Test of Time-Reversal Invariance at COSY (TRIC)

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Abstract At the Cooler Synchrotron COSY a novel (P-even, T-odd) null test of time-reversal invariance to an accuracy of 10^{-6} is planned as an internal target transmission experiment. The parity conserving time-reversal violating observable is the total cross-section asymmetry $A_{y,xz}$. This quantity is measured using a polarized proton beam with an energy of 135 MeV and an internal tensor polarized deuteron target from the PAX atomic beam source. The reaction rate will be measured by means of an integrated beam current transformer. Thus, in this experiment the cooler synchroton ring serves as ideal forward spectrometer, as a detector, and an accelerator.

Introduction

So far, the only link to a violation of time-reversal symmetry is given via the CPT-theorem and the observation of CP-violation in the neutral Kaon- and B-systems. Since the origin of the CP- or T-violation is not clear, further experimental tests of CP- or T-invariance are necessary to probe the manifestation of the interaction responsible for the observed or possible new CP-violating effects.

We intend to probe the time-reversal invariance with parity being conserved in contrast to experiments which test parity and time reversal invariance (TRI) simultaneously (cf. tests of the electric-dipole moment of elementary particles).

Usually P-even TRI tests compare two observables [1] (cf. tests of detailed balance or P-A tests). Since in these experiments two observables have to be compared, the experimental accuracy [2] is limited to $10^{-3} - 10^{-2}$. The accuracy can be increased by orders of magnitude up to 10^{-6} [3] if a true null experiment is performed i.e. a non-vanishing value of one single observable proves that the

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symmetry involved is violated. In this context the term “true” stresses the concept that the intended test has to be completely independent from dynamical assumptions. Therefore, the interpretation of the result is neither restricted nor subject to: Final state interactions, special tensorial interactions or, Hamiltonians of a certain form. True null tests are based on the structure of the reaction matrix only, as determined by general conservation laws [3].

On the other hand, it has been proven [3,4] that there exists no true null test of TRI in a nuclear reaction with two particles in and two particles out, except for forward scattering, by which in turn a total cross section can be measured. Based on this exception, Conzett [5] could show that a transmission experiment can be devised, which constitutes a true TRI null test. He suggested to measure the total cross-section asymmetry $A_{y,xz}$ of vector polarized spin 1/2 particles interacting with tensor polarized spin 1 particles.

The proposed Time Reversal Invariance experiment at COSY (TRIC) at the Forschungszentrum Jülich is a P-even T-odd null test of TRI. The experiment intends to measure the TRI violating observable $A_{y,xz}$ in proton-deuteron forward scattering with an accuracy of 10^{-6}. This accuracy is compatible to the theoretical upper bound from edm measurements [6].

Basic Considerations

The optical theorem is a consequence of the unitarity of the S-matrix and holds even if the Schrödinger equation is not applicable. The difficulties with respect to the Coulomb interaction for its singularity at the origin and the infinite range can be solved in practice. In the presence of a short range interaction the partial-wave optical theorem for two potential scattering is applicable [7]. The infinite range problem is only a theoretical one, since one can always find some radius R_{screen}, beyond which the contributions of the Coulomb interaction are negligible due to screening. Ultimately the universe is neutral; practically the electrons of the atoms do the screening, so R_{screen} is of the order of 10^{-8} cm.

The elastic forward amplitude $f_0^{elastic}$ comprises an imaginary part that reflects the fact that some particles have been removed from the beam by elastic- or non-elastic scattering. Therefore, the optical theorem can be written:

$$\mathrm{Im}(f_0^{\mathrm{elastic}}) = \sigma_{\mathrm{tot}}^{\mathrm{elastic}} + \sigma_{\mathrm{tot}}^{\mathrm{non\text{-}elastic}}$$

For the elastic scattering R.M. Ryndin [8] has proven that the Final State Interaction (FSI) is absent. The idea of this proof is given by V. Gudkov in [9].

For the non-elastic scattering it is worth while noting, that in any two particle reaction with some Q- value the particles in forward direction have a different energy compared to the circulating protons in COSY and will not survive (COSY acts as an ideal forward spectrometer). The particles scattered off the beam have to be rescattered into the forward direction by some short range secondary reaction, in order to contribute to $\sigma_{\mathrm{tot}}^{\mathrm{non\text{-}elastic}}$. This interaction has to fulfil three conditions with respect to the TRIC experiment: i) Only protons can survive in COSY, ii) the Q-value has to be compensated, and iii) the rescattering has to deflect the scattered particles from the primary reaction to the forward angle (0°) exactly. The phase space for this to happen is virtually zero.

