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Far-forward neutral particle asymmetry measurements in the RHICf experiment

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The RHICf experiment installed an electromagnetic calorimeter in front of the Zero-Degree Calorimeter (ZDC) of the RHIC-STAR experiment in 2017 to measure the transverse-spin asymmetries of the far-forward neutral particles produced from transversely polarized proton collisions at RHIC. It is known that the far-forward neutrons produced in transversely polarized proton collisions have a large transverse-spin asymmetry, and the ZDC at RHIC serves as a polarimeter to monitor the polarization in the collision experiments. In particular, it is an important tool for tuning the polarization direction at the collision point. The electromagnetic calorimeter installed in the RHICf experiment was able to obtain high-precision position information, and furthermore, by moving the detector position, the kinematic region that can be measured was greatly extended and improving the precision of the measurement. In addition to neutrons, we also measured the far-forward asymmetry of neutral π mesons and collected new data on particle production in the far-forward region. Furthermore, we are conducting a combined analysis with the STAR detectors to advance our understanding of the particle production mechanism.

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1. Introduction

Understanding nuclear forces and strong interactions has difficulties that differ from understanding gravity and electromagnetic forces because of their strength. One research approach is to measure the particles produced when protons collide with protons or nuclei. However, the mechanism by which particles are produced is not well understood. The development of theories and calculations for particle production has been a long-standing research topic, and its development is desired for understanding air showers caused by high-energy cosmic rays in the atmosphere.

Observation of ultra-high energy cosmic rays is a very important tool for understanding astronomical phenomena in the extreme environment of the universe. Cosmic rays are observed using a phenomenon called air showers, which is caused by the reaction between cosmic rays and the Earth's atmosphere. However, cosmic ray measurements are hampered by the fact that the production mechanism of particles produced by the collision between protons, which constitute cosmic rays, and the atmosphere is not clearly understood.

Research on the mechanism of particle production by proton collisions began with measurements of the energy and angular distribution of the produced particles, but in the 1960s, studies began to use the spin possessed by protons. The spin direction can be artificially aligned and polarized. In collisions of polarized protons, the scattered protons and the produced particles can be biased to the left or right of the original proton spin direction relative to the axis of the polarized proton collision. The magnitude and sign of this left-right asymmetry are closely related to the mechanism of scattering and particle production and have been the subject of numerous studies.

When a polarized proton collides with a target particle, the π meson produced in front of the collision direction has a large left-right asymmetry, which was discovered in the 1970s in an experiment using the accelerator at Argonne National Laboratory in the United States. At that time, the energy of polarized protons was about 10 GeV. Around 1990, a 200 GeV polarized proton beam became available at the Fermi National Accelerator Laboratory (FNAL) in the U.S., and experiments were conducted at higher energies (19.4 GeV at the center-of-mass system energy), showing that the left-right asymmetry did not disappear even with polarized protons at high energies [1]. This led to a major development in research to explain the left-right asymmetry using perturbative quantum chromodynamics (perturbative QCD), a theory that describes the dynamics of quarks and gluons, the elementary particles that make up the proton. The method of calculation based on the theory of perturbative QCD is very useful because it allows precise calculations for high-energy processes. In perturbative QCD, the left-right asymmetry of forward-produced π mesons was considered to be small at high energies. However, as a result of the development of theoretical studies, we succeeded in explaining the experimental results of left-right asymmetry even at high energies obtained by FNAL, and came to the conclusion that asymmetric particle production has its origin in the direct scattering of quarks and gluons, which has become a common understanding in this field.

In the 2000s, the polarized proton collider RHIC began operating at Brookhaven National Laboratory (BNL) in the U.S., colliding two 100 GeV protons moving in opposite directions in a vacuum, making it possible to conduct experiments with a center-of-mass system energy 10 times higher than that of FNAL. It was then shown that even at a center-of-mass system energy of 200 GeV, the left-right asymmetry of the forward-produced π mesons had a magnitude similar to that of the FNAL experiment [2, 3]. Subsequently, however, a series of experimental data were obtained

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that forced a revision of the conventional interpretation using perturbative QCD. At RHIC energies, quarks and gluons scatter and produce various particles in the form of jets. The left-right asymmetry of the jets produced forward by RHIC was examined, and it was found that, contrary to expectations, the jet as a whole and π meson in the jet do not show left-right asymmetry. This result indicates that the reaction causing the left-right asymmetry may not be the direct scattering of quarks and gluons treated in perturbative QCD.

