PAX: Polarized Antiprotons eXperiments

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Abstract

Polarized antiprotons produced by spin filtering with an internal polarized gas target provide access to a wealth of single– and double–spin observables, thereby opening a window to physics uniquely accessible with the HESR at FAIR. This includes a first measurement of the transversity distribution of the valence quarks in the proton, 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. In polarized and unpolarized $p\bar{p}$ elastic scattering open questions like the contribution from the odd charge–symmetry Landshoff–mechanism at large $|t|$ and spin–effects in the extraction of the forward scattering amplitude at low $|t|$ can be addressed.

Introduction

The possibility to achieve polarized proton-antiproton interactions at the High Energy Storage Ring (HESR) at FAIR has been proposed last year by the PAX Collaboration [1]. Polarized antiproton-proton interactions will provide unique access to a number of new fundamental physics observables, which can be studied neither at other facilities nor at HESR without transverse polarization of protons and antiprotons.

Physics case

Transversity

The transversity distribution is the last leading–twist missing piece of the QCD description of the partonic structure of the nucleon. It describes the quark transverse polarization inside a transversely polarized proton [2]. Unlike the more conventional unpolarized quark distribution $q(x, Q^2)$ and the helicity distribution $\Delta q(x, Q^2)$, the transversity $h_1^q(x, Q^2)$ can neither be accessed in deep–inelastic scattering of leptons off nucleons nor can it be reconstructed from the knowledge of $q(x, Q^2)$ and $\Delta q(x, Q^2)$. It may contribute to some single–spin observables, but always coupled to other unknown functions. The transversity distribution is directly accessible uniquely via the **double transverse spin asymmetry** A_{TT} in the Drell–Yan production of lepton pairs. The theoretical expectations for A_{TT} in the Drell–Yan process with transversely polarized antiprotons interacting with a transversely polarized proton target at HESR are in the 0.3–0.4 range [3, 4]; with the expected beam polarization achieved using a dedicated low–energy antiproton polarizer ring (APR) of $P \approx 0.3$ and the luminosity of HESR, the PAX experiment is uniquely suited for the definitive observation of $h_1^q(x, Q^2)$ of the proton for the valence quarks. The determination of $h_1^q(x, Q^2)$ will open new pathways to the QCD interpretation of single–spin asymmetry (SSA) measurements [5].

Magnetic and electric form factors

The origin of the unexpected Q^2–dependence of the ratio of the magnetic and electric form factors of the proton as observed at the Jefferson laboratory [6] can be clarified by a measurement of their relative phase in the time–like region, which discriminates strongly between the models for the form factor. This phase can only be measured via SSA in the annihilation $\bar{p}p^\uparrow \to e^+e^-$ on a transversely polarized target [7, 8]. The first ever measurement of this phase at PAX will also contribute to the understanding of the onset of the pQCD asymptotics in the time–like region and will serve as a stringent test of dispersion theory approaches to the relationship between the space–like and time–like form factors [9, 10, 11]. The double–spin asymmetry will allow independently the $G_E - G_M$ separation and serve as a check of the Rosenbluth separation in the time–like region which has not been carried out so far.

Hard scattering

Arguably, in $p\bar{p}$ elastic scattering the hard scattering mechanism can be checked beyond $|t| = \frac{1}{2}(s - 4m_p^2)$ accessible in the t–u–symmetric pp scattering, because in the $p\bar{p}$ case the u–channel exchange contribution can only originate from the strongly suppressed exotic dibaryon exchange. Consequently, in the $p\bar{p}$ case the hard mechanisms [12, 13, 14] can be tested at t almost twice as large as in pp scattering. Even unpolarized large angle $p\bar{p}$ scattering data can shed light on the origin of the intriguing oscillations around the s^{-10} behavior of the 90^0 scattering cross section in the pp channel and put stringent constraints on the much disputed odd–charge conjugation Landshoff mechanism [15, 16, 17]. If the Landshoff mechanism is suppressed then the double transverse asymmetry in $p\bar{p}$ scattering is expected to be as large as the one observed in the pp case.

