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TOWARDS POLARIZED ANTIPROTONS AT FAIR

P. Lenisa
Dipartimento di Fisica
Universitá di Ferrara
44100 Ferrara, Italy

F. Rathmann
Institut für Kernphysik,
Foschungszentrum Jülich
52425 Jülich, Germany

Abstract

In the framework of the FAIR project the PAX Collaboration has suggested new experiments using polarized protons and antiprotons. In order to provide polarized antiprotons, the polarization build-up by spin-dependent interaction (spin-filtering) must be studied. The goal of these investigations is to understand the physics of the spin-filtering process with stored protons at COSY, and shed light into the role of polarized electrons for the polarization buildup. Later on the dependence of the proton-antiproton interaction will be investigated at the Antiproton Decelerator ring (AD) at CERN.

1 Motivation

An entirely new chapter in the study of the spin structure of the proton might unfold with the advent of a polarized antiproton beam at the Facility for Antiproton and Ion Research (FAIR) at GSI, Darmstadt. A cornerstone of the hadronic physics program at FAIR is the collection, cooling, storing and acceleration of antiprotons in the 15 GeV High Energy Storage Ring (HESR). The PAX Collaboration [1] has suggested to convert HESR into an asymmetric polarized proton-polarized antiproton collider. The study of double polarized antiproton-proton Drell-Yan reactions will allow the first direct measurement of transversity. No other existing or future facility will be ever able to directly measure the transversity in a competitive way. The physics case for experiments with polarized antiprotons is outstanding and covers additional items like the measurement of the moduli and absolute phases of the electromagnetic form-factors in the time-like region; measurements of double-polarized proton-antiproton hard scattering. Also hadron spectroscopy studies will definitely benefit from polarization of beam and/or target particles, because the initial spin state of the system can be prepared at will.

2 Polarized Antiprotons

For more than two decades, physicists have tried to produce beams of polarized antiprotons, generally without success. Conventional methods like atomic beam sources (ABS), appropriate for the production of polarized protons and heavy ions cannot be applied, since antiprotons annihilate with matter. Polarized antiprotons have been produced from the decay in flight of hyperons at Fermilab. The intensities achieved with antiproton polarizations $P > 0.35$ never exceeded $1.5 \times 10^5 s^{-1}$. Scattering of antiprotons off a liquid hydrogen target could yield polarizations of $P \approx 0.2$, with beam intensities of up to $2 \times 10^3 s^{-1}$. Unfortunately, both approaches do not allow efficient accumulation in a storage ring, which would greatly enhance the luminosity. Spin splitting using the Stern-Gerlach separation of the given magnetic substates in a stored antiproton beam was proposed in 1985, but it has never been experimentally demonstrated. Different methods to polarize antiprotons have been recently reviewed in a Workshop held at Daresbury (UK), August 29-31, 2007 [2].

There is only one viable method demonstrated so far that could yield a beam of polarized antiprotons: namely spin-filtering of a stored beam through repetitive interaction with a polarized internal target.

2.1 Spin filtering

Spin filtering is based on the effect of selective removal of (anti)protons of a stored beam by a polarized target. The total cross section consists of a transverse and a longitudinal part:

$$\sigma_{tot} = \sigma_0 + \sigma_\perp \vec{P} \cdot \vec{Q} + \sigma_\parallel (\vec{P} \cdot \vec{k})(\vec{Q} \cdot \vec{k}) \tag{1}$$

In equation 1 $\vec{P}$ and $\vec{Q}$ represent the beam and target polarization respectively, while $\vec{k}$ the beam momentum direction. For an initially equally populated $\uparrow$ $(m = +\frac{1}{2})$ and $\downarrow$ $(m = -\frac{1}{2})$ states in the beam, the cross sections for the transverse and longitudinal cases become:

$$\sigma_{tot\pm} = \sigma_0 \pm \sigma_\perp Q \qquad \sigma_{tot\pm} \sigma_0 \pm (\sigma_\perp + \sigma_\parallel) Q \tag{2}$$

Experimental evidence for spin filtering has been given in 1992 in an experiment at the Test Storage Ring (TSR) at MPI Heidelberg where an initially unpolarized 23 MeV proton beam has been polarized by spin-dependent interaction with a polarized hydrogen gas target [3]. The measured polarization cross section was $\sigma_\perp = 72.5 \pm 5.8$ mbarn.

