collisions at HERA, are mainly described by one-pion exchange. At PHENIX, significant negative $A_N$ was observed in the forward region, and no significant backward $A_N$ was observed. We also measured $\sqrt{s}$ and $p_T$ dependence of $A_N$ of very forward neutron production at $\sqrt{s}$ from 62.4 to 500 GeV. The observed large asymmetry of neutron production is considered to come from the interference between the spin-flip amplitude of the pion exchange and spin-non-flip amplitude of all Reggeon exchange. Therefore, the neutron asymmetry has a sensitivity to other Reggeon exchange amplitude even if it is a small amplitude.

1. Introduction
The origin of the nucleon spin 1/2 has been investigated with polarized proton collisions in the PHENIX experiment at RHIC. Polarized DIS experiments found that the origin of the nucleon spin was not explained by the quark spin. First goal of the RHIC spin project is a measurement of the gluon spin contribution to the nucleon spin. The helicity structure of the nucleon is measured by the double-helicity asymmetries ($A_{LL}$) in longitudinally-polarized proton collisions.

For $A_{LL}$ measurements, a good local polarimeter at the interaction point (IP) is necessary for systematic understanding of the beam polarization. At RHIC, polarized protons are stored with transverse polarization, and it is monitored by the proton-carbon CNI (Coulomb-nuclear interference) polarimeter [1] and polarized atomic hydrogen gas-jet polarimeter [2] located around the IP12 area. For the longitudinally-polarized collisions in the collider experiments at PHENIX (IP8) and STAR (IP6), spin-rotator magnets rotate the proton polarization into the longitudinal direction. The longitudinal polarization is monitored at each IP by the local polarimeter by using physics processes with single transverse-spin asymmetry ($A_N$).

Before beginning the longitudinal-spin polarized proton collisions, we needed to find a good physics process to monitor the polarization at PHENIX. One candidate process was a forward $\pi^0$ asymmetry which was found at Fermilab-E704 experiment. At PHENIX, there was a space in...
the very forward area (zero-degree area) to locate a polarimeter. Since the $\pi^0$ asymmetry in the very forward region had not been measured at Fermilab-E704, the very forward $\pi^0$ asymmetry was measured at RHIC. We installed an EM calorimeter in the very forward region on one side of the IP12 in 2001-2002 and measured the asymmetry of photons mainly from $\pi^0$ decay. In this experiment, we found that the photon asymmetry, or $\pi^0$ asymmetry in the very forward region was not large enough for the polarimeter, but a large asymmetry of very forward neutron production [3], $A_N = -0.090 \pm 0.006\text{(stat)} \pm 0.009\text{(syst)}$, was discovered. The neutron asymmetry was confirmed with a hadron calorimeter which was installed on the other side of the IP12.

The discovery of the large asymmetry of neutron production is also a new important information to understand the production mechanism of very forward neutron production. Cross section of very forward neutron production had been measured at ISR and Fermilab [4, 5]. They measured a forward peak in the $x_F$ distribution around $x_F = 0.8$ and found only a small $\sqrt{s}$ dependence. One-Pion Exchange (OPE) model gave a reasonable description on the measurements. In OPE models [6, 7, 8, 9, 10, 11, 12], the incoming proton emits a pion which scatters on the other proton as described in Figure 1.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{A schematic diagram of the neutron production, $p + a \rightarrow n + X$, on the Reggeon exchange model shown with Lorentz invariant variables $s', Q^2$ and $t$. "a" is a proton or electron/positron for $p + p$ or $e + p$ reactions. $R$ indicates a Regge trajectory with isospin odd such as $\pi, \rho, a_2$ and Pomeron-$\pi$ in the Regge theory. In case of the pion exchange, $R$ means $\pi$.}
\end{figure}

Very forward neutron cross section was measured at HERA in $e + p$ collisions with a high resolution $p_T$ distribution [13, 14]. They found a suppression of the forward peak. CERN-NA49 also measured very forward neutron cross section in $p + p$ reaction [15]. Their cross section was twice large as those measured at ISR and Fermilab, and consistent with that at HERA. In order to understand the production mechanism of the forward neutron, more data are necessary, and the asymmetry measurement gives a new information.

2. Experimental setup
At PHENIX, we measured the cross section and $A_N$ of very forward neutron production in polarized $p + p$ collisions with the local polarimeter. The PHENIX local polarimeter was made with an existing ZDC (Zero-Degree Calorimeter) by adding a position-sensitive SMD (Shower Maximum Detector) [16]. A plan view of the experimental setup for very forward neutron measurement at PHENIX is shown in Figure 2.

The ZDC is composed of Cu-W alloy absorbers with PMMA-based communication grade optical fibers and it corresponds to 1.7 nuclear interaction length for one module. A
photomultiplier collects Cherenkov lights via the optical fibers in one module. Three ZDCs are located in series at ±1800 cm away from the collision point within the small acceptance, covering 10 cm in the transverse plane. It has 5.1 nuclear interaction length and 149 radiation length by combining three ZDC modules, and has energy resolution about 20% for 100 GeV neutron.

The SMD consists of $x$-$y$ scintillator strip hodoscopes and they are inserted between the first and second ZDC modules at the position of maximum hadronic shower approximately. The $x$-coordinate (horizontal) is sampled by 7 scintillator strips of 15 mm width, while the $y$-coordinate (vertical) is sampled by 8 strips of 20 mm width, tilted by 45 degree. It gives a position by calculating the center of gravity of shower generated in the first ZDC module. Its position resolution is estimated to be about 1 cm for 50 GeV neutron in the simulation study.

