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Measuring the Proton Beam Polarization From The Source To RHIC

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Abstract. Polarimeters are necessary tools for measuring the beam polarization during the acceleration process as well as a yardstick for performing spin physics experiments. In what follows, I will describe the principles of measuring the proton beam polarization and the techniques that are employed at various energies. I will present a tour of the polarimetry employed at the BNL Relativistic Heavy Ion collider (RHIC) polarized proton complex as it spans the full spectrum from the source to collider energies.

Keywords: Polarized protons, polarimeters, gas jet target.
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INTRODUCTION

A polarimeter is a tool that measures the beam polarization, the degree of alignment of the spins of an ensemble of protons in a beam with respect to a specific direction. This is generally done by sampling the spin projection of a large number of particles in a scattering process that is sensitive to the spin direction.

In an accelerator, polarimeters are used at various stages primarily as diagnostic tools to maintain the beam polarization during beam transport, acceleration, and storage. Of course, the final goal is the physics program and polarimeters are often employed as a first stage of an experiment to measure the polarization of the beam impinging on the target. This normalizes the final result and the error in the polarization measurement has a direct statistical impact on the result. While the accuracy from electron beam polarimeters is now well below 5%, this represents a lofty goal for proton beam polarimeters and is the desired goal for the polarized proton physics program at RHIC.

BEAM POLARIZATION

The degree of beam polarization along a certain direction is defined as:

$$P = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$

Where $N_\uparrow$ and $N_\downarrow$ are the number of protons with spins parallel and antiparallel to the desired direction. In an accelerator, the stable spin direction is usually transverse to the momentum vector and along the vertical. The task is to find proton induced reactions that are sensitive to the spin alignment of the beam. Such reactions are in a plane perpendicular to the beam polarization direction and are usually sensitive to the spin-spin or the spin-orbit interactions between the incoming proton beam particle and the target nuclei. The yield depends on whether the beam is polarized up or down and is reflected in the number of detected scatters or events of particular interest.

Typically one tries to measure the number of events with the beam polarized up versus those with the beam polarized down making sure that the experimental conditions remain unchanged. The resulting beam polarization is:

$$P = \frac{1}{A} \frac{n_\uparrow - n_\downarrow}{(n_\uparrow + n_\downarrow)}$$

Where $n_\uparrow$ and $n_\downarrow$ refer to the number of scatters, properly normalized to the beam intensity, with the beam polarization up and down respectively and A is the "analyzing power" of the reaction, a measure of the sensitivity of the process to the beam polarization. Similarly, an apparatus that can measure the number of scatters to beam-left, n_L, and beam-right, n_R, simultaneously will determine the degree of up and down polarization independently by substituting n_L and n_R in the above equation. In general both methods are utilized and combined in order to reduce systematic errors and the potential dependence on geometrical or acceptance effects.

The statistical error in these measurements is a function of both the analyzing power A and the total number of events N [$(n_\uparrow + n_\downarrow)$ or $(n_L + n_R)$] or the sum of all four terms if a combined measurement is performed.

$$\Delta P = \frac{1}{A} \frac{1}{\sqrt{N}}$$

It is therefore important to utilize reactions with large analyzing power as well as large cross section. The latter is a measure of the frequency of the reaction given a certain number of protons impinging on a specific target. In the design of a polarimeter, the quantity to optimize is the figure of merit:

$$N \cdot A^2$$

In general a beam polarimeter should serve the following requirements:

- A polarization monitor capable of several samples over a reasonable time period.
- A diagnostic tool that samples on demand and a turn key operation primarily for machine tuning with measurements and feedback provided within a few minutes.
- A large analyzing power, high cross section and low background.

- A large dynamic range specially when dealing with the acceleration cycle. At RHIC the range is from 24 GeV at injection to 250 GeV at top energy.
- Finally, fiscal constraints require building such apparatus at reasonable cost.

