Letter–of–Intent
for

Spin–Filtering Studies at COSY

($\mathcal{PAX}$ Collaboration)

Jülich, April 2006

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Abstract

Understanding the interplay of the nuclear interaction with polarized protons and the electromagnetic interaction with polarized electrons in polarized atoms is crucial to progress towards the PAX goal to eventually produce stored polarized antiproton beams at FAIR. Presently, there exist two competing theoretical scenarios: one with substantial filtering of (anti)protons by atomic electrons, while the second one suggests a self-cancellation of the electron contribution to filtering. The issue can be clarified by studying the energy dependence of the polarization buildup in a proton beam at COSY at energies in the range from 20 to about 800 MeV. This Letter–of–Intent summarizes the physics case and possible experimental approaches to these studies at COSY.

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Contents

1 Introduction

In this Letter–of–Intent, the PAX collaboration suggests to study the polarization buildup in a proton beam at COSY at energies in the range from 20 to about 800 MeV. The main scientific objectives of this experiment at COSY relate to the physics of the polarization buildup in a stored beam. The energy dependence of spin filtering will be studied as a tool to disentangle the relative contributions to filtering from polarized protons (deuterons) and electrons in the polarized internal target (PIT). Specifically, at present there exist two theoretical scenarios for spin filtering of stored (anti)protons. In the first scenario, suggested by H.O. Meyer [1], the stored beam gets polarized by the QED process of spin transfer from polarized electrons in a PIT. On the other hand, the 2005 scrutiny of the filtering process suggests a cancellation of the electron contribution to the polarization of the transmitted stored beam and beam particles elastically scattered off electrons — the deflection of the latter is negligibly small and they all stay within the beam. In the second scenario only the nuclear interaction would contribute to spin filtering. Understanding which of these two scenarios is really at work is crucial to progress towards the goal to eventually produce stored polarized antiproton beams. The answer must be obtained experimentally in a situation where one knows well the spin-dependent ingredients of the two scenarios. Therefore, we suggest to carry out spin–filtering studies at COSY using stored protons.

The PAX collaboration has recently suggested in a Letter–of–Intent to the SPS committee of CERN [2] to study the polarization buildup by spin filtering of stored antiprotons by multiple passage through a polarized internal hydrogen gas target. Through this investigation, one can obtain 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 the unique opportunity to study transverse spin physics in the hard QCD regime. Such a collider has been proposed recently by the PAX Collaboration [3] 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).

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 [3] has recently been submitted to the FAIR project. The uniqueness and the strong scientific merits of the PAX proposal have been well received [4], and there is an urgency to convincingly demonstrate experimentally that a high degree of antiproton polarization could be reached with a dedicated APR.

Here we recall, that for more than two decades, physicists have tried to produce beams of polarized antiprotons [5], 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} [6]. 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} [7]. 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 [8]. Although the theoretical understanding has much improved since then [9], 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 [10].

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 subsequently to the COSY experiments spin filtering experiments using stored antiprotons at the AD–ring of CERN. Once this experimental data base will be available, the design of a dedicated APR can be targeted.

2 Physics Case

2.1 Polarization buildup in a stored proton beam: Theory and the FILTEX Result

The spin filtering in storage rings is based on the multiple passage of a stored beam through a polarized internal gas target (PIT). When the interaction depends on the relative spin orientations of beam and target, the target polarization is transferred to the beam in precisely the same way as in the familiar polarization of light transmitted through an optically active medium [11, 12]. In the realm of strongly interacting particles, spin filtering works by removing (absorbing out) one of the spin states of the incident beam.

The celebrated example is the extremely effective polarized ^{3}He filter for cold, thermal and hot neutrons: neutrons with spin component antiparallel to the nuclear spin have a gigantic cross section of capture into a broad resonance, $J^\pi = 0^+$, in the intermediate ^{4}He*, which decays to $t + p$, and the transmitted neutron beam gets polarized parallel to the nuclear spin (see ref. [13] and references therein).

In the optical experiments, one usually deals with the polarization of the transmitted light which propagates at exactly zero angle. The above described ^{3}He also polarizes the transmitted neutron beam. In particle scattering experiments, one is after the polarization of scattered (recoil) particles, and the transmitted beam and the scattered paricles are not mixed with each other.

Spin filtering of (anti)protons in storage rings is rich in subtleties noticed by H.O. Meyer [1]. Firstly, a unique geometrical feature of storage rings is that particles scattered off a PIT within the ring acceptance angle $\theta_{\rm acc}$, remain in the beam. Such a scattering–within–the–ring (SWR) mixes the polarization of transmitted beam and scattered particles. Secondly, polarized atoms of a PIT contain polarized electrons. The interaction of the spin of the electron with the spin of stored (anti)protons is a non–negligible one. At low energies, for instance, this interaction is responsible for the hyperfine splitting in atoms. At high energies, it describes the spin transfer from a polarized electron beam to the scattered protons — the recent polarimetry of scattered nucleons at MAMI, BATES and Jefferson Lab has led to major discoveries in the physics of electromagnetic form factors of nucleons (for a review see ref. [14]). Under the conditions of the FILTEX experiment, the spin transfer from atomic electrons to the stored protons is comparable to that from the nuclear interaction of the stored protons with the polarized protons in the PIT [15]. Finally, at low to intermediate energies, proton–proton scattering at angles below and close to $\theta_{\rm acc}$ is strongly dominated by the Coulomb interaction, and an accurate evaluation of Coulomb–nuclear interference (CNI) effects is called upon. As a matter of fact, no direct experimental observations of pp scattering at angles $\theta \lesssim \theta_{\rm acc}$ are possible, such interactions are of relevance only to storage rings.