The PAX proposal

Accelerator scheme

The possibility to test the nucleon structure via double spin asymmetries in polarized proton–antiproton reactions at the HESR ring of FAIR has been suggested by the PAX collaboration with a Letter–of–Intent submitted on January

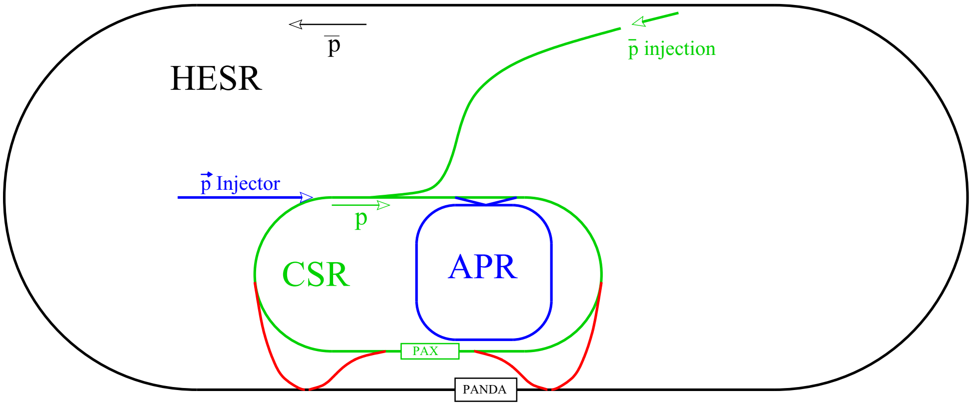

Figure 1: The proposed accelerator set–up at the HESR (black), with the equipment used by the PAX collaboration in Phase I: CSR (green), APR, beam transfer lines and polarized proton injector (all blue). In Phase II, by adding two transfer lines (red), an asymmetric collider is set up. It should be noted that, in this phase, also fixed target operation at PAX is possible.

15, 2004 [1]. The physics program of PAX has been positively reviewed by the QCD Program Advisory Committee (PAC) on May 14–16, 2004. Following the QCD–PAC report and the recommendation of the Chairman of the committee on Scientific and Technological Issues (STI) and the FAIR project coordinator, the PAX collaboration has optimized the technique to achieve a sizable antiproton polarization [18] and a Technical Proposal for experiments at GSI with polarized antiprotons [19].

The overall machine setup of the HESR complex is schematically depicted in Fig. 1. Its main features are:

1. An Antiproton Polarizer (APR) built inside the HESR area with the crucial goal of polarizing antiprotons, to be accelerated and injected into the other rings. The polarization method is based on spin-filtering of the circulating beam by an internal target to the storage ring. This technique has been successfull demonstrated with protons [20] and tests are foreseen with an antiproton beam.

2. A second Cooler Synchrotron Ring (CSR, COSY–like) in which protons or antiprotons can be stored with a momentum up to 3.5 GeV/c. This ring shall have a straight section, where a PAX detector could be installed, running parallel to the experimental straight section of HESR.

3. By deflection of the HESR beam into the straight section of the CSR, both the collider or the fixed–target mode become feasible.

It is worthwhile to stress that, through the employment of the CSR, effectively a second interaction point is formed with minimum interference with PANDA. The proposed solution opens the possibility to run two different experiments at the same time.

Staging

The PAX collaboration proposes an approach that is composed of two phases. During these the major milestones of the project can be tested and optimized before the final goal is approached: An asymmetric proton–antiproton collider, in which polarized protons with momenta of about 3.5 GeV/c collide with polarized antiprotons with momenta up to 15 GeV/c. These circulate in the HESR, which has already been approved and will serve the PANDA experiment. The proposed phases are the following:

Phase I

A beam of unpolarized or polarized antiprotons with momentum up to 3.5 GeV/c in the CSR ring, colliding on a polarized hydrogen target in the PAX detector. This phase is independent of the HESR performance.

This first phase, at moderately high energy, will allow for the first time the measurement of the time–like proton form factors in single and double polarized $\bar{p}p$ interactions in a wide kinematical range, from close to threshold up to $Q^2 = 8.5\ \mathrm{GeV}^2$. It would enable to determine several double spin asymmetries in elastic $\bar{p}^{\uparrow}p^{\uparrow}$ scattering. By detecting back scattered antiprotons one can also explore hard scattering regions of large t: In proton–proton scattering the same region of t requires twice the energy. There are no competing facilities at which these topical issues can be addressed. For the theoretical background, see the PAX Technical Proposal [19] and the recent review paper [21].