It is not always possible to combine all these features and compromises are sometimes necessary. In what follows I will describe the polarimeters employed at each stage in RHIC polarized proton complex, Fig.1, with some justification as to the choices made.
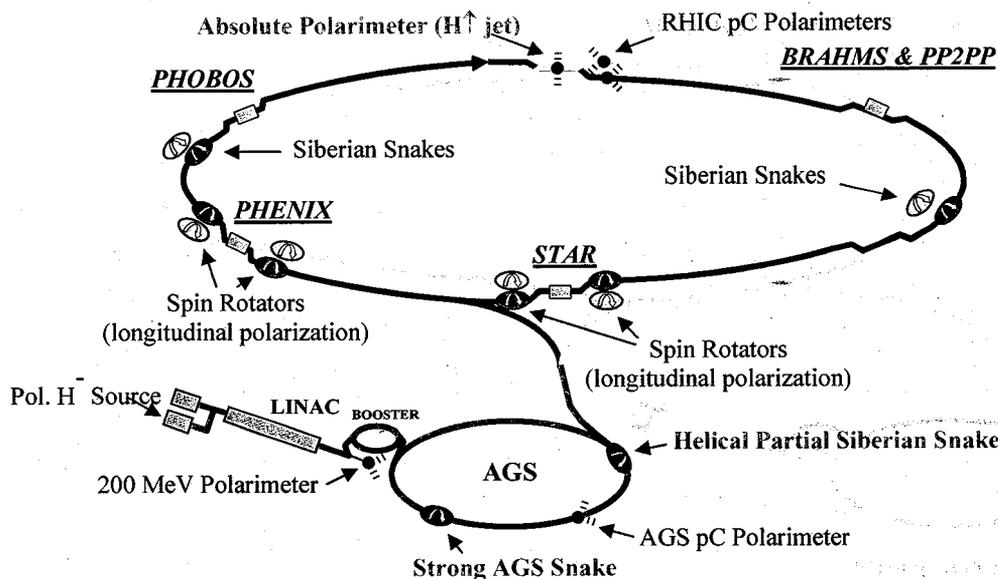

FIGURE 1. The RHIC polarized proton collider showing the locations of all the polarimeters used at various energies.

Unlike electromagnetic reactions where the analyzing power and cross section are calculable, proton induced reactions are not precisely calculable especially at high energies. Thus one reverts to empirical experimental results. These measurements are generally done with polarized proton targets the polarization of which is well measured using NMR techniques and Masers. Until recently, these targets were not pure hydrogen and the target material presents undesired background especially in inclusive measurements. This is not an impediment for exclusive reactions such as p-p elastic scattering when both outgoing particles are detected with good kinematic constraints.

The Lamb shift polarimeter at the source to measure the beam polarization from 2-35 keV

The Lamb-shift polarimeter developed at INR, Moscow and TRIUMF [1], [2] was optimized for the low duty-factor operation of the RHIC OPPIS (Optically Pumped Polarized Ion Source). The advantages of this polarimeter are a low energy operation, a large analyzing power and high counting rate.

For polarization measurements, a longitudinally polarized H⁻ ion beam from OPPIS is bent 47.4 deg (at this rotation angle the nuclear spin direction remains longitudinal) and is passed through a He-gas stripping cell for conversion to protons. The He-cell is situated in a 2.0kG solenoidal field to preserve the polarization during the stripping process. The proton beam is focused by an Einzel lens and directed into the Lamb-shift polarimeter. The proton beam is converted to a meta-stable atomic beam in a sodium-vapor cell. The hyperfine levels populations of the meta-stable atoms (which depend on the initial proton polarization) are analyzed by the spin-filter [1]. The intensity of the meta-stable atoms passed through the spin-filter is measured by a Lyman-alpha (Lα) detector. Micro channel plates are used in this device to measure the Lyman-alpha photons (121.6 nm wavelength) produced when the meta-stable states are quenched by an electric field.