Meyer noticed that because of the very small mass of the electron, the deflection of the much heavier protons in pe interactions is so small, $\theta \leq m_e/m_p \ll \theta_{\rm acc}$, that all protons scattered off electrons stay within the beam. Meyer argued that with the $\uparrow\uparrow$ hyperfine state of the hydrogen in the PIT of FILTEX, the polarization transfer from electrons to scattered protons is crucial for a quantitative interpretation of the filtering rate measured by the FILTEX collaboration. In the pure transmission picture, the FILTEX polarization rate as published in 1993, can be re–interpreted in terms of the effective polarization cross section as $\sigma_{\rm eff}({\rm FILTEX}) = 63 \pm 3$ (stat.) mb. The transmission effect from absorption by pure nuclear elastic scattering at all scattering angles, $\theta > 0$, based on the pre-93 SAID database [16], was

$$\sigma_1({\rm Nuclear}; \theta > 0) = 122 \text{ mb}. \tag{1}$$

The factor of two disagreement between $\sigma_{\rm eff}({\rm FILTEX})$ and σ_1 called for an explanation. Meyer pointed out that scattering at angles $\theta \leq \theta_{\rm acc}$ does not contribute to the absorption of the stored beam. He also noticed the importance of CNI effects and, based on the pre-93

SAID database, he evaluated the CNI corrected value to be

$$\sigma_1(\mathrm{CNI}; \theta > \theta_{\mathrm{acc}}) = 83 \text{ mb}. \tag{2}$$

This substantial departure from 122 mb of Eq. (1) is entirely due to the interference of the Coulomb and double–spin dependent nuclear amplitudes.

The estimate in Eq. (2) was still about seven standard deviations from the above cited σ_{eff}(FILTEX). The spin transfer from polarized target electrons to scattered protons, which in *ep* interactions all stay within the beam, amounts to a very large correction to Eq. (2) [1, 15]

$$\delta\sigma_1^{ep} = -70 \quad \text{mb}. \tag{3}$$

Finally, Meyer added the polarization transfer from polarized protons in the PIT to stored protons scattered elastically within the acceptance angle,

$$\delta\sigma_1^{pp}(\mathrm{CNI}; \theta_{\mathrm{min}} < \theta < \theta_{\mathrm{acc}}) = +52 \text{ mb}, \tag{4}$$

which brought the theory to a perfect agreement with the experiment: $\sigma_{\mathrm{eff}} = (83 - 70 + 52)$ mb $= 65$ mb.

The experimental database on the double–spin dependence of the antiproton–proton interaction is basically nonexistent. For this reason, the success of Meyer's explanation of the FILTEX result, and the large value of $\delta\sigma_1^{ep} = -70$ mb, has prompted the idea to base the antiproton polarizer of the PAX experiment on the spin filtering by polarized electrons in a PIT [17]. In the context of the PAX proposal, the feasibility of the electron mechanism of spin filtering has thus become a major issue. During the past year, two groups of theorists from the Budker Institute [18] and the Institute of Kernphysik of Forschungszentrum Jülich [19] revisited the impact of SWR on the spin filtering process. Two very different formalisms have been used: the kinetic equation for the spin state population numbers by the Budker group, and the quantum evolution equation for the spin–density matrix of the stored beam in the Jülich approach. The final conclusions are identical, though. Roughly speaking, in the spin filtering by transmission one must divide the effect into the contribution from spin–dependent absorption by scattering of protons beyond the acceptance angle, $\theta \geq \theta_{\mathrm{acc}}$, and within the ring, *i.e.* $\theta \leq \theta_{\mathrm{acc}}$. The polarization brought into the stored beam by protons scattered within the beam, basically cancels the latter contribution of the transmission effect. For the pure electron target, both groups find a full cancellation of the transmission and SWR effects — polarized electrons would not polarize stored protons. In the proton–proton interaction, the cancellation of the transmission and SWR effects is broken by spin–flip scattering (a full summary of formulas for the evolution of the beam polarization is given in Appendix A). However, numerically the spin–flip cross sections turn out to be negligibly small, and for all practical purposes, the effective polarization cross section can be evaluated from Meyer's Eq. (2):

$$\sigma_{\mathrm{eff}} = \sigma_1(\mathrm{CNI}; \theta > \theta_{\mathrm{acc}}). \tag{5}$$

What then is the status of the Budker-Jülich interpretation of the FILTEX result? The conversion of the FILTEX polarization buildup rate, which by itself is the 20 (statistical) standard deviation measurement, into the polarization cross section σ_{eff} depends on the target polarization and the areal density of the PIT. The recent reanalysis [20] gave $\sigma_{\text{eff}}(\text{FILTEX}) = 72.5 \pm 5.8$ mb, where both the statistical and systematical errors are included. The theoretical calculation of $\sigma_1(\text{CNI}; \theta > \theta_{\text{acc}})$ requires a careful extrapolation of the SAID output to extremely small scattering angles $\theta \leq \theta_{\text{acc}}$, way beyond the angular range SAID was ever supposed to be applied. The latest version of the SAID database, SAID-SP05 [16], gives $\sigma_{\text{eff}} = 85.6$ mb, which is consistent with the FILTEX result within the quoted error bars. The above result is found upon the extrapolation of separate spin observables which enter in σ_1 (see Appendix A). If the whole integrand is extrapolated, which is advisable, one finds $\sigma_{\text{eff}} = 83$ mb, as shown in Fig. 1. Starting with the Nijmegen nuclear phase shifts [21], and adding in the Coulomb interaction effects, the Budker group finds for the same quantity 89 mb [18].

