Precision, absolute proton polarization measurements at 200 MeV beam energy

A Zelenski¹, G Atoian¹, A Bogdanov², D Raparia¹, M Runtso², E Stephenson³

¹Brookhaven National Laboratory, Upton, NY, 11967, USA
²Moscow Engineering Physical Institute (MEPHI), Moscow 115409, Russia
³IUCF, Bloomington, 47408, USA

E-mail: zelenski@bnl.gov

Abstract. A new polarimeter for absolute proton beam polarization measurements at 200 MeV to accuracy better than ±0.5% has been developed as a part of the RHIC polarized source upgrade. The polarimeter is based on the elastic proton-carbon scattering at 16.2° angle, where the analyzing power is close to 100% and was measured with high accuracy. The elastically and in-elastically scattered protons are clearly identified by the difference in the propagation through variable copper absorber and energy deposition of the protons in the detectors. The elastic scattering polarimeter was used for calibration of a high rate inclusive 12° polarimeter for the on-line polarization tuning and monitoring. This technique can be used for accurate polarization measurements in energy range of at least 160-250 MeV.

1. Polarization measurements technique

The polarized beam for RHIC spin physics experimental program is produced in the optically-pumped polarized H⁺ ion source (OPPIS) and then accelerated in linear accelerator (Linac) to 200 MeV beam energy for strip-injection to Booster and further acceleration to 24.3 GeV in AGS for injection in RHIC. RHIC is the first collider where the “Siberian snake” technique was very successfully implemented to suppress the resonance depolarization during beam acceleration in AGS and RHIC [1].

Precision, absolute polarization measurements in the wide energy range from a few keV (in the source) to 250 GeV (top RHIC energy) are required for accelerator tuning to minimize depolarization and finally for experimental data normalization. Therefore, the polarimetry is an essential component of the polarized collider facility. A complete set of polarimeters includes: Lamb-shift polarimeter at the source energy, a 200 MeV polarimeter after the linac, and polarimeters in AGS and RHIC based on proton-Carbon scattering in Coulomb-Nuclear Interference region [2]. A polarized hydrogen jet polarimeter was used for the absolute polarization measurements in RHIC [3].

A 200 MeV polarimeter is based on proton-Carbon inclusive scattering at 12° angle and was calibrated to ±5% absolute accuracy in calibration experiment by comparison with proton-Deuteron elastic scattering. This polarimeter is used for the source development polarization tuning and optimization. The ongoing program of the polarized source upgrade to 10 mA H⁺ intensity and 85%...
polarization [4] requires more accurate absolute polarization measurements at very high peak intensity.

![Figure 1](image)

**Figure 1:** Measurements of the analyzing power for proton scattering from $^{12}$C at 200 MeV. The blue (green) curves correspond to protons exiting from the ground (4.44-MeV) state. The black curve represents the sum of the two data sets /7/.

The precision absolute measurements at injection to Booster and AGS are also essential for depolarization studies in Booster and AGS. The 200 MeV inclusive polarimeter was upgraded and calibrated in 2009 Run to absolute accuracy better than ±0.5% by using the proton-Carbon elastic scattering measurements in additional 16.2° arms. The analyzing power $A_y$ for proton-Carbon elastic scattering at 200 MeV has been precisely measured in experiments at IUCF. “These measurements are based on basic constrains imposed polarization observables for reaction with spin structure: $1\frac{1}{2} + 0 \rightarrow 1\frac{1}{2} + 0$ (proton+ Carbon) and represent some of the most accurately known spin observables at intermediate energies”[5]. The results are presented in figure 1. The analyzing power for elastic scattering is: $A_y = 99.35\pm0.1\%$ at 16.2° scattering angle. Since the $A_y$ is reaching maximum at this angle, the systematic error contribution to $A_y$ due to the energy measurement accuracy ~1.0 MeV and scattering angle accuracy of a 0.1° does not exceed ~0.1%.

The elastic scattering was selected by using the copper absorber with the variable thickness. Without separation the $A_y$ for inclusive scattering at 16.2° angle is diluted by inelastic processes to about 52% [6]. The well known first exited state in Carbon is at 4.44 MeV energy. The cross section and analyzing power for the ground and 4.44-MeV states in $^{12}$C has been reported by Meyer et al. [7]. The cross-sections for the elastic scattering state and the 4.44-MeV state excitation are shown in figure 1. At 16.2°, contamination of the analyzing power amounts to 2.2%, if all of the 4.44-MeV state is not suppressed. At this angle the energy of elastically scattered protons is 198.4 MeV, excitation of the 4.44-MeV state reduce this energy to ~193.6 MeV.
2. Experimental setup

The AGS cycle for polarized beam operation is about 4 seconds. The OPPIS operates at 1 Hz repetition rate and additional source pulses are directed to a 200 MeV p-Carbon polarimeter by a pulsed bending magnet in the high-energy beam transport line (for polarization measurements and continuous monitoring). The polarimeter layout after upgrade is shown in figure 3. Five carbon strip targets of different sizes are attached to the target ladder, which situated inside the square vacuum chamber with thin mylar vacuum windows. A new quadrupole focusing and steering magnets were installed in the beam line for better control of the beam size and position at the target. A beam diagnostic system includes Secondary Emission Monitors and multi-wire beam profile monitor in the front of polarimeter chamber. Using these tools background signals in the detectors (from beam halo scattering on the Al target ladder and upstream beam transport pipes) were reduced to below 0.3% level even in inclusive 12° arms. In 16.2° arms an additional suppression at elastic events selection reduces background to below 0.01% level.