The proton polarization is determined from Lα counting rate asymmetry at the spin-flip in the OPPIS: $P = (1/0.5) (P^+-P^-)/(P^++P^-)$ [1]. The counting rate is about 1MHz and provides a 1% statistical accuracy in a 3 min measurement (1 Hz, 300 us pulse duration). The systematic error of these measurements is about 5-10%, which was determined from cross-calibration with the 200 MeV polarimeter. The Lamb-shift polarimeter is proven to be an essential tool for the OPPIS polarization studies.

The 200 MeV polarimaters

The beam intensity at the exit of the 200 MeV Linac is upwards of 2×10^{11} protons per 300 usec pulse and the polarimeter is positioned at the exit of the Linac just downstream of where the beam is deflected for injection into the Booster. At this energy, we have a large body of experimental data at our disposal. Experiments and calibration of this polarimeter were done using the 200 MeV polarized proton beam at IUCF [3].
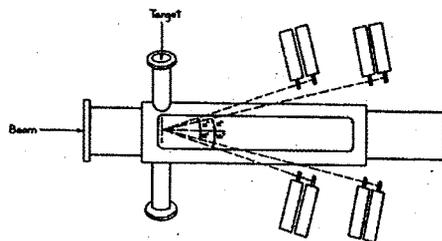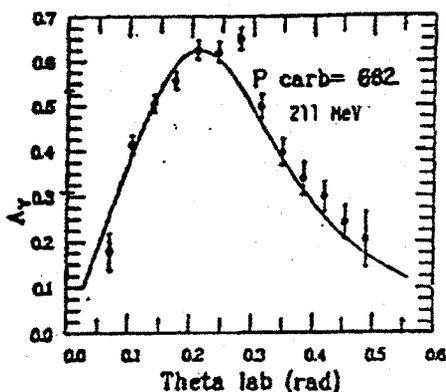

FIGURE 2. The analyzing power vs. scattering angle in inclusive p-Carbon scattering at 211 MeV and the plan view of the polarimeter two scattering arms at 12 and 16 degrees respectively.

The cross sections are large and the analyzing power is appreciable reaching unity in some cases. The task is easy and the apparatus is straightforward. This polarimeter

scatters polarized protons from a carbon target filament. The detectors are scintillators counters viewed by fast photo tubes, Fig. 2. The beam polarization is vertical and we measure the scattering in the horizontal plane. Two identical Left/Right spectrometers subtending angles of 12 and 16 degrees in the laboratory frame on either side of the beam measure the left-right scattering of the proton beam. A third spectrometer looks at 12 degrees in the vertical direction that serves two purposes: to measure any beam polarization component in the horizontal direction perpendicular to that plane, and as an intensity monitor of the accumulated up versus down data. The polarization at the source is flipped on alternate pulses and the data of the two polarization states are accumulated simultaneously.

With the increase in beam intensity, the scintillators were moved further away from the target in order to reduce the solid angle and the counting rate to below 1 MHz to assure no saturation or pile up. In addition, a second polarimeter utilizing p-d elastic scattering was also employed for calibration purposes. This 200 MeV polarimeter provides a 1% statistical accuracy in a few pulses.

Polarimeters at energies between few and 24 GeV

This is the domain of the AGS. Traditionally pp elastic scattering has served this energy range quite well where the analyzing power at four-momentum transfer values of 0.1-0.3 GeV^2/c^2 is utilized. This has been measured precisely using polarized proton targets to better than 5 % up to energies of 12 GeV. Beyond that the cross sections are lower and the accuracy is worse. A representative compilation is shown in Fig. 3. The asymmetry falls off with increasing beam energy as ($\sim 1/P$) and at the AGS the analyzing power ranges between 5 and 2 % [4].
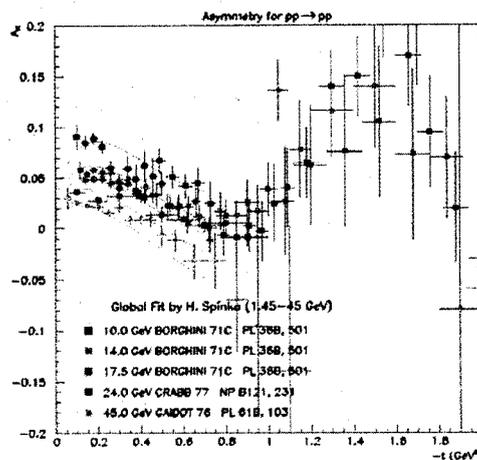

FIGURE 3. The Analyzing power in p-p elastic scattering.