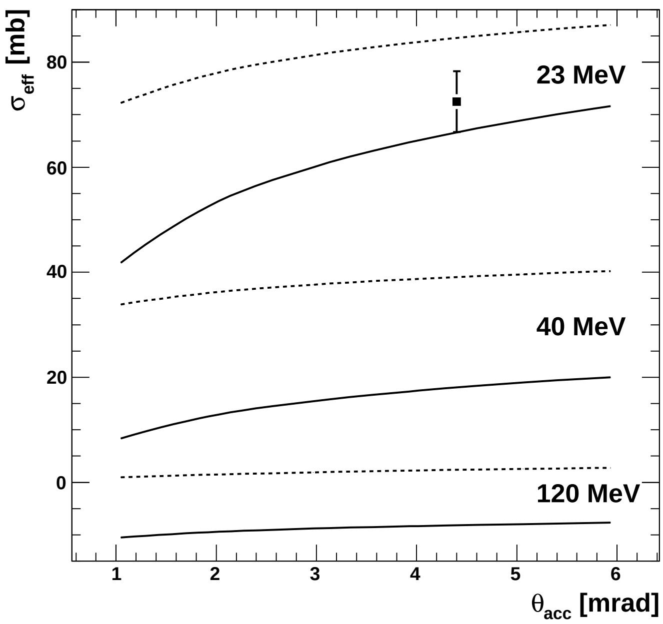

Figure 1: Experimentally observed polarization buildup cross section σ_{eff} for a 23 MeV proton beam in the TSR experiment [10] after re–analysis [20] as function of the ring acceptance angle θ_{acc}. The solid curves show the prediction from Meyer's approach which includes filtering on electrons of the polarized atoms [1, 15]. The dashed curves denote the prediction of the Budker-Jülich approach with self–cancellation of filtering on electrons [18, 19].

2.2 How to distinguish the two polarization buildup scenarios?

There is a fair agreement between the Budker-Jülich evaluation and the FILTEX result, perhaps, not as perfect as with Meyer's estimate (Fig. 1). The two competing approaches to the theoretical evaluation of $\sigma_{\rm eff}$ differ in their treatment of cancellations between the transmission and scattering–within–the–ring effects. One would reiterate that double–spin QED interaction between the electron and antiproton is well known, the hope of profiting from this knowledge is a quite natural one, and whether the self–cancellation of spin filtering on polarized electrons is correct or not, must be tested *experimentally* in a proton storage ring before proceeding to filtering experiments with antiprotons.

The ideal solution would be the null experiment with two hyperfine states in the PIT such that the net nuclear polarization of the target is zero. This requires operating the PIT with longitudinal target polarization and the stable beam spin direction must be aligned longitudinally at the target as well to preserve the longitudinal polarization of the stored protons, which at present is precluded since COSY is not equipped with a Siberian snake. 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 section, shown in Fig. 1. At COSY, an upper limit for the expected acceptance angle is ~ 2 mrad, and the Budker-Jülich and Meyer predictions for filtering at $T = 40$ MeV differ by a factor ≈ 3. One would conclude that a precision measurement of $\sigma_{\rm eff}$ at this energy would be sufficient to disprove or prove the presence of filtering on polarized electrons. The second null experiment — for the pure nuclear mechanism — can be performed by injecting two hyperfine states with identical proton polarizations and opposite electron polarizations. Such a pure nuclear polarization in the target can only be realized in a strong longitudiinal holding field. That would require installation of a Siberian snake, but in the long run such an investment could well be worth the trouble, because the longitudinal filtering cross section is dramatically larger than the transverse one, as we discuss briefly below.

The Horowitz–Meyer *ep* contribution to $\sigma_{\rm eff}$ decreases with kinetic energy $\sim 1/T$. In contrast to that, the contribution from the nuclear *pp* interaction has a distinctly different energy dependence. In Fig. 2 we show predictions from the Budker-Jülich model for the energy dependence of the polarization of stored protons after filtering for 2 to 5 beam lifetimes τ_b. The actual beam lifetime depends on the target density. In Fig. 3, the calculated beam lifetime

$$\tau_b(T) = \frac{1}{\sigma_{\rm tot}(T)\, d_{\rm eff}\, f_{\rm rev}(T)} \tag{6}$$

is shown. Here $d_{\rm eff} = d_t + d_{rg}$, where d_t is the areal thickness of the PIT and d_{rg} is the areal density of the residual gas in the ring, evaluated assuming a residual gas pressure of 10^{-9} mbar, produced mainly by H_2, $f_{\rm rev}$ denotes the revolution frequency. The achievable target thickness with the ANKE and HERMES target [22] is discussed in more detail in Sec. 4.1. The total cross section including the Coulomb interaction is obtained using the SAID-SP05 solution by evaluation of

$$\sigma_{\rm tot} = \int_{\theta_{\rm acc}}^{\theta_{\rm max}} \frac{d\sigma}{d\Omega} d\Omega\,. \tag{7}$$

