The Time Reversal Invariance Experiment at COSY (TRIC)

Why?

Baryon Asymmetry of the Universe

Observed: \( \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6 \cdot 10^{-10} \)

SM Expected: \( \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18} \)

WMAP+COBE, 2003
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Why?

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8 orders of magnitude are missing!

Three conditions \((A.\text{Sakharov JETP Lett. 5,24})\)

- Baryon number conservation is violated
- Violation of CP ↔ T Violation (since TPC holds)
- A non-thermalized system
Consider T violation (with and without P conservation):

\[ L = L_{SM} + \alpha_{TVPV} L_{TVPV} + \alpha_{TVPC} L_{TVPC} + \ldots \]

EDM and TRIC probe different extensions of the SM
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What kind of experiment is performed?

5.9 MeV Neutron Transmission Experiment through $^{165}$Ho

Observable: $\vec{p} \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)(\vec{p} \cdot \vec{\sigma}_2)$

Since the tensor polarization in $^{165}$Ho is generated by one valence nucleon, the effect is diluted by the other 164 nucleons

Therefore:
Restrict experiment to most simple Spin$^{1/2}$ – Spin1 system, i.e. $\vec{p} - \vec{d}$ scattering at COSY (as an internal experiment)
Two independent theoretical calculations suggest to perform TRIC below 200 MeV
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What are the Goals for TRIC?

• (Most) **accurately** probe TRI (T-odd, P-even) in nuclear matter

• Dynamics independent;
especially: **Not** sensitive to Final State Interaction (FSI)

• Only dependent on the structure of the reaction matrix as determined by general conservation laws „True test of TRI“

• Simple reaction (Two particles in → two particles out)

**True TRI Null-Test**
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What is the Goal for TRIC?

But:
There is no such TRI Null-Test for any reaction in atomic nuclear or elementary physics


Loophole: Proof holds for bilinear observables only.

H.E. Conzett, „7th Int. Conf. on „Pol. Phen. Nucl. Phys.“, Paris (1990) 2D

Measure forward scattering amplitude and thus total cross sections via the Optical Theorem

Measure total $A_{y,xz}$ in $\vec{p} - \vec{d}$ scattering
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The Experimental Setup

External Fixed Target

Scattering-Cones and Detector-Sensitivity

\[ p + d \rightarrow \pi^+ p d^- \]

Transmission Detector

Proton -Beam

Deuteron -Target

Detector Wall

Sensitivity around 0°
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The Experimental Setup
The Time Reversal Invariance Experiment at COSY (TRIC)

The Principle Idea of the Experimental Setup

The Principle of the Time Reversal Invariance test at COSY (TRIC)
The Time Reversal Invariance Experiment at COSY (TRIC)
Principal Error Analysis

Involved Spins: \( \frac{1}{2} + 1 \rightarrow \frac{1}{2} + 1 \)

Line cancels because of: Proton spin flip
\( p_x, p_z \) negligible for protons

Quantity cancels because of: \( \mathcal{R}, \mathcal{P} \)
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Some Experimental Details

\[
\delta A_{y,xz}^{\text{meas}} \propto \frac{\sqrt{\Delta t}}{h\sqrt{H}} \delta I
\]

with: \( \Delta t \) is the time interval between two consecutive current measurements on a slope [s]

\( h \) is the spin flip period of the target [h]

\( H \) is the total measuring time [h]

\( \delta I \) is the error of the current measurement in the interval \( \Delta t \) [A]

When are these accuracies equal?

\[
\delta A_{y,xz}^{\text{meas}} = \delta A_{y,xz}^{\text{shot}}
\]

\[
h_{\text{min}} \propto \delta I
\]
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Some Experimental Details

COSY-Quadupoles

Target chamber with storage cell and detector system

ABS

BRP

Low-β quadrupoles

P. Lenisa and F. Rathmann CERN-SPSC-2012-013/SPSC-SR-099
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First Test of the Novel Measurement Method

BCT-response run

Preliminary result:

\[ A_{y,y} (\vec{p} - \vec{d}) = 0.06 \pm 0.09 \]
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Summary

• TRIC probes physics beyond the SM

• The TRIC experiment at COSY constitutes a precision transmission T-odd, P-even True TRI Null-Test

• For the TRIC experiment COSY serves as accelerator, ideal forward spectrometer and detector

• COSY is ready for the TRIC experiment
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Thank You
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CP/T Violation in Early Universe

Big Bang → Time → Today

Matter & Antimatter

CP/T violation in the SM is too weak

New CP/T violation beyond the SM must exist!