A typical p-p elastic scattering polarimeter has two arms to simultaneously measure the forward scattered and recoil protons. However, the physical constraints in the AGS, the vacuum pipe and the 10ft long straight sections, permit the placement of the

forward arms that subtend a few degrees from the beam line which serve the lowest energies. Otherwise, the measurement is done with the recoil proton only at kinetic energy of approximately 500 MeV and scattering angle of approximately 76 degrees with respect to the beam direction, Figure 4. Time of flight, energy range, and energy angle correlation is utilized to select the pp elastic scattering reaction from the inelastic scatters. The detectors are scintillation counters viewed by extremely fast photo tubes. Special threshold cuts allow for fast retrieval of the data with minimal online computer processing time. As such it is a counting experiment of the data that pass the trigger cuts.
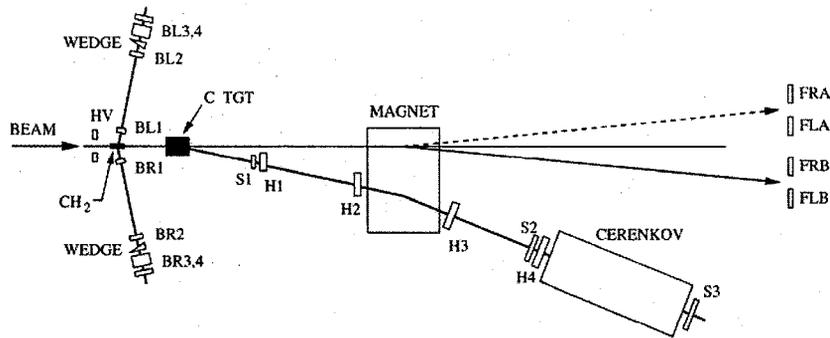

FIGURE 4. A typical layout of an elastic scattering polarimeter with two sets of forward and recoil arms set at specific laboratory angles to measure the scattered protons at the appropriate kinematics.

Choice of reactions for polarimetry at higher energies

From the above discussion, it becomes clear that as we proceed to higher energies, we need to employ different scattering processes with the hope of obtaining a better figure of merit and viability over a wide energy range. Experiments using polarized proton beam scattering from unpolarized hydrogen targets carried out at 12 GeV/c at the ZGS [5] and at 200 GeV/c at Fermilab [6], observed large left-right asymmetries reaching over 30% in the inclusive production of pions, Figure 5. The copious production of pions and such a large analyzing power seems to be ideally suited for a polarimeter application at RHIC energies. These data and the systematics of which provide a 10% absolute measurement were considered adequate for beam commissioning and early physics results.