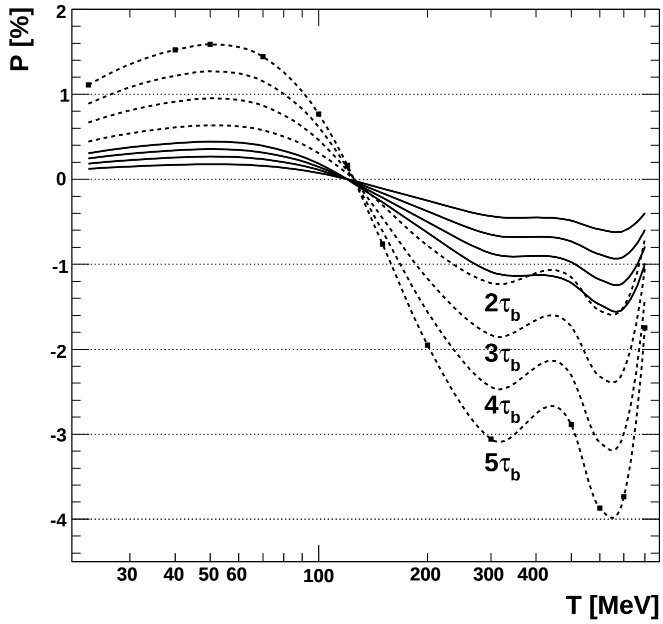

Figure 2: Polarization buildup in the COSY ring as function of beam energy for an acceptance angle of $\theta_{\rm acc} = 1$ mrad (solid lines) and for 2 mrad (dashed) using the Budker-Jülich approach [19]. The duration of the filtering process is given in units of the beam lifetime τ_b for the dashed curves (the pattern repeats for the curves corresponding to $\theta_{\rm acc} = 1$ mrad). The squares shown indicate the meshpoints where the calculations were carried out.

The energy dependence of the resulting beam polarization in COSY, shown in Fig. 2, closely follows, although because of the CNI effects it is not identical to the experimentally measured energy dependence of the transverse total cross section $\Delta\sigma_T$, shown in Fig. 4. The results for $\sigma_{\rm eff}$ from our calculations show that CNI makes $\sigma_{\rm eff}$ substantially smaller than $\Delta\sigma_T$ — the same trend as seen from a comparison of the results in Eq. (1) and Eq. (2).

At present, electron cooling at COSY is available only up to kinetic energies around $T =$ 120 MeV, and the interesting energy dependence at higher energies can not be exploited. However, the possibility of filtering at 800 MeV, where stochastic cooling becomes available, must be further explored.

One could increase the polarization buildup rate by filtering with an isoscalar deuterium target. Firstly, because of the different mass, the target density for deuterium atoms in the cell is higher by a factor $\sqrt{2}$. Secondly, $\Delta\sigma_T$ in the isospin zero channel is larger than in pp scattering, as shown in Fig. 5a. Consequently, one could hope to gain in the filtering cross section and in target density while having the same Coulomb losses as for the hydrogen target. In proton–proton scattering, the longitudinal cross section asymmetry $\Delta\sigma_L$, shown in Fig. 6, is substantially larger than $\Delta\sigma_T$. From a comparison with the isoscalar cross

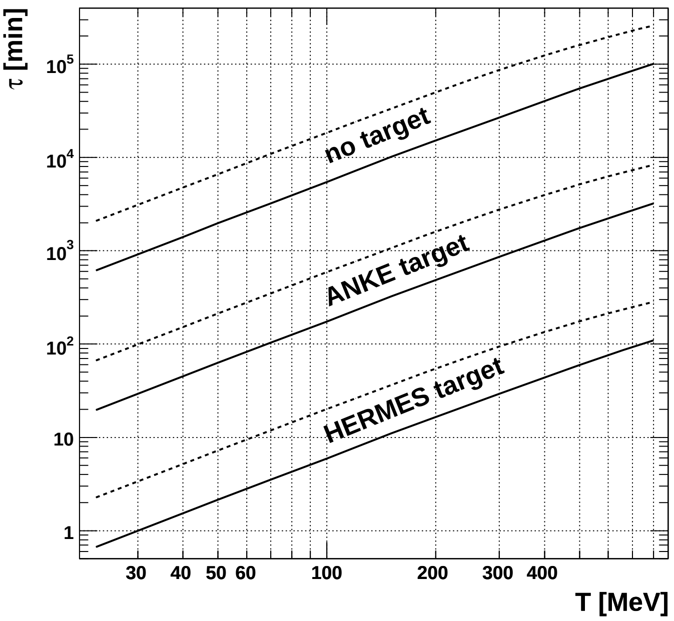

Figure 3: Lifetime of the COSY beam calculated using Eq. (6) for a target thickness $d_t^{\mathrm{ANKE}} = 2 \times 10^{13}$ atoms/cm^2 and $d_t^{\mathrm{HERMES}} = 6 \times 10^{14}$ atoms/cm^2, and a residual gas pressure of of 10^{-9} mbar, produced mainly by H_2. (A discussion of the density achievable with the new low–β section for the HERMES target is given in Sec. 4.1.)

section shown in Fig. 5b, in the case of longitudinal target spin orientation during filtering, one would prefer the hydrogen target. A careful study of CNI effects for both hydrogen and deuterium targets is called upon for more definitive conclusions.

