OVERVIEW OF POLARIMETRY AT RHIC AND ELASTIC $p \uparrow C \to pC$ SCATTERING AT VERY LOW MOMENTUM TRANSFER

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Abstract

Preliminary results from the '03 RHIC Proton Spin Run on the spin dependence in the elastic scatterring of polarized protons off a carbon target at very low momentum transfer ($0.005 < |t| < 0.05$ GeV$^2/c^2$) are presented and discussed. Proton polarimeters based on this process are used in RHIC and AGS to measure reliably and in very short times the polarization of the proton beams. Polarimetry results from the just completed RHIC polarized proton run are also presented.

1. Introduiction

The analyzing power A_N is defined as the left-right asymmetry of the cross section in the scattering plane normal to the beam polarization. A_N arises from the interference between a spin-flip and spin-nonflip amplitude and thus provides important information on the spin dependence of the interaction.

In high energy pp and pA elastic scattering at very low momentum transfer t, A_N originates from the interference between the imaginary electromagnetic (Coulomb) spin-flip amplitude, which is generated by the proton's anomalous magnetic moment, and the real hadronic (Nuclear) spin-nonflip amplitude (CNI = Coulomb Nuclear Interference). A_N has a maximum value of about 4% around a 4-momentum transfer $-t$ of 3×10^{-3} (GeV$/c)^2$ and decreases with increasing $|t|$.

The existence of a potential hadronic spin-flip amplitude interfering with a real electromagnetic spin-nonflip amplitude introduces a deviation from A_N calculated with no hadronic spin-flip amplitude [1]. While the former contribution is fully calculable, the latter can be tackled only in Regge type phenomenological approaches and it is expected to diminish gradually with increasing energy [2]. The hadronic spin-flip amplitude carries important information on the static properties and on the constituent quark structure of the nucleon. Within Regge phenomenology, one can probe the long standing question of the magnitude of the Pomeron spin-flip amplitude through the study of A_N in the CNI region. A significant hadronic spin-flip amplitude, at a 15% level, was required to fit pC elastic scattering data at 22 GeV from experiment E950 at BNL [3].

2. The polarimeters

The main motivation for studying A_N^{pC} in elastic pC scattering in the CNI region, however, comes from the RHIC polarized proton collider at BNL. This process is used for high energy proton polarimetry, since the acceleration of polarized proton beams and experiments with them require fast and reliable measurements of the beam polarization P_B. Most of the current beam polarimetry at RHIC and the AGS is based on pC elastic scattering at very small proton scattering angles. Typical 4-momentum transfers squared are $-t \sim 0.005 - 0.05$ GeV$^2/c^2$, corresponding to recoil carbon nuclei kinetic energies of $T_{lab} \sim 0.2 - 2$ MeV, altough only a portion of this range is normally used.

In this t region A_N^{pC} is small, of the order of ~ 1 %. The figure of merit, however, is very high, since the pC elastic cross section is very large in this kinematic region. The small value of A_N^{pC} makes it necessary to collect large data samples, of the order of $\sim 2 \times 10^7$ events per measurement. Event rates, however, are relatively high, of the order of 10^5 elastic events / polarimeter channel / sec. A typical measurement in RHIC lasts only 30 sec.

The theoretical uncertainties from the unknown hadronic spin-flip amplitude limit the predictive power for this process, thus requiring that the pC CNI polarimeters be experimentally calibrated over the RHIC energy range before they can provide precise measurements of P_B. With the current knowledge on A_N^{pC} from the E950 experiment, P_B cannot be determined to better than ±30% (relative) at RHIC injection E_B of 25 GeV, while at the RHIC flattop of 100 GeV the unceratinty on P_B is even larger due to extrapolation uncertainties to the higher energy.

Three polarimeters, based on this process, were operated during the '03 polarized proton run: one in the AGS ring, and one in each of the yellow and blue beams in RHIC rings. For more details on the operation, performance, and results from RHIC pC CNI polarimeters see O. Jinnouchi talk and written contribution to this workshop [4].

pC elastic scattering events are identified by detecting the recoil carbon nuclei. Slow recoil carbon nuclei emerge at almost 90° w.r.t. the incident beam and are detected with silicon detectors, which provide energy and time of flight (t.o.f) information. On the basis of the energy – t.o.f correlation, carbon recoil events are identified and selected. Since the energies of the recoil carbon nuclei are extremly low all the detectors must be located inside the accelerator vacuum system at 15 and 25 cm in RHIC and AGS, respectively. An ultra thin carbon ribbon of 3 – 5 μg/cm^2 is used as target and is inserted into the beam during the measurement.

