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Test of Time Reversal Invariance and COSY

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Abstract. Test of Time Reversal Invariance in $pd$ scattering is planned at the COoler-SYnchrotron COSY-Jülich using the PAX internal target station. Feasibility test, performed in September 2012, have shown possibility to perform such an experiment using COSY and PAX. In parallel to the PAX upgrade a new high precision beam current measurement system will be constructed by the end of 2014. After these modifications, it will be possible to improve the current upper limit on a strength of T-odd P-even $NN$ potential by an order of magnitude.

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Introduction

The Standard Model of fundamental particles is not able to explain the Baryon Asymmetry of the Universe. A plausible explanation for the Baryon Asymmetry problem has been suggested in Ref. [1] and implies presence of additional sources of the CP-violation in nature, which are not yet observed and implemented into the Standard Model. All sources of the CP-violation, known up to now, are incorporated in to the Standard Model of fundamental interaction using the Kobayashi–Maskawa matrix.

An electric dipole moment (EDM) of an elementary particle [2] is one of the possible new sources of the CP-violation which provides very high sensitivity to the physics beyond the Standard Model. Only upper limits for the EDM of elementary particles or atoms have been reported in literature up to now. However, the electric dipole moment of elementary particle violates P and T-symmetries simultaneously, and hence additional theoretical model must be used in order to link it to the CP-violation [3].

Invariance of T-symmetry has been tested in different experiments using different approaches. Violations of T-odd P-even symmetry so far have been only observed in decays of $K^0$ [4] and, recently, $B$ [5] mesons. There are plans to perform a similar kind of tests in the decay of the entangled $\phi$ mesons [6]. However, for the $NN$ systems only upper limits on the strength of the T-odd P-even potential are reported. At present, upper limit on the strength of the potential is obtained from the measurements of neutron scattering off a tensor polarised $^{165}\text{Ho}$ and hence contains some model dependence [7].

An experiment to test T-invariance using $pd$ scattering, the simplest $NN$ system suitable for such a test, is in preparation at a COoler-SYnchrotron COSY-Jülich. In this experiment, COSY will serve as an: accelerator, detector and ideal zero degree spectrometer. The Time Reversal Invariance experiment at COSY (TRIC) aims for an improvement of the upper limit on the
strength of the $NN$ T-odd potential by one order of magnitude compared to present value by measuring the $A_{y,xz}$ scattering amplitude [8].

Principle of the experiment

In Ref. [9] theorem has been proven which say that exist no null test of time reversal invariance with two particles in and two particles out which is independent on dynamical assumptions. However, this theorem is not applicable for the total cross section, as it was pointed out in Ref. [10]. Based on this exception, a concept of a transmission experiment in $pd$ scattering has been suggested which aims to measure the true T-odd null observable $A_{y,xz}$. In case of scattering of a vector polarised proton beam on a tensor polarised deuterium target the only observable from the scattering amplitude which remains is the $A_{y,xz}$. Thus, in this case the measurement of the total cross section is equivalent to the measurements of $A_{y,xz}$ and serves as a true T-odd null observable.

The principle of the proposed experiment in the center of mass system is illustrated in Fig. 1. A vector polarised proton beam interacts with a tensor polarised deuterium target. If one applies the T-symmetry operator to the initial system it is transformed to a system where a tensor polarised deuteron beam interacts with a vector polarised proton target. However, since the system is invariant under rotation around the X and Y-axes, these two situations are equivalent to a simple flip of the direction of beam and target polarisation vectors.

Experiment at COSY

At the COoler-SYncrotron COSY Jülich experiment to perform such an transmission experiment has been proposed [8]. In this measurement vector polarised proton beam is circulating in the storage ring and interact with a tensor polarised deuterium target. A decrease of the beam current, due to the beam-target interaction, which is directly proportional to the total cross section in $pd$ scattering, will be measured using a high precision beam current measurement system implemented in the COSY ring.

Figure 1. Principle of the TRIC experiment. A vector polarized beam of spin-half particles interacts with a tensor polarized spin-one target.
At COSY there is a lot of experience in preparation and handling of unpolarised and polarised beams of protons and deuterons up to the maximum beam momentum of 3.7 GeV/c. In the storage ring electron- and stochastic-cooling systems are available and allow not only to compensate for the beam energy loss due to the interaction with the target but also to control the transversal dimensions of the beam. This allows to use a storage cell systems of relatively small diameter (up to 10 mm) at the internal target station and hence provide a high areal-thickness of a polarised atomic gas target. The EDDA internal polarimeter, located in one of the straight sections of the ring, allows to measure the beam polarisation online using a thin solid target. Thus, the necessary spin gymnastics in order to overcome depolarising resonances of the machine can be performed, and hence high degree of polarisation in the beam up to the maximum COSY beam energy can be preserved.

