Outline

- Defining the Goal.
- The Experimental Setup
- Final State Interaction
- Most Basic Error Analysis
- Some Experimental Details
- Summary

Defining the Goal

- (Most) accurately test TRI (T-odd, P-even) in nuclear matter
- Dynamics independent;
  especially: Not sensitive to Final State Interaction
- 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**

Defining the Goal

TRIC

But:

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

*F.Arash, M.J. Moravcsik and G.R. Goldstein, Phys.Rev.Lett. **54** (1985) 2649*
*M.Simonius, Phys. Lett. **B58** (1975) 147*