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 [10]: 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.

The polarization buildup of the beam as a function of filter time t can be expressed in the absence of depolarization as [10]

$$P(t) = \tanh(t/\tau_1) \tag{8}$$

The time constant τ_1, which characterizes the rate of polarization buildup, for transverse

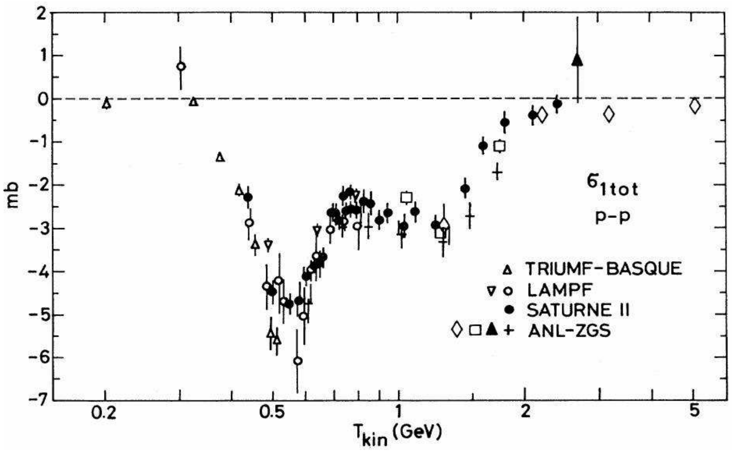

Figure 4: Energy dependence of $\sigma_1(pp) = -\frac{1}{2}\Delta\sigma_T(pp)$ (Figure from ref. [23].)

($\perp$) and longitudinal ($||$) orientation of beam and target polarization Q is

$$\tau_1^{\perp} = \frac{1}{\sigma_1 Q d_t f_{\text{rev}}} \quad \text{and} \quad \tau_1^{||} = \frac{1}{(\sigma_1 + \sigma_2) Q d_t f_{\text{rev}}} \tag{9}$$

where d_t is the target thickness in atoms/cm^2 and f_{rev} 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. (9) 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 COSY, as well as in the AD. It is important to note that the buildup cross sections σ_1 and σ_2, which we eventually intend to measure at the AD 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 COSY

The commissioning of a dedicated spin–filtering experiment at COSY will require the installation of new components in the COSY ring, namely a PIT in a new low–β section, the development of an efficient polarimeter for the target and the beam polarization, and (possibly) a Siberian snake to maintain the longitudinal polarization in the ring. The design of these new elements will take into account their re–utilization in the subsequent experiment with antiprotons at the AD of CERN, for which the experiment at COSY will provide a fully commissioned setup.

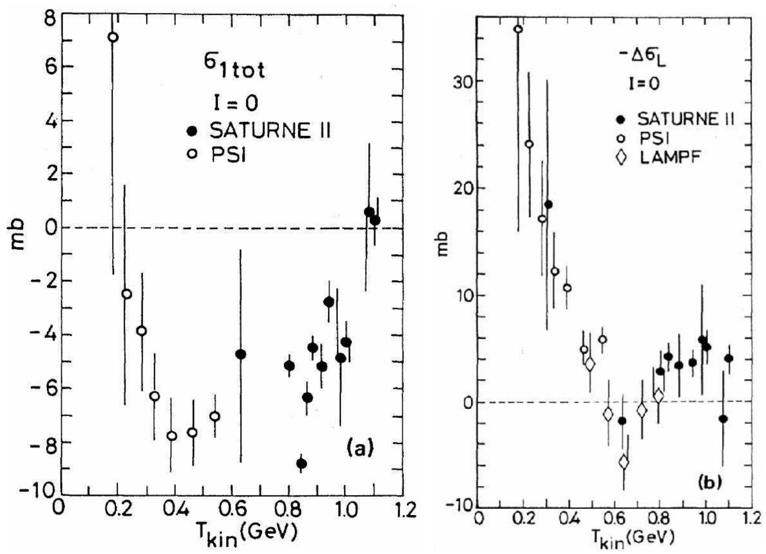

Figure 5: Energy dependence of $\sigma_1(pp) = -\frac{1}{2}\Delta\sigma_T(pp)$ (panel a) and $-\Delta\sigma_L(pp)$ (panel b) in the isoscalar channel deduced from *pp* and *pn* data. (Figure from ref. [23].)

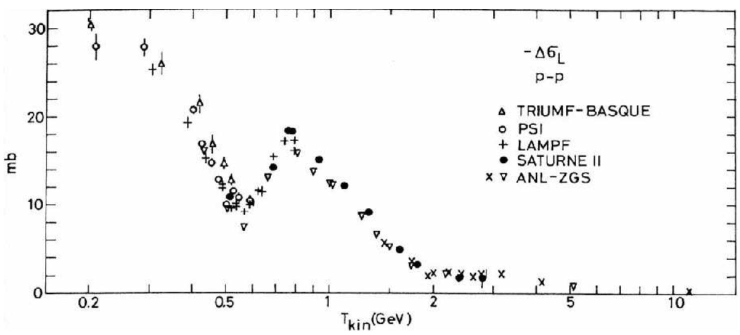

Figure 6: Energy dependence of $-\Delta\sigma_L(pp)$. (Figure from ref. [23].)