In 1994 Horowitz and Meyer explained this result by three effects [4]: selective scattering of protons out of the acceptance of the storage ring; scattering of target protons into the acceptance of the storage ring and spin transfer from polarized target electrons. The theoretically calculated cross section by Meyer and Horowitz was $\sigma_\perp = 65$ mbarn. On the other hand the 2005 scrutiny of the filtering process by Milstein and Strakhovenko [5] and Nikolaev and Pavlov [6] suggests a cancellation of the electron contribution to the polarization of the transmitted stored beam and beam particles elastically scattered off electrons. In this second scenario only the nuclear interaction would contribute to spin filtering. The estimated cross section is $\sigma_\perp = 85.6$ mbarn, also in fair agreement with the measured one.

Understanding which of these scenario is really at work is crucial to progress towards the goal to eventually produce stored polarized antiproton beams.

3 Experiments at COSY

3.1 Polarization build-up experiments

The ideal solution to distinguish between the two scenarios would be the null experiment with two hyperfine states in the Polarized Internal Target (PIT) such that the net nuclear polarization of the target is zero, while the net electron polarization is large. This requires operating the PIT with longitudinal target polarization in a strong longitudinal guide field, where the stable beam spin direction must be aligned longitudinally at the target as well to preserve the longitudinal polarization of the stored protons.

Two possible null experiments can be performed. The first, by injecting two hyperfine states with identical electron and opposite nuclear polarization, will evidence the pure electron interaction, while the second, for the pure nuclear mechanism, can be performed by injecting two hyperfine states with identical proton polarizations and opposite electron polarizations. The situation is summarized in Table 1

In a single hyperfine state mode, one could rely upon the different energy dependences of the electron and nuclear mechanisms. This point is made clear by the expected energy dependence of the effective polarization cross

Table 1: Polarization build-up experiments with one or two H hyperfine states injected. By injecting in the target cell two states in a strong field pure lectron (P_e) or nuclear polarization P_z can be obtained.

Injected states	P_e	P_z	Interaction	Holding field	
$\|1\rangle$	+1	+1	Elm.+had	transv. and long.	weak (20 G)
$\|1\rangle + \|4\rangle$	0	+1	only had.	long.	strong (30 kG)
$\|1\rangle + \|2\rangle$	+1	0	only elm.		

section, shown in the left plot of Fig. 1. In the right plot of Fig. 1, we show the predictions from the Budker-Jülich model for the energy dependence of the polarization of stored protons after filtering for 2 to 5 beam lifetimes both using the ANKE and new a PIT at TP1.

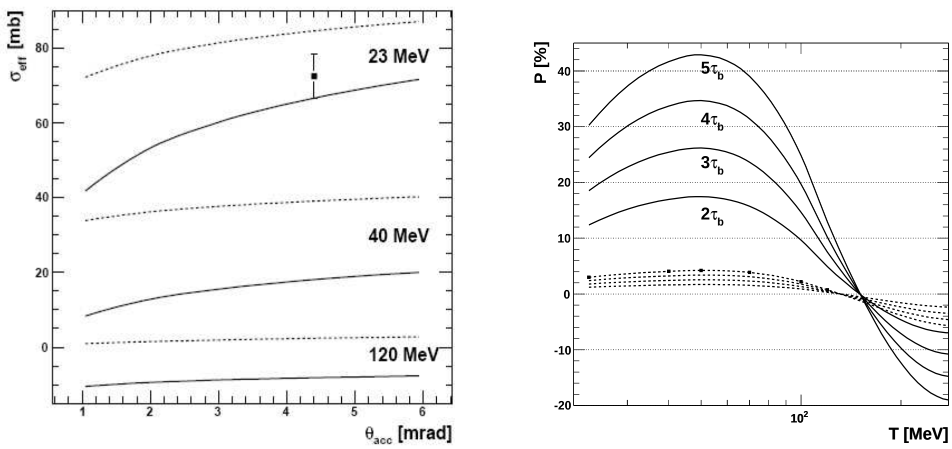

Figure 1: Polarization build-up studies with a single hyperfine state injected. Left plot: Calculated polarization cross section as a function of the ring acceptance for the Meyer-Horowitz (solid line) and Nikolaev and Pavlov (dots) models. Right plot: Comparison of the expected polarization buildup at the ANKE IP and in a new IP at TP1 of COSY for the Nikolaev and Pavlov model.