A new detector telescope arms were installed at 16.2°. The telescope includes three scintillator detectors, with fast photomultipliers. The first detector of a 6.4×6.4 mm$^2$ is situated at a distance 250 cm from the Carbon target. It is accurately aligned at 16.2° angle on the common for all detectors flat table. A high polarized peak current (typically ∼ 200 µA) produced a high peak event rate (∼ 3-5 MHz) in this small solid angle with thin Carbon strip targets (strip width ∼1-4 mm, thickness 60-100 µm). The second and third plastic scintillators are 12×12 mm$^2$ and 10 mm thick. A variable copper absorber is situated in between first and second detector. The absorber consists of three Cu blocks of a 12.7 mm thickness and two variable step shaped copper ladders. The first ladder is made with 1.0 mm step, the second with 0.1 mm step (see Figure 4). This layout allowed the measurement in the absorber thickness range from zero to 49 mm (total absorption length for 198.4 MeV protons is about 43mm).

With the thickness of the copper absorber chosen to be 41.5 mm thick, the elastic protons passed through the absorber and absorbed into the second scintillator, depositing 20.0 MeV of energy. The energy thresholds for the second and third detectors were set at 15 MeV, which further suppress the background. For the same configuration, inelastic protons from the formation of the 4.44-MeV state had a range in the copper absorber of 40.4 mm and came to a stop before entering the second detector.
Figure 3: A 200 MeV polarimeter layout. The inclusive 12° polarimeter and elastic 16.2° polarimeter are installed and aligned at the common table. The distance from carbon target to the elastic scattering detectors is 210 cm, the distance to 12° detectors is 250 cm.

Figure 4: Detector telescope and absorbers layout. The absorber in between S1 and S2 detectors consists of three 12.7 mm copper blocks. S1,S2,S3-detectors, absorber, collimator are mutually aligned on common base plate.

3. Experimental results
a). Energy calibration. The energy of the proton beam out of the Linac can be varied by the RF-cavity phase tune. The energy measurements and calibration to at least ±0.5 MeV accuracy were done by using the magnetic spectrometer and cross-checked at injection to Booster. The experimental results of the counting rate measurements (S1^S2 coincidence) at different beam energies are presented in figure 5. At the absorber thickness 41.5 mm the suppression factor for 194.0 MeV scattered beam energy (which corresponds to a 4.4 MeV state excitation) is about 20 times in agreement with GEANT simulations. These measurements directly confirm the feasibility of elastic scattering separation by the absorber of properly fine tuned thickness.

At 41.5 mm absorber thickness, the elastically scattered protons of “correct” 198.0 MeV beam energy are completely stopped in the second detector, therefore the rate in the third telescope detector...
is very low. The Linac beam energy can drift in time, The S2/S1 rate ratio is then used for the beam energy monitoring and tuning to improve polarization measurement accuracy.

Figure 5: S2/S1 rate ratio after absorber vs. the absorber thickness at different primary beam energies (diamonds-200 MeV, circles-195.6 MeV). S1, S2 are the counting rates in the first and second telescope detectors. The suppression factor of about 20 at absorber thickness 41.5 mm is in agreement with GEANT simulations.

b). $A_y$ vs. copper absorber thickness. The measurements of $A_y$ vs. absorber thickness are presented in figure 6. Since at 41.5mm absorber thickness the analyzing power is completely determined by elastic scattering (as demonstrated above) the $A_y$ should be saturated at 99.35% value, as precisely measured in experiments at IUCF [5]. Then the beam polarization of about 80-82% was calculated back from experimentally measured asymmetries. The analyzing power for inclusive 12° polarimeter was also calculated and then beam polarization measured by 12° polarimeter was used for 16.2° analyzing power measurements vs. absorber thickness (see Figure 6). At zero thickness the $A_y$ (16.2°) = 52% in agreement with old calibrations [6].

Figure 6: $A_y$ (16.2°) measurement vs. copper absorber thickness. Three data sets were taken by variation of the movable absorbers with 12.7 mm, 25.4mm and 38.1mm permanent absorber blocks in between S1,S2 detectors. The scale is normalized for $A_y$ saturation at 0.9935 value extrapolated from precision measurements [5].
c). **Systematic errors.** As mentioned above the small cross-section and additional strong suppression of inelastic (4.4 MeV state) by absorber reduce the elastic $A_y$ dilution by inelastic component admixture to less than 0.1%. The beam energy and scattering angle errors are minimal for the analyzing power measurements near maximum value and do not exceed 0.1%. The estimate of the extrapolation error for 200 MeV beam energy and 16.2° angle was estimated at about 0.2%.

4. **Summary**

A new polarimeter for absolute proton beam polarization measurements at 200 MeV to accuracy better than ±0.5% has been developed as a part of the RHIC polarized source upgrade. The polarimeter is based on the elastic proton-carbon scattering at 16.2° angle, where the analyzing power is large 99.35% and was measured with high accuracy. The elastically and in-elasitically scattered protons are clearly identified by the difference in the propagation through variable copper absorber and energy deposition of the stopped protons in the detectors. The rate difference in the subsequent detectors of telescope arms was used for the beam energy monitoring and tuning to improve polarization measurement accuracy. The 16.2° elastic scattering polarimeter was used for calibration of a high rate inclusive 12° polarimeter, which was used for the on-line polarization tuning and monitoring.

**References**

1. Roser T, *AIP Conf. Proc.* 980 2008 pp 15
2. Makdisi Y, *AIP Conf. Proc.* 980 2008 pp 58
3. Zelenski A et al., "Absolute polarized H-jet polarimeter for RHIC" *NIM* A536 2005 pp 248
4. Zelenski A et al., “RHIC polarized source upgrade” this conference
5. Wissink S W et al., *Phys. Rev., C*, 45 1992 pp405
6. Rice J A, Master theses, Rice University, Houston, Texas, 1983
7. Meyer H O et al., *Phys. Rev., C*, 27 1983 pp 459