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# Time Reversal Invariance Test at the COSY Ring

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Time reversal violation ($\mathcal{T}$–V), like the equivalent violation of the combined symmetries of charge ($\mathcal{C}$) and parity ($\mathcal{P}$) ($\mathcal{CP}$–V), is a necessary ingredient for any theory aiming to address the mystery of the matter–antimatter asymmetry of our Universe - one of the biggest problems in contemporary physics and cosmology. It is widely accepted that a solution of this puzzle will involve new physics Beyond the Standard Model (BSM) of elementary particle physics.
At the COoler SYnchroton (COSY) a null test ($\mathcal{P}$–even, $\mathcal{T}$–odd) of time reversal invariance is under feasability study as an internal transmission experiment. The parity conserving time–reversal violating observable is the spin correlation parameter $A_{Y,XZ}$ in the double–polarized proton–deuteron scattering, which can be accessed by using a polarized proton beam passing through an internal tensor polarized deuterium target.

**KEYWORDS:** Time Reversal, Polarization, Storage Ring

## 1. Introduction

$\mathcal{CP}$–invariance violation, or the complementary $\mathcal{T}$–invariance violation, under conservation of $\mathcal{CPT}$–theorem, is required to account for Baryon Asymmetry of the Universe (BAU) [1]

The Big Bang theory predicts that in the initial stage of the Universe matter and antimatter were produced in equal amounts. Our everyday experience shows, however, that today the world around us consists almost entirely of matter. Investigations on invariance violation are fundamental challenges for the Standard Model (SM) of elementary particle physics, which predicts a BAU of many orders of magnitude below observations.

The Standard Model is founded on the concept of symmetries, which is why precision experiments, that test fundamental symmetries, offer the highest potential for the discovery of physics beyond the SM. One of the cornerstones of the SM is the $\mathcal{CPT}$–theorem that links $\mathcal{C}$ (charge), $\mathcal{P}$ (parity) and $\mathcal{T}$ (time) symmetries: according to this theorem, all physical processes are invariant under the simultaneous transformation of all three symmetries. However, individual symmetries and combinations of two can be violated, for example the $\mathcal{CP}$–symmetry and hence, assuming the $\mathcal{CPT}$–theorem, the $\mathcal{T}$–symmetry is violated in weak interactions [2]. All the known $\mathcal{CP}$–violating processes, discovered up until to now, can be accounted for in the SM by introducing a phase in the Cabibbo–Kobayashi–Maskawa quark–mixing matrix of electroweak interactions [3]. In Quantum Chromodynamics the $\mathcal{CP}$–violating process can be parametrized by a so called "$\theta$–term" [4], the smallness of which, inferred from the neutron Electric Dipole Moment (EDM) limit, is not yet understood at all. It must be emphasized that a much larger $\mathcal{CP}$–violation is necessary to explain the BAU and thus our existence in the world. This is why searches for $\mathcal{T}$–violation and $\mathcal{CP}$–violation have such an outstanding importance in the scientific programs at different experimental facilities all over the globe. The project $\mathcal{TIVOLI}$ ($\mathcal{T}$ime $\mathcal{I}$nvariance $\mathcal{V}$i$\mathcal{OL}$ating $\mathcal{I}$nteractions), which we propose for its realization at COSY, will play a unique role among these searches, since the experiment will enable us to improve the current upper limit of the "Time Reversal Violating, Parity Conserving" ($\mathcal{T}$–V, $\mathcal{P}$–C), or "$\mathcal{T}$–odd, $\mathcal{P}$–even" strength by one to two orders of magnitude.

The primary objectives of the $\mathcal{TIVOLI}$ project are:

a) To investigate experimentally $\mathcal{T}$–symmetry violation at the COoler–SYnchrotron (COSY), operative in the Forschungszentrum of Jülich, using a polarized proton beam and an internal tensor–polarized deuterium target. This will be achieved by using a novel method to measure the total cross–section in an internal target experiment [5].

b) To provide the needed theoretical developments and thus create the proper framework for the interpretation of the new data as well as a comparison with complementary results, *e. g.* from EDM searches.

This combined effort will advance the understanding of $\mathcal{T}$–violation processes in a baryonic reaction and shed light on the mystery of the Baryon Asymmetry of the Universe.