Each silicon detector channel (strip) is connected to a waveform digitizer. A deadtimeless DAQ system, based on waveform digitizer (WFD) modules with *on-board* event analysis, is used in order to handle the very high rates. An algorithm in conjunction with on board FPGAs in the WFD units is used to extract energy and time information from the recorded waveforms. The kinetic energy is determined from the maximum pulse height within the ~ 100 nsec window between consecutive bunch crossings, after corrections for the entrance window (deead layer) on the surface of the silicon detector are made and the anergy calibration is obtained from a ^{241}Am radioactive α source. The timing is measured relative to the accelerator RF, and corresponds to the time when the amplitude is one quarter of the peak pulse height on the rising edge of the waveform. The *timing* algorithm simulates the function of a constant farction discriminator, while the *energy* algorithm the function of a peak sensing ADC.

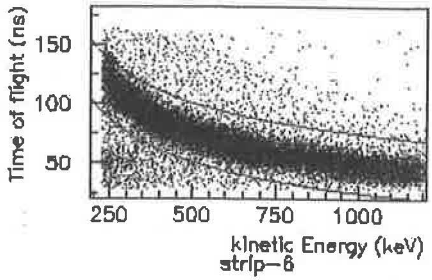

Figure 1: Time of flight versus kinetic energy in a silicon strip of a CNI polarimeter. The lines shows the location of the *banana cut*. Backgrounds under the pC elastic scattering band can be seen to be small.

Figure 1 shows a typical time of flight versus kinetic energy correlation in a single silicon strip detector. The pC elastic events are clearly apparent as a band in this Figure. This band is referred to as *carbon banana*, and a so called *banana cut* is made to select events in this band. Typical backgrounds under the elastic band are estimated to be below 1%.

3. Recent Measurements

Figure 2 shows A_N^{pC} for elastic pC scattering as a function of the recoil carbon energy T_{rec}. At proton beam energies E_B below 10 GeV a very weak $|t|$ dependence is observed, which is quite different from the *typical* CNI-type behavior. In addition, A_N^{pC} decreases from $\sim$ 6% to $\sim$ 2% with E_B increasing from 4 GeV to 10 GeV. At higher E_B above 20 GeV the $|t|$ dependence resembles the CNI-type behavior consistent with a hadronic spin-flip amplitude at a 10–15% level. A very similar t dependence of A_N^{pC} at E_B of 25 and 100 GeV is also observed.

Figure 3 is an example of proton beam polarization measurements at AGS flattop ($E_B \approx 25$ GeV) using the CNI polarimeter.

4. Ramp measurements

Figure 4 shows the asymmetry $\varepsilon_N = A_N \cdot P_B$ measured during the acceleration of the polarized proton beam in the AGS as a function of $G\gamma$, where G is the proton anomalous magnetic moment and γ the Lorentz boost factor. $G\gamma$ is related to E_B by $G\gamma = 1.91 \cdot E_B$. $G\gamma$ is directly connected to the spin motion of particles in a storage ring and it gives the number of spin precessions during one orbit.

During the acceleration, whenever the value of $G\gamma$ is an integer, an *imperfection* depolarizing resonance is crossed with consequent loss of beam polarization. To avoid such polarization losses, when crossing these resonances, the beam polariziation is reversed with the use of a partial solenoidal siberian snake.