The TRI test can be performed at any beam energy; but since the time-reversal violation (TRV) processes are of short-range nature - the relatively long range contributions for these processes may be parameterized by a ρ vector meson or a f_1 axial-vector meson exchange [10]. The experiment is intended to be performed at 135 MeV (~521 MeV/c), since at this energy the sensitivity with respect to a possible TRV force is considered maximal (cf. Fig 1). In addition, this low energy has the advantage that only (at most) one depolarizing resonance has to be considered and the experiment can be carried out with a permanently electron cooled COSY-beam.

The principal scheme in the center of mass system is depicted in Fig. 2. The time reversed situation - as given by the reaction matrix - shows the situation in Fig. 2b).

We plan to study the TRV quantity $A_{y,xz}$ in a transmission experiment using the internal PAX deuteron target with an openable cell in the cooler synchrotron COSY. The transmission losses of the circulating polarized proton beam are measured with high precision by an integrated beam current transformer as a function of the vector- and tensor-polarization P_y and P_{xz}, respectively. Thus, in this experiment the COSY facility will not only be used as an accelerator, but also as an ideal forward spectrometer and detector.

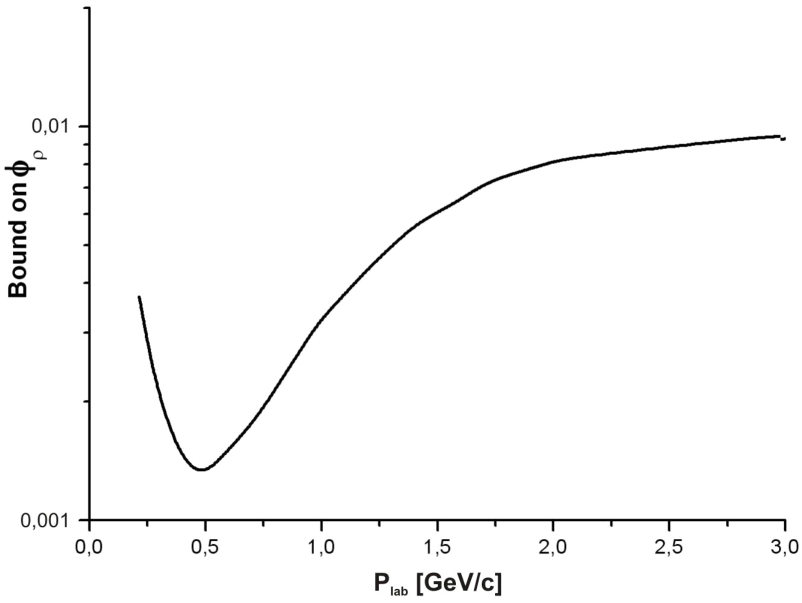

Fig. 1 The achievable upper bound of the dominating T-odd strength parameter Φ_ρ, is given as the ratio of the parity conserving T-odd over the T-even ρM-N coupling constants, mediated by the ρ-meson (derived from Fig. 2 in[10]). For this plot it is assumed that the error of the observable $\delta A_{y,xz}=10^{-6}$.