3.2 Depolarization experiments

A different approach to address the contribution of the polarized electrons consists in reversing the role of the beam and target polarizations: from the viewpoint of the kinetics of the spin-filtering, depolarization of polarized stored protons in an unpolarized electron target is equivalent to the buildup of the polarization of the initially unpolarized beam proton by multiple passage through the polarized electron target.

Gas target as unpolarized electron target

A possible way to provide an unpolarized electron target is to make use of a D_2 cluster target. An advantage of this target is that at COSY injection energy (45 MeV) elastic polarized p-d scattering provides good counting rates and analyzing power and it can be used to measure the beam polarization.

The experimental task is to determine the polarization lifetime of COSY together with the depolarizing effect predicted by Meyer-Horowitz (MH) due to the unpolarized electrons in the D_2 target. The total polarization lifetime (τ_p^{total}) can be written as:

$$\frac{1}{\tau_p^{total}} = \frac{1}{\tau_p^{COSY}} + \frac{1}{\tau_p^{MH}} \tag{3}$$

where τ_p^{COSY} denotes the polarization lifetime of COSY alone, while τ_p^{MH} is attributed to the depolarizing effect due to the target electrons.

To avoid possible systematic variations, τ_p^{COSY} should be traced simultaneously with the measurements. Thus, a proper measuring cycle has to be introduced composed of three parts of duration $T = T_1 + T_2 + T_3$, during T_1, the D_2 target is switched on, during T_2, the target is switched off, and during T_3 the target is again switched on. From cycle to cycle the beam spin will be alternated from $\uparrow$ to $\downarrow$ to zero.

The p-d elastic scattering will be detected by two Silicon Tracking Telescopes (STT) left and right of the target area. The detectors are placed to cover the region, where the Factor of Merit (FOM) exhibits a maximum. The $FOM = d\sigma/d\Omega(\theta_{cm}) \cdot A_y(\theta)^2$ has been evaluated on the basis of experimental data and for an energy of 45 MeV has been found to maximum near $\theta_{lab}^{proton} = 80°$. The count rates have been determined on the basis of Monte Carlo simulations and show that a signficance of 4-5 σ in 4 weeks of data taking can be reached (Figure 2).

Electron cooler beam as unpolarized electron target

A slightly different approach from the one reported in previous paragraph is the use of the electron cooler beam as unpolarized electron target with low relative energy with respect to the proton beam. This approach is motivated by a recent publication of Walcher et al. [7] describing a new QED calcula-

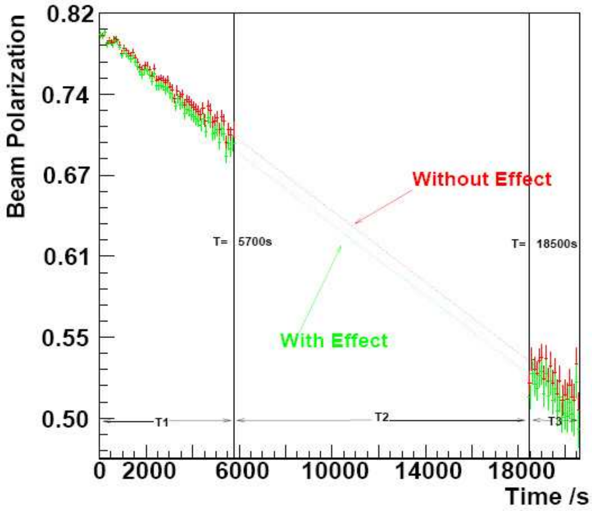

Figure 2: Depolarization study by using a D_2 cluster target. Resulting accuracy of the time dependpent beam polarization vs measuring time. The cycle is composed by three parts of duration $T = T_1 + T_2 + T_3 = 20600$ s, target-off times are $5700 \text{ s} < t < 18500$ s.

tion which extends the calculation of Meyer to very low relative velocities of protons and electrons.

A dedicated set of measurements is foreseen at COSY to directly determine the spin-exchange cross section by using a stored polarized proton beam and the unpolarized electron cooler beam. Although the electron cooler has a much smaller thickness compared to a gas target, the new calculation suggests a very large cross-section for the spin-exchange between protons and electrons. As an example for an electron energy of 1 keV in the rest frame of the proton, i.e. at a relative velocity $v/c \approx 0.001$, the predicited spin-exchange cross section amounts to $< \sigma P_{zz} > \approx 2 \cdot 10^{13}$ barn.