For RHIC it was recognized that carbon is the only simple target that can withstand the beam heating but such a target presented another dilemma. Is the production from a nuclear target likely to dilute the observed asymmetry compared to that from hydrogen? Is the asymmetry large enough at lower energies? The available negative pion data at lower energy are not similar to what is observed at higher energy.
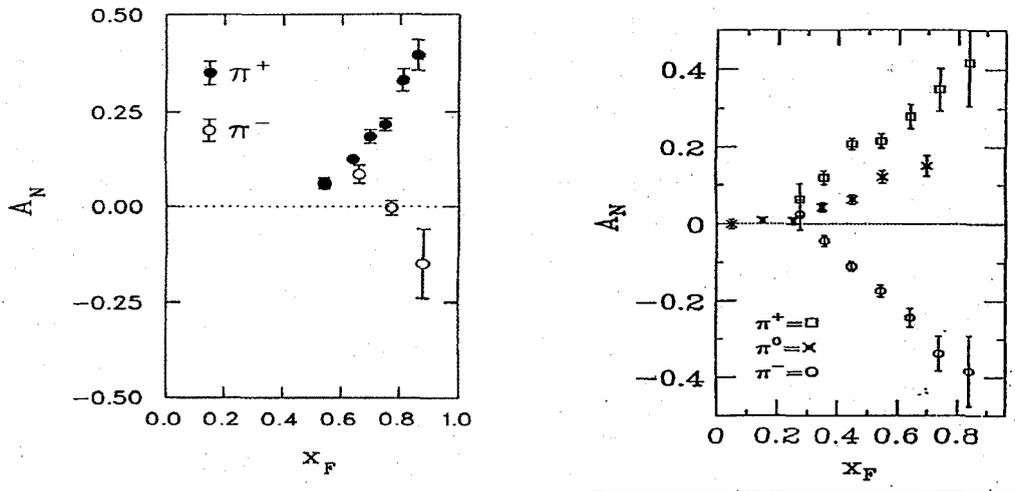
FIGURE 5. Asymmetries in pion production measured at the Argonne ZGS at 12 GeV/c (left) and Fermilab at 200 GeV/c (right) incident beam momenta respectively.

These questions were answered by a dedicated measurement (the apparatus is shown in Figure 4) of the asymmetry in pion production using an extracted AGS polarized proton beam at 22 GeV incident on a hydrogen, carbon and CH2 targets [7]. The data, Figure 6, indicate similar asymmetries to those obtained at 200 GeV/c and no dilution due to the nuclear target. This allowed a design of a polarimeter for RHIC based on the measurement of inclusive negative pion production. One drawback was the size of the apparatus (30 meters) and another was the significant cost.
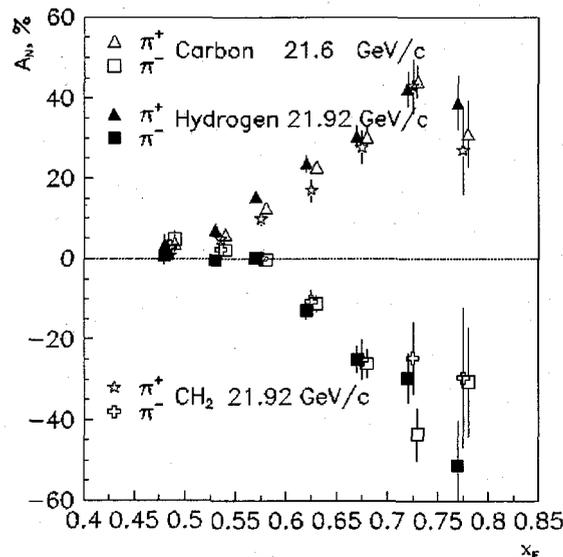

FIGURE 6. Asymmetries in pion production measured at the AGS at 22 GeV/c indicating similar results from hydrogen and carbon targets.