## 2. Study of New Sources of Time Reversal Violation

The $\mathcal{CPT}$–symmetry has been tested to a very high precision and it is believed to be a genuine symmetry of Nature. If this is accepted then $\mathcal{CP}$–V implies $\mathcal{T}$–V to compensate each other. All $\mathcal{T}$–symmetry violating mechanisms implemented in the SM simultaneously violate $\mathcal{P}$. One of the established ways to search for the simultaneous violation of $\mathcal{T}$– and $\mathcal{P}$–symmetries ($\mathcal{T}$–V and $\mathcal{P}$–V) is to look for an Electric Dipole Moment (EDM) of an elementary particle. The SM predicts the EDM of the neutron to be less than $10^{-31}$ e cm [6], while the current experimental upper limit is of the order of 3 $10^{-26}$ e cm [7]. In the next generation of experiments it is planned to reach a precision of $10^{-28}$ e cm for the EDM of the neutron in roughly ten years after the start of the project. Recently, a new project, called Jülich Electric Dipole moment Investigations (JEDI) [8] has been launched at COSY-Jülich to reach a similar level of precision for the EDM of the charged particles proton and deuteron. Complementary to the EDM searches dealing with $\mathcal{T}$–V and $\mathcal{P}$–V interactions, the $\mathcal{TIVOLI}$ project will focus on gaining new insights into $\mathcal{T}$–V and $\mathcal{P}$–C interactions, which is deeply discussed in the contribution of P. Lenisa in this meeting [9].

There are model-dependent ways to estimate the strength of the $\mathcal{T}$–V and $\mathcal{P}$–C interaction using the current result for the neutron EDM [10]. However, a more recent analysis [11] suggests that there are in fact ways to generate an EDM of an elementary particle without implicating a limit on a $\mathcal{T}$–V and $\mathcal{P}$–C interaction. Hence, any upper limit for the $\mathcal{T}$-V $\mathcal{P}$-C interaction obtained from the EDM of an elementary particle will involve significant model dependencies, which are difficult to control. The discovery of an EDM of only one of the particles, *e.g.* electron, proton, neutron, deuteron, or$^3$He, will not allow one to identify uniquely the origin of the EDM effect. Taking into account the time lines of the EDM projects all over the world, which typically plan for an order–of–magnitude improvement over the next decade, the studies of the $\mathcal{T}$–V and $\mathcal{P}$–C interaction, now proposed within the $\mathcal{TIVOLI}$, have a high potential for the discovery of physics beyond the Standard Model, independent of the EDM measurements. The upper limit improvements will provide most valuable constraints for SM extensions.

As no indications for $\mathcal{T}$–V and $\mathcal{P}$–C–interactions have been reported in the literature, such effects have yet to be implemented in the Standard Model of the particle physics and their discovery would be a strong indication for the nature of physics beyond the Standard Model. Experimental upper limits on the strength of $\mathcal{T}$–V and $\mathcal{P}$–C interaction $a_T$ are relatively weak.

A limit $a_T < 7.1\ 10^{-4}$ has been obtained using a polarized neutron beam and tensor polarized $^{165}$Ho target [12]. It is important to stress that there is some uncertainty in this value due to corrections associated with the use of the complex tensor polarized nuclear target. The $\mathcal{TIVOLI}$ experiment has the aim to improve the upper limit on $a_T$ by at least an order of magnitude by using a vector polarized proton beam and tensor polarized deuterium target. Due to the use of the simplest tensor polarized nucleus, the deuteron, the upper limit on the strength of the $\mathcal{T}$–V potential extracted by the $\mathcal{TIVOLI}$ experiment will be free from the model–dependent corrections associated with the $^{165}$Ho target.

## 3. Experimental Exploitation of Spin as a "*Time–Reversal Knob*"

It has been shown [13] that, in double–polarized proton–deuteron elastic scattering, the spin-correlation parameter $A_{Y,XZ}$ is a true $\mathcal{T}$–odd, $\mathcal{P}$–even "null observable": any finite value of $A_{Y,XZ}$ will thus be a signature of a $\mathcal{T}$-V and $\mathcal{P}$–C interaction (Fig. 1). This fact provides unique experimental advantages over any other investigations of $\mathcal{T}$–violating observables, since it reduces the sources of systematic uncertainties. A storage ring like COSY at Forschungszentrum Jülich offers an unmatched opportunity to access this quantity in a transmission experiment by using a polarized proton beam in combination with a tensor polarized deuterium target. This is just accomplished reversing for istance the spin of the proton beam, which means switching from the configuration in Fig. 1.(a) to Fig. 1.(d). While it is extremely difficult to measure double–polarized total cross sections in a standard particle–physics experiment to very high precision, the $\mathcal{TIVOLI}$ experiment relies on the determination of total cross sections by a measurement of the reduction of the beam current as a function of time for different polarizations of proton and deuteron, rather than the detection of the scattered particles [5]. The beam–lifetime in a storage ring is affected by the beam losses all over the ring, but only the losses