Phase II

This phase will allow the first ever direct measurement of the quark transversity distribution h_1, by measuring the double transverse spin asymmetry A_{TT} in Drell–Yan processes $p^{\uparrow}\bar{p}^{\uparrow} \to e^+e^-X$ as a function of Bjorken x and Q^2 $(= M^2)$

$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^{\overline{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \overline{q}(x_2, M^2)}, \tag{1}$$

where $q = u, \overline{u}, d, \overline{d} \ldots$, M is the invariant mass of the lepton pair and $\hat{a}_{TT}$, of the order of one, is the calculable double–spin asymmetry of the QED elementary process $q\overline{q} \rightarrow e^+e^-$. The most promising scenario forsees a beam of polarized antiprotons from 1.5 GeV/c up to 15 GeV/c circulating in the HESR, colliding on a beam of polarized protons with momenta up to 3.5 GeV/c circulating in the CSR. Deflection of the HESR beam to the PAX detector in the CSR is necessary (see Fig. 1). By proper variation of the energy of the two colliding beams, this setup would allow a measurement of the transversity distribution h_1 in the valence region of Bjorken-$x > 0.05$, with corresponding $Q^2 = 4 \ldots 100$ GeV^2 (Fig. 2).

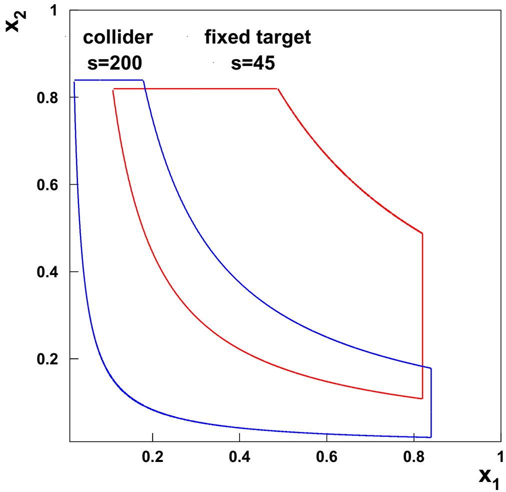

Figure 2: Kinematic region covered by the h_1 measurement at PAX in phase II. In the asymmetric collider scenario (blue) antiprotons of 15 GeV/c impinge on protons of 3.5 GeV/c at c.m. energies of $\sqrt{s} \sim \sqrt{200}$ GeV and $Q^2 > 4$ GeV^2. The fixed target case (red) represents antiprotons of 22 GeV/c colliding with a fixed polarized target ($\sqrt{s} \sim \sqrt{45}$ GeV).

A_{TT} is predicted to be larger than 0.3 over the full kinematic range, up to the highest reachable center–of–mass energy of $\sqrt{s} \sim \sqrt{200}$ (Fig. 3).

The cross section is large as well: With a luminosity of $5 \cdot 10^{30}$ cm$^{-2}s^{-1}$ about 2000 events per day can be expected For the transversity distribution h_1, such an experiment can be considered as the analogue of polarized DIS for the determination of the helicity structure function g_1, i.e. of the helicity distribution $\Delta q(x, Q^2)$; the kinematical coverage (x, Q^2) will be similar to that of the HERMES experiment.

Detector

An extensive program of studies has been started to investigate different options for the PAX detector configuration, aiming at an optimization of the achievable performance. The primary goal of the PAX experimental program is to carry out a direct measurement of the h_1 transversity distribution. The proposed detector, described in the PAX technical proposal and shown in Fig. 4, is well-suited to provide large invariant-mass e^+e^- pair detection, from both Drell-Yan reactions and $\bar{p}p$ annihilations. In addition, such a detector is able to efficiently detect secondaries in two body reactions, like elastic scattering events, where the over-constrained kinematic simplifies the event reconstruction and reduces the particle identification requirements. Alternative detector scenarios, e.g. with $\mu^+\mu^-$ Drell-Yan pair detection capability, with an instrumented forward section or with extended hadron particle identification, are also under study.

