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The H and D Polarized Target for Spin–Filtering Measurements at COSY

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In the main frame of the PAX (Polarized Antiproton eXperiments) collaboration, which engaged the challenging purpose of polarizing antiproton beams, the possibility to have H or D polarized targets requires a daily switchable source and its diagnostics: mainly change is a dual cavity tunable for H and D. The commissioning of PAX has been fullfilled, for the transverse case, on the COSY (COoler SYnchrotron) proton ring, achieving milestones on spin–dependent cross–section measurements. Now the longitudinal case could provide sensitive polarization results. An H or D source allows the exploration of the spin–filtering process with a deuterium polarized target, and opens new chances for testing Time Reversal Invariance at COSY (TRIC).

Keywords: Polarized and other targets; polarized beams; cyclic accelerators and storage rings.

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1. Introduction

The PAX (Polarized Antiproton eXperiments) collaboration,[1] addressed the possibility of obtaining polarized antiproton beams via the interaction of stored

unpolarized beams with polarized hydrogen atoms in an internal gaseous target (spin–filtering). Important milestones have been achieved at the storage ring COSY(COoler SYnchrotron) in the ForschungsZentrum of Jülich(FZJ)-Germany.[2,3]

The understanding of the spin–dependent cross–sections between unpolarized proton beam and polarized proton target was the viable way for the commissioning of the apparatus.

The spin–dependent cross–section studies and results, confirmed and clarified for the transverse case on proton,[3] together with the possibility of polarized deuteron gaseous target, have excited theoretical studies on $\overline{\text{p}}$-d$_\uparrow$ interaction predictions. A large discrepancy in cross–section are reported in Ref. 4 due to missing information on $\overline{\text{p}}$-p$_\uparrow$ interaction.

The efforts of the PAX collaboration, to fulfill the complete scheme of interaction p-p$_\uparrow$, is itself challenging in extracting the spin–dependent cross–sections, but also, it opens the possibility to explore the p-d$_\uparrow$ interaction, in the way to prepare the apparatus for p and $\overline{\text{p}}$ beams, together with a more ductile target of polarized proton and deuteron.

2. Spin–Filtering: How it Works

The interaction between a stored unpolarized proton beam and a polarized gaseous target can be explained, starting from the polarization $P = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow)$, where $N_\uparrow$ ($N_\downarrow$) is the population with the same (opposite) spin orientation.

By indicating Q the target polarization, and P that of the stored beam, with respect to a quantization axis, for the target its magnetic holding field, for the beam the vertical axis, the essential quantity for the p-p$_\uparrow$ interaction is the total cross–section σ_{tot}:

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

where σ_0 is the spin–independent contribution to the total cross–section, σ_1 and σ_2 the spin–dependent ones, $\boldsymbol{Q}$ the vector polarization of the target, $\boldsymbol{P}$ the vector polarization of the beam, and $\boldsymbol{k}$ the beam momentum versor.

Two cases can be distinguished in (1): transverse, quantization axis ($\boldsymbol{q} = \boldsymbol{Q}/Q$) of the target orthogonal to the momentum axis of the beam $\boldsymbol{k}$, and the longitudinal, $\boldsymbol{q}$ parallel to $\boldsymbol{k}$. σ_{tot}, for an initially equal populated state of spin 1/2, becomes respectively: for the transverse case ($\boldsymbol{q} \cdot \boldsymbol{k} = 0$) $\sigma_{tot\pm} = \sigma_0 \pm \sigma_1 Q$; for the longitudinal ($\boldsymbol{q} \cdot \boldsymbol{k} = 1$), $\sigma_{tot\pm} = \sigma_0 \pm (\sigma_1 + \sigma_2)Q$. The sign $\pm$ by convention is taken positive (negative) for same (opposite) orientation of the spin of the circulating beam with respect to $\boldsymbol{q}$. Particles of the beam with the same orientation of the target polarization are deflected less than the ones, having opposite orientation of the spin (σ_1 and σ_2 are negative). The unpolarized beam, in its repeated interaction with the polarized target, becomes polarized like the target, and loses intensity, as a result P follows the time law $P(t) = \tanh(t/\tau)$.[3]

"Effective" cross–sections ($\tilde{\sigma}$) have to be considered, taking in consideration the ring constrains. The effective spin–dependent cross–section can be extracted

from the time constant τ of the polarization build–up (dP/dt):[3] for the transverse case $dP/dt \approx 1/\tau_\perp = \tilde{\sigma}_1 Q d_t f$, instead for the longitudinal one $dP/dt \approx 1/\tau_\parallel = (\tilde{\sigma}_1 + \tilde{\sigma}_2) Q d_t f$. The build–up time constants depend on the nuclear polarization Q and the thickness of the target d_t (or areal density), the beam revolution frequency f, and $\tilde{\sigma}$, which takes into account that only particles scattered at an angle θ larger than the acceptance angle contribute to the spin–filtering process.

