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Abstract. The construction of the PAX installation was inspired by the idea to make a beam of polarized antiprotons available for the experiments at the HESR FAIR. A spin filtering experiment with transversally polarized protons was realized using the new PAX installation at COSY. The results of this measurement are in perfect agreement with the FILTEX experiment. Hence, filtering is a viable method to produce a stored beam of polarized antiprotons. Another experiment which can be pursued using the PAX installation is the test of Time Reversal Invariance at COSY (TRIC). The goal of the TRIC experiment is to improve the present upper limit on violation of the T-odd P-even interaction by an order of magnitude using a genuine null observable available in a double polarized pd scattering. The status of the PAX spin filtering experiments as well as present understanding of the possible systematic uncertainties in TRIC are presented in this contribution.

PAX spin filtering experiments

High intensity polarized antiproton beams are not yet available for the experiments, although the potential of studies with polarized antiproton beams for physics is enormous. A detailed physics program with polarized beams of protons and antiprotons can be found in Ref. [1]. The Polarized Antiproton eXperiments (PAX) collaboration has taken over this challenge, and formulated the way to produce high intensity beams of polarized antiprotons. On the first stage of the PAX program all the methods and equipment should be tested for use with proton beams. As a second step, experiments with antiproton beams should be performed to demonstrate that it is possible to produce the first ever high intensity beam of polarized antiprotons. Finally, the HESR installation should be extended to realize the ambitious physics program with double polarized proton-antiproton experiments proposed by the PAX collaboration [1].

There are two ways to polarize an initially unpolarized beam of spin 1/2 particles stored in the accelerator: particles with undesired directions of spin either should change the orientations of their spins (spin flip) or should be eliminated from the beam (spin filtering). The spin flip method would allow to preserve beam intensity and hence would be preferable over spin filtering. However, no reliable method for spin flipping has been proposed up to now. In Ref. [2] the possibility of producing beams of polarized antiprotons using the interaction between antiproton beams and polarized beams of positrons was suggested. To test the feasibility of this method the PAX collaboration performed a measurement of the spin flip cross section using an

initially polarized proton beam and an unpolarized electron beam. The observed *ep* spin flip depolarization cross section measured by PAX [4] is many orders of magnitude lower than the prediction from [2]. Hence, it is not feasible to polarize beams of antiprotons by using polarized positrons as was suggested in Ref. [2].

The spin filtering method is based on the spin-dependence of the strong interaction. The total cross section for the scattering of unpolarized protons on a polarized target contains a term which differs depending on whether the spins of the beam and the target are codirectional or not. Hence, in case a stored beam of unpolarized protons continuously interacts with a polarized proton target, after a certain time an initially unpolarized beam becomes polarized. Due to the lack of experimental data on antiproton-proton scattering, it is hard to predict the level of the effect for antiprotons; but there are very solid calculations for proton-proton scattering available in the literature [5]. The FILTEX experiment at the TSR Heidelberg has demonstrated the feasibility of the spin filtering method for protons at 23 MeV [3]. The only facility where spin filtering experiments with antiprotons can be realized presently is the Antiproton Decelerator (AD) storage ring at CERN. The CERN SPSC have requested the PAX collaboration to perform a complete construction and commissioning of the PAX installation and realize a spin filtering experiment with protons stored in the storage ring at a different energy before the preparation for the experiments at the CERN AD will be started [6].

The PAX installation has been constructed for the COoler-SYnchrotron COSY-Jülich at the Forschungszentrum Jülich [7]. In parallel, a complete PAX section for the AD storage ring, fully compatible with the PAX detector system from COSY, has been prepared. The PAX installation at COSY consist of: low-β section, Atomic Beam Source (ABS), Breit-Rabi target Polarimeter (BRP), holding field system, and target chamber, which accommodates a storage cell and a beam polarimeter. The PAX installation with a closed storage cell was used for the spin filtering experiment at COSY [8] in 2011, except PAX silicone detector which is presently being set up and commissioned. The experiment was performed at COSY using an unpolarized proton beam at 49.3 MeV. An initially unpolarized proton beam was injected, accelerated and stored in the storage ring. After its acceleration to 49.3 MeV a polarized hydrogen gas from the PAX ABS was injected into the storage cell located in the target chamber for the duration of filtering of 12000 and 16000 s. During a complete spin filtering cycle the PAX holding field system serves as a guiding field for the hydrogen gas in the target storage cell, while the BRP is used to continuously monitor gas polarization using a fraction of the gas from the beam-target interaction region. At the end of a spin-filtering period a polarized hydrogen flux at PAX is switched off and beam polarization is measured using unpolarized cluster-jet target and Silicone Tracking Telescopes (STT's) placed at ANKE [9]. The resulting total spin filtering cross section measured at 49.3 MeV is in good agreement with the theoretical model which consistently describes both FILTEX and PAX results [8]. The physics program of PAX at COSY can be further extended with a longitudinal spin filtering experiment in case a Siberian-snake becomes available.