D.Eversheim        INPC2016, Adelaide
The Time Reversal Invariance Experiment at COSY (TRIC)

The Experimental Setup

For the interaction the bending field is irrelevant; only the relative orientation of the polarization matters.

For the interaction the location of the target is irrelevant.
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The Experimental Setup

- **Magnetic Field and Proton Vector Polarisation**
- **Deuteron Target Tensor Alignment**
- **Proton Beam**
- **Bending Force**

**For the interaction the bending field is irrelevant; only the relative orientation of the polarization matters.**

**For the interaction the location of the target is irrelevant.**
The Time Reversal Invariance Experiment at COSY (TRIC)

Some Experimental Details

Fast Current Transformer (FCT):
• Commercial device (Bergoz)
• Sensor for bunched beam

Readout Electronics:
• Lock-In-Amplifiers
• High resolution ADC

• With the FCT we can detect down to 40 000 protons stored in COSY
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The Experimental Setup

The total pol. correlation $A_{y,xz}$ is measured via the forward scatt. amplitude $F(0)$

$$\sigma_{\text{tot}} = \frac{4\pi}{k} \text{Im} F(0) \rightarrow \frac{4\pi}{k} \text{Im} \text{tr} (\rho \, F(0))$$

$F(0)$ - Forward scatt. amplitude for unpolarized particles
$\rho$ - Density matrix
$\mathcal{F}(0)$ - Forward scatt. amplitude (matrix) for polarized particles

$A_{y,xz}$ is proportional to the relative difference of the current slopes of the circulating proton beam with respect to the chosen polarization configuration (+/-) of the proton beam and deuteron target.
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DC transformer

AC transformer

Capacitive pick up

1) COSY BCT $\sigma_i = 0.5 \mu A/\sqrt{Hz}$
2) NPCT Bergoz $\sigma_i = 0.3 \mu A/\sqrt{Hz}$
3) CCC GSI $\sigma_i = 0.25 nA/\sqrt{Hz}$
4) ICT Bergoz $\sigma_i = 1 nA/\sqrt{Hz}$
5) ICT Bergoz/CRYRING $\sigma_i = 0.1 nA/\sqrt{Hz}$
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In 2014 at the PAX target place will be available:

- Atomic Beam Source and Breit-Rabi Polarimeter will be capable to operate with deuterium
- Opennable storage-cell for highly polarized target density
- Holding field system to preserve and flip the target polarization during a measurement cycle
- \( \phi \) - symmetric multipurpose PAX detector for beam and target polarimetry
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Injection, cooling at Inj., Acceleration

COSY can provide as with a beam through the PAX storage cell
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The Time Reversal Invariance Experiment at COSY (TRIC)
Final State Interaction

Concerning FSI:

Reading the Optical Theorem carefully:
\[ \frac{4\pi}{k} \text{Im} F^\text{el}(0^\circ) = \sigma^\text{el}_\text{tot} + \sigma^\text{inel}_\text{tot} \]

Has been proven by R.M. Ryndin
(proceeding of 3rd LNPI Winter School, Test of T-invariance in strong interactions),
the idea of the proof can be found in: V. Gudkov and Young-Ho Song,

Unitarity → Optical Theorem → \( F_i(0^\circ) = F_i(0^\circ) \) → Unitarity
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Final State Interaction

\[ \frac{4\pi}{k} \text{Im} F^\text{el} (0^\circ) = \sigma^\text{el}_\text{tot} + \sigma^\text{inel}_\text{tot} \]

For all inelastic processes the following conditions have to be fulfilled by the (FSI) scattered particles in order to be transported by COSY:

i) The e/m has to be that of a proton to \( 10^{-4} \)

ii) The momentum \( p \) has to match to at least \( 10^{-4} \)

iii) The scattering angle \( \theta \) must not exceed a few mrad

The phase space is considered to be virtually Zero
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TRI and Parity Tests

\[ \gamma - \gamma \]  correlation in $^{57}$Fe

Detailed Bal. in $p + ^{27}$Al $\rightarrow ^{4}$He + $^{24}$Mg

$P - A$ in $\bar{p}$ - $p$ scattering

Neutron EDM

Atomic EDM in $^{199}$Hg

CSB $\Delta A$ for $\bar{n}$ - $p$ and $\bar{p}$ - $n$ scatt.

