Letter–of–Intent
for

Measurement of the Spin–Dependence of the $\bar{p}p$ Interaction at the AD–Ring

($\mathcal{PAX}$ Collaboration)

Jülich, November 2005

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Abstract

An internal polarized hydrogen storage cell gas target is proposed for the AD–ring to determine for the first time the two total spin–dependent cross sections σ_1 and σ_2 at antiproton beam energies in the range from 50 to 200 MeV. The data will allow the definition of the optimum working parameters of a dedicated Antiproton Polarizer Ring (APR), which has recently been proposed by the PAX collaboration for the new Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt, Germany. The availability of an intense beam of polarized antiprotons will provide access to a wealth of single– and double–spin observables, thereby opening a new window to QCD transverse spin physics. The physics program proposed by the PAX collaboration includes a first measurement of the transversity distribution of the valence quarks in the proton, a test of the predicted opposite sign of the Sivers–function, related to the quark distribution inside a transversely polarized nucleon, in Drell–Yan (DY) as compared to semi–inclusive Deep Inelastic Scattering, and a first measurement of the moduli and the relative phase of the time–like electric and magnetic form factors $G_{E,M}$ of the proton.

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Contents

1 Introduction

In this Letter–of–Intent, the PAX collaboration suggests to study the polarization buildup in an antiproton beam at the AD–ring at CERN at energies in the range from 50–200 MeV. The scientific objectives of this experiment are twofold. The polarization buildup by spin filtering of stored antiprotons by multiple passage through a polarized internal hydrogen gas target gives a direct access to the spin dependence of the antiproton–proton total cross section. Apart from the obvious interest for the general theory of $p\bar{p}$ interactions, the knowledge of these cross sections is necessary for the interpretation of unexpected features of the $p\bar{p}$, and other antibaryon–baryon pairs, contained in final states in J/Ψ and B–decays. Simultaneously, the confirmation of the polarization buildup of antiprotons would pave the way to high–luminosity double–polarized antiproton–proton colliders, which would provide a unique access to transverse spin physics in the hard QCD regime. Such a collider has been proposed recently by the PAX Collaboration [1] for the new Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt, Germany, aiming at luminosities of 10^{31} cm^{-2}s^{-1}. An integral part of such a machine is a dedicated large–acceptance Antiproton Polarizer Ring (APR).

Here we recall, that for more than two decades, physicists have tried to produce beams of polarized antiprotons [2], 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 $\bar{\Lambda}$ hyperons at Fermilab. The intensities achieved with antiproton polarizations $P > 0.35$ never exceeded $1.5 \cdot 10^5$ s^{-1} [3]. Scattering of antiprotons off a liquid hydrogen target could yield polarizations of $P \approx 0.2$, with beam intensities of up to $2 \cdot 10^3$ s^{-1} [4]. 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 [5]. Although the theoretical understanding has much improved since then [6], spin splitting using a stored beam has yet to be observed experimentally. In contrast to that, a convincing proof of the spin–filtering principle has been produced by the FILTEX experiment at the TSR–ring in Heidelberg [7].

The experimental basis for predicting the polarization buildup in a stored antiproton beam is practically non–existent. The AD–ring 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 buildup studies. Therefore, it is of highest priority for the PAX collaboration to perform spin filtering experiments using stored antiprotons at the AD–ring of CERN. Once the experimental data base will be made available by the AD experiments, the final design of a dedicated APR can be targeted. In addition, a few dedicated spin filtering experiments carried out with protons at the Cooler Synchroton COSY at Jülich, Germany, will enhance our general understanding of these processes and allow us to commission the additional equipment needed for the spin filtering experiments at the AD.

2 Physics Case

2.1 $N\bar{N}$ Double-Spin Observables from Spin Filtering

The two double–spin observables, which can be measured by the spin–filtering technique, are the spin–dependent cross sections σ_1 and σ_2 in the parameterization of the total hadronic cross section σ_{tot} [8], written as

$$\sigma_{\text{tot}} = \sigma_0 + \sigma_1(\vec{P}\cdot\vec{Q}) + \sigma_2(\vec{P}\cdot\hat{k})(\vec{Q}\cdot\hat{k}) \,, \tag{1}$$

where σ_0 denotes the total spin–independent hadronic cross section, σ_1 the total spin–dependent cross section for transverse orientation of beam polarization P and target polarization Q, σ_2 denotes the total spin–dependent cross section for longitudinal orientation of beam and target polarizations. (Here we use the nomenclature introduced by Bystricky, Lehar, and Winternitz [9], where $\hat{k} = \vec{k}/|\vec{k}|$ is the unit vector along the collision axis.) Such observables would improve substantially the modern phenomenology of proton–antiproton interactions based on the experimental data gathered at LEAR (for a review and references, see [10]).