4.1 Low–β–Section

The measurements require implementing a PIT in the straight section of COSY, opposite to ANKE. The thickness of a storage cell target depends strongly on the transverse dimension of the cell. In order to provide a high target density, the β–function at the storage cell should be about $\beta_x^{\rm New} = \beta_y^{\rm New} = 0.3$ m. Scaling the target thickness recently observed with the ANKE PIT of $d_t^{\rm ANKE} = 2 \times 10^{13}$ atoms/cm^2, where $\beta_x^{\rm ANKE} = \beta_y^{\rm ANKE} \approx 3$ m with $(\beta^{\rm ANKE}/\beta^{\rm New})^{3/2} = 10^{3/2} \approx 30$ would bring the target density of the so–modified HERMES target up to $6 \cdot 10^{14}$ atoms/cm^2. 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. The section which houses the new 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 COSY.

We envision to utilize the HERMES PIT [22] (HERA/DESY), which has become available at the beginning of 2006, to feed the new storage cell target. 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. Most likely, the cell cannot be cooled to temperatures around 60 K, which would yield another factor of $\sqrt{5}$ in density, because the detection of both recoil and scattered protons during the low energy measurements precludes the use of a 100 μ thick cell wall.

The polarization obtained after filtering, say for two beam lifetimes, is the same whether one uses the ANKE or the new PIT. But one must note, that only through the substantially enhanced increase in target thickness at the new target place, the measurements at the higher energies, e.g. above 800 MeV where stochastic cooling is possible, become feasible. The reason is that with the ANKE PIT, the beam lifetimes in COSY reach inconveniently large values of a few thousand minutes, as indicated in Fig. 3.

4.2 Beam and Target Polarimetry

Prior to the spin filtering, the target polarization needs to be determined. Unfortunately, the proton–proton analyzing powers are very small at low energies envisaged for the spin filtering studies. Their maximum varies between $A_y(T = 120\,\text{MeV}) \approx 0.15$ and $A_y(T = 40\,\text{MeV}) \approx 0.015$ [21]. The target polarization therefore needs to be measured prior to the filtering by ramping the unpolarized proton beam up to energies around 800 MeV, where the proton–proton analyzing powers reach values around 0.5 and stochastic cooling is available. Obviously, the target polarization does not depend on the beam energy. During spin filtering with vertical target polarization, due to the buildup of beam polarization P, an Up-Down asymmetry produced by $P_y \cdot Q_y \cdot A_{xx}$ in the detector system can be used to observe the buildup. The spin correlation parameter A_{xx} at $T = 40$ MeV is about -0.8 at all polar angles. After the filtering process has ended, the target polarization can be reversed rapidly every few seconds to determine the final polarization more accurately. In addition, it is conceivable to also reverse the beam polarization frequently by using the available COSY spin flipper to reduce systematic asymmetries.

With the storage cell of the ANKE PIT, we have already achieved through cooler stacking beam intensities around 1.5×10^{10} protons stored in the ring and accelerated to 600 MeV (see Fig. 2 of ref. [24]). After filtering for 5 beam lifetimes, the COSY beam intensity has dropped to $1/e^5 \approx 1/150$ of its inital value, *i.e.* to about 10^8 stored protons. Using this beam intensity, the beam polarization resulting from the spin filtering process has to be measured. Thus the proton–proton elastic reaction rates to be expected using the ANKE PIT amount to about $R^{\text{ANKE}}(40\,\text{MeV}) = \mathcal{L}^{\text{ANKE}} \cdot \sigma^{pp}_{\text{tot}} = 10^8 \cdot 500\ \text{s}^{-1} \cdot 2 \times 10^{13}\ \text{cm}^{-2} \cdot 50\,\text{mb} \approx 50\ \text{s}^{-1}$, while with the new PIT, rates $R^{\text{New}}(40\,\text{MeV}) \approx 1500\ \text{s}^{-1}$ could be reached.

If we assume an acceptance angle during filtering of 2 mrad, we would reach after filtering for 5 beam lifetimes at $T = 40$ MeV, a beam polarization of about 0.015. In order to determine such a small value of the beam polarization accurately, say with a statistical uncertainty of about $\Delta P = 10^{-3}$, the number of events required is of the order $N = (A_{xx} \cdot \Delta P)^{-2} = (0.8 \cdot 10^{-3})^{-2} \approx 2 \cdot 10^6$. This leads for the new PIT to a measuring time of about 20 min, while due to the reduced target thickness the same measurement with the ANKE PIT would last for about 60 h. It is conceivable to determine the beam polarization after filtering with an unpolarized H_2 target, where one could increase the target thickness. In this case, in order to avoid large systematic errors, the beam polarization should be reversed frequently during the measurement using the COSY spin flipper.

The target thickness of the PIT can be either obtained from the observed deceleration of the stored beam when the electron cooling is switched off, as shown in ref. [25], or it can be inferred from the measured rates in the polarimeter. 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 is presently being built for ANKE ([26] (more recent information on the detection system can be found in ref. [27]).

5 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 COSY will not require all PAX collaborators. We are envisioning to submit the full proposal the to the Fall 2006 PAC meeting.

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

2006–2007	Design and Construction Phase
2008	Polarization buildup studies with the new low–β section, with the HERMES PIT at COSY.
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.