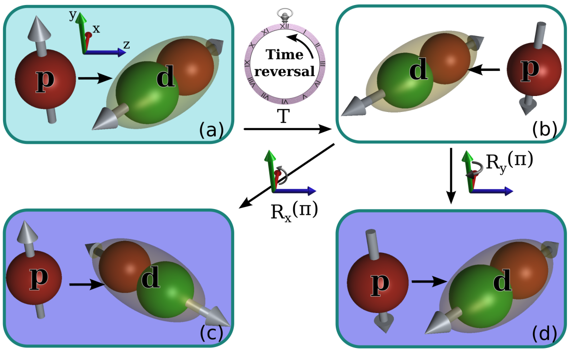


**Figure 1.** The $\mathcal{TIVOLI}$ experiment will test a $\mathcal{T}$–Violating and $\mathcal{P}$–Conserving (also indicate here like $\mathcal{T}$–V and $\mathcal{P}$–C) interaction in double polarized proton–deuteron elastic scattering. The figure illustrates the concept. In (a) the basic system is shown. In (b) the time reversal operation is applied. In order to enable a direct comparison between (a) and (b), two rotations $R_x$ or $R_y$ by 180° about the $y$– or $x$–axis are applied, leading to the (c) and (d), respectively. This is allowed, since the scattering process is invariant under spatial rotations.

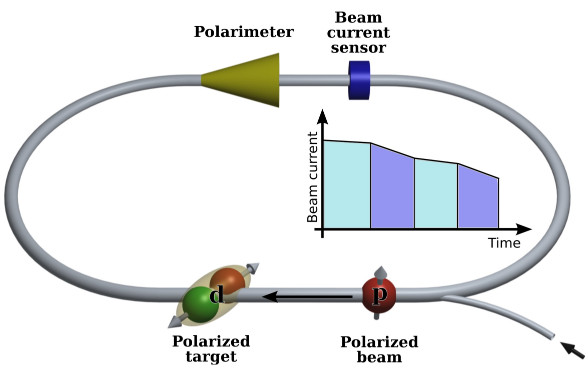


**Figure 2.** Main components of the experimental setup at COSY: polarized beam from the injector cyclotron, polarized deuteron target from an atomic beam source, polarimeter and beam current sensor. Time reversal invariance will be accessed by detecting the difference in the beam lifetime between the situations in Fig. 1.(a) and Fig. 1(c) and/or between the situations in Fig. 1.(a) in Fig. 1.(d).

in the polarized target are sensitive to the beam and target polarizations. When the tensor polarization of the deuterium in the target lies in the horizontal ($XZ$) plane and the polarization of the proton beam is vertical (along the $Y$ axis), the $A_{Y,XZ}$ term remains the only ($\mathcal{T}$ –odd, $\mathcal{P}$–even) null observable contributing to the total cross section and it can be directly measured by observing a change in the beam–lifetime as a function of time (Fig. 2) as reported in Ref. [5]. In this respect, the $\mathcal{TIVOLI}$ experiment proposes a novel method by which to measure a double–polarized total cross–section in a storage ring by transmission through a polarized internal target. Thus, COSY will serve not only as an accelerator, but also as an ideal zero degree spectrometer/detector allowing for the application of the optical theorem, which relates the forward scattering amplitude to the total cross–section. In addition, the $\mathcal{TIVOLI}$ experiment will study total cross–sections and its results will therefore be independent of corrections associated with Final State Interactions (FSI) [14] compared to other approaches that make use of nuclear targets and require detailed modeling [15]. In Ref. [5], it was demonstrated that the total cross section $\sigma_{tot}$ for a polarized–proton beam scattering on a purely tensor–polarized deuterium target in a storage ring, can be written in the form:

$$\sigma_{tot} = \sigma_{Y,XZ} + \sigma_{loss} = \sigma_0 \left(1 + P_Y^{beam} P_{XZ}^{target} A_{Y,XZ}\right) + \sigma_{loss} \tag{1}$$