The experiment will take place at the PAX internal target station, which is very well suited for the proposed measurement [11]. The target chamber is placed in the low-beta section of the COSY accelerator, and hence a storage cell of only 10 mm diameter can be used for the experiment, providing target densities up to $6 \times 10^{13}$ 1/s×cm$^2$. The PAX facility is equipped with a Breit-Rabi polarimeter which allows to monitor the target polarisation on-line. A specially designed system of coils, provides with a holding field in the storage cell region, and allows to preserve the target polarisation along the cell. After upgrade in 2014, PAX will be equipped with: openable storage cell, multipurpose detector, and openable flow limiters. These modifications should allow to perform a TRIC experiment and reach the desired goals after four weeks of beam time [8].

In Ref. [8] different options for the hight precision beam current measurement systems have been considered. It was shown that in order to reach the desired statistical precision in $A_{y,z}$ after one month of measurement at 135 MeV it is necessary to perform the experiment with a bunched beam. Normally, COSY operates with a DC beam and the RF cavity is not used after the acceleration. The electron cooler at COSY, although commissioned and constructed to operate at 100 kV, was never in operation at voltages higher then 65 kV. Therefore, it was necessary to perform a commissioning run at $T_p=135$ MeV with electron cooler and bunched beam in order to find out if it is possible to perform the TRIC experiment or substantial modifications are needed. Furthermore, the initial motivation for building the PAX facility was a spin filtering experiment [11], which has to be performed at the lowest possible energy of the proton beam. Therefore, it was not planned to accelerate with the PAX magnets and a closed storage cell in the target chamber. Thus, the goal of the first beam time was to shown the feasibility of the proposed experiment at COSY using the PAX facility.

Feasibility test

During the first commissioning beam time in September 2012 following milestones have been achieved:

- It was shown that it is possible to accelerate the COSY proton beam up to the 135 MeV with the PAX magnets and a closed storage cell (length 400 mm, diameter 10 mm) in the PAX target chamber.

- The electron cooler was operated at 74 kV during the beam time without major problems. Tests at 100kV have been done successfully.

- After careful adjustment of COSY orbit and improvements of the vacuum conditions the beam life time of 10000 s has been regularly observed with electron cooled proton beam at the energy of the experiment.

- Bunching with the COSY RF system at the flat top reduces the beam life time by 10-20 % depending on the amplitude in the bunching cavity.
Bunching with the Barrier Backet system of COSY allows to produce a bunched beam of sufficient quality and almost do not influence beam life-time.

A beam size of 2.2 mm after cooling at the energy of experiment has been measured using a beam profile monitor.

Using a frame system installed in the PAX target chamber the COSY ring acceptance of 6.45 mrad has been measured at 135 MeV.

A COSY cycle with $4 \times 10^9$ unpolarised protons in a bunch, suitable for the TRIC experiment, was prepared and regularly observed during all the beam time.

The PAX target and COSY rest gas thicknesses were measured using the Schottky system. According to the first estimates the target thickness was $5.5 \times 10^{13} \text{ } 1/\text{s}\text{ } \text{cm}^2$.

A beam life time of the order of 10000 s has been observed without target in the storage cell. Switching the PAX target on change the beam life time by 20%.

In Fig. 2 COSY beam current as a function of time measured at 135 MeV with bunched beam is presented for the two cycles with (black line) and without (red line) PAX target. The green line at the bottom shows the $H^0$ rate detected in $H^0$-monitor used for the adjustment of electron cooler. Beam life times for the cycles with and without target are 8510 and 11050 s, respectively.

**Conclusions**

A test beam time, performed in September 2012, have shown that COSY can provide a bunched beam of sufficient quality with the PAX low-beta section. The PAX target and the storage cell have shown designed performance and can be used for the real TRIC beam time after the PAX deuterium source commissioning in 2014. A new high precision beam current measurement system should be developed in order to achieve final goals of the planned TRIC experiment.
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