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High Energy Hadron Polarimetry

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Abstract. Proton polarimetry at RHIC uses the interference of electromagnetic (EM) and hadronic scattering amplitudes. The EM spin-flip amplitude for protons is responsible for the proton's anomalous magnetic moment, and is large. This then generates a significant analyzing power for small angle elastic scattering. RHIC polarimetry has reached a 5% uncertainty on the beam polarization, and seems capable of reducing this uncertainty further. Polarized neutron beams are also interesting for RHIC and for a polarized electron-polarized proton/ion collider in the future. In this case, deuterons, for example, have a very small anomalous magnetic moment, making the approach used for protons impractical. Although it might be possible to use quasi-elastic scattering from the protons in the deuteron to monitor the polarization. 3-He beams can provide polarized neutrons, and do have a large anomalous magnetic moment, making a similar approach to proton polarimetry possible.

Keywords: proton polarimetry; neutron polarimetry; pQCD test; nucleon transverse spin structure; Drell-Yan.
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USING THE PROTON ANOMALOUS MAGNETIC MOMENT

Schwinger [1] suggested using the spin flip amplitude that generates the neutron anomalous magnetic moment to obtain polarized neutrons, shortly after the development of Quantum Electrodynamics. In 1974, Kopeliovich and Lapidus presented the expected analyzing power for polarized protons scattering elastically from unpolarized protons [2]. The analyzing power comes from an interference of the electromagnetic spin flip amplitude, known from the proton anomalous magnetic moment, with a hadronic spin nonflip amplitude. This is calculable. The first observation of the predicted CNI (Coulomb nuclear interference) peak was published in 2006 [3], and is shown in Figure 1. This analyzing power is being used to measure the beam polarization at RHIC. This analyzing power is large, it is largely energy-independent, and the cross section for this process is high, making CNI scattering ideal for proton polarimetry at RHIC. However, an unknown contribution to the analyzing power from a possible hadronic spin-flip amplitude leads to the need to calibrate the polarimeter.

RHIC polarimetry uses a polarized atomic hydrogen jet at a RHIC location where either RHIC beam can be steered onto the jet [4], to obtain the absolute beam polarization; and this result is used to calibrate separate carbon target polarimeters in each RHIC beam [5]. Both types of polarimeters make use of CNI scattering. The basis of the absolute beam polarization comes from the measurement of the atomic hydrogen polarization of the jet, using a Breit-Rabi polarimeter. The present uncertainty in the RHIC polarization, Delta P/P=5%, is dominated by uncertainty in the beam polarization profile. Improvement in the carbon target mechanism is expected to largely eliminate this uncertainty, providing profile measurements for each RHIC fill. The remaining systematic uncertainties are for the hydrogen molecular fraction in the jet (2%) and from scattering background in the jet (about 2%). The statistical uncertainties for the jet and carbon polarimeters are negligible.

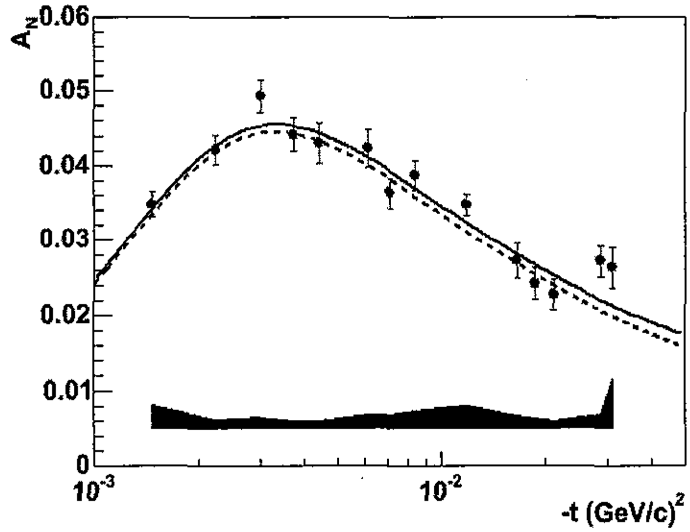

FIGURE 1. Analyzing power vs. four momentum transfer squared, t, for elastic proton-proton scattering, for the RHIC beam energy 100 GeV, scattering from a fixed target. The dashed curve is the prediction assuming no hadronic spin flip; the solid curve is the best fit. Reference [3].

POLARIZED NEUTRONS IN RHIC?

