THE TEST OF TIME REVERSAL INVARIANCE AT COSY (TRIC)*

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An experiment to test the Time Reversal Invariance is planned at the synchrotron COSY-Jülich (TRIC). TRIC is constructed as a transmission experiment at the storage ring which will use a genuine T-odd P-even null observable available in double polarised *pd* scattering. The goal of the experiment is to improve the present limit on a T-odd P-even interaction by at least one order of magnitude. In this contribution, the status of the preparatory work, advantages of the experiment, and a new formalism which links beam current measurement resolution and precision of the experiment are reported.

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1. Test of Time Reversal Invariance at COSY

The test of Time Reversal Invariance at COSY (TRIC) was proposed as one of the first precision experiments at the COoler-SYnchrotron COSY-Jülich [1]. Experiment is planned as a transmission experiment at a storage ring with an internal polarised gas target. The experiment aims on improvement of the present upper limit on a T-odd P-even interaction [2] by one order of magnitude. To reach this goal, it is planned to study a unique genuine null observable $A_{Y,XZ}$, available in the double polarised proton–deuteron scattering, to the precision of $\sim 10^{-6}$. Since TRIC is planned as a transmission experiment, it will utilize the optical theorem for the measurement of the total cross section in the double polarised *pd* scattering

$$\sigma = \sigma_0 \left(1 + A_{Y,XZ} P^{\mathrm{b}}_Y P^{\mathrm{t}}_{XZ} + A_{Y,Y} P^{\mathrm{b}}_Y P^{\mathrm{t}}_Y + \ldots\right) , \tag{1}$$

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where $P_Y^{\rm b}$ stands for the beam polarisation, $P_Y^{\rm t}$ and $P_{XZ}^{\rm t}$ for the vector and tensor target polarizations, and $A_{Y,XZ}$ and $A_{Y,Y}$ for the relevant double polarised spin observables. Due to the use of a transversely polarised proton beam and tensor polarised deuterium target, from Eq. (1) only the observable of interest $A_{Y,XZ}$ will contribute to the difference of cross sections for two beam-target spin configurations used in TRIC.

As a test for T-symmetry violation, the TRIC experiment is motivated by the search for the physics beyond the Standard Model. As it was formulated by Sakharov in Ref. [3], strong CP violation is one of the prerequisites to explain the observed Baryon Asymmetry of the Universe. Due to the existence of CPT symmetry, CP violation implies T-symmetry violation, which can be studied in the searches for the T-odd P-even symmetry violations. In contrast to the Electric Dipole Moment (EDM) experiments, which test T-odd P-odd symmetry, the TRIC experiment tests exclusively for time symmetry, and hence represents another approach to the search for the physics beyond the Standard Model. In Ref. [4], it was demonstrated that it is not possible to model independently to get a limit on a T-odd P-even interaction from the much stronger limit on the T-odd P-odd interaction obtained from the EDM of an elementary particle.

There are several theoretical studies which analyze the prospects of searching for the T-odd P-event interaction in the *pd* system. Two of them from Ref. [5] and [6] independently suggest that the optimal proton beam energy for such an experiment is below $\sim$ 200 MeV. However, in a more recent analysis [7], authors of Refs. [6, 7] suggest performing a measurement at a somewhat higher energy of about 1 GeV.

At COSY, polarised and unpolarised beams of protons and deuterons in the energy range of 45–2880 MeV are available for internal and external experiments. The accelerator COSY is equipped with stochastic and electron cooling systems, which can be used for better beam acceptance control during the entire experiment. The TRIC experiment will use a tensor polarised deuterium target at the PAX installation, where a low-β section allows the installment of a storage cell of a small diameter [8]. Use of the so-called storage cell enables the increase of target density by almost two orders of magnitude, at the expense of the accelerator acceptance. Both the PAX low-β section and the electron cooler are operational up to the energy of 182 MeV, which limits the range of possible energies for the first generation TRIC experiment. Due to the existence of high quality polarimetry data at 135 MeV [9], it is natural to perform the first TRIC experiment at this energy, since in this case, no major modifications in the construction of COSY and the PAX installation are needed.