The suggested spin–filtering experiment at the AD of CERN constitutes a unique opportunity to measure for the first time these observables in the 50–200 MeV energy range. The measurements of σ_1 and σ_2 will be carried out in the transmission mode. The separation of the elastic scattering and annihilation contributions to σ_1 and σ_2 requires the integration of the double–polarized elastic cross section over the full angular range. Although such measurements seem not feasible with the anticipated luminosity using the HERMES internal polarized target installed at the AD, the obtained results on σ_1 and σ_2 for the total cross section would serve as an important constraint for a new generation of baryon–antibaryon interaction models, which will find broad application to the interpretation of the experimental data in heavy quark physics. Regarding the main goal of the proposed experiment – the antiproton polarization buildup – the expectations from the first generation models for double–spin dependence of $p\bar{p}$ interaction are encouraging, see Fig. 1. With filtering for two lifetimes of the beam, they suggest that in a dedicated large–acceptance storage ring, antiproton beam polarizations in the range of 15–25 % seem achievable [14].

2.2 $N\bar{N}$ Interaction from LEAR to J/Ψ and B-decays

The evidence for threshold enhancements in $B-$ and J/Ψ–decays containing the baryon–antibaryon pairs – $p\bar{p}$, $p\bar{\Lambda}$, $\Lambda\bar{p}$, etc. – was found recently at the modern generation electron–positron colliders BES [15, 16, 17, 18], BELLE [19, 20, 21, 22] and BaBar [23, 24]. These findings added to the urgency of understanding low and intermediate energy $p\bar{p}$ interactions, which appear to be more complex than suggested by the previous analyses [12, 25, 11, 26, 27] of the experimental data from LEAR. The direct measurements of σ_1 and σ_2 would facilitate the understanding of the role of antibaryon–baryon final state interactions, which are crucial for the re–interpretation of the B–decay dynamics in terms of the Standard
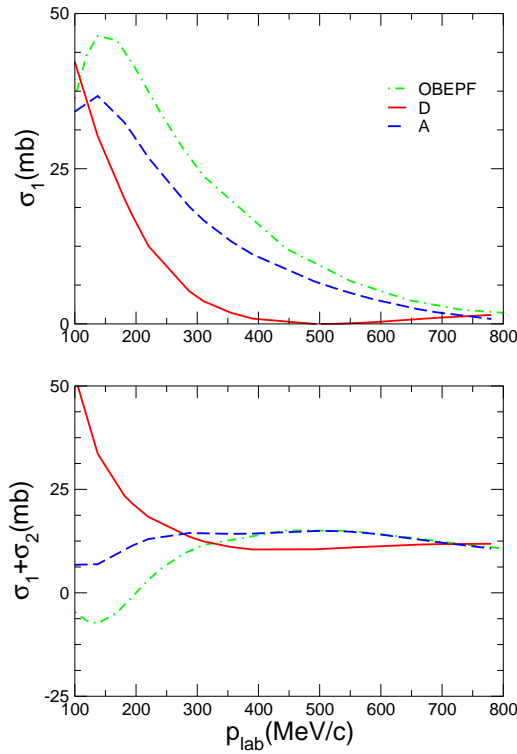
Figure 1: The spin–dependent cross sections σ_1 and $\sigma_1+\sigma_2$, cf. Eq. (1), as predicted by the $N\bar{N}$ models D [11], A [12] and OBEPF [13] of the Jülich group.