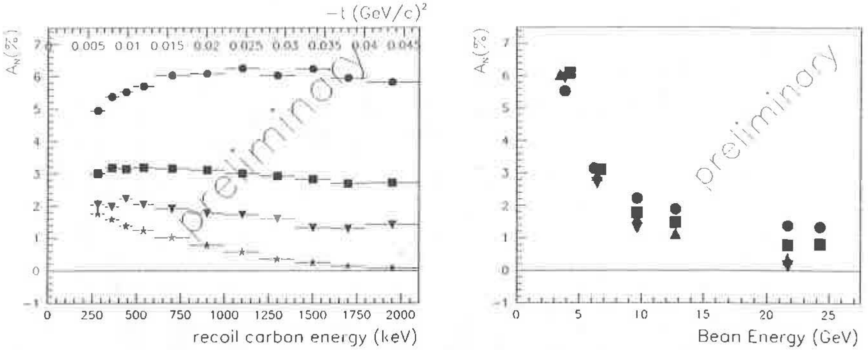

Figure 2: **left:** A_N^{pC} for $pC \to pC$ as function of the recoil carbon kinetic energy $T_{rec} = |t|/2M_C$ measured with the AGS polarized proton beam at 4 different energies; starting from top at 3.9 GeV, 6.5 GeV, 9.7 GeV, and 21.7 GeV. The displayed errors are statistical only. The estimated normalization error (i.e. ΔP_B) is $\sim$ 10% for the lowest energy data points and increases to $\sim$ 20% for the highest ones. P_B has been measured concurrently with an internal inelastic polarimeter ($pC \to p + p + X$). The systematic error, which comes mainly from backgrounds below the elastic pC peak, pileups and electronic noise, is estimated to be $< 20\%$.
right: A_N^{pC} as a function of the incident beam energy for different intervals of t: full circles $t \sim -0.01$ GeV$^2/c^2$, squares $t \sim -0.02$ GeV$^2/c^2$, triangles pointing up $t \sim -0.03$ GeV$^2/c^2$, triangles pointing down $t \sim -0.04$ GeV$^2/c^2$. At larger values of the beam energy, there appears to be a weak or no energy dependence. This behavior is suggestive of the onset of an asymptotic regime.

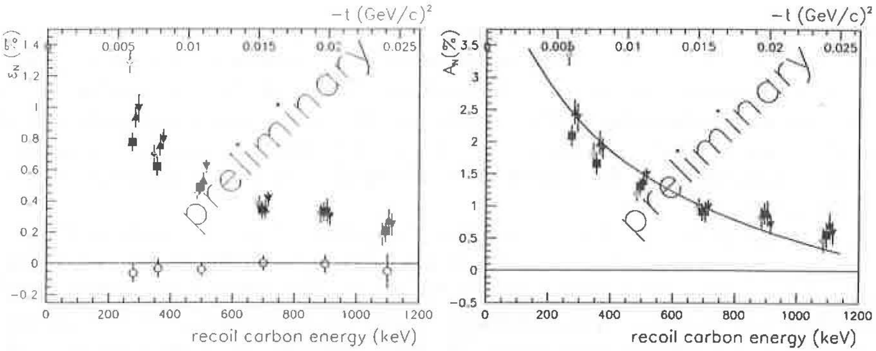

Figure 3: **left:** Several measurements of $\varepsilon_N = A_N \cdot P_B$ with the AGS CNI polarimeter as a function of T_{rec} at E_B of 24.7 GeV with similar P_B. Each measurement lasted about 5 minutes. The open circles are the asymmetries measured with an unpolarized beam.
right: A_N^{pC} for $pC \to pC$ at 24.7 GeV extracted from the measured ε_N. In order to determine A_N^{pC} from ε_N, P_B has been estimated by normalizing ε_N to a phenomenological fit to the E950 data (full line [5]). For these measurements $P_B \sim 0.4$. The overall error on P_B thus determined is around $\pm 30\%$ (relative) and comes mainly from the uncertainties in the E950 data.

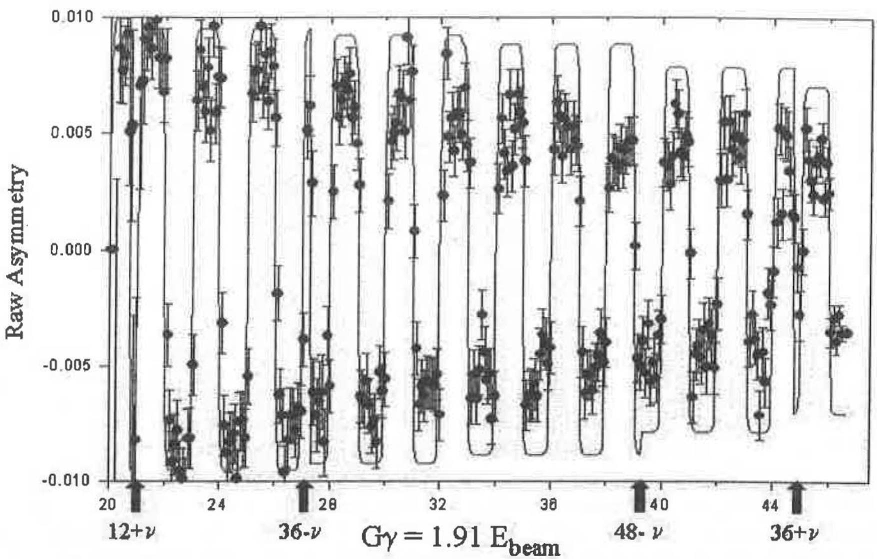

Figure 4: Measured asymmetry $\varepsilon_N = A_N \cdot P_B$ during the acceleration of the polarized proton beam in AGS as a function of $G\gamma = 1.91 \cdot E_B$ from $E_B \sim 10$ GeV to extraction at 24.7 GeV. Each point corresponds to an increase of E_B of ~ 50 MeV (1 msec measurement time). The continous line is a simulation of depolarization effects during the acceleration, assuming the analyzing power of the polarimeters is constant.