After the spin–filtering process, the polarization of the beam is measured via $p_\uparrow$-d elastic scattering, the details of the polarization measurements are presented in Refs. 2 and 3.

3. Setup, Results, and Plans

The whole setup (target, beam optics, polarimeters) have been commissioned for the transverse case, due to the "natural" preservation of the transverse polarization in COSY, and for its direct and clear access to σ_1. The confirmation of the spin–filtering process and the extracted spin–dependent cross–section for the transverse case has been fulfilled in the 2011.[3] The upgrading of the COSY ring for this purpose involved many parts, requiring vacuum improvement along the whole ring, optics matching for low beam loss in the accelerator and at the PAX interaction point, and tuning and improved beam control, in order to avoid depolarization phenomena.

The next steps are completing the full panorama of the spin–dependent cross–section, commissioning the longitudinal case, and showing sensible and useful polarization.[3] The chance to have a polarized deuteron target, for the study of p $(\overline{p})$-d$_\uparrow$, will give more chances for the investigation of the process with polarized deuteron.

3.1. *Transverse case*

For the full understanding of the spin–filtering process, it is mandatory to access the quantities $\tilde{\sigma}_1$ and $\tilde{\sigma}_2$, with the constrains of the ring and the insertion of the accumulation cell of the target inside it. The target/filter of PAX, reported in Fig. 1 consists of a polarized Atomic Beam Source (pABS), an accumulation cell, which increases the integrated thickness of the target, and the dignostics system of a sampled gas from the center of the cell.[5] The diagnostics system consists of two parts: the Target Gas Analyzer (TGA) and the Breit-Rabi Polarimeter (BRP). A vertical magnetic field of 1.0 mT (along the y axis in Fig. 1), limited to this low field in order to avoid orbit perturbations, is provided at the target chamber. In a low target holding field one hyperfine state can be preserved, providing a measured target thickness of the cell $d_t = (5.5 \pm 0.2) \cdot 10^{13}$ atoms cm^{-2} as expected.[5]

In the pABS for H, only one MFT (Medium Field Transition) was used during run and during the calibration of the BRP, injecting state $|1 >$ (during run), and for the BRP calibration state $|2 >$ and both state also.[5]

In the BRP we have to manage all the possible hyperfine states, in order to measure the polarization of the sampled gas from the center of the cell. Combinations

of MFT and SFT (Strong Field Transition) of the BRP allow measurements of the populations of each hyperfine state of the sampled gas.[5−7]

The perfomance of the target was very stable during the spin–filtering time (up to 16 000 s), allowing the second measurement of σ_1 at a different energy than in Ref. 8, which confirms the present understanding of the p-p$_\uparrow$ interaction.

3.2. *Towards the longitudinal case*

For the longitudinal case, the upgrades required on the COSY ring are reported in Ref. 9 at this symposium. From the target side the polarized source commissioned for H in the transverse case, can be operated for the longitudinal case too, with the target magnetic field oriented along the beam momentum $\boldsymbol{k}$ (z axis in Fig. 1). Outside the target chamber three sets of Helmholtz coils are installed, allowing a 3D orientation of the magnetic field.

Meanwhile COSY is under upgrading for longitudinal polarized beam,[9] the preliminary requirement, studying the spin–filtering polarization by a vector polarized deuteron target, can be fullfilled pushing efforts to organize the target in a more ductile way.
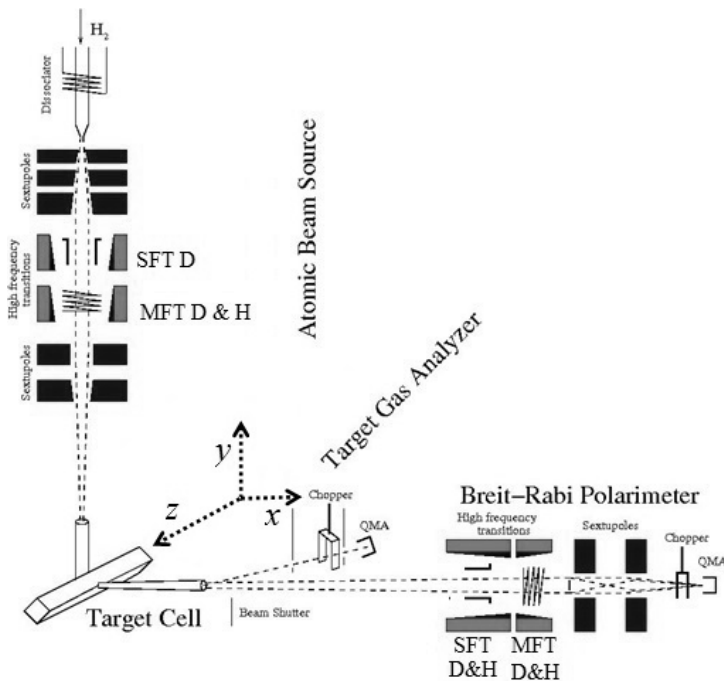

Fig. 1. Scheme of the PAX target used as a filter. The pABS, the accumulation cell, and the dignostic system which consists of the TGA (Target Gas Analyzer) and the BRP (Breit-Rabi Polarimeter.)