After the successful completion of the transversal spin-filtering experiment at COSY [8] it is possible to conclude that spin-filtering is an established way to polarize protons, which can potentially be applicable to antiprotons. Due to the lack of experimental data on antiproton-proton scattering, it is very hard to make solid predictions for the spin-filtering cross section for the antiprotons [5]. Only experiments with antiproton beams will allow one to estimate the parameters of the antiproton polarizing ring reliably, which should be built to provide polarized antiproton beams for the experiments at HESR, as was suggested by PAX [1].

Recently, the CERN SPSC have informed spokespersons of PAX that collaboration plans to modify the AD ring are now not compatible with the current physics program pursued at the ring. Hence, the PAX activities will be postponed. In this situation the PAX collaboration have started to extend their experimental program at COSY. One of the important pieces of

this program is an experiment to test Time Reversal Invariance at COSY (TRIC) which can be realized using PAX at COSY.

The test of Time Reversal Invariance at COSY (TRIC)

The Big Bang theory assumes that right after the Big Bang matter and antimatter were produced in equal amounts. However, there is very little antimatter observed in the visible part of the Universe. One of the explanations of the Baryon Asymmetry of the Universe presupposes strong CP and C violations [11]. All the CP and T violating effects discovered up to now are relatively weak and can not explain the predominance of matter in the universe. Hence, it is necessary to search for the new sources of the CP or T violations in baryon systems. The discovery of such an effect would be a direct indication for the physics beyond the Standard Model.

The TRIC experiment aims to improve the present upper limit on the strength of the T-odd P-even interaction by an order of magnitude [10]. It is planned to perform a measurement of a genuine null observable, $A_{y,xz}$, available in a double-polarized proton-deuteron scattering. In this experiment a polarized proton beam of COSY will continuously interact with a tensor polarized deuterium target located at PAX. The measurement will be done using a transmission technique utilizing an optical theorem for the total cross section measurement in a double polarized pd scattering. The spin-dependent part of the total cross section will be extracted by comparing the difference in the beam current slopes for the cycles with different beam-target spin configurations. The PAX installation at COSY is ideally suited for the realization of the TRIC experiment because of the availability of the high density polarized target, holding field system, and beam and target polarimeters. It is possible to identify the following advantages in the way the TRIC experiment is constructed:

- In comparison to the present upper limit, obtained from the experiment on Ho^{165} [12] target, the TRIC experiment will be free from any model dependent corrections associated with the target nuclei because of the use of the simplest tensor polarized nuclei (deuteron).

- The limit on the T-odd P-even interaction obtained from the experiment with a proton beam will be complementary to the present upper limit obtained using a beam of polarized neutrons.

- The TRIC experiment will utilize an optical theorem measuring the difference in the total cross sections. Hence, this experiment is free from any corrections due to the final state interactions significant for other T-symmetry tests.

- The possibility to independently flip the polarization of the beam and the target in TRIC will allow to keep systematic errors under control and hence provide a reliable upper limit.

1. Possible systematic uncertainties in TRIC

As with any precision measurement, the TRIC experiment requires significant and continuous efforts toward understanding the possible systematic uncertainties present in it. In this contribution our present idea of the possible systematic uncertainties in the experiment is summarized [13].

1.1. General formulas

In the most general form, the total cross section for pd scattering σ can be written as

$$\sigma = \sigma_0 \left(1 + A_{y,xz} P_y^b P_{xz}^t + \sum_l A_{y,l} P_y^b P_l^s + \sum_{mn \neq xz} A_{y,mn} P_y^b P_{mn}^s \right), \qquad (1)$$

where σ_0 is the unpolarized total cross section, $A_{y,xz}$ the genuine T-odd P-even null observable, $A_{y,l}$ and $A_{y,mn}$ other spin correlation coefficients, P_y^b transversal beam polarization, P_{xz}^t desired

tensor polarization of the deuterium target, P_l^s and P_{mn}^s vector and tensor polarizations of rest gas in the ring. The TRIC experiment is planned as a transmission experiment, which means that the $A_{y,xz}$ from Eq. (1) will be extracted from the beam current measurement performed during subsequent cycles with different configurations of beam and target polarizations.