In addition to the *imperfection* resonances, four *intrinsic* resonances are visible in Figure 4. $12 + \nu$, $36 - \nu$, $36 + \nu$ are the so called strong resonances, where the copuling between the orbiting proton spin and the transverse fileds in the focusing quadrupoles are strong, thus generating major polarization losses. $48 - \nu$ is a weaker resonance. ν is the betatron oscillation frequency and $\nu \sim 8.7$ in the AGS. When crossing these resonances the beam polarization is reversed using an AC RF dipole (*spin flipper*) in order to preserve the polarization.

The curve in Figure 4 is from a simulation of depolarization effects in the AGS during the acceleration, assuming the analyzing power of the polarimeter is constant (energy independent). The curve is normalized to the data at the low energy end ($G\gamma \sim 20$). The qualitative features are well reproduced, in particular the polarization reversal when crossing the strong intrinsic resonances. The data, however, are more consistent with a continous polarization loss during the beam acceleration rather than polarization losses at particular spots.

5. Determination of the absolute beam polarization

The RHIC Spin program [6] aims to determine the spin asymmetries with one or both beams polarized for a variety of processes with high precision, such to allow significant

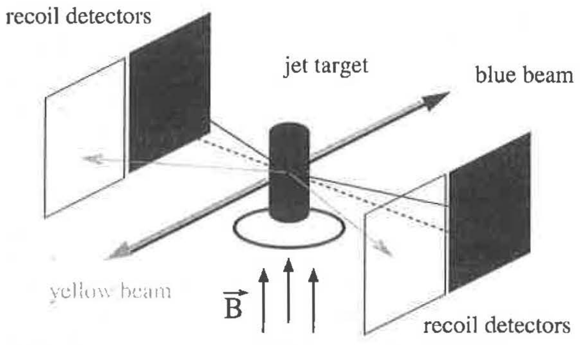

Figure 5: Schematic view of the polarimeter set-up showing the jet target, the recoil detectors and the target holding magnetic field.

comparison with theoretical predictions and possibly unveil new physics. A crucial requirement is the knowledge of the absolute polarization of the RHIC polarized proton beams to 5% of its value or better and its continous monitoring.

For this purpose an absolute polarimeter using an internal polarized hydrogen gas jet target is being built [7]. The jet target will cross the RHIC beams in the vertical direction with its polarization also directed vertically (i.e. normal to the horizontal plane). The polarized target is a free atomic beam jet. The state-of-art atomic polarized source will deliver polarized protons with a polarization better than 90% and a density in excess of 10^{12} p/cm^2. The target polarization will be determined with a Breit-Rabi polarimeter to better than 3%. The jet target, its properties, performace and operation, have been discussed in great detail at this workshop by A. Zelenski [8]. The current plan is to install the polarimeter for the year 2004 run with the initial goal of determining the beam polarization to about 10%. In 2005 our plan is to reach the desired precision of 5% on the beam polarization.

The chosen polarimetric process is elastic *pp* scattering at very small momentum transfer t in the Coulomb Nuclear Interference (CNI) region of $0.001 < |t| < 0.02$ $(\text{GeV}/c)^2$, where the analyzing power A_N^{pp} reaches a maximum value of about 0.045 [1]. The present knowledge of A_N^{pp} from previous experiments and theory, however, is not sufficient to obtain the desired precision. Therefore, a new measurement of A_N^{pp} to about ± 0.001 is required.

This measurement can be performed *in situ* at RHIC, with the same apparatus measuring the beam polarization, at any energy of interest, independent of theoretical assumptions, using the so called *self-calibration* method. The transverse spin asymmetry in elastic *pp* scattering of a polarized beam on an unpolarized target is identical in magnitude but with opposite sign to the unpolarized beam – polarized target one in the same kinematical region: $A_N^{p\uparrow p} = -A_N^{pp\uparrow}$. This symmetry relation, which holds for elastic scattering only, permits the direct transfer of the target polarization P_{target} to the beam polarization P_{beam}, i.e. P_{beam} can be expressed in terms of P_{target}.