where $\sigma_0$ is the unpolarized p–d cross–section, $P_Y^{beam}$ is the vector polarization of the proton beam, $P_{XZ}^{target}$ is the tensor polarization of the deuterium target, $\sigma_{loss}$ is the total cross section of the proton beam interacting with the unpolarized rest gas in the storage ring. The spin–correlation parameter $A_{Y,XZ}$, obtained if the vertical polarization of the proton beam is oriented along the $Y$–axis and the tensor polarized deuterium target lies in the $XZ$–plane, is the observable of interest. In the above equation, the reference frame is defined as follows: the $Y$–axis, pointing up, coincides with proton polarization direction, the $Z$–axis is defined in the direction of the proton beam, while the $X$–axis points left to complete a right handed coordinate system as is also reported in Fig. 1.(a). The expression for $\sigma_{tot}$ presented in (1) is justified in Ref. [5] by showing that $A_{Y,XZ}$ is a true $\mathcal{T}$–V, $\mathcal{P}$–C null observable in a double-polarized proton deuteron scattering experiment, any other contributions cancel each other. Thanks to this dependence on the beam and target polarizations, $A_{Y,XZ}$ can be extracted from two subsequent measurements by reversing the sign of the $P_Y^{beam} P_{XZ}^{target}$ product, which can be accomplished by either reversing the vector polarization of the proton beam or the sign of the angle of 45° between the tensor polarization of the deuterium target and the $Z$–axis ( Fig. 1).

## 4. Implementation at the COSY Storage Ring

Precise cross–section measurements can be performed either as transmission experiments or, according to the optical theorem, by measuring the forward scattering amplitude. In the first case, the accuracy is limited by the mutual calibration of the involved detectors with respect to all possible particles, energies and solid angles. In the latter case, the accuracy is limited by statistics, as the ideally allowed solid angle in forward direction should be zero. Performing the experiment with an internal target, as proposed in $\mathcal{TIVOLI}$, has the advantage that its precision basically relies on the accuracy of the beam current measurement [5]. This is a transmission experiment too, since the losses due to scattering within the target cell can be measured by the intensity decrease of the beam circulating through the target about $10^6$ times per second. The highest sensitivity to a $\mathcal{T}$–V and $\mathcal{P}$–C-interaction is reached for proton beam energies around 150 MeV [16,17], COSY can provide bunched and continuous proton beams at the so called PAX internal target station with beam lifetimes of about $10^4$ seconds. Furthermore, it was shown that the COSY proton beam can be cooled and accelerated from injection up to 135 MeV through a 40 cm long storage cell [18]. The internal target station of the PAX experiment [19] that will be adopted for $\mathcal{TIVOLI}$ is installed in one of the straight sections of COSY. It is equipped with a high intensity Atomic Beam Source (ABS) for polarized deuterons, a storage cell, a multi–purpose vertex–detector, a magnetic holding field, and a so called Breit–Rabi polarimeter. In addition to the beam and target polarimeter, a high precision beam current monitor has been developed and integrated into the COSY ring [20] - together with a calibration scheme and all the necessary readout electronics. By using such a beam current measurement system in the experiment, COSY will serve as an accelerator, a storage ring, and an ideal zero degree spectrometer and detector.

The $\mathcal{TIVOLI}$ experiment will make large use of the PAX installation that has been basically already successfully commissioned. The crucial part to be implemented is a high–sensitivity beam current monitor, to reach the required accuracy in the proposed measurements. A beam current monitor, exactly a Fast Current Transformer (FCT), presenting the required characteristics has been acquired by the COSY accelerator group and studied on a test bench. In the framework of the $\mathcal{TIVOLI}$ experiment, we plan to commission it in the COSY Ring and adapt it to the needs of the proposed measurements. To increase the experimental statistical sensitivity, the implementation of an openable storage cell is also foreseen, a prototype was already commissioned in the framework of PAX [19].

### *4.1 Existing Setup*

The internal target section of the PAX experiment matches the $\mathcal{TIVOLI}$ experiment requirements and also the following items are available:

**The low–$\beta$ section:** the low–$\beta$ section in order to control the beam dimensions during acceleration and the experiment. The low–$\beta$section successfully operated by the COSY accelerator group during the PAX experimentation allows the use of an internal storage cell to increase density of the internal target and the sensibility of the measurement [18]. It will be adopted for the $\mathcal{TIVOLI}$ experiment.