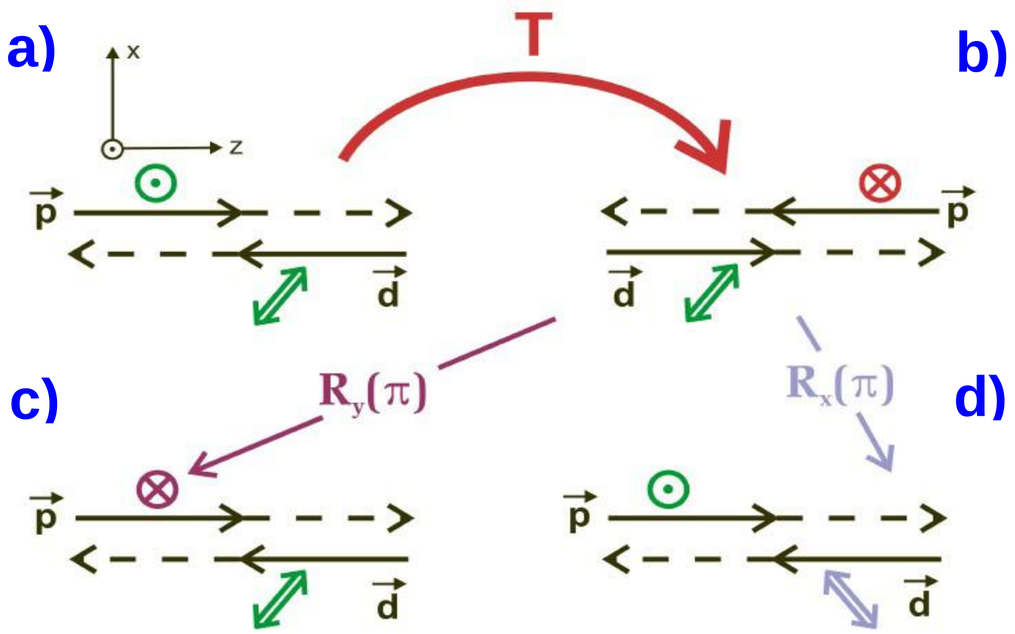

Fig. 2 Principal demonstration that a time-reversed situation is prepared by either a proton or a deuteron spin-flip. a) The basic system is shown. b) The time reversal operation is applied (momenta and spins are reversed and the particles are exchanged). In order to have a direct comparison between situation a) and b), two rotations $R_y(\pi)$ or $R_x(\pi)$ by 180° about the y- or x-axis are applied, leading to the situations c) and d), respectively. This is allowed, since the time reversal operation is invariant under rotations.

⊙ Proton spin up (y-direction), ⊗ Proton spin down, <=> Deuteron tensor polarization

The Quantity of Interest

The time-mirrored situation can be created experimentally either by reversing the vector polarization P_y of the proton beam, or by changing the alignment of the tensor polarization P_{xz} of the deuteron target. As a consequence, depending on the polarizations any TRV results in different transmissions through the internal tensor polarized deuteron target. The different transmissions cause different slopes of the decreasing proton beam intensity as the beam passes turn after turn through the target. This current decrease can be measured to very high precision. A total cross-section experiment involving polarized particles is described by the generalized optical theorem [10]:

$$\sigma_{tot} = 4\pi/k \; \mathrm{Im}(\mathrm{Tr}(\rho)\cdot F(0))$$

with:
- σ_{tot} Total cross-section
- k Wave number
- ρ Density Matrix
- $F(\vartheta)$ Scattering amplitude matrix for scattering at angle ϑ

The density matrix ρ reflects the experimental set-up, whereas the scattering matrix F(0) of the forward scattering amplitudes contains the physics, which is to be tested.

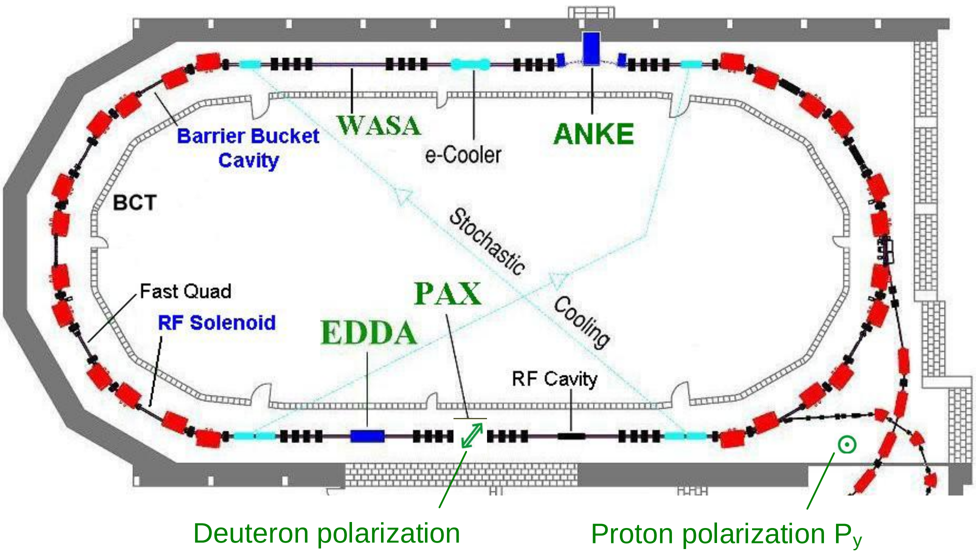

Fig. 3. The scheme of the TRIC experiment at COSY.

Assuming a proton beam with normal polarization P_y, the target has to be at least a spin 1 particle, in order to be able to offer a tensor polarization P_{xz} aligned in the x-z (cf. Fig. 2) direction. Deuterons fulfil this requirement. Thus, the quantity of interest is the total cross-section asymmetry $A_{y,xz}$ for proton-deuteron scattering. $A_{y,xz}$ is measured by flipping the spins of the interacting particles. By flipping the spins in this particular system the time reversed situation is prepared too. This is shown in Fig. 2a-d. The experimental situation is depicted in Fig. 3.