The beam current losses in the accelerator can be associated with different factors; in the most general form, beam current in the storage ring at any moment of time can be written in the form:

$$I(t) = I_0(1 - \langle\sigma,\rho\rangle|_{ring})^{\nu t} = I_0 \exp\left(\nu t \times \ln(1 - \langle\sigma,\rho\rangle|_{ring})\right), \qquad (2)$$

where: I_0 is the initial beam current, σ total cross section, ρ effective target thickness integrated over the complete ring, ν beam revolution frequency, and t the moment of measurement. Performing a Taylor series expansion of Eq. (2) and restricting our consideration only to the first part of series one can end up with a simple formula for the beam current losses:

$$I(t) \approx I_0 \exp\left(-\nu t\langle\sigma,\rho\rangle|_{ring}\right) = I_0 \exp\left(-t/\tau\right). \qquad (3)$$

On the basis of the expected conditions of the TRIC experiment, it can be demonstrated that the difference between equations (2) and (2) is as small as 10^{-18} [13]. Beam losses due to the interaction with an internal target are continuous, if the beam current has no time structure, and discrete, if the beam is bunched. If a bunched beam is used, both the beam current and beam losses have some time structure, hence it only makes sense to discuss an averaged beam current. Here and later in the discussion we are only going to operate with the averaged beam current $I(t)$ which can be defined for both types of the beams. Using equations (1) and (3), a formula for the $A_{y,xz}^{+-}$ measured using the difference in $1/\tau$ of the cycles with different polarization states ($+$ and $-$) can be written:

$$A_{y,xz}^{+-} = \frac{A_{y,xz}}{\nu(\langle\sigma,\rho\rangle|_{ring}^+ - \langle\sigma,\rho\rangle|_{ring}^-)} \times \left[1/\tau^+ - 1/\tau^-\right] \qquad (4)$$

where $A_{y,xz}^{+-}$ is the genuine null observable. Equation (4) can be rewritten in a form which directly contains the averaging time for each state t_s:

$$A_{y,xz}^{+-} = \frac{A_{y,xz}}{\nu(\langle\sigma,\rho\rangle|_{ring}^+ - \langle\sigma,\rho\rangle|_{ring}^-)} \times \left[\frac{\langle\sigma,\rho\rangle|_{period}^+}{t_s^+} - \frac{\langle\sigma,\rho\rangle|_{period}^-}{t_s^-}\right] \qquad (5)$$

1.2. Possible systematic errors in TRIC

The coefficient $A_{y,xz}$ is a null observable, meaning that it should be equal to zero in case T-symmetry is conserved, and any deviation of its value from zero would be either a discovery of a T-symmetry violation or a systematic error. Our goal is to keep all the possible systematic biases associated with any kind of effects in the experiment suppressed and under control to the accuracy better than the desired precision for the observable of interest. From the simple analysis of Eq. (5) the following classification of biases not associated with particular measurement apparatus can be used: bias associated with cross section, bias associated with beam polarization, bias associated with target polarization, bias associated with gas density, and bias associated with time measurements.

It is important to stress that the vacuum system of the PAX installation is fully integrated into the COSY vacuum system, hence there are no clear and solid borders of the target region, and essentially all the rest gas in the vacuum system of COSY will give some contribution to beam loss. For the same reason, target polarization must be modeled not only in the region of the nominal holding field but also in the region where it is inhomogeneous [13]. Since TRIC is a transmission experiment it is sensitive to the total of beam loss, only a fraction of which

will be happening in the beam-target interaction region, where there are polarized deuterium gas and guiding field present. Due to the fact that $A_{y,xz}$ is a unique null observable in a double polarized pd scattering, all the other contributions to the total beam loss in COSY will be the same for the two beam-target polarization configurations and hence canceled out in Eq. (5).

Using equations from Sec. 1.1 the following equation for the $A_{y,xz}$ observable measured in the experiment can be written:

$$A_{y,xz} = A_{y,xz}^0(1 + B_{time})[1 + B_{beam} + B_{target}] + \Delta_{y,y} \qquad (6)$$

here: $A_{y,xz}^0$ is the genuine value of the observable of interest, B_{time}-bias associated with time measurements, B_{beam}-bias associated with beam polarization, B_{target}-bias associated with target polarization, $\Delta_{y,y}$-bias associated with a background observable $A_{y,y}$.