A competing idea for a polarimeter utilizes p-p and p-C elastic scattering in the Coulomb Nuclear Interference region. The asymmetry of which arises from the interference between the electromagnetic spin flip amplitudes with the hadronic spin nonflip amplitude is calculable. A complication arises from the unknown single flip hadronic amplitude which was estimated at about 15% and was likely to decrease as we go higher in energy. The advantage of this approach lies in the fact that the analyzing power peaked at a respectable 5% and 4% for pp and pC respectively at a 4-momentum transfer value of 10^{-3} GeV^2/c^2, Fig 7.
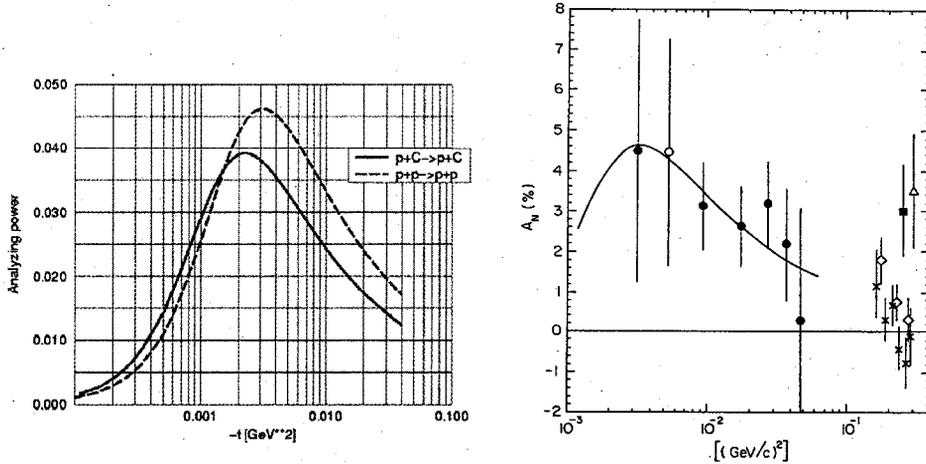

FIGURE 7. The calculated analyzing power in pp and p-C elastic scattering in the CNI region. The respective measurement at 200 GeV/c is from Fermilab experiment E704 [8].

The polarimeter apparatus is compact and the elastic reactions can be characterized by measuring the recoil particles at energies of a few MeV at angles slightly forward of 90^0 in the laboratory frame. This concept is shown schematically in Figure 8.
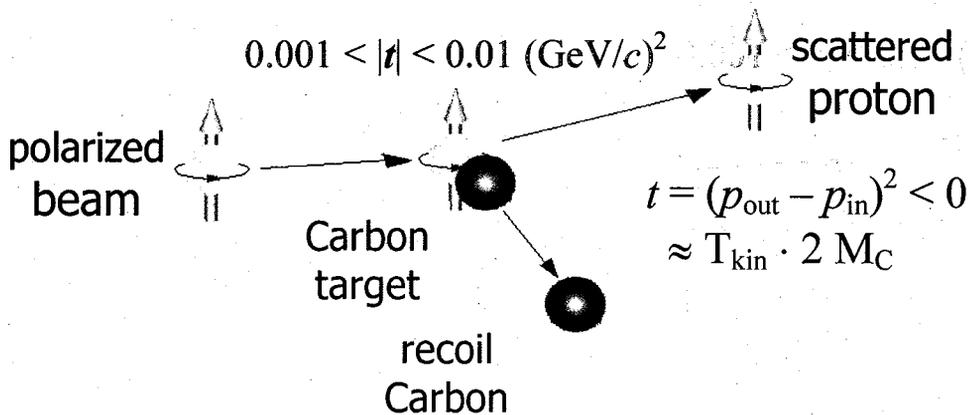

FIGURE 8. A schematic of the p-C elastic scattering in the CNI region

Figure 9 shows the RHIC polarimeter apparatus which is employed separately in the Blue and Yellow beam lines. These polarimeters utilize carbon targets 5-10 um wide and 3.5 ug/cm2 thick. The recoil carbon were detected using 3 pairs of silicon strip detectors situated at 15 cm to the left and right of the target at 90 degrees and 45 degrees up and down respectively. A similar set up is also employed in the AGS. This allows a direct comparison between the beam polarization at the AGS extraction energy and that measured at RHIC injection.
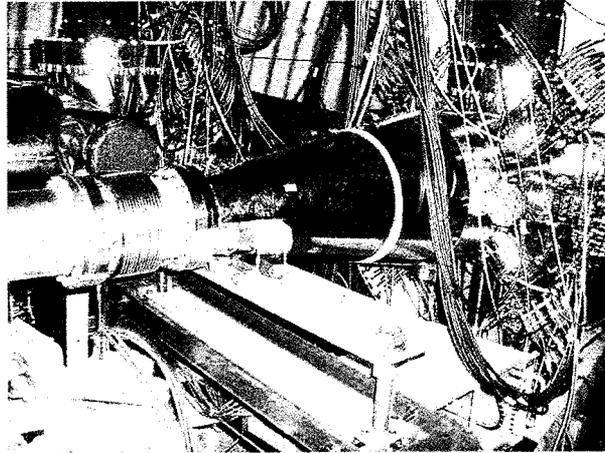