Polarization Observables faking TRV

Table 1. Polarization observables of the total cross-section in $\vec{p}-\vec{d}$ scattering. The first index refers to the proton polarization, the second and third index refers to the deuteron vector- and tensor-polarization. All quantities with a hat cancel, since they are R_z-odd. All quantities which are doubly underlined are P_z-odd

Line	Observable						Line cancels because of:
1	$I_{o,o}$	$\underline{\underline{\hat{A}_{o,x}}}$	$A_{o,y}$	$\underline{\underline{\hat{A}_{o,z}}}$			protonspinflip
2	$\underline{\underline{\hat{A}_{x,o}}}$	$A_{x,x}$	$\underline{\underline{A_{x,y}}}$	$\underline{\underline{\hat{A}}}_{x,z}$			P_x negligible for protons
3	$\underline{\underline{\hat{A}}}_{y,o}$	$\underline{\underline{A_{y,x}}}$	$A_{y,y}$	$\underline{\underline{\hat{A}_{y,z}}}$			
4	$\underline{\underline{A_{z,o}}}$	$\underline{\underline{\hat{A}}}_{z,x}$	$\underline{\underline{\hat{A}_{z,y}}}$	$A_{z,z}$			P_z negligible for protons
5	$A_{o,xx}$	$A_{o,yy}$	$A_{o,zz}$	$\underline{\underline{A_{o,xy}}}$	$\underline{\underline{\hat{A}_{o,yz}}}$	$\underline{\underline{\hat{A}}}_{o,xz}$	protonspinflip
6	$\underline{\underline{\hat{A}_{x,xx}}}$	$\underline{\underline{\hat{A}_{x,yy}}}$	$\underline{\underline{\hat{A}_{x,zz}}}$	$\underline{\underline{\hat{A}}}_{x,xy}$	$A_{x,yz}$	$\underline{\underline{A_{x,xz}}}$	P_x negligible for protons
7	$\underline{\underline{\hat{A}}}_{y,xx}$	$\underline{\underline{\hat{A}}}_{y,yy}$	$\underline{\underline{\hat{A}}}_{y,zz}$	$\underline{\underline{\hat{A}_{y,xy}}}$	$\underline{\underline{A_{y,yz}}}$	$A_{y,xz}$	
8	$\underline{\underline{A_{z,xx}}}$	$\underline{\underline{A_{z,yy}}}$	$\underline{\underline{A_{z,zz}}}$	$A_{z,xy}$	$\underline{\underline{\hat{A}}}_{z,yz}$	$\underline{\underline{\hat{A}_{z,xz}}}$	P_z negligible for protons

If $A_{y,xz}$ is calculated from changing the proton polarization each time the ring is filled, all observables of Table 1 in line 1 and 5 cancel. Since only the proton polarization P_y is an eigenvector in the ring, all observables with respect to the proton polarization P_x and P_z cancel too (the average of P_x and P_z should be $< 10^{-8}$ in a 30 days run). This is also true for lines 2, 4, 6, and 8 in Table 1.

In the remaining lines 3 and 7 of Table 1 all quantities with a hat cancel, because they are not R_z-even. $A_{y,x}$ and $A_{y,yz}$ violate parity conservation. Therefore, since $\vec{p}-\vec{d}$ scattering is an elementary process, these quantities are expected to be of the order of 10^{-7}, even if parity is violated (by weak interaction). Thus, besides our quantity of interest $A_{y,xz}$, only $A_{y,y}$ "survives". Since $A_{y,y}$ in $\vec{p}-\vec{d}$ scattering is not known at 135 MeV it has to be determined in a dedicated measurement.

The effect of $A_{y,y}$ in $\vec{p}-\vec{d}$ scattering is expected to be small, because i) there must be a deuteron vector polarization in the target prepared for tensor polarization, and ii) there must be a misalignment between the COSY beam direction and the deuteron beam, so that a deuteron vector polarization is able to generate a P_y deuteron vector polarization. The deuteron vector polarization can be adjusted to be close to zero in the atomic beam source. This polarization can be continuously monitored in the dump of the atomic beam source.

Assuming the deuteron vector polarization can be limited to 0.01, and the deuteron source and the proton beam can be aligned to better than 0.1°, then a false deuteron vector polarization $P_y < 2 \cdot 10^{-5}$. If $A_{y,y}$ in $\vec{p}-\vec{d}$ scattering is < 0.05 the error contribution is $< 10^{-6}$.

Conclusions

We discussed a novel (P-even, T-odd) true null test of time-reversal invariance that has the ability to verify the theoretical upper bounds derived from edm experiments. In contrast to many other tests of TRI the time-reversal violation is mediated by the ρ- or f_1-meson rather than caused by final state interaction. The signature of the time-reversal violating observable $A_{y,xz}$ can only be faked by $A_{y,y}$, the influence of which is estimated to be neglectable.

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