In the TRIC experiment, accelerator COSY will be used as a storage ring and an ideal zero degree spectrometer, while the beam current measurement system will serve as a detector. In this case, instead of measuring all the particles which scatter from the beam, the beam particles which did not interact in the target will be detected, with the help of a high resolution beam current measurement system. Performing these measurements continuously and comparing the beam slopes (β) in cycles with the appropriate beam and target spin configurations, one can get access to the $A_{Y,XZ}$ observable. Of course, such measurements depend crucially on the precision of the beam current measurement system, which has to be constructed for the experiment. For a detailed discussion about the high-resolution beam current measurement system for the TRIC experiment, please refer to Ref. [10].

Besides the beam current measurement system, polarised beam and target, as well as polarimeters, must be prepared for the conditions of the TRIC experiment. During two preparatory beam times in 2012 and 2016, it was demonstrated that COSY can provide a polarised proton beam of sufficiently long beam lifetime and polarisation for the realization of the TRIC experiment at 135 MeV with the PAX installation. A polarised deuterium gas target and a Breit–Rabi gas polarimeter were commissioned, and tensor polarisation of the deuterium gas in the storage cell measured, in 2016. During the third beam time in 2017, the first commissioning of the silicone multi-purpose polarimeter detector was performed. The first data analysis done during this experiment gives promising results, which confirm the performance of the PAX detector within the designed parameters. Hence, after three preparatory beam times at COSY, the PAX Collaboration is on the good way towards the first stage of the TRIC experiment.

Although a lot of steps necessary for the successful realization of the TRIC experiment have already been done, there are still many open questions, and things to be prepared. In the next sections, we concentrate on the short summary of the advantages of the experiment in Sec. 2, the presently available formalism to estimate the possible precision of the experiment using the resolution of the beam current measurements in Sec. 3, and the first consideration of the influence of possible systematic effects on the accuracy of determining $A_{Y,XZ}$ in Sec. 4.

2. Advantages of TRIC

The T-symmetry tests in meson systems and even the T-violation reported recently in [11] are in perfect agreement with the Standard Model and are taken into account using the CKM matrix mechanism. In contrast to these experiments, TRIC will test T-symmetry in a system of baryons, and any indication for the effect in the experiment will imply the discovery of physics beyond the Standard Model.

It was shown in [12], that the $A_{Y,XZ}$ observable in double polarised *pd* scattering is a T-odd P-even genuine null observable. This is hugely beneficial for a precision experiment, because it helps reduce the number of possible systematic effects influencing the final result. For the null experiment, any deviation of a single observable from zero would be an indication for the physics beyond the Standard Model. TRIC will search for T-symmetry violation using a polarised gas target with the simplest spin one particle available. Hence, the experimental result will be free from any model dependence, which might be an important factor in the experiments where heavy spin oriented targets, like ^{165}Ho, are used [2].

TRIC is formulated as a transmission experiment in a storage ring which utilizes the optical theorem for the total cross-section measurement. It was shown several times in the literature (see, for instance, [6]) that such measurements are, in fact, independent from any correction associated with the initial and final state interactions, which are crucial for T-symmetry tests in nuclear decays [13]. Furthermore, the TRIC experiment will use the storage ring as an ideal zero degree spectrometer in the transmission experiment. This is why the application of the optical theorem, which is rigorous only under the zero degree condition, is well-justified in the case of TRIC. For example, the present upper limit on the T-odd P-even interaction has been obtained from the transmission experiment with a solid angle of 3.2° [2]. In the TRIC experiment's case, the solid angle is limited by the acceptance angle of the storage ring $\sim 0.4°$, which can be further reduced artificially by using scrapes installed in the ring, allowing to study possible systematic effects.

The most crucial possible systematic effect in the TRIC experiment is, in fact, connected with difficulties in producing an ideal tensor polarised deuterium jet in the target atomic beam source. Vector polarised deuterium gas in the tensor polarised target during the $A_{Y,XZ}$ measurement can lead to a fake signal in the experiment, connected with the non-zero $A_{Y,Y}$ observable in Eq. (1). However, there are technical options for suppressing the influence of $A_{Y,Y}$ on the final result. Present knowledge about possible systematic uncertainties in the TRIC experiment can be found in Ref. [14].

