Toward polarized antiprotons: machine development for spin-filtering experiments at COSY

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Abstract
In 2011 the Polarized Antiproton eXperiments Collaboration has performed a successful spin-filtering test using protons at $T_p = 49.3$ MeV at the COSY ring in Jülich, which allowed the determination of the spin-dependent polarizing cross section, that compares well with the theoretical prediction from the nucleon–nucleon potential and it confirms that spin filtering can be adopted as a method to polarize a stored beam. The document concentrates on the commissioning of the experimental equipment and the machine studies conducted to achieve the required beam lifetimes of $\tau = 8000$ s in the presence of a dense polarized hydrogen storage cell target of areal density $d_t = (5.5 \pm 0.2) \times 10^{13}$ atoms cm$^{-2}$. The developed techniques can be directly applied to antiproton machines and allow for the determination of the spin-dependent $\bar{p}p$ cross sections via spin filtering.

Keywords: accelerators, polarized beams in particle accelerators, antiproton-induced reactions, beam handling, beam transport

(Some figures may appear in colour only in the online journal)

1. Introduction

Polarized antiprotons allow unique access to a number of fundamental physics observables. One example is the transversity distribution which would be directly measurable via Drell–Yan production in double polarized antiproton–proton collisions. This and other observables, which are accessible via $\bar{p}p$ scattering experiments [1], led the Polarized Antiproton eXperiments (PAX) collaboration to propose such investigations at the high energy storage ring of the Facility for Antiproton and Ion Research [1].

The preparation of a polarized beam of antiprotons with considerable beam intensity and polarization is a task which has not yet been solved. Selectively discarding particles in one spin state, also called spin filtering, using the spin-dependent part of the nucleon–nucleon interaction is the only experimentally demonstrated viable method to polarize antiprotons. After the first experimental evidence with a 23 MeV proton beam at the TSR ring in Heidelberg [2], an additional measurement has recently been performed at COSY to provide an independent confirmation of the method and of its present theoretical interpretation [3–5]. The other purpose of this measurement was to commission the experimental setup for the proposed $\bar{p}p$ experiment at the Antiproton Decelerator of CERN [6] and to learn how the machine has to be set up to provide beam lifetimes of several thousand seconds.

2. Measurement principle and setup

A dedicated spin-filtering cycle starts with the injection of an unpolarized proton beam into COSY. After electron cooling and subsequent acceleration to the chosen kinetic energy (49.3 MeV for the transversely polarized case) the polarized hydrogen gas target [7, 8], causing the polarization buildup, is switched on. Subsequent to the filtering period of several hours, the achieved beam polarization is determined by detecting elastically scattered protons [9] of a deuterium
cluster target [10] by means of two silicon tracking telescopes [11].

The observed polarization buildup as function of time \( P(t) \) allows one to determine the spin-dependent effective polarizing cross section \( \bar{d}_1 \) via [12]

\[
P(t) = \tanh \left( \frac{t}{\tau_1} \right), \quad \text{where} \quad \tau_1 = (\bar{d}_1 Qd f)^{-1}
\]

denotes the polarization buildup time, \( d_1 \) is the target areal density in atoms cm\(^{-2}\), and \( f \) the particle revolution frequency. \( \bar{d}_1 \) accounts for the fact that only protons scattered at angles larger than the acceptance angle of the storage ring \( \Theta \) contribute to the spin-filtering process \( \bar{d}_1 = \sigma_1(\theta > \Theta) \). The spin-filtering experiment at COSY yielded an effective polarizing cross section of

\[
\bar{d}_1 = -23.4 \pm 3.9 \text{(stat.)} \pm 1.9 \text{(syst.)} \text{mb}
\]

at 49.3 MeV, which confirmed that only \( pp \) scattering contributes to the polarization buildup [12].