Model mechanisms (see [28, 23, 29] and references therein). Especially strong theoretical activity ([28, 30, 31, 32, 33, 34, 35, 36, 37, 37, 38, 39, 40] and references therein) has been triggered by the BES finding [15] of the pronounced threshold enhancement in the reaction $J/\Psi \rightarrow p\bar{p}\gamma$, including the revival of the baryonium states [41, 42] in the $p\bar{p}$ system [35, 36, 37, 37, 38, 39]. Equally important is the recent confirmation by the BaBar collaboration [24] of the near–threshold structure in the timelike form factor of the proton, observed earlier at LEAR [43]. In conjunction with the BES enhancement, the LEAR–BaBar data suggest a non–trivial energy dependence in both the spin–singlet and spin–triplet $p\bar{p}$ interactions, hence our special interest in σ_1 and σ_2.

2.3 Applications of Polarized Antiprotons to QCD Spin Studies

The QCD physics potential of experiments with high energy polarized antiprotons is enormous, yet hitherto high luminosity experiments with polarized antiprotons have been impossible. The situation could change dramatically with the realization of spin filtering and

storing of polarized antiprotons, and the realization of a double–polarized high–luminosity antiproton–proton collider. The list of fundamental physics issues for such collider includes the determination of transversity, the quark transverse polarization inside a transversely polarized proton, the last leading twist missing piece of the QCD description of the partonic structure of the nucleon, which can be directly measured only via double polarized antiproton–proton Drell–Yan production. Without measurements of the transversity, the spin tomography of the proton would be ever incomplete. Other items of great importance for the perturbative QCD description of the proton include the phase of the timelike form factors of the proton and hard antiproton–proton scattering. Such an ambitious physics program has been formulated by the PAX collaboration (Polarized Antiproton eXperiment) and a Technical Proposal [1] has recently been submitted to the FAIR project. The uniqueness and the strong scientific merits of the PAX proposal have been well received [44], and there is an urgency to convincingly demonstrate experimentally that a high degree of antiproton polarization could be reached with a dedicated APR.

3   Measurement Technique

At the core of the PAX proposal is spin filtering of stored antiprotons by multiple passage through an internal polarized gas target. The feasibility of the spin filtering technique has convincingly been demonstrated in the FILTEX experiment at TSR [7]: for 23 MeV stored protons, the transverse polarization rate of $dP/dt = 0.0124 \pm 0.0006$ per hour has been reached with an internal polarized atomic hydrogen target of areal density 6×10^{13} atoms/cm^2. For a proton impinging on a polarized hydrogen gas target, the spin–dependent interaction leading to the buildup of polarization in the beam is known; recent investigations [45, 14] have shown that an understanding and interpretation of the FILTEX result in terms of the proton–proton interaction is available.

The polarization buildup of the beam as a function of filter time t can be expressed in the absence of depolarization as [7]

$$P(t) = \tanh(t/\tau_1) \tag{2}$$

The time constant τ_1, which characterizes the rate of polarization buildup, for transverse ($\perp$) and longitudinal ($\parallel$) orientation of beam and target polarization Q is

$$\tau_1^{\perp} = \frac{1}{\sigma_1 Q d_t f} \quad \text{and} \quad \tau_1^{\parallel} = \frac{1}{(\sigma_1 + \sigma_2) Q d_t f} \tag{3}$$

where d_t is the target thickness in atoms/cm^2 and f is the revolution frequency of the particles in the ring. σ_1 and σ_2 denote the spin–dependent total cross sections for filtering with transverse and longitudinal target polarization. From the measurement of the polarization buildup, the spin–dependent cross sections can be determined. For small beam polarizations P, the polarization buildup is linear in time. The spin–dependent cross sections can be extracted from Eq. (3) using the known target polarization, thickness, and the orbit

frequency. In order to extract both spin–dependent total cross sections, a measurement with transverse and longitudinal beam polarization buildup is required. The latter involves the operation of a Siberian snake in the AD. It is important to note that the buildup cross sections σ_1 and σ_2, which we intend to measure as a function of the incident beam energy and as a function of the ring acceptance angle, provide a very convenient way to extract information about the spin–dependent antiproton–proton interaction.

4 Experimental Requirements for the AD–Ring

At present, the AD of CERN is actually the only place world wide, where the proposed measurements can be performed. The effort involved is substantial. Although we will perform most of the design work outside of CERN, it is obvious, that many aspects in the design require a close collaboration with the CERN machine group. The new components that need to be installed in the AD are described in the following sections. They shall all be tested and commissioned at the Cooler Synchrotron COSY in Jülich. During these tests, we plan to perform a few dedicated spin filtering experiments with protons.