$\bar{n}$ - transm. through $^{165}$Ho

\[ \bar{\alpha}_X \leq 5 \cdot 10^{-6} \]

\[ \bar{\alpha}_X \leq 10^{-3} \]

\[ \bar{g}_Y \leq 3 \cdot 10^{-2} \]

\[ \bar{g}_{TP} \leq 10^{-11} \]

\[ \bar{g}_{\rho \gamma} \leq 1.5 \cdot 10^{-3} \]

\[ \bar{g}_{\rho \gamma} \leq 1 \cdot 10^{-2} \]

\[ \bar{g}_{\rho \gamma} \leq 6.7 \cdot 10^{-3} \]

\[ \bar{g}_{\rho \gamma} \leq 2.3 \cdot 10^{-2} \]

Null-tests

A_L in $\bar{p}$ - $p$ scattering ($\delta A \sim 2 \cdot 10^{-8}$)

A_{\gamma,xz} in $\bar{p}$ - $d$ scattering (potentially $0.1 \cdot \bar{g}_{\rho \gamma}$ of $^{165}$Ho)

$\bar{\alpha}_X$ Strength of eff. T-violating N-core potential

$\bar{g}_Y / \bar{g}_{TP}$ Strength of T-violating / TP-violating NN potential

$\bar{g}_{\rho \gamma}$ Strength of T-violating $\rho$-MN coupling constant
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Parity Violation

Why can $A_z$ be measured to the $10^{-7}$ level?

- $A_z$ measurement is a **Null-Experiment**.
- **Signature** of $A_z$ is **unique** compared to other observables.
- As $A_z$ is a polarization observable, it is a **relative measurement**.

In addition:

- **Reduce sensitivities** to errors by proper set-up/alignment.
- Reduce „error amplitudes“ by **feedback control**.
- **Correct** for remaining errors.
- Convince yourself by measurement, that error contributions thought to be negligible, are negligible.
- Is the reduced $\chi^2$ after all corrections close to 1?
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Parity Violation

Number of Spin\(^{1/2} + \) Spin\(^{1/2}\) Observables

Example:

\[
\sigma_0 = \sum_i a_i a_i^* \\
\sigma_{\text{pol}} = \sum_{i,j} \pm a_i a_j^* 
\]

Naiv + P + T + \(\gamma \rightarrow \infty\)

Pauli

(N-N) (p-p) (e-N)

256 128 36 25 3

M=f(a_1 \cdots a_5)

M=f(a_1 \cdots a_6)

D.Eversheim     INPC2016, Adelaide
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Defining the Goal for TRIC

The atomic EDM  

The nuclear EDM  

The nucleon EDM

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Defining the Goal for TRIC

EDM of an elementary particle:

Observable: $\vec{\sigma} \cdot \vec{E}$

$\uparrow$  P-odd/T-odd experiment

Upper limit from n-EDM

Prediction: Deduced Strength for P-even/T-odd: $\bar{g}_{\rho X} < 1.5 \cdot 10^{-3}$


Experiment: From $A_5 = 8.6 \pm 7.7 \cdot 10^{-6}$ gives:

$\bar{g}_{\rho X} : 2.3 \pm 2.1 \cdot 10^{-2}$

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Some Experimental Details

- The error in the TRI sensitive observable $A_{y,xz}$ depends on:
  
  i) The accuracy with which the current of circulating protons are measured
  
  ii) The number of turns of the proton beam through the target

\[ \Delta T_{y,xz} = \frac{T^+ - T^-}{T^+ + T^-} = \frac{\exp(-\chi^+) - \exp(-\chi^-)}{\exp(-\chi^+) + \exp(-\chi^-)} \]

with:

- $T^+$ - Transmission factor for the proton-deuteron spin-configuration with $P_y \cdot P_{xz} > 0$

- $T^-$ - Transmission factor for the time reversed situation, i.e. $P_y \cdot P_{xz} < 0$

- $\chi^+/-$ - Is the product of the factors $(\sigma_{tot} \cdot Qd \cdot n)$ with respect to the proton-deuteron spin-alignment

\[ \Delta T_{y,xz} = \sigma_o Qd n P_y P_{xz} A_{y,xz} =: -S A_{y,xz} \]

with:

- $S$ - Is the sensitivity of the experiment with respect to $A_{y,xz}$

- $n$ - Number of turns the beam takes through the target
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Outline

● Why is this experiment interesting?
● What do we measure?
● How do we measure?
● Some Tricks of TRIC
● Summary
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