The focus of RHIC spin has been to understand the helicity structure of the proton. This program uses the strongly interacting quarks and gluons of the longitudinally polarized protons in one beam to probe the spin structure of the longitudinally polarized protons in the other beam. This helicity program features particular sensitivity to the polarization of the protons carried by gluons, and the measurement of flavor-separated anti-quark polarizations, for ubar and dbar, using the parity-violating production of W bosons. The helicity program does not require polarized neutrons. During this work, measurements were also made with transverse polarization, to explore the transverse spin structure of the proton. Very large spin asymmetries were observed at RHIC with transverse spin (Figure 2 and [6]). At the same time, surprising large asymmetries were also seen in transverse spin for deep inelastic scattering of leptons from polarized protons. This has led to considerable theoretical activity to try to understand the origin of these asymmetries, and this has led to a new interest in colliding polarized neutrons in RHIC.

At least two polarized neutron beam experiments have exciting possibilities. The first is to explore the transverse spin asymmetries seen for proton beams (Fig. 2) with polarized neutrons. It is believed that the asymmetries at RHIC energy are due to the hard scattering of the valence quarks in the polarized protons. This belief is supported by the successful perturbative QCD description of the cross sections for pion production at RHIC, which describes the scattering as the hard scattering of the gluons and quarks in each beam. However, a similar pattern of transverse spin asymmetry is seen at fixed target energy [7], where the measured cross section is considerably higher than the pQCD description [8]. Production by a polarized neutron beam would reverse the roles of the valence u and d quarks in the beam, compared to polarized protons. If the scattering is due to valence quarks, one should see Fig. 2, reversed in sign for the charged pions. One could probe the origin of this effect, comparing the results from polarized neutrons and polarized protons, versus energy, transverse momentum of the pions, and longitudinal momentum fraction carried by the pions..

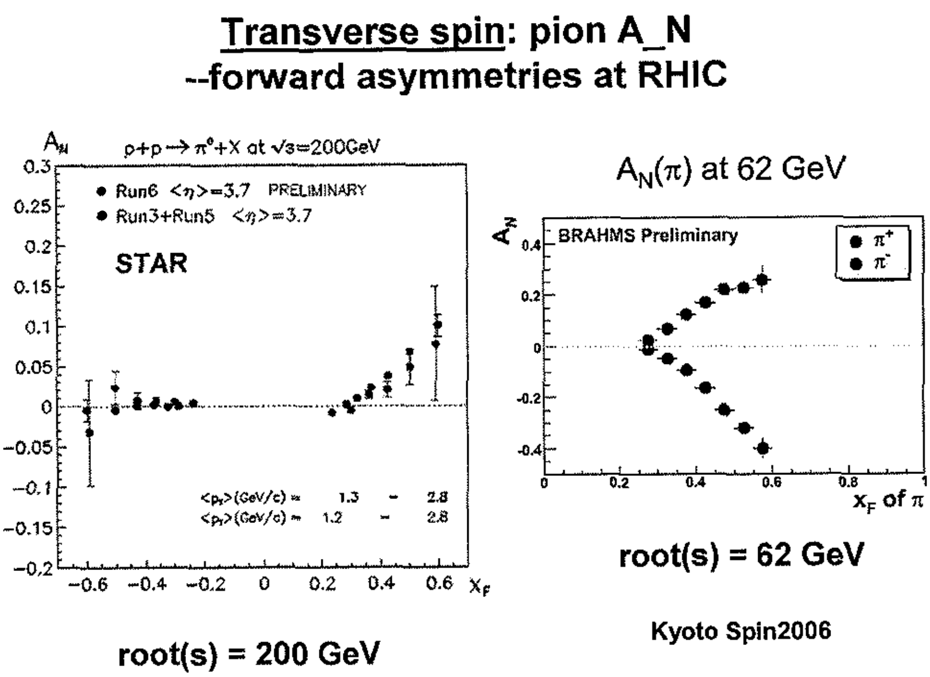

FIGURE 2. Transverse spin asymmetries at RHIC, reported to Spin2006 at Kyoto. The left panel shows results from the STAR experiment, for forward and backward pi^0 production with one beam polarized. The right panel shows results from the BRAHMS experiment, for collisions at lower energy, for charged pions produced forward [6].

The second experiment that would benefit from having both polarized neutron and polarized proton beams is transversely polarized Drell-Yan pair production. The orbital angular momentum of the quarks in the proton is believed to drive the transverse spin asymmetry observed for pion production from a polarized proton target in deep inelastic scattering [9]. The result is shown in Figure 3a. To obtain the asymmetry, the theoretical description requires the interference of production amplitudes, and the necessary phase for the interference is believed to be generated by a final state interaction between the struck quark and the proton remnant [10]. For Drell-Yan production, the same amplitudes should contribute, but with the opposite phase, due to an initial state interaction generating the phase. The signs are determined by the color charges of the states, and are opposing for DIS and Drell-Yan.