**The PAX polarized target:** the PAX polarized target, which consists of a polarized hydrogen/deuterium Atomic Beam Source (ABS), the accumulation cell, and the so called Breit–Rabi Polarimeter (BRP), successfully used by the PAX Collaboration (in 2011) for the demonstration of spin filtering as a viable technique to polarize a stored proton beam filtered by a polarized hydrogen target, which has been converted to deuterium [19]. It will provide the vector polarized deuterium target for the measurement of $A_{Y,Y}$, which is expected to be absent or low, but due to the fact that it can mimic the $A_{Y,XZ}$ has to be precisely determined, and then it will provide tensor polarized deuterium for the measurements of $A_{Y,XZ}$.

**The PAX detector:** The silicon tracking multipurpose detector originally conceived for the PAX experiment, which consists of four silicon telescopes in a diamond shape. It was originally designed to identify p–p, p̄–p and p–d elastic scattering and p–d break–up events with beam energies below 150 MeV and will be ideally suited for $\mathcal{TIVOLI}$ as well. The detector has been successfully commissioned in the COSY ring in April 2017 with a proton beam of 135 MeV scattering off a vector polarized deuterium target. Its use during the $\mathcal{TIVOLI}$ experiment will be crucial to determine beam and target polarization during the measurement. In addition its tracking capability will be of extreme importance for the control of the beam position in the interaction region with the target.

### *4.2 Foreseen Upgrades for $\mathcal{TIVOLI}$*

As the $A_{Y,XZ}$ observable will be determined from the difference in the beam lifetimes measured for two independent beam and target spin-polarization states, the $\mathcal{TIVOLI}$ experiment puts demanding requirements on the precision of the beam lifetime determination and consequently on the resolution of the beam current measurement. The goal of improving the upper limit on $\mathcal{T}$ violation by one to two orders of magnitude can be achieved during one month of beam time with a resolution in the beam current measurement of better than $10^{-4}$ during a measurement time of one second [5].

**The Fast Current Trasformer** A high sensitivity and resolution device has been developed on a test bench at COSY for the measurement of the average current of a bunched beam making use of inductive pick–ups , the so called Fast Current Transformer (FCT). A promising preliminary test in the COSY ring performed in 2016 has shown that the developed FCT is able to detect stored beam currents in the range between 4 $10^4$ and 2 $10^9$ stored protons. A final commissioning on the COSY ring is required.

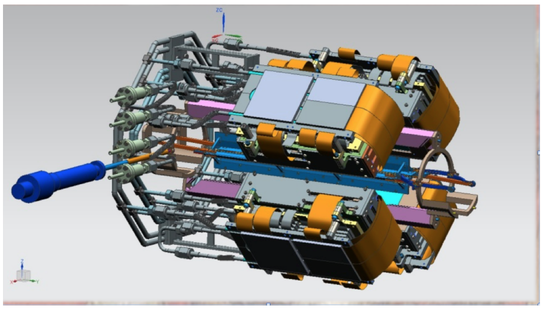

**Figure 3.** Drawing of the PAX multipurpose detector.

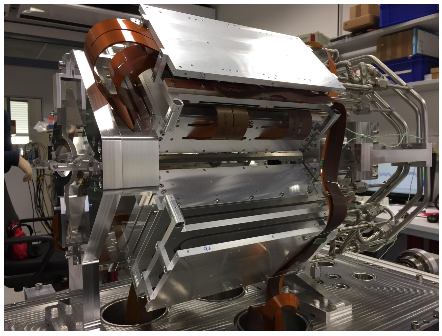

**Figure 4.** The detector during its installation on the COSY ring for its commissioning with a deuterium polarized target.

**Openable Cell** The requested beam time to reach the desired precision is directly related to the achieved reaction rate. Since the experiment will use an internal polarized gas target, a storage cell will be employed to increase the target density in the beam–target interaction region. While this leads to an increased luminosity during the experiment, the storage cell will also limit the machine aperture at injection and hence the intensity available for the experiment. For the final phase of the experiment, an openable storage cell (opened up during beam injection and acceleration and closed for the measurement phase) could be used, a prototype of which has been designed and realized for the PAX experiment [19]. The device perfectly fits the requirements of $\mathcal{TIVOLI}$, its commissioning in COSY will be one of the tasks of the beam preparation studies.

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