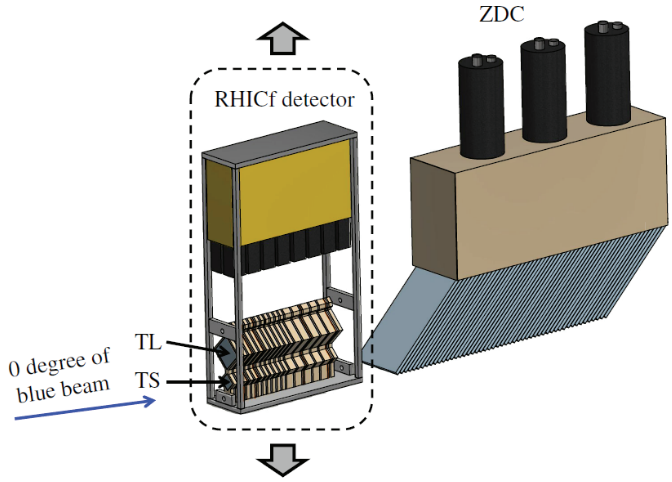

Figure 1: Setup of the RHICf experiment. The data were taken by moving the RHICf detector to cover a wide p_T range of 0.0 to 1.0 GeV/c.

In search of an answer to this puzzle, we conducted the RHICf international collaboration in 2017 to measure a previously unmeasured left-right asymmetry at the far-forward of the collision position, where the contribution of direct quark and gluon reactions is small [4]. We placed an electromagnetic calorimeter with excellent position measurement performance in the direction of zero degrees far-forward of the collision point of the STAR experiment, beyond the dipole magnet downstream of the collision point and in front of the zero degree calorimeter (ZDC) of the STAR experiment as shown in Fig.1. In this region, charged particles are swept out by the dipole magnet, so neutrons and photons, which are neutral particles, are mainly detected. Since neutral π mesons decay into two photons, they are detected and recognized by measuring these two photons, and their energy and incident position are precisely measured.

2. RHIC polarimeter

A more direct motivation for the measurement of the far-forward zero-degree of polarized proton collisions at RHIC is the measurement of polarization in polarized proton collisions. RHIC and its injection accelerators are equipped with several polarimeters to measure the polarization of protons at different stages, but what was needed at the beginning of the experiment was a polarimeter at the collision point where the collider experiment was to be performed. Spin rotator magnets are installed before and after the PHENIX and STAR experiments to adjust the polarization direction at the collision point.

RHIC polarized proton collisions were initiated in 2001 at collision energy of 200 GeV, and a calorimeter was installed behind the dipole magnet downstream of the collision point in the direction of zero degree far-forward of the 12 o'clock collision point at RHIC during 2001-2002. The protons are transversely (vertically) polarized, and we investigated whether there is left-right asymmetry in the neutral particles incident on the calorimeter in the far-forward direction. As a result, we found that there is a large asymmetry in neutrons produced in the far-forward direction [5]. The neutron production cross section was found to be large enough to monitor the proton polarization with high precision.

To measure this left-right asymmetry in the PHENIX and STAR experiments and to use it as a polarimeter, the ZDC installed in the direction of zero degrees in the far-forward of both experiments was made available as a polarimeter. The ZDC consists of three stages of calorimeters, each with 1.7 interaction lengths, for a total of 5.1 interaction lengths. Plastic scintillator hodoscopes, which can detect the vertical (7 segments) and horizontal (8 segments) position of hadron showers, were installed between the first and second stages as shower maximum detectors. When this polarimeter was used to adjust the 2003 longitudinal polarization collisions, it was able to find errors in the setting of the current of the spin-rotator magnet by detecting finite up/down asymmetry values where the left/right and up/down asymmetries should have been zero.

