Proton polarimeter at 200 MeV energy

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Abstract
The precise measurements of proton beam polarization at energy 200 MeV (after the linac before injection to Booster) are required for the polarization measurements (monitoring and optimization) out of the source, for the spin-rotator tune for the vertical polarization and for the study of the polarization losses in the Booster and AGS. For this purpose, we have investigated two possible solutions: polarimeters based on elastic pp and pD scattering. We compare these two polarimeters by estimating their factor of merit, statistical and systematical precisions and quality of the experimental apparatus. The absolute polarization measurements of about ±1% can be achieved at 200 MeV by using very accurate value of pD analyzing power [8].

RHIC is the first collider where the “Siberian snake” technique was very successfully implemented to avoid the resonance depolarization during beam acceleration in AGS and RHIC. Polarimetry is another 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. A polarized hydrogen jet polarimeter was used for the absolute polarization measurements in RHIC. Also local polarimeters for tuning of longitudinal polarization are installed at STAR and PHENIX detectors.

The polarized proton source operates at about 1 Hz repetition rate and additional source pulses were directed to the 200 MeV p-Carbon polarimeter for the source polarization measurements and optimization, spin-rotator tuning and continuous polarization monitoring. The p-Carbon polarimeter was calibrated in comparison with the elastic p-deuteron scattering where analyzing power was measured to less than 0.5% absolute accuracy at IUCF. This polarimeter is described in the papers [1,2].

The polarimeter schematic layout is shown in Fig.1. The targets are exchangeable carbon and CD₂ polyethylene foils. The measurements of elastic proton-deuteron collisions and complete collision kinematics reconstruction provide more accurate absolute polarization measurement. However low counting rate requires a long measurement time (typically about
8 hrs for +/-2% measurement accuracy). This limits the accuracy of calibration since the source polarization can vary during the measurements.

![Diagram of 200 GeV proton polarimeter](image)

**Fig. 1. Layout of 200 GeV proton polarimeter.**

The use of carbon nuclei as a scattering target material has the following shortcomings, stated in [3]. In this scattering besides pure elastic scattering, when C¹² atom remains in ground state there are the events, when C¹² atom passes to the first excited state with the energy 4.44 MeV. So the polarimeter detecting system must have high-energy resolution which is hard to achieve because of low statistics and limited polarization measurement time. In addition cross section and analyzing power of pC polarimeter sharply depends on proton scattering angle that leads to significant false asymmetries if the beam traverses the polarimeter not precisely in the center or with some angular displacement. So there is no possibility to separate scattered protons of interest from beam halo protons and other background events.

We were forced to use pC polarimeter because of higher cross-section of this process comparatively to pp or pD processes as for low luminosity and low duty factor (repetition rate 0.5 Hz and pulse duration 300 us) gives very low rate for the deuteron events (about 1 event/s at 25 uA beam current). Now when the accelerator begins to work at higher current (up to 200 uA) it appears the possibility to use as scattering centers deuterons and protons. In this case the time-of-flight measurements in two channels corresponding to scattered proton and recoil proton or deuteron will allow in addition to the choice of detector energy deposit spectra intervals corresponding to once scattered protons and deuterons considerably reduce the number of background events but will require detectors to operate at very high counting rate.
To choose the optimal type of polarimeter we shall compare pp and pD polarimeters by such characteristics as factor of merit (FoM), and absolute accuracy of polarization measurements.

Factor of merit $M$ is defined as [3]:

$$M = \frac{d\sigma}{d\Omega} \cdot A_v^2,$$  \hspace{1cm} (1)

where $\frac{d\sigma}{d\Omega}$ is differential by the angle elastic scattering cross-section and $A_v$ is the polarimeter analyzing power.

To define the angle dependence of cross-section the equation from [4] was used:

$$\sigma(\theta) = \left[ \frac{\eta}{2k \sin^2(\theta/2)} \right]^2 + \frac{\eta A_r(0)}{k \sin^2(\theta/2)} \sin(\eta \ln \sin^2(\theta/2)) - \frac{\eta A_i(0)}{k \sin^2(\theta/2)} \cos(\eta \ln \sin^2(\theta/2)) + \sum_{l=0}^{\infty} a_{2l} \cos^{2l} \theta. \hspace{1cm} (2)$$

Here $\eta = e^2/\hbar v$, $v$ is the velocity in the laboratory system, $hk$ and $\theta$ are momentum and scattering angle in the center-of-mass system. The imaginary part of the amplitude $A_i(0)$ is defined by optical theorem from the total scattering cross-section $\sigma_t$:

$$A_i(0) = k \sigma_t / 4\pi. \hspace{1cm} (3)$$

The real part of the amplitude $A_r(0)$ and the values $a_{2l}$ also are taken from [4]. The derived dependence is shown in Fig. 2. The points show experimental data from [5].

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Fig. 2. Elastic pp-scattering cross-section vs scattering angle.
Experimental angular dependence of analyzing power $A_n$ for the beam proton energy 210 MeV is taken from [6], where it is fitted by function:

$$P(\theta)\sigma(\theta) = \sin \theta \cdot \cos \theta \sum_{n=0}^{2} b_{2n} \cos^{2n} \theta,$$

(4)

where $b_0=2.78\pm0.16$, $b_2=-2.24\pm0.17$, $b_4=2.96\pm0.77$, and is shown in Fig. 3.