Figure 5 shows the schematic setup of the polarimeter. The recoil protons from elastic *pp* scattering will emerge close to 90° with respect to the beam direction and will be detected in the horizontal plane with silicon detectors. These detectors will provide good energy, position and time measurements of the recoil particle. Because of the very low energy of the recoil protons ($0.5 < T_{rec} < 10$ MeV) the detectors must be positioned inside the RHIC vacuum. They will be located in two recoil-arm cylindrical chambers, attached to the central jet target vaccum chamber, on the left and on the right of the beams at about 80 cm from the jet axis.

The recoil protons angle ϑ_R varies between 1° and 5° in the considered t range and the recoil protons emerge in the same hemisphere as the scattered proton. Therefore, two separate sets of silicon detectors will be used for each of the two RHIC beams as illustrated in Figure 5. In order to cover a 15° angle in azimuth on both sides of the beam, each set of detectors will consist of a vertical array of three silicon detectors. The silicon detectors will have a double sided readout in order to measure the azimuthal angle as well as scattering angle ϑ_R of the recoil particles. To fully stop 10 MeV recoil protons about 800 μ of silicon is required. Rather than build a single thick detector, a stack of two silicon detectors will be used. The second detector will be also used as a veto for punch through particles.

This setup will allow to study A_N^{pp} in polarized *pp* elastic scattering in the kinematical range of $0.001 < |t| < 0.02$ $(\mathrm{GeV}/c)^2$ and $\sqrt{s}$ up to 22.4 GeV with a very high accuracy of $\Delta A_N^{pp} < 10^{-3}$. With both target and beam polarized also the double spin parameter A_{NN}^{pp} will be studied with similar precision.

The measurement of the absolute beam polarization and the calibration of the *fast pC* polarimeters will require several measurements of spin asymmetries, most of them performed simultaneously, as illustrated below:

$$P_{target} \to A_N^{pp} \to P_{beam}^{pp} \to A_N^{pC} \to P_{beam}^{pC} \quad .$$

At each step some measurement errors will accumulate. The uncertainty on the absolute beam polarization measurement will be dominated by the uncertainty on the target polarization, estimated at about 3%, and the background below the elastic peak, which will contribute an uncertainty around 1%. Statistics will also contribute an error of about 1% to the measurement.

With frequent reversals of the target polarization, bunches of opposite polarization in the RHIC rings and reversal of the beam polarization with the spin flippers several systematic effects in the extraction of A_N^{pp} and P_{beam} can be controlled and minimized. Further, the reversal of the target holding magnetic field will allow the supression of most left – right acceptance effects. In particular, comparing A_N^{pp} for the two RHIC beams, will be a strong indicator for systematic effects.

The overall anticipated error on the beam polarization based on the expected performance of the *pp* polarimeter and on the performance of the *fast pC* polarimeters is about 6% of the beam polarization value (i.e. relative error):

$$\frac{\Delta P_{beam}}{P_{beam}} = \frac{\Delta P_{target}}{P_{target}} \oplus \frac{\Delta A_N^{pp}}{A_N^{pp}} \oplus \frac{\Delta P_{beam}^{pp}}{P_{beam}^{pp}} \oplus \frac{\Delta A_N^{pC}}{A_N^{pC}} \oplus \frac{\Delta P_{beam}^{pC}}{P_{beam}^{pC}} \tag{1}$$

$$\frac{\Delta P_{beam}}{P_{beam}} = 3\% \oplus 2\% \oplus 2\% \oplus 4\% \oplus 2\% = 6\% \;: \tag{2}$$

6. Summary

The t−dependence of A_N in pC elastic scattering in the CNI region has been measured with relative polarimeters from 3.8 to 100 GeV/c. The results at 3.8 and 6.5 GeV/c are nearly constant for $-t \geq 0.01$ GeV$^2/c^2$. The shapes of A_N at 24 and 100 GeV/c are quite similar, and show a drop in magnitude with increasing $|t|$ consisten with a hadronic spin-flip amplitude which is 10 − 15% of the non-flip amplitude. These polarimeters will continue to play a central role in the future polarized proton operations at RHIC because of their fast and reliable measurements of the beam polarizations.

A polarized gas jet target is being installed to determine the RHIC proton beam polarization to better than 5% and to calibrate the *fast pC* polarimeters to a similar precision.

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