FIGURE 9. The p-C elastic scattering polarimeter installed at RHIC. A similar set up is installed in the AGS

The AGS polarimeter was calibrated using the internal pp elastic scattering polarimeter [9]. The RHIC polarimeters were calibrated using the polarized jet target (see later). Representative asymmetries are shown in Figure 10.
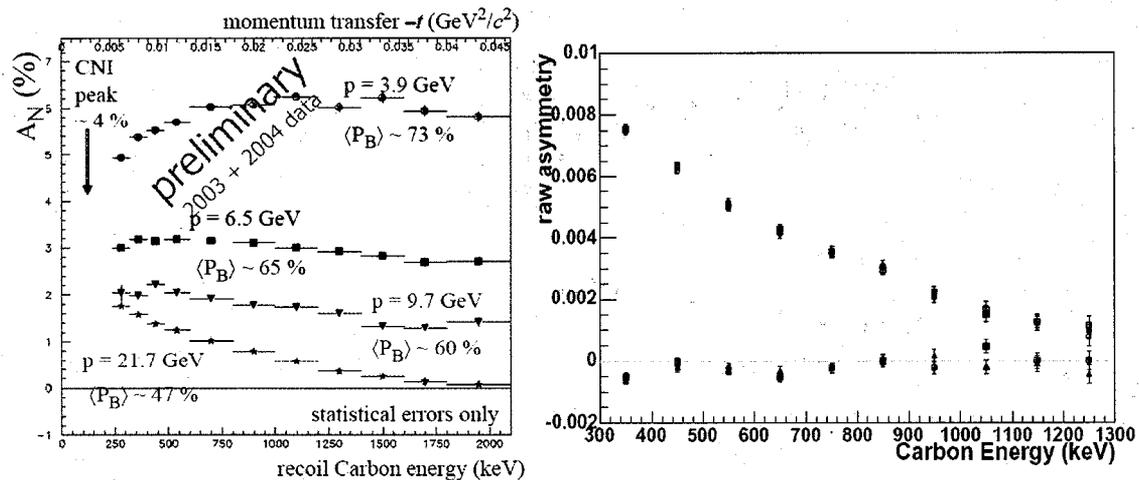

FIGURE 10. Asymmetries in p-C elastic scattering measured at the AGS (left) and at 100 GeV/c at RHIC (right).