The sign change, shown in Fig. 3, is a fundamental prediction of pQCD, in the context of understanding the transverse spin structure of the proton [11]. RHIC sensitivity, at higher luminosity, will allow this fundamental test [12].

Polarized neutrons would furnish the separation of u and d quark orbital angular momentum effects. The sign of the orbital angular momentum for the valence u and d quarks in the proton are expected to be opposite, and the photon coupling of Drell-Yan is weighted by the quark charge square, emphasizing u quarks over d quarks. For neutrons, the valence u and d quarks change roles, and the contributions from the orbital angular momentum of the valence u an d quarks would have opposite sign from the u and d quarks in protons. With the quark charge square weighting, the different contributions for the neutron and proton beams allow the separation of the u and d quark orbital angular momentum contributions in the nucleon. Therefore, a transversely polarized neutron beam would provide important new information on the spin structure of the nucleon.

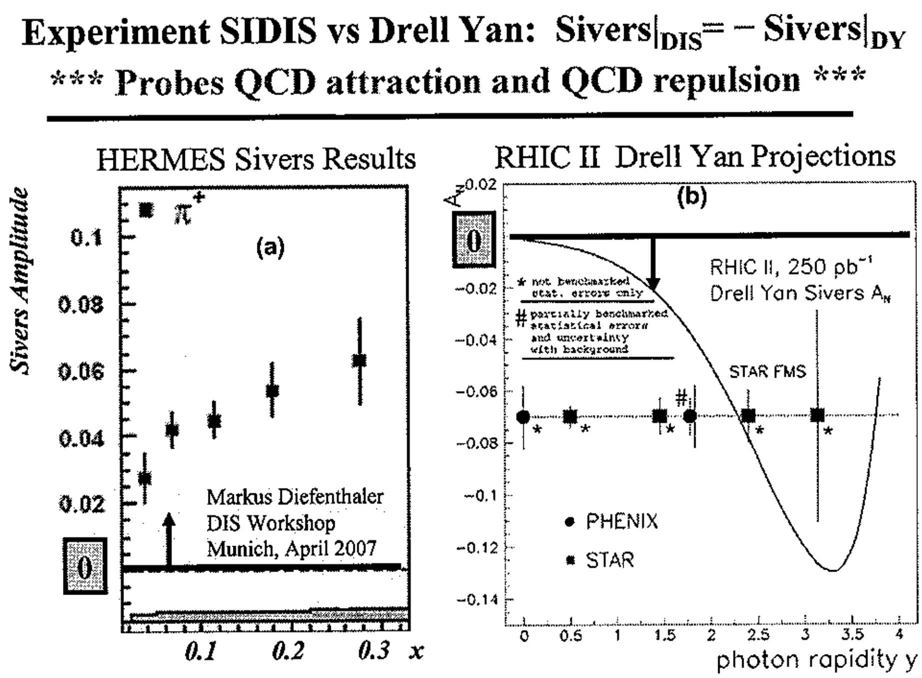

FIGURE 3. A Drell-Yan experiment with transverse spin. (a) shows a semi-inclusive DIS result from the HERMES experiment, where the observed transverse spin asymmetry is believed to result from the orbital angular momentum of the quarks in the proton (mainly the u quark) [9]. (b) shows the prediction from pQCD for the asymmetry of Drell-Yan pairs at RHIC, with expected sensitivity [12].

POLARIMETRY FOR POLARIZED NEUTRONS

Polarized neutrons could be provided using polarized deuteron or polarized He-3 beams [13]. For transverse spin experiments, polarized deuterons would be very attractive, since one could simultaneously measure scattering from polarized neutrons and polarized protons by tagging the spectator proton or neutron, respectively. However, the deuteron anomalous magnetic moment is very small, making both acceleration of polarized deuterons and polarimetry based on CNI scattering, with sensitivity due to the anomalous magnetic moment of the beam, problematic. The polarimetry could possibly be handled using scattering of the proton in the deuteron, tagging the proton interactions with the spectator neutron. However, the acceleration issues appear daunting [13]. Furthermore, also due to the small deuteron anomalous magnetic moment, polarized deuterons could not provide longitudinally polarized neutrons which are needed for the DIS experiments in eRHIC.

Polarimetry for polarized He-3 beams could possibly use CNI elastic scattering, with an expected asymmetry due to the large He-3 anomalous magnetic moment. This was discussed by Larry Trueman at this workshop [14]. Since a significant hadronic helicity flip is possible, it is necessary to calibrate such a polarimeter using a polarized He-3 jet in RHIC, for which the polarization would need to be known through low energy polarimetry. Such a jet would need to be developed. There are plans developing to hold a workshop on this topic, possibly in October 2008, just prior to Spin 2008.

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