By a measurement of the beam polarization lifetime as a function of the relative energy between proton and electron beams, we will be able to measure the spin-exchange cross section responsible for the beam depolarization. The variation of the relative energy of the two beams can be obtained by varying the acceleration potential of the electron cooler beam.

A possible complication arises from the fact that although the cooling force is small when the electron beam is detuned, the proton beam will nevertheless slowly change its momentum until again the velocities are matched. Therefore, one has to detune the cooler voltage for a short period of time and return to the nominal voltage to make sure that the proton beam reamins well-cooled. The measuring cycle will be realized by alternating the cooler voltage between *nominal* and *detuned*.

Figure 3 shows the reachable accuracy in the determination of the depolarization cross section as a function of the measured depolarization.

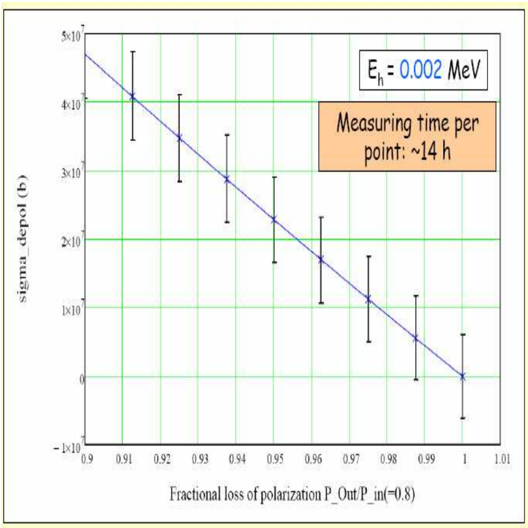

Figure 3: Depolarization study by using the electron cooler beam. Depolarizing cross section as a function of the measured fractional loss of polarizaion.

4 Experiments at AD

The experimental basis for predicting the polarization build-up in a stored antiproton beam is practically non-existent. The AD facility at CERN is a unique facility at which stored antiprotons in the appropriate energy range are available and whose characteristics meet the requirements for the first ever antiproton polarization build-up studies.

The two physics observables which can be measured by the spin-filtering technique, are the spin-dependent cross sections $\sigma_\perp$ and $\sigma_\parallel$ adopted in the parametrization of the hadronic cross section presented in equation 1. Such observables would improve substantially the modern phenomenology of the proton-antiproton interactions based on the experimental data gathered at LEAR.

5 Experimental setup for spin filtering

The commissioning of a spin filtering experiment in a storage ring requires the design, production and installation of three major components: a low-beta section, a polarized internal target making use of a storage cell and a detector system.

The design of the elements is taking into account their utilization both in the COSY ring environment for the experiments with protons and in the AD ring for the subsequent experiments with antiprotons.

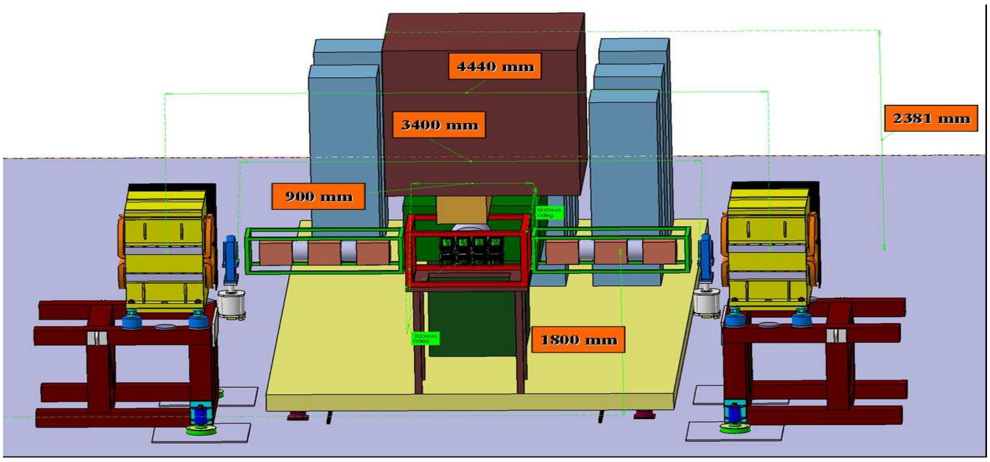

Figure 4: Layout of the interaction region for spin-filtering experiments. On top the Polarized Atomic Beam Source. Left and right to the scattering chamber, two sets of three quadrupoles are shown. Inside the scattering chamber, the silicon detectors are visible.