3.3. *Extension to deuterium by a new dual cavity*

The whole system of the target to be switched from H to D requires, in the diagnostic system, a dedicated SFT, resonating at a frequency a little higher than the zero-field hyperfine splitting frequency. The MFTs can be operated at a different frequency without exchanging them.

In Refs. 7 and 10 more details are reported on the operation of the the pABS and the diagnostic system, in its configuration for the HERMES experiment at DESY (Hamburg), and in Ref. 5 it is presented its upgrading for PAX, matching the transverse case requirements. The Ultra High Vacuum (10^{-10} mbar) of the diagnostic system shown in Fig. 1 has to be broken, the SFT cavity has to be exchanged, and time is needed for vacuum chamber bake-out, tuning the cavities, calibrating the BRP and so on. As a result the change between H and D, in both directions, for the diagnostic system takes usually weeks or months.

In order to have a possibilty to switch from H to D, during a beam time experiment, a new cavity (Fig. 2a) was designed and developed at Ferrara,[11] tested for its resonance frequency, in order to obtain an oscillating magnetic field (B_{RF} at 45° with respect to the static magnetic field of the cavity itself) allowing the σ and π transitions between hyperfine states.[12]

For the pABS in respect to the H operation, which requires only a MFT,[5] we'll use only a SFT σ. The whole PAX target is under re-commissiong for H and D in a test area at FZJ, meanwhile the upgrading program of the COSY ring for the longitudinal run is going on.[9] For D we need to put in operation for the pABS a SFT (a σ cavity, that means the B_{RF} oscillates parallel to the homogeneous field, allowing the 2↔6 and 3↔5, transitions for D). In the dignostic system we need to scan all the possible states of D, therefore we will operate the SFT dual cavity for D (σ and π cavity, the π are 1↔6, 2↔5, and 3↔6) combined with a MFT transition.
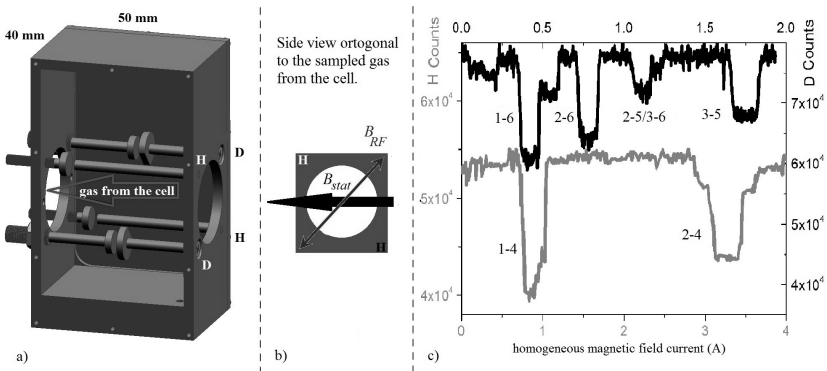

Fig. 2. a) The SFT H&D dual cavity. Coupled rods for H and D are tilted by 45° with respect to the homogeneous and gradient (static) fields. b) Static field of the cavity and oscillating field for H, for D the oscillating field will be orthogonal to that. c) Scans of homogeneous magnetic field with evident transitions for H and D.

In 2014, the dual cavity was installed in the diagnostic system and the scan of the homogeneous field, shown that the cavity is operating in the proper way for H (two transitions visible Fig. 2c), and for D (four transitions visible in Fig. 2c), as expected from the "*ex situ*" measurements of the oscillating RF field. In the next future we plan to update the calibration program, in order to provide measured efficiencies of the cavity for H and D and for σ and π transitions.

The chance to have a deuterium target and the right combination of RF transition units allow to provide a tensor polarized deuterium beam oriented in the xz–plane (see Fig. 1) at $\pm$ 45° in respect to the beam axis (z axis) in order to investigate the Time Reversal Invariance at COSY, the requirement and constrains of this program is also presented in Ref. 13 at this symposium.

4. Conclusions

The PAX collaboration measured the spin–dependent cross–section of a proton beam interacting with a polarized target of Hydrogen in the transverse case. The result agreed with the theoretical expectation. Future plans involve the upgrading of the COSY ring, for operating it with longitudinal polarized beam.

The target is straighforward for the longitudinal case of H, but open questions on the $\overline{\text{p}}$-d spin–dependent cross–section, and new program on test of Time Reversal at COSY are pushing the collaboration to prepare a daily switchable H or D polarized target/filter.

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