4.1 Low–β–Section

The measurement requires implementing an internal polarized storage cell target (PIT) in one of the straight sections of the AD. Targets of this kind have been operated successfully at TSR in Heidelberg [46], later on they were also used at HERA/DESY [47] at Indiana University Cyclotron Facility, and at MIT–Bates. A new PIT is presently being commissioned at ANKE–COSY [48]. A recent review can be found in ref. [49]. Typical target densities range from a few 10^{13} to 2×10^{14} atoms/cm^2 [47]. The target density depends strongly on the transverse dimension of the storage cell. In order to provide a high target density, the β–function at the storage cell should be about $\beta_x = \beta_y = 0.3$ m. In order to minimize the β–functions at the cell, a special insertion has to be prepared, which includes additional quadrupoles around the storage cell. The low–β section should be designed in such a way that the storage cell does not limit the machine acceptance. A careful machine study has to be carried out in order to maintain the machine performance at injection energy and at low energies for the other AD experiments. The section which houses the PIT has to be equipped with a powerful differential pumping system, that is capable to maintain good vacuum conditions in the other sections of the AD.

We will utilize the HERMES PIT (HERA/DESY), which will become available at the beginning of 2006, to feed the storage cell. The target will be operated in a weak magnetic guide field of a about 10 G. The orientation of the target polarization can be maintained by a set of Helmholtz coils in transverse and longitudinal direction.

4.2   Siberian Snake

In order to determine σ_2, the stable beam spin direction has to be longitudinal at the position of the PIT. Therefore, in the straight section opposite the PIT, a solenoidal Siberian snake must be implemented. A set of four skewed quadrupoles needs to be installed, two before and two behind the snake to correct for the phase–space rotation by the solenoid. We have begun to investigate whether existing snakes can be utilized or modified to be used at the AD. In any case, a careful machine study has to be carried out before final conclusions can be reached.

4.3   Electron Cooler

The filtering experiments require to compensate multiple scattering in the target by electron cooling. The present AD electron cooler is capable to provide electron energies of up to 30 keV, corresponding to antiproton beam energies of 50 MeV. In order to carry out the proposed measurements in the energy range between 50 and 200 MeV, the electron cooler at the AD should be upgraded to about 120 keV. Technically, this solution seems feasible, whereas the installation of a new cooler, such as the one previously installed at the TSL, involves major modifications and re–commissioning of cooler and machine. At this point, we believe that such an investment is not indicated, before we have measured the spin–dependent cross sections at energies below 200 MeV.

4.4   Intensity Increase in the AD through Stacking

At present, the AD provides about 3×10^7 stored antiprotons. Through stacking, one may be able to increase the number of stored antiprotons by about a factor of five, wherefrom the other experiments at the AD would benefit as well. With a beam current corresponding to about 10^8 stored antiprotons, a luminosity of $L = N_{\bar{p}} \cdot f \cdot d_t = 10^8 \cdot 10^6 \, \text{s}^{-1} \cdot 10^{14} \, \text{atoms/cm}^2 = 10^{28} \, \text{cm}^{-2}\text{s}^{-1}$ may be achievable. For the purpose of polarimetry, this leads to elastic antiproton–proton rates of several hundred events per second. To achieve a larger number of stored antiprotons in the AD in the first place is important, because after spin filtering for a few beam lifetimes one wants to be left with a substantial beam intensity to carry out beam polarization measurements. Once we have polarized the beam, an unpolarized target can be used to determine the beam polarization, thus the loss in beam intensity during filtering can be compensated by an increase in target thickness.

5   Polarimetry

The experiments of the polarization buildup using stored antiprotons should provide a measurement of the effective polarization buildup cross section. The spin–dependent cross sections can be extracted from the measured dP/dt, once the target polarization, the target thickness, and the orbit frequency are known. The target density can be either obtained from the observed deceleration of the stored beam when the electron cooling

is switched off, as shown in ref. [50], or it can be inferred from the measured rates in the polarimeter using the quite well established elastic antiproton–proton differential cross sections, measured at LEAR [10]. Thus an important subject is the development of a polarimeter that allows one to efficiently determine the polarizations of beam and target. Such a polarimeter based on silicon microstrip detectors has recently been developed for the ANKE spectrometer operated at the internal beam of COSY ([51], more recent information on the detection system can be found in ref. [48]). The use of this system as a polarimeter for our experiments would neither require any additional R&D, nor additional costs.