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A Evolution of the spin-density matrix of the stored beam

In fully quantum-mechanical approach, the beam of stored antiprotons must be described by the spin-density matrix

$$\hat{\rho}(\boldsymbol{p}) = \frac{1}{2}[I_0(\boldsymbol{p}) + \boldsymbol{\sigma}\boldsymbol{s}(\boldsymbol{p})], \tag{10}$$

where $I_0(\boldsymbol{p})$ is the density of particles with the transverse momentum $\boldsymbol{p}$ and $\boldsymbol{s}(\boldsymbol{p})$ is the corresponding spin density. As far as the pure transmission is concerned, it can be described by the polarization dependent refraction index for the hadronic wave, given by the Fermi-Akhiezer-Pomeranchuk-Lax formula [11]:

$$\hat{n} = 1 + \frac{1}{2p}N\hat{\mathsf{F}}(0). \tag{11}$$

The forward NN scattering amplitude $\hat{\mathsf{F}}(0)$ depends on the beam and target spins, and the polarized target acts as an optically active medium. It is convenient to use instead the Fermi Hamiltonian (with the distance z traversed in the medium playing the rôle of time)

$$\hat{H} = \frac{1}{2}N\hat{F}(0) = \frac{1}{2}N[\hat{R}(0) + i\hat{\sigma}_{tot}], \tag{12}$$

where $\hat{R}(0)$ is the real part of the forward scattering amplitude and N is the volume density of atoms in the target. The anti-hermitian part of the Fermi hamiltonian, $\propto \hat{\sigma}_{tot}$, describes the absorption (attenuation) in the medium.

In terms of the Fermi hamiltonian, the quantum-mechanical evolution equation for the spin-density matrix of the transmitted beam reads

$$\begin{aligned} &\frac{d}{dz}\hat{\rho}(\boldsymbol{p}) = i\Big(\hat{H}\hat{\rho}(\boldsymbol{p}) - \hat{\rho}(\boldsymbol{p})\hat{H}^{\dagger}\Big) \\ &= \underbrace{i\frac{1}{2}N\Big(\hat{R}\hat{\rho}(\boldsymbol{p}) - \hat{\rho}(\boldsymbol{p})\hat{R}\Big)}_{\text{Pure refraction}} - \underbrace{\frac{1}{2}N\Big(\hat{\sigma}_{tot}\hat{\rho}(\boldsymbol{p}) + \hat{\rho}(\boldsymbol{p})\hat{\sigma}_{tot}\Big)}_{\text{(Pure attenuation)}} \end{aligned} \tag{13}$$

In the specific case of spin-$\frac{1}{2}$ protons interacting with the spin-$\frac{1}{2}$ protons (and electrons) the total cross section and real part of the forward scattering amplitude are parameterized as

$$\begin{aligned} \hat{\sigma}_{tot} &= \sigma_0 + \underbrace{\sigma_1(\boldsymbol{\sigma}\cdot\boldsymbol{Q}) + \sigma_2(\boldsymbol{\sigma}\cdot\boldsymbol{k})(\boldsymbol{Q}\cdot\boldsymbol{k})}_{spin-sensitive\ loss}, \\ \hat{R} &= R_0 + \underbrace{R_1(\boldsymbol{\sigma}\cdot\boldsymbol{Q}) + R_2(\boldsymbol{\sigma}\cdot\boldsymbol{k})(\boldsymbol{Q}\cdot\boldsymbol{k})}_{\boldsymbol{\sigma}\cdot\text{Pseudomagnetic field}} \end{aligned} \tag{14}$$

Then, upon some algebra, one finds the evolution equation for the beam polarization $\boldsymbol{P} = \boldsymbol{s}/I_0$

$$
\begin{aligned}
d\boldsymbol{P}/dz &= \underbrace{-N\sigma_1(\boldsymbol{Q} - (\boldsymbol{P}\cdot\boldsymbol{Q})\boldsymbol{P}) - N\sigma_2(\boldsymbol{Qk})(\boldsymbol{k} - (\boldsymbol{P}\cdot\boldsymbol{k})\boldsymbol{P})}_{\text{(Polarization buildup by spin-sensitive loss)}} \\
&+ \underbrace{NR_1(\boldsymbol{P}\times\boldsymbol{Q}) + nR_2(\boldsymbol{Qk})(\boldsymbol{P}\times\boldsymbol{k})}_{\text{(Spin precession in pseudomagnetic field)}}, \qquad (15)
\end{aligned}
$$

where we indicated the rôle of the anti-hermitian – attenuation – and hermitian – pseudomagnetic field – parts of the Fermi Hamiltonian. It is absolutely important that the cross sections $\sigma_{0,1,2}$ in the evolution equation for the transmitted beam describe all-angle scattering.

Although the effects of precession of the spin of the stored beam in the psedomagnetic field of the PIT are missed in kinetic equation approach [18], upon the averaging over these precessions the density matrix approach [19]simplifies gives the same results as the kinetic equation for spin population numbers.