3. RHICf experiment

The electromagnetic calorimeter detector used in the RHICf experiment was built to understand air showers caused by high-energy cosmic rays in the atmosphere, and were used in two different proton collider experiments: the Large Hadron Collider (LHC) at CERN and the RHIC at BNL. The experiment at the LHC was named the LHCf experiment, and at RHIC it was named the RHICf experiment [4]. The LHCf experiment cannot measure left-right asymmetry because it cannot use polarized protons, but the RHICf experiment, which can accelerate polarized protons, succeeded in measuring left-right asymmetry for the first time.

The calorimeter consists of two sampling calorimeters with excellent positional measurement precision, one called the small tower (TS) with dimensions of 20 mm × 20 mm, and the other called the large tower (TL) with dimensions of 40 mm × 40 mm. The energy absorbing layers of tungsten have a total radiation length (X_0) of 44 and an interaction length (λ_{int}) of 1.6. The energy sampling layers are GSO crystals with a total of 16 layers, plus 4 position detection layers. Each of the position detection layers is a hodoscope of 1 mm square GSO bars in two directions and is read by MAPMT (Multi-Anode Photo Multiplier Tube).

The experiment was performed for polarized proton collisions with a collision energy of 510 GeV in 2017. The RHIC was set up for the RHICf experiment with $\beta^* = 8$ m, the polarization direction was adjusted to the radial direction of the RHIC ring, and four stores, totaling 28 hours of operation were performed for the physics experiment. For each of the four stores, the vertical position of the RHICf calorimeter was moved, and data covering a wide transverse momentum (p_T) region were collected by making measurements at three different positions. A total of 110 M events were recorded as data volume, with an integrated luminosity of approximately 700 nb^{-1}.

4. Neutral π meson asymmetry

The RHICf experiment measured the left-right asymmetry (A_N) of neutral π mesons in the far-forward of the collision point, which was not measured before, for transversely polarized proton collisions at collision energies of 510 GeV, where the contribution of direct quark and gluon reactions is considered small [6]. A large A_N was found to exist even in the low $p_T < 1$ GeV/c region. The A_N tends to increase with both p_T and the longitudinal momentum fraction (x_F).

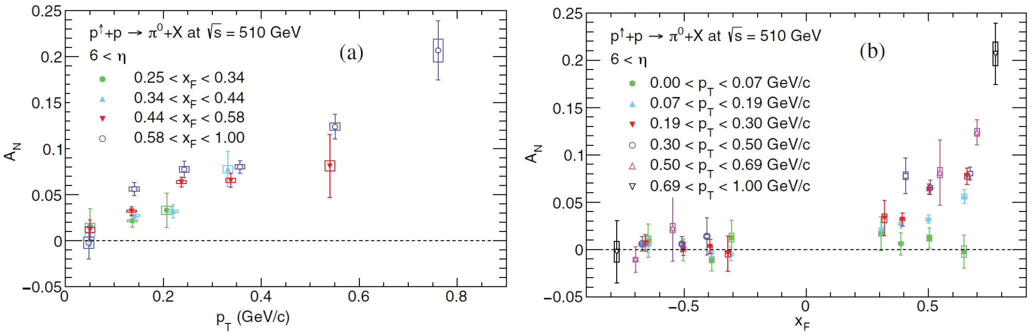

Figure 2: A_N for far-forward neutral π meson production as functions of (a) p_T and (b) x_F. Error bars represent the statistical uncertainties, and the boxes represent the systematic uncertainties.

Figure 2 shows the results of the RHICf experiment. The A_N of the neutral π meson is present even at small angles near zero degrees, and furthermore, its magnitude increases rapidly near zero degrees, reaching almost the same magnitude as the value at large angles. This experimental result of having 5-10% A_N from a small p_T of about 0.1 GeV/c cannot be explained by the perturbative QCD used to interpret the data in the past. When the aforementioned small A_N of the jet is taken into account, the interpretation of particle production in high-energy proton collisions is forced to undergo a major revision. The small far-forward angle at which the left-right asymmetry was obtained corresponds to the energy region where protons induce excited states, and the contributions of diffraction and resonance may be a clue to solving the puzzle.