5.1 Low-beta section and polarized internal target

The insertion of a polarized target using a storage cell in the COSY and AD rings requires the redesign of the magnetic lattice of the ring. The solution which has been developed for the COSY (AD) ring foresees the substitution of one of the existing quadrupoles in a straight section of the ring with two sets of tow (three) quadrupoles before and behind the target.

The polarized source used formerly at the HERMES experiment (DESY-Hamburg) has been transported to Jülich and its operation restored.

The operation of the AD ring requires injection of an uncooled antiproton beam at 3.5 GeV and subsequent cooling and deceleration to the experiment energies. Prior to the cooling process the beam occupies the whole acceptance of the machine. Under these conditions, the size of the beam is so large that it requires the use of an openable cell that should not limit the machine acceptance at injection. In order to allow for the detection of low-energy recoil protons ($T_{rec} < 8MeV$) the cell walls will be realized with a thin ($5\mu m$) Teflon foil.

5.2 Detector

The detector for the spin-filtering experiments constitutes a multipurpose device which should work as beam polarimeter and recoil detector for the measurement of the spin-dependent cross-sections, cope with a broad range of beam energies (50-500 MeV), and fit into the lattices of the COSY and AD rings. The final configuration of the detector forsees the use of (at least) three series of four silicon telescopes in a diamond-shaped configuration, properly displaced along the storage cell (see Figure 5). Each telescope consists of two sensors.

The choice of the sensors has fallen on the TIGRE sensors from Micron-Semiconductors. These are, $97 \times 97\ mm^2$ double sided detectors, of 300 μm thickness and a pitch of 758 μm. The same sensors have been also used for the recoil detector of the HERMES experiment (DESY, Hamburg).

A complete simulation has been performed in order to evaluate the obtainable vertex resolution and the covered acceptance. A vertex resolution better than 2 mm has been obtained for all three vertex coordinates. This resolution allows the separation of the tracks coming from the gas target from the ones originating in the cells wall that constitute the background. The resolution is limited by the multiple scattering in the cell walls and in the sensors themselves. The right plot of Figure 5 shows the covered acceptance for elastic events in antiproton-proton scattering for a beam energy of 120 MeV. The detector acceptance is about 0.17. By using the obtainable luminosity in the AD ring, this translates 10 events/s.

6 Conclusions and timeline

Spin-filtering represents at the moment the only credible technique which might lead to the first beam of polarized antiprotons. To better understand its principles and define the basis for its practical exploitation, measurements with protons are forseen at COSY in the next two years and at the AD ring starting in 2010.

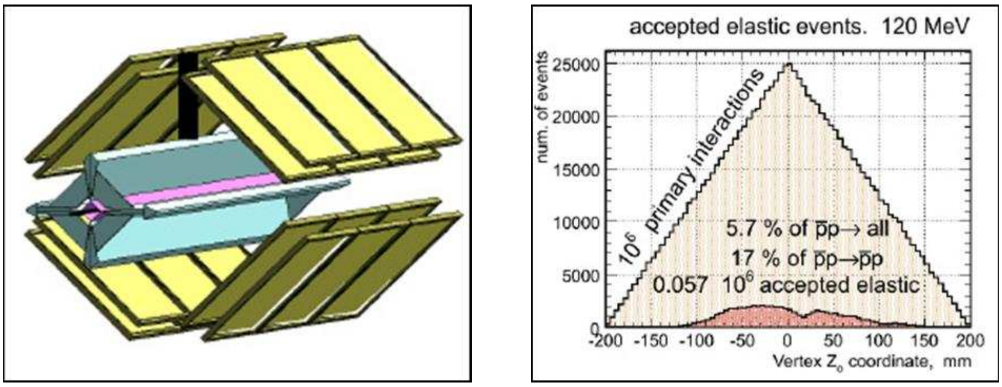

Figure 5: Left plot: layout of the detector for the spin-filtering experiments. The storage cell is shown in the center of the detector. Right plot: event distribution along the longitudinal z coordinate in the cell with the number of generated and accepted events in the detector.

References

[1] The proposals of the PAX Collaboration can be found at the PAX website at: *http://www.fz-juelich.de/ikp/pax*.

[2] The presentation of the workshop can be downloaded from the site: *http://www.cockroft.ac.uk/Polanti-p/Presentations*.

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