There exist quite a number of analyzing power measurements for antiproton–proton elastic scattering that can be employed [10]. However, using the hydrogen PIT with an unpolarized antiproton beam, it is possible to independently determine a suitable polarization analyzer signal, which, when utilized in the analysis of a polarized antiproton beam impinging on an unpolarized target, provides through CPT invariance the polarization of the stored antiproton beam. The beam polarization achieved after spin filtering in a longitudinally polarized target can be measured by switching off adiabatically the Siberian snake, and subsequent left–right asymmetry measurements. It is interesting to note that using the PIT, a direct determination of the longitudinal spin correlation parameter A_{zz} in elastic antiproton–proton scattering becomes possible. Once this parameter is established for the beam energies of interest, the longitudinal beam polarization could be determined directly.

6 Manpower and Cost Estimate, Timetable

The present Letter–of–Intent is fully supported by the PAX collaboration. It should be noted, that in all likelihood the amount of work involved in setting up and running the proposed experiments at the AD will not require all PAX collaborators. We are envisioning to have available for the full proposal, which we plan to submit not earlier than Summer 2006, a listing of the institutional responsibilties for the AD experiment.

Below, we give an approximate timetable for the activities outlined in this Letter–of–Intent. Prior to the installation, all components will be tested off–site.

2006–2007	Design and Construction Phase
2008	Test of the low–β target section, including the HERMES PIT and the Siberian Snake at COSY Jülich.
2009	Installation of all components at the AD.
2009	2 months of beam time at the AD, plus extra weeks of machine commissioning prior to the run.
2010	2 months of beam time at the AD, plus extra weeks of machine commissioning prior to the run.

In Table 1 the main components required for the proposed studies are listed, as well as a distribution of work from the side of the PAX collaboration and CERN. The estimated costs are listed for those items that require constructive efforts.   [2]

7 Acknowledgement

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item	Component	Work^2 man–weeks	Cost kEuro
1	**Low–β Section: $\beta_x = \beta_y = 0.3$ m**		
1.1.1	What is possible with small changes of the AD-lattice	1	
1.1.2	Complete redesign of the Target Straight Section	8	
1.2	Lattice Study	12	
1.3	Tracking Study	8	
1.4	Documentation	4	
1.5	Inegration into the AD system	3	
2	**Straight Sections**		
2.1	Documentation of the actual System, Drawings etc.	2	
2.2	Detector Design	10	
2.3	Changes, space requirements	4	
2.4	Slow control	16	120
2.5	Vacuum System Straight Sections	6	500
2.6	Target Differential Pumping System	10	500
2.7	Construction Off–Site	12	
2.8	10 Quadrupoles low-β Section		400
2.9	Electronics Experiment		150
3	**Electron Cooler**		
3.1	Upgrade existing Cooler to 120 keV	40	200
3.2	Construction	12	
3.3	Commissioning	12	
3.4	Integration and Control	16	
4	**Siberian Snake**		
4.1	Snake Design	4	
4.2	Existing Snakes Decision Finding	6	6
4.3	Transport & Hardware Tests	6	7
4.4	Lattice study for Implementation of Snake	8	
4.5	Integration into AD system	12	
4.6	Power Supplies for Snake and 4 skewed Quadrupoles		100
5	**Beam Diagnostics**		
5.1	Design of near–target Beam Position Monitors	6	
5.2	Controls and low–level Electronics	4	
5.3	Four Pickups with Electronics		120
6	**Construction On–Site: 12 weeks**		
6.1	Target Section: 2 Engineers, 2 Technicians, 2 Workers	72	
6.2	Electron Cooler: 1 Engineer, 1 Technician, 2 Workers	48	
6.3	Siberian Snake: 1 Engineer, 1 Technician, 2 Workers	48	
7	**Commissioning: 12 weeks**		
7.1	3 Engineers, 3 Technicians, 2 Workers	96	
7.2	Miscellaneous Electronic Material		60
	Invest Total		2163
	Travel Costs		180

Table 1: List of components, amount of work and cost estimates, required for the AD Experiment.

8 Appendix A

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