It is clear from Eq. (6) that the most crucial task is to suppress the $\Delta_{y,y}$ bias to the level of at least 10^{-6}. All the other biases are multiplied by the value of $A_{y,xz}$ and hence it is sufficient to keep them below 10^{-1}. It is important to stress here that in case only the beam polarization is flipped, to simulate two spin configurations for the $A_{y,xz}$ measurements, the holding field profile in the target region remains the same and hence $\Delta_{y,y}$ should be equal to zero. Hence, the possibility to flip beam and target polarizations independently allows to control $\Delta_{y,y}$ in the experiment.

1.2.1. Bias associated with the $A_{y,y}$ observable
From Eq. (6) it is clear that the precision to which $A_{y,xz}$ can be measured is in direct correspondence with the level to which the $\Delta_{y,y}$ bias can be suppressed in the experiment. There is no measurement for the $A_{y,y}$ under the zero degree available in the literature. Hence, it is planned to utilize a dedicated beam time, during which a complete installation for the TRIC experiment will be commissioned and used for the $A_{y,y}$ measurements. The bias $\Delta_{y,y}$ will be reduced in the TRIC experiment using the following experimental techniques: vector polarization in tensor polarized gas from ABS will be suppressed, the holding field in the storage cell region will be provided in the horizontal plane only, and adjusted to reduce the effect from $A_{y,y}$ in the experiment. Much more detail to the way $\Delta_{y,y}$ will be estimated can be provided, but this not a subject of this contribution.

1.2.2. Bias associated with time measurements
The precision of time measurements will have influence on all the biases in Eq. (6). However, the expected accuracy of about 100 μs, which will be provided using a high stability generator and scaler system, is sufficient to reduce B_{time} to 10^{-4} [13].

1.2.3. Bias associated with beam
The $A_{y,xz}$ depends on the polarization of the beam, hence all the beam losses which do not depend on the orientation of the proton spin are canceled out. For the TRIC experiment only the averaged value of beam polarization during measurements is crucial, and this is why the experiment is not sensitive to the particular orbit of the polarized particles in the storage ring (Stern-Gerlach experiment). It is essential for the experiment that beam polarization life time should be kept much longer than the averaging time for one beam-target configuration. According to the current experience at COSY, polarization life-time at COSY lasts for as long as 10^5 s [14], but several measurements of this value should be realized during the experiment to keep this effect under control. The effect of the beam's synchrotron oscillation, together with the finite size of the distribution of its momentum, can lead to a bias B_{beam}, which, according to our estimates, is as small as 10^{-4} [13]. The beam spin flip efficiency, important for the control over $\Delta_{y,y}$, is as high as 99 % [8], and hence should not lead to any sizable bias.

1.2.4. Bias associated with the target

The total cross section of the *pd* scattering is relatively small, hence beam loss due to the beam-target interaction is relatively slow. Due to the fact that the PAX polarized target is located inside the accelerator, a polarized proton beam sees a complete vacuum system of the accelerator as a continuous gas target. The COSY rest gas outside of the PAX target region will be unpolarized and hence will have no influence on the $A_{y,xz}$. The rest gas in the accelerator is under the influence of a constant vertical guiding field from the COSY dipoles, which does not change direction. Therefore, any effect associated with rest gas in the $A_{y,xz}$ measurement will be the same for the cycles with different beam-target spin configurations, and hence cancel out. Since the PAX target chamber is part of the COSY vacuum system it is not possible to set a clear border between the polarized target region and the rest of the vacuum system. Hence, by the (polarized) target in this experiment we mean a region in which a horizontal holding field is provided. To reduce any kind of uncertainties associated with the holding field, it is crucial to provide a guiding field in the horizontal plane in the storage cell region with as little as possible of the vertical component, which will be symmetrically reflected in case target polarization is flipped. A detailed modeling of the effects associated with the guiding field is complicated and dependent on the real field configuration which is presently unknown. Simple estimates for the holding field configuration and target gas density distribution show $B_{target} < 10^{-3}$ [13].

Conclusions

After the successful realization of the spin-filtering experiment at COSY the PAX collaboration is ready to start filtering experiments with antiprotons. Unfortunately, the CERN SPSC conclude that modifications to the CERN AD, suggested by the PAX collaboration, are not compatible with the present physics program at the AD. Hence, the PAX spin filtering experiments with antiprotons are put on hold. The test of Time Reversal Invariance at COSY (TRIC) can be realized using the present PAX installation. This experiment aims to improve the present upper limit on the T-odd P-even interaction using a genuine null observable $A_{y,xz}$ available in a double-polarized *pd* scattering. The status of the spin filtering experiments, as well as our present understanding of the possible systematic uncertainties in the TRIC experiment, are presented in this contribution.

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