![Fig. 3. Analyzing power $A_n$ vs scattering angle in center-of-mass (CM) frame for pp scattering, representing the fit from [6] at 210 MeV.](image)

Using equation (1) factor of merit (FoM) for the polarimeter on pp scattering was found. It’s angular dependence in center-of-mass (CM) frame is shown in Fig. 4.

![Fig. 4. Factor of merit (FoM) vs scattering angle in center-of-mass (CM) frame for pp scattering.](image)

Let the moving particle A and target particle B generate elastically scattered particles C and D. Let us recalculate primary proton scattering angle in CM frame ($\theta^*_{CM}$) to the scattering angle in the laboratory frame ($\theta^*_{lab}$) using the equation [7].

$$\tan \theta^*_{CM} = v^*_{CM} \sqrt{1-v^2} \sin \theta^*_{lab}/(v+v^*_{CM} \cos \theta^*_{CM}),$$

(5)
Here $v_C^*$ is particle C velocity in CM frame and $v = p / (E_A + m_b)$ is the CM frame velocity relative to laboratory frame velocity.

After recalculation we see that maximal value of Factor-of-Merit, achieved at 40° in CM frame corresponds to 19.1° of the scattered proton in the laboratory frame.

For the recoil angle of target proton we use the equation from [7]:

$$\theta_C^* + \theta_D^* = \pi$$

Maximal value of Factor-of-Merit, achieved in CM frame at 40° corresponds to 69.1° of the recoil proton angle in the laboratory frame. Now we shall define the recoil proton kinetic energy dependence on recoil angle for pp elastic reaction from the expression [7]:

$$E_D^* = \frac{\sqrt{s E_D^*(E_A + m_b)} + p_A \cos \theta_D^* \left[ s \left( p_D^* \right)^2 - m_b^2 p_A^2 \sin^2 \theta_D^* \right]^{1/2}}{(E_A - m_b)^2 - p_A^2 \cos^2 \theta_D^*}.$$ (7)

Here $E_D^* = \frac{\sqrt{s}}{2}$. This dependence is shown in Fig. 5.

![Fig. 5. The recoil proton kinetic energy dependence on recoil angle for pp elastic reaction. Just a number for proton energy will be fine. I believe the paper volume is limited.](image)

We can define that 70° recoil angle corresponds to the recoil proton energy 20 MeV.

Now we shall consider the polarimeter based on pD scattering. The pD scattering cross-section at 200 GeV is two times higher than pp scattering cross-section [8].

We shall use the analyzing power dependence on the scattering angle in the laboratory frame, measured with high precision in [3] and shown in Fig. 6 for the proton beam energy 200 MeV.
Fig. 6. Deduced values for the p+D analyzing power at 200 MeV as a function of the deuteron scattering angle observed in the laboratory frame [3]. Error bars represent only the statistical uncertainties.

In [9] is given the value of an angle in the laboratory frame with maximal analyzing power equal to $42.6^\circ$ and is given the maximal value of the analyzing power, equal to $A_{pD} = 0.507 \pm 0.002$, that gives relative statistic uncertainty better, than 0.5 %. This high precision allows use the pD polarimeter to improve the absolute accuracy of polarization measurements.

Fig. 7 shows the analyzing power for pD polarimeter as a function of the beam energy.

Fig. 7. Values for the analyzing power as a function of the beam energy. The values are positive because they are referred to the observations of recoil deuterons.
This picture is taken from [8], contains the results from [8] and [3], and demonstrates the accuracy of measurements and consistency of different measurements.

Fig. 6 shows, that near maximum the variation of analyzing power is weak, which reduce the systematic error.

According the expression (7) the dependence of recoil deuteron kinetic energy on recoil angle for pD reaction was calculated.

Maximum of Factor-of-Merit being reached at 42.6° corresponds to 110 MeV of recoil deuteron kinetic energy. Factor-of-Merit for pD polarimeter in maximum is equal 2.5 and approximately 5 times larger, than for pp polarimeter.

So we choose pD polarimeter for further development. In this case we shall choose the laboratory angles for scattered protons and recoil deuterons as in [8] being 64.5° and 42.6° respectively.

We estimate proton rate from the scattering on carbon 2-3 times higher than on deuterons. This background can be discriminated by time-of-flight measurements for scattered proton and recoil deuteron and deuteron energy measurements.

The use of contemporary fast detectors (and DAQ) would allow higher rate and better statistical error. For application in pD polarimeter we shall investigate as scintillators new materials like LYSO (Lu$_{1.8}$Y$_{2.2}$SiO$_5$) with high light output, small energy resolution (8%) and short time rise (10 ns) and decay (40 ns). High density of this material (~7 g/cm$^3$) will provide full absorption of deuteron in the scintillator with the thickness less than 1 cm. Also we shall examine new plastic scintillators with exclusively short timing properties.

We estimate the counting rate of pD polarimeter as some MHz. Scintillators will provide this possibility, but significant modifications must be made in DAQ.

As light sensors will be investigated Silicon photomultipliers (SiPM) or for the application in high magnetic fields special vacuum photomultipliers like Hamamatsu R-5505-70.

References.