3. Evaluation of possible precision in TRIC experiment

In the transmission-experiment method of determining a double-polarized observable, one estimates the beam's rate of decay by fitting a linear model to the log-transformed beam current measurements

$$\begin{aligned} \tilde{I}_t &= I_0\, e^{-\nu\sigma\Theta\cdot t} + \epsilon_t^I = I_t + \epsilon_t^I\,, \\ \ln \tilde{I}_t &= \ln I_0 + \beta t + \delta_t^I\,, \end{aligned}$$

where ν is the circulation frequency, σ is the total scattering cross section from Eq. (1), Θ is the target thickness, ϵ_t^I is the measurement error at time t, I_t is the actual beam current, $\tilde{I}_t$ is the measured beam current, and $\delta_t^I = \epsilon_t^I / I_t$.

The observable of interest A can then be estimated as a difference statistic of the slopes β from a pair of appropriate polarization cases

$$\hat{A} = C\left[\hat{\beta}^- - \hat{\beta}^+\right], \qquad C = \left(\nu\sigma_0\Theta P_y^{\mathrm{b}} P_{xz}^{\mathrm{t}}\right)^{-1}.$$

Hereinafter, C is the constant linking the beam current slope estimates $\hat{\beta}$ with the estimate $\hat{A}$ of the observable of interest A. To a first approximation, C can be estimated using the parameters of the experiment summarized in Table I. The variance of $\hat{A}$ will be proportional to the sum of the variances of the constituent slope estimates

$$\sigma\left[\hat{A}\right] = C\sqrt{2}\,\sigma\left[\hat{\beta}\right].$$

TABLE I

Parameter values (June 2016).

Parameter	Symbol	Value	Dimension
Beam revolution frequency	ν	0.79	MHz
Target thickness	Θ	1.1×10^{14}	at$\times$cm^{-2}
Target polarization	P^{t}	0.88	—
Beam polarization	P^{b}	0.74	—
pd scattering cross section	σ_0[a]	70	mb
Slope-to-asymmetry proportionality coefficient	C	1.26×10^5	sec

[a]From Particle Data Group
`http://pdg.lbl.gov/2016/hadronic-xsections/rpp2014-pd_pn_plots.pdf`

For the mean statistic, its precision depends on the precision of the slope estimate $\sigma[\hat{\beta}]$ as in

$$\sigma\left[\left\langle\hat{A}\right\rangle\right] = \frac{\sigma\left[\hat{A}\right]}{\sqrt{N}} = \sqrt{2}\sqrt{\frac{h}{H}}\,\sigma\left[\hat{A}\right] = 2C\sqrt{\frac{h}{H}}\,\sigma\left[\hat{\beta}\right], \tag{2}$$

where H is the beam time, h the cycle length, and so the maximum number of estimate pairs $N = H/2h$.

Under the Gauss–Markov conditions, the Ordinary Least Squares estimator of the slope is zero-bias, minimum-variance, and has a standard error of

$$\sigma\left[\hat{\beta}\right] = \frac{\sigma\left[\delta^I\right]}{\sqrt{\sum_{k=1}^{K}(t_k - \langle t\rangle)^2}}\,, \tag{3}$$

where $\sigma[\delta^I]$ is termed the beam current resolution, K is the sample size, and t_k is the measurement time. For samples taken uniformly in time with step Δt, at sample sizes $K = h/\Delta t \gg 1$, the denominator can be expressed in physical terms as

$$\sqrt{\sum_{k=1}^{K}(t_k - \langle t\rangle)^2} \approx \frac{h\sqrt{h}}{2\sqrt{3}\sqrt{\Delta t}}\,,$$

and hence

$$\sigma\left[\hat{\beta}\right] = 2\sqrt{3}\sqrt{\frac{\Delta t}{h}}\frac{\sigma\left[\delta^I\right]}{h}\,. \tag{4}$$

Using Eq. (2),

$$\sigma\left[\left\langle\hat{A}\right\rangle\right] = 4\sqrt{3}C\,\frac{\sqrt{\Delta t}}{h\sqrt{H}}\,\sigma\left[\delta^I\right]\,, \tag{5}$$

from which the required measurement resolution can be estimated for the given precision $\sigma[\langle\hat{A}\rangle]$, beam time H, and cycle duration h.