5. Neutron asymmetry

The measurement of the neutron A_N at small angles near zero degrees was carried out at different collision energies using the ZDC in the PHENIX experiment, where large A_N were measured as p_T to 0.4 GeV/c. The results showed that the magnitude of A_N tends to increase in proportion to the magnitude of p_T. As a theoretical model to explain this, neutron production by one π meson exchange model was presented [7]. In this theoretical model, the interference term between the exchange of the spin-flip π meson and the non-spin-flip a_1 meson yields A_N, which explains the experimental results. However, the results of this PHENIX experiment were limited by the size and position resolution of the ZDC. In the RHICf experiment, neutron A_N was measured in the p_T range up to 1 GeV/c with excellent momentum precision using a calorimeter with excellent position resolution. The dependence of the x_F was also investigated.

Figure 3 shows the results at a collision energy of 510 GeV [8]. In the high x_F region, A_N increases with its magnitude up to the high p_T region, while in the low x_F region, A_N reaches a

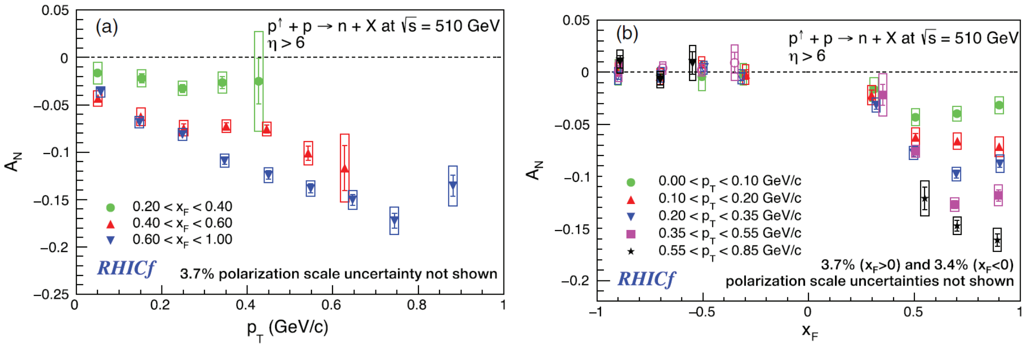

Figure 3: A_N for far-forward neutron production as functions of (a) p_T and (b) x_F. Error bars represent the statistical uncertainties and the boxes represent the systematic uncertainties.

plateau in the low p_T region. Also in the low p_T region, A_N reaches a plateau at low values and the x_F dependence is small. This is consistent with the results of the PHENIX experiment at low collision energy of 200 GeV [9], indicating that the dependence on collision energy is small. On the other hand, in the high p_T region, the x_F dependence is shown to exist and a plateau tends to be reached at high x_F. An additional theoretical model is necessary to describe the neutron A_N's over the whole kinematic region measured.

6. Combined analysis with STAR detectors

Thus far we have shown the results of the analysis using the RHICf calorimeter alone, and now we are performing a combined data analysis with the STAR detector. By comparing the asymmetry obtained with the RHICf calorimeter with the STAR detector, we are trying to investigate the mechanism of the origin of the asymmetry by separating diffractive and non-diffractive events. Diffractive events are considered when no particles are detected in the central detector of a STAR experiment, but only in the forward or backward detectors. Non-diffractive events consider the case where particles are detected in many detectors in a wide range of the central and forward detectors of the STAR experiment. This new data analysis is currently underway.

7. Summary

The asymmetry measurement of the far-forward neutral particles is a very useful method for polarimeter applications, but it is also an important research tool that provides a variety of new data for understanding the mechanisms of their production. It also provides important new data for understanding atmospheric showers produced by high-energy cosmic rays in the atmosphere. The RHICf experiment has performed measurements at RHIC using a far-forward electromagnetic calorimeter detector with high-precision position detection capability, and has measured neutral π mesons and neutron asymmetries. The asymmetry measurements over a wide range of p_T and x_F have given many unexpected results. In the future, we will combine this with the detectors of the STAR experiment in a combined analysis to advance our understanding of the particle production mechanism.

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