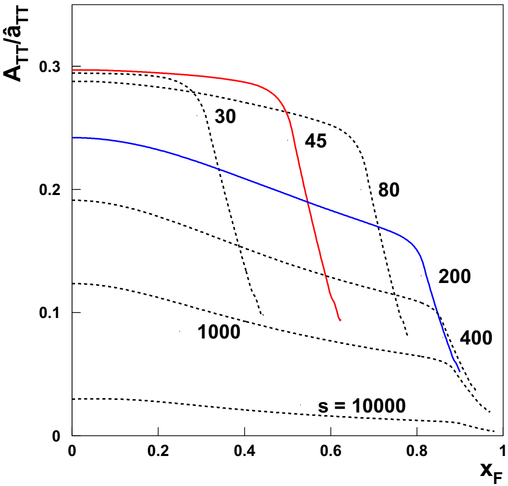

Figure 3: Expected asymmetry as a function of Feynman x_F for different values of s and $Q^2 = 16$ GeV^2.

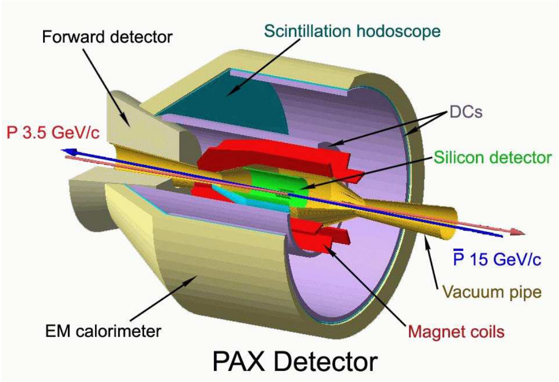

Figure 4: Conceptual design of the PAX detector.

Signal estimate

A detailed Monte Carlo study has been started to test the feasibility of the Drell-Yan measurement with the proposed detctor layout in Phase II. The achievable precision of the ratio between the transverse h_1^u and the well known unpolarized u(x) distributions of the proton, in different intervals of the Bjorken-x and after one year of data-taking is shown in Fig. 5. The h_1^u distribution can be measured in a wide x range, from $x = 0.7$ down to $x = 0.05$, practically covering the whole valence region and extending to low value of x, where the theoretical predictions show the largest deviations. It should be noticed that in principle the beam energies in the two rings of the collider can be tuned to best explore different x intervals. Indeed the highest sensitivity is achievable for $x \approx 1/\sqrt{p_p p_{\bar{p}}}$.

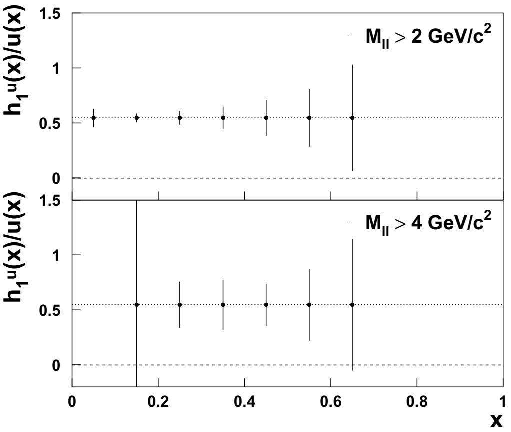

Figure 5: Expected precision of the $h_1^u(x)$ measurement for one year of data taking in the collider mode at PAX. A luminosity of $2 \cdot 10^{30}$ cm^{-2}s$^{-}1$ and a polar angle acceptance between 20° and 120° were assumed. The top panel shows the precision achievable within the full $Q^2 > 4GeV^2$ kinematic range, whereas the bottom panel shows the precision achievable in the restricted $Q^2 > 16GeV^2$ range.

Spin-filtering studies

As a first step towards the ambitious program of the PAX Collaboration a complete understanding of the mechanism of polarization buildup in a storage ring is mandatory. Therefore dedicated tests are forseen with protons at the COSY storage ring in Jülich, and a Letter of Intent [24] has been submitted to CERN in Nov. 2005 to perform spin filtering experiments using stored antiprotons in the AD ring. The final design for the APR ring will be defined only after these studies will be completed.

Conclusion

The PAX Collaboration has presented a rich and innovative physics program to be realized in the upcoming FAIR hadron facility. The storage of polarized antiprotons at HESR will open unique possibilities to test QCD in hitherto unexplored domains and make of FAIR a facility without competitors. In order to achieve a complete understanding of the spin-filtering process proposed for the production of the polarized antiprotons, dedicated studies are forseen in the next years at the COSY and AD ring.

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