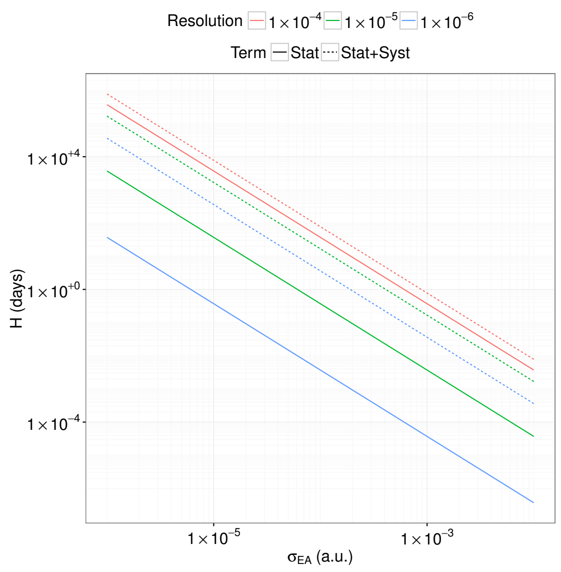

Fig. 1. Required beam time as a function of $\hat{A}$ precision for three different beam current resolutions. Solid lines are obtained for the inherent slope variation $\sigma^2[\beta] = \mathrm{s}^{-2}$ and single polarisation state time $h = 15$ min, while the dashed lines are for $\sigma^2[\beta] = 10^{-15}\ \mathrm{s}^{-2}$ and h_{best} from Table II.

Using Eq. (5) and parameters of the experiment from Table I, the expected precision of the experiment as a function of the total beam time can be estimated. In Fig. 1, the results of this calculation, assuming individual cycles for each spin configuration h to be equal to 15 min, for different beam current measurement resolutions are presented. It is clear that the easiest way to reach the goal of the project is to use a high resolution beam current measurement system. The presently achieved resolution of 10^{-4} [10] allows to reach the goal of the experiment after one month of measurement, but only in case very long cycles (several hours) are used. However, there is still room for improvement in the parameters of the new high resolution beam current measurement system [10].

4. Resolution lower bound

The first estimates for the possible precision of the determination of $A_{Y,XZ}$ were done in [15], and later repeated in [1]. Those calculations, although slightly different from the calculations presented in Sec. 3, do not take into account possible systematic effects connected with slow beam current slope variations.

In the real experiment, the beam current slope can vary due to such factors as the degradation of the target thickness with time after regeneration, or the binomial nature of the beam current. Those variations will influence the standard error of the estimate in accordance with the law of total variance

$$\sigma^2\left[\hat{\beta}\right] = E_\beta\left[\sigma^2\left[\hat{\beta}\,|\,\beta\right]\right] + \sigma^2_\beta\left[E\left[\hat{\beta}\,|\,\beta\right]\right] . \tag{6}$$

Here,

$$\begin{aligned} E\left[\hat{\beta}\,|\,\beta\right] &= \beta\,, \\ \sigma^2\left[\hat{\beta}\,|\,\beta\right] &= 12\frac{\Delta t}{h}\frac{\sigma^2\left[\delta^I\right]}{h^2}\,, \qquad \text{(essentially Eq. (4))} \end{aligned}$$

and hence, using Eq. (5),

$$\sigma^2\left[\left\langle\hat{A}\right\rangle\right] = \frac{4C^2}{H}\left(12\Delta t\,\frac{\sigma^2\left[\delta^I\right]}{h^2} + h\,\sigma^2[\beta]\right) . \tag{7}$$

In this equation, the first term describes the statistical precision of the estimate, the second its accuracy. While the first term is connected only with the resolution of the beam current measurement system, the second has been modeled in detail in Ref. [16] and presently consists of two main factors.