The RHIC physics program requires a polarization measurement accuracy of 5%. This was achieved by installing a polarized hydrogen jet target, Figure 11, at the 12 o'clock interaction region along with a polarimeter comprising left and right silicon detectors to measure the recoil protons in pp elastic scattering. The jet had an intensity of 12.4 x 10^{16} H atoms/sec and a beam width 6.6 mm at FWHM. A Breit Rabi polarimeter measured the jet atomic hydrogen polarization in-situ and averaged 95.8% +/- 0.1% for both up and down polarization respectively. The molecular hydrogen component was measured at 1.5% is assumed to be unpolarized. This represented a net 3% nuclear dilution for an effective jet polarization of 92.4% +/- 1.8%. The primary error lies in the molecular component measurement [10,11,12]. First the jet measured the asymmetry in pp elastic scattering using the jet polarization and averaging over the beam polarization. This is normalized by the jet polarization to give the analyzing power [13] of the reaction, Figure 11. Next the process is reversed and the same data were used to measure asymmetry using the beam polarization while averaging over the jet polarization. The ratio of the two asymmetries gives the average beam polarization. With this setup the jet alternates running between the Blue and Yellow beams in order to provide an overall calibration of both polarimeters over a run. In 2006 the jet statistical accuracy calibrated the RHIC polarimeters to an accuracy of 5% at the incident beam energy of 100 GeV/c. Calibrations were also carried out at 24 and 32 GeV/c respectively but to worse accuracy. The beam intensities have reached a level at which the jet can provide a 10% beam calibration over a 6 hour store.
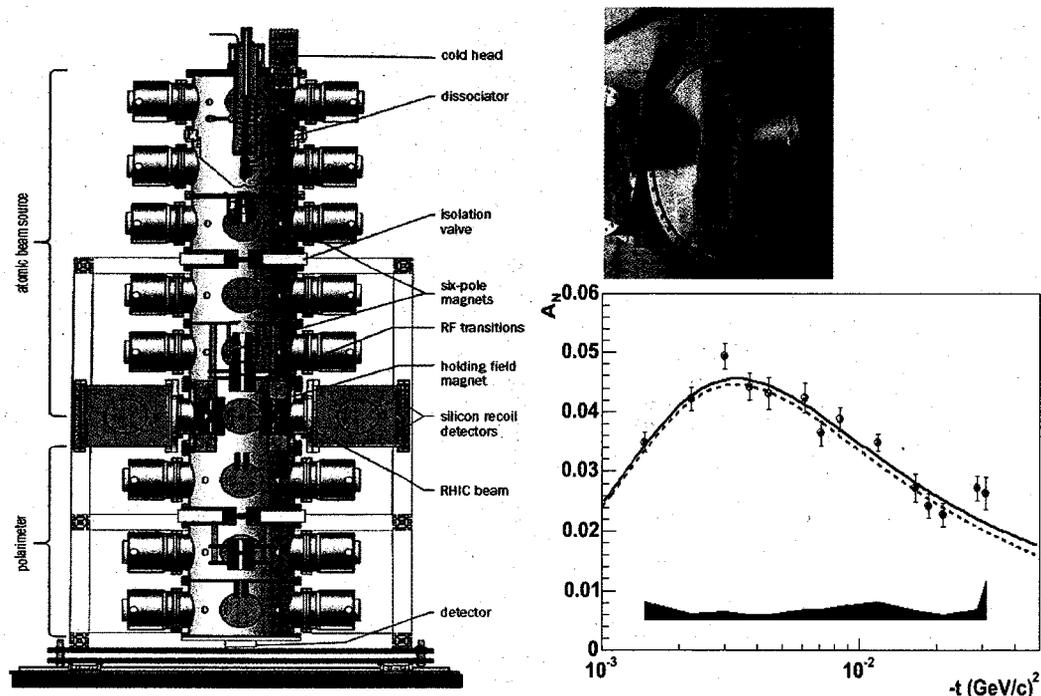

FIGURE 11. The polarized jet target assembly, a set of silicon detectors and the measured analyzing power in pp elastic scattering measured at 100 GeV/c at RHIC.

The combination of the polarized jet and p-C polarimeters allows similar calibration at any energy that the RHIC program desires. The accuracy is limited by the knowledge of the molecular hydrogen component, the first measurement of which was carried out using a 12 mm QMA which covered the full jet beam. Later a different method was employed utilizing an electron beam to ionize the gas followed by a magnetic analysis. While the latter yielded a similar result as above, our confidence in the measurement was not high since we were not able to reproduce the ionizing cross section [14]. This approach may still be a viable one if we replace the magnetic analysis with a time-of-flight system which may not suffer from acceptance issues [15]. We are also working on an idea of measuring the atomic and molecular components in situ utilizing the luminescence produced when the proton beam impinges on the jet and using a CCD camera with special filters. Alternately a spectrometer is also being tested for the same. The goal is to improve this measurement to an accuracy of 1%.

ACKNOWLEDGMENTS

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