Detectors are located downstream of the RHIC-DX dipole magnet so that charged particles from collisions are expected to be swept out. A forward scintillation counter, covering 10 cm × 12 cm, has been installed in front of the ZDC to remove charged-particle backgrounds from other sources.

As a beam luminosity monitor, Beam Beam Counters (BBCs) are used. The BBC consists of 64 sets of PMTs and 3 cm thick quartz Cherenkov radiator. BBCs are mounted around beam pipe located ±144 cm away from the collision point. They cover ±(3.0–3.9) and 2π in $\eta$ and $\phi$ spaces, respectively.

The data was collected by two sets of triggers for the neutron measurement. One was the ZDC trigger for neutron inclusive measurements by requiring energy deposit in either side of the ZDC (the north side or the south side) above 5 GeV. The other was the ZDC$\otimes$BBC trigger, a coincidence trigger of the ZDC trigger with BBC hits which were defined as one or more charged particles in both sides of BBCs.

3. Results

3.1. Measurements at $\sqrt{s} = 200$ GeV

The cross section in the integrated $p_T$ region, $0 < p_T < 0.11 \times x_F$ GeV/c was measured by assuming $p_T$ distribution from the ISR result. The result is shown in Figure 3. We couldn’t measure $p_T$ distribution due to the limited acceptance and position resolution. Our cross section result showed consistency with the ISR data. $x_F$ scaling was satisfied in higher center of mass energy.

The azimuthal modulation of very forward neutron production is shown in Figure 4. The single transverse-spin asymmetry with the ZDC trigger was $A_N = -0.066 \pm 0.006(stat)$, and that with the ZDC$\otimes$BBC trigger was $A_N = -0.083 \pm 0.004(stat)$. The result was consistent with the IP12 measurement with BBC hits in the trigger requirement within the errors.
Figure 3. Cross section of very forward neutron production from $p + p$ collisions at $\sqrt{s} = 200$ GeV (circles). Squares show the ISR results of various center of mass energies.

Figure 4. The azimuthal modulation of very forward neutron production with the ZDC trigger (left) and that with the ZDC$\otimes$BBC trigger (right).

The $x_F$ dependence of $A_N$ of very forward neutron production is shown in Figure 5. A significant negative $A_N$ was seen in the positive $x_F$ region and there was no energy dependence within the errors in both trigger sets. No significant backward neutron asymmetry was observed.

3.2. $\sqrt{s}$ dependence
We also studied $\sqrt{s}$ dependence of $A_N$ from three different collision energies, 62.4 GeV, 200 GeV, and 500 GeV. The result is shown in Figure 6. At higher collision energy, the absolute value of the asymmetry was higher. The hit position dependence on the detector, or the polar angle dependence of the neutron direction was measured at each energy, although it was largely smeared by the position resolution. The result was converted to the $p_T$ dependence. It showed
Figure 5. The $x_F$ dependence of very forward neutron production at $\sqrt{s} = 200$ GeV with the ZDC trigger (top) and that with the ZDC⊕BBC trigger (bottom).

a hint of $p_T$ scaling property of $A_N$ of the very forward neutron production.

4. Discussion
The asymmetry is caused by interference between spin-flip and non-flip amplitudes with a relative phase. Kopeliovich et al. [17] studied the asymmetry from only pion exchange. Because spin-flip amplitude and non-flip amplitude have the same phase, absorption correction was considered for a relative phase. The absorption correction was also important for cross section calculation, but the gained shift between spin-flip and non-flip amplitude was too small to explain the large asymmetry. Next Kopeliovich et al. [18] studied interference with other Reggeons. They considered interference of pion and $a_1$, or pion and $\rho$ in the $1^+S$ state. As a result, the data agreed well with independence of energy. The asymmetry has a sensitivity to the presence of different mechanisms, e.g. Reggeon exchange with spin-non-flip amplitude even if they are small amplitudes.
Figure 6. The measured asymmetries of very forward neutron production as functions of $p_T$ with the ZDC trigger (top) and that with the ZDC⊗BBC trigger (bottom).

5. Summary

We measured the $x_F$ dependence of $A_N$ and cross section of neutron production in very forward kinematics with the PHENIX detector at $\sqrt{s}=200$ GeV. Significant negative $A_N$ was observed in the forward region, and no significant backward $A_N$ was observed. The observed asymmetries were consistent with the previous result at RHIC-IP12 [3] within the error. Asymmetry showed almost no $x_F$ dependence. The measured cross section at $\sqrt{s}=200$ GeV has no violation of $x_F$ scaling with the results from the ISR experiment. These cross sections for large $x_F$ neutron production, as well as those in $e^+p$ collisions at HERA, are mainly reproduced in one pion exchange model.

We also measured $\sqrt{s}$ and $p_T$ dependence of $A_N$ of very forward neutron production at $\sqrt{s}$ from 62.4 to 500 GeV. The observed large asymmetry of neutron production is considered to come from the interference between the spin-flip amplitude of the pion exchange and spin-non-flip amplitude of all Reggeon exchange. Therefore, the neutron asymmetry has a sensitivity to other Reggeon exchange amplitude even if it is a small amplitude.
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