The first factor is due to the binomial nature of the beam current decrease, and can be estimated (using parameters from Table I) to be $\sigma^2_{\mathrm{beam}}(\beta_0) \approx 8 \times 10^{-16}$ s^{-2}. The second factor, $\sigma^2_{\mathrm{target}}(\beta_0) \approx 1 \times 10^{-16}$ s^{-2}, is related to the slow degradation (approximately 10%/day) of the target density after regular atomic beam source regenerations during the experiment. Overall, the inherent slope variation was estimated to be $\sigma^2[\beta] \approx 10^{-15}$ s^{-2} [16].

In Fig. 2, estimates of the standard error of $\hat{A}$ as a function of polarisation state time h, computed using Eq. (7), for three different beam current resolutions have been presented. All the curves in Fig. 2 have a minimum, connected with the optimal spin configuration time h for the given parameters of the experiment. From Eq. (7), the best variance is achieved at

$$h_{\mathrm{best}} = \sqrt[3]{24\,\Delta t}\left(\frac{\sigma^2\left[\delta^I\right]}{\sigma^2[\beta]}\right)^{1/3}. \tag{8}$$

The optimal cycle durations h_{best} for a single spin configuration at the given value of $\sigma^2[\beta] = 10^{-15}$ sec^{-2} have been estimated for the three beam current resolutions using parameters from Table I, and presented in Table II.

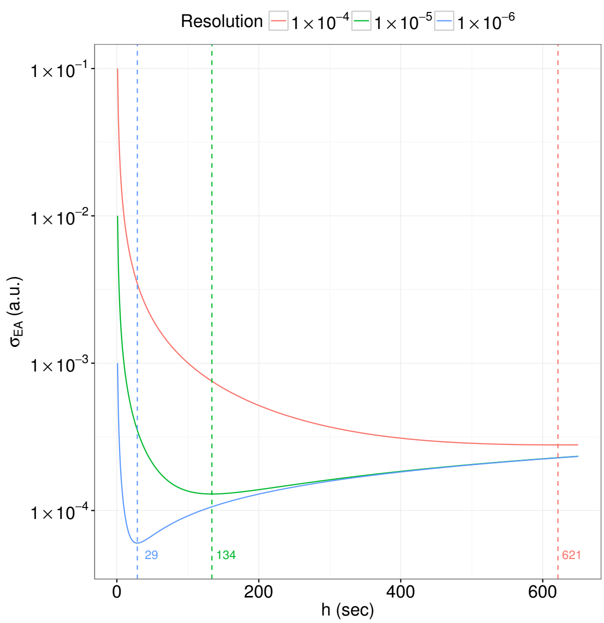

Fig. 2. The standard error of the mean A estimate as a function of cycle length when the inherent slope variation $\sigma^2[\beta] = 10^{-15}$ s^{-2}. The inherent variation limits the accuracy of the estimate.

TABLE II

Best achievable precision of $\hat{A}$ for three different beam current resolutions achieved after one month measurement with experiment parameters from Table I at the optimal single spin state time h_{best}, and at 30 days of beam time.

$\sigma\left[\delta^I\right]$	h_{best} [sec]	$\sigma[\langle\hat{A}\rangle]$
1×10^{-4}	621	2.8×10^{-4}
1×10^{-5}	134	1.3×10^{-4}
1×10^{-6}	29	6.0×10^{-5}

Depending on the value of the beam current resolution, the optimal single spin configuration time h_{best} changes significantly. In order to analyze possible effects of inherent slope variation $\sigma^2[\beta]$ on the precision of the complete experiment, the beam times required for the given precision of the $A_{Y,XZ}$ estimate for the different cases of h_{best} from Table II have been computed and presented in Fig. 1 by dashed lines. The inherent slope variation effect significantly limits the accuracy of the experiment, and needs further understanding.

5. Conclusion

The TRIC experiment is aimed at the improvement of the present upper limit on a T-odd P-even interaction by at least one order of magnitude after one month of beam time. After three preparatory beam times at COSY, the PAX Collaboration have demonstrated that it is possible to realize this ambitious precision experiment. The present status of the experiment, and the link between resolution in beam current measurement and the final precision of the experiment, have been presented.

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