3. Machine development for spin-filtering experiments

The quality of the polarized beam can be expressed in terms of the figure of merit [13]

\[
\text{FOM} = \frac{P(t)^2}{I(t)},
\]

where \( I(t) \) and \( P(t) \) are the beam intensity and the beam polarization (equation (1)) as function of time, respectively. Aiming for maximal figure of merit several parameters have to be optimized. For instance, the kinetic energy of the beam has to be chosen wisely with respect to \( \bar{d}_1 \), \( f \) and also the polarimetry. Furthermore, the beam lifetime has to be made as long as possible in the presence of a polarized gas target of maximum possible density and polarization. This requirement could only be achieved by means of extensive machine studies [14] including among other things the steps named in the following paragraphs.

- **Betatron tune mapping:** in order to increase the beam lifetime a search for the optimal betatron tunes was performed for several machine settings. In this procedure, called tune mapping, the currents in the quadrupole magnet families of the COSY arcs were varied in the range of \( \pm 3\% \), while the beam lifetime was determined from an exponential fit to the beam current.

  The betatron tune scans showed a large variation in the beam lifetime by a factor six in a rather small region of betatron tunes. Maximum beam lifetimes were observed close to a working point of \( Q_x = 3.58 \) and \( Q_y = 3.62 \) [14].

- **Orbit correction:** due to misalignment or field errors of magnets, the real orbit in a machine deviates from the ideal one. In regions where the \( \beta \)-functions are large, these deviations lead to local restrictions of the machine aperture, and thus reduce the lifetime of the beam. A closed orbit correction scheme, based on the orbit response matrix [15], was implemented to increase the machine acceptance and to improve the beam lifetime [14, 16].

- **Commissioning of a low-\( \beta \) section at the PAX interaction point:** utilizing a narrow storage cell of diameter \( d = 9.6 \text{ mm} \) and length \( l = 400 \text{ mm} \) in order to maximize the target areal density in the experiment would significantly restrict the machine acceptance for a standard COSY lattice. Assuming single Coulomb scattering as dominating particle loss mechanism this is directly accompanied by a reduction of the beam lifetime. To obtain small \( \beta \)-functions and thereby overcome the acceptance limitation at the target, a low-\( \beta \) insertion consisting of four additional quadrupole magnets was installed in the drift space in front and behind the target.

  An experimental determination of the \( \beta \)-functions at the position of the PAX quadrupoles was accomplished by changing the quadrupole strength by \( \Delta k \) and measuring the corresponding tune change \( \Delta Q \) of the machine (see figure 1, left panel) using [17]

\[
\bar{p}_{x,y} = \frac{4\pi}{I} \left| \frac{\Delta Q_{x,y}}{\Delta k} \right|
\]

The resulting \( \bar{p}_x \) and \( \bar{p}_y \), shown in figure 1 (right panel), agree very well with the lattice model calculation and therefore allow to estimate the \( \beta \)-functions at the center of the target to \( \beta_x = 0.31 \) and \( \beta_y = 0.46 \text{ m} \) [14]. Consequently, the implemented low-\( \beta \) section avoids a restriction of the machine acceptance.

- **Space charge studies:** studying space-charge effects in terms of particle losses implies studying the effect of the beam emittance on the beam lifetime. Changing the beam emittance, while the intensity is kept constant, was achieved by adjusting the cooling performance of the electron cooler by means of tilting its beam with respect to the proton beam.

  The investigations showed an increase of the beam lifetime from 6300 to 9200 s while the four-dimensional beam emittance \( \epsilon = \epsilon_x \epsilon_y \) [18] was increased from about 0.2 to 1.3 mm\(^2\)mrad\(^2\). This effect can qualitatively be explained by the repulsion between the charged particles in the beam, leading to a betatron amplitude-dependent incoherent tune shift for a non-uniform charge distribution [19]. This so-called tune spread decreases with increasing beam emittance, the associated area in the tune diagram shrinks, fewer betatron resonances are excited, and therefore the observed beam lifetime increases. This theoretical consideration is consistent with the results published in [14].

4. Conclusion

The interplay of the investigations presented in this document fulfilled the demanding beam conditions for the first spin-filtering experiment at COSY. The presented results comprise a
A recipe about how to set up a beam for spin-filtering experiments in a storage ring, directly applicable for the anticipated spin-filtering studies with antiprotons at the AD of CERN [6].

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