Mixing of spins of transmitted beam and of particles scattered within the ring is described as follows [19]. The quasielastic proton-atom collsiions can well be approximated by an incoherent sum of *ep* and *pp* differential cross sections:

$$
\frac{d\hat{\sigma}_E}{d^2\boldsymbol{q}} = \frac{1}{(4\pi)^2}\hat{\mathsf{F}}(\boldsymbol{q})\hat{\rho}\hat{\mathsf{F}}^\dagger(\boldsymbol{q}) = \frac{1}{(4\pi)^2}\hat{\mathsf{F}}_e(\boldsymbol{q})\hat{\rho}\hat{\mathsf{F}}_e^\dagger(\boldsymbol{q}) + \frac{1}{(4\pi)^2}\hat{\mathsf{F}}_p(\boldsymbol{q})\hat{\rho}\hat{\mathsf{F}}_p^\dagger(\boldsymbol{q}) \qquad (16)
$$

The evolution equation for the spin-density matrix, corrected for SWR, takes the form

$$
\begin{aligned}
\frac{d}{dz}\hat{\rho} = i[\hat{H},\hat{\rho}] &= \underbrace{i\frac{1}{2}N\Big(\hat{R}\hat{\rho}(\boldsymbol{p}) - \hat{\rho}(\boldsymbol{p})\hat{R}\Big)}_{Pure\ precession\ \&\ refraction} \\
&- \underbrace{\frac{1}{2}N\Big(\hat{\sigma}_{tot}\hat{\rho}(\boldsymbol{p}) + \hat{\rho}(\boldsymbol{p})\hat{\sigma}_{tot}\Big)}_{Evolution\ by\ loss} \\
&+ \underbrace{N\int^{\Omega_{acc}}\frac{d^2\boldsymbol{q}}{(4\pi)^2}\hat{\mathsf{F}}(\boldsymbol{q})\hat{\rho}(\boldsymbol{p}-\boldsymbol{q})\hat{\mathsf{F}}^\dagger(\boldsymbol{q})}_{\text{Lost \& found: scattering within the beam}} \qquad (17)
\end{aligned}
$$

Notice the convolution of the transverse momentum distribution in the beam with the differential cross section of quasielastic scattering. This broadening of the momentum distribution is compensated for by the focusing and the beam cooling in a storage ring.

The *ep* scattering is pure SWR and the *ep* contribution to the transmission effect is exactly cancelled by the *ep* contribution to elastic SWR - electrons in the target are invisible. Upon some algebra, one finds the SWR-corrected coupled evolution equations

$$
\frac{d}{dz}\begin{pmatrix} I_0 \\ s \end{pmatrix} = -N\begin{pmatrix} \sigma_0(>\theta_{\rm acc}) & Q\sigma_1(>\theta_{\rm acc}) \\ Q(\sigma_1(>\theta_{\rm acc}) + \Delta\sigma_1) & \sigma_0(>\theta_{\rm acc}) + 2\Delta\sigma_0 \end{pmatrix}\cdot\begin{pmatrix} I_0 \\ s \end{pmatrix}, \qquad (18)
$$

Here the spin-flip cross sections $\Delta\sigma_{0,1}$ describe the imperfect cancellation between the transmission ans SWR effects from proton-proton scattering within the acceptance angle. In terms of the standard observables as defined by Bystricky et al. (our θ is the scattering angle in the laboratory frame) [28]

$$
\begin{aligned}
&\sigma_0^{el}(>\theta_{\rm acc}) = \frac{1}{2}\int_{\theta_{\rm acc}} d\Omega \frac{d\sigma}{d\Omega},\\
&\sigma_1^{el}(>\theta_{\rm acc}) = \frac{1}{2}\int_{\theta_{\rm acc}} d\Omega \Big(d\sigma/d\Omega\Big)\Big(A_{00nn}+A_{00ss}\Big)\\
&\Delta\sigma_0 = \frac{1}{2}[\sigma_0^{el}(\leq\theta_{\rm acc}) - \sigma_0^{E}(\leq\theta_{\rm acc})]\\
&= \frac{1}{2}\int_{\theta_{\rm min}}^{\theta_{\rm acc}} d\Omega \frac{d\sigma}{d\Omega}\Big(1-\frac{1}{2}D_{n0n0}-\frac{1}{2}D_{s'0s0}\cos(\theta)-\frac{1}{2}D_{k'0s0}\sin(\theta)\Big)\\
&\Delta\sigma_1 = \sigma_1^{el}(\leq\theta_{\rm acc}) - \sigma_1^{E}(\leq\theta_{\rm acc})\frac{1}{2} = \int_{\theta_{\rm min}}^{\theta_{\rm acc}} d\Omega\frac{d\sigma}{d\Omega}\\
&\times\Big(A_{00nn}+A_{00ss}-K_{n00n}-K_{s'00s}\cos(\theta)-K_{k'00s}\sin(\theta)\Big) \qquad (19)
\end{aligned}
$$

The SWR-corrected coupled evolution equations have the solutions $\propto \exp(-\lambda_{1,2}Nz)$ with the eigenvalues

$$
\begin{aligned}
\lambda_{1,2} &= \sigma_0 + \Delta\sigma_0 \pm Q\sigma_3\\
Q\sigma_3 &= \sqrt{Q^2\sigma_1(\sigma_1+\Delta\sigma_1)+(\Delta\sigma_0)^2}, \qquad (20)
\end{aligned}
$$

The polarization buildup follows the law

$$
P(z) = -\frac{Q(\sigma_1+\Delta\sigma_1)\tanh(Q\sigma_3 Nz)}{Q\sigma_3+\Delta\sigma_0\tanh(Q\sigma_3 Nz)}. \qquad (21)
$$

The effective small-time polarization cross section equals

$$
\sigma_{eff} \approx -Q(\sigma_1+\Delta\sigma_1). \qquad (22)
$$

For all the practical purposes, it is entirely dominated by σ_1. Also, the effect of spin-flip $\Delta\sigma_0$ on both the beam lifetime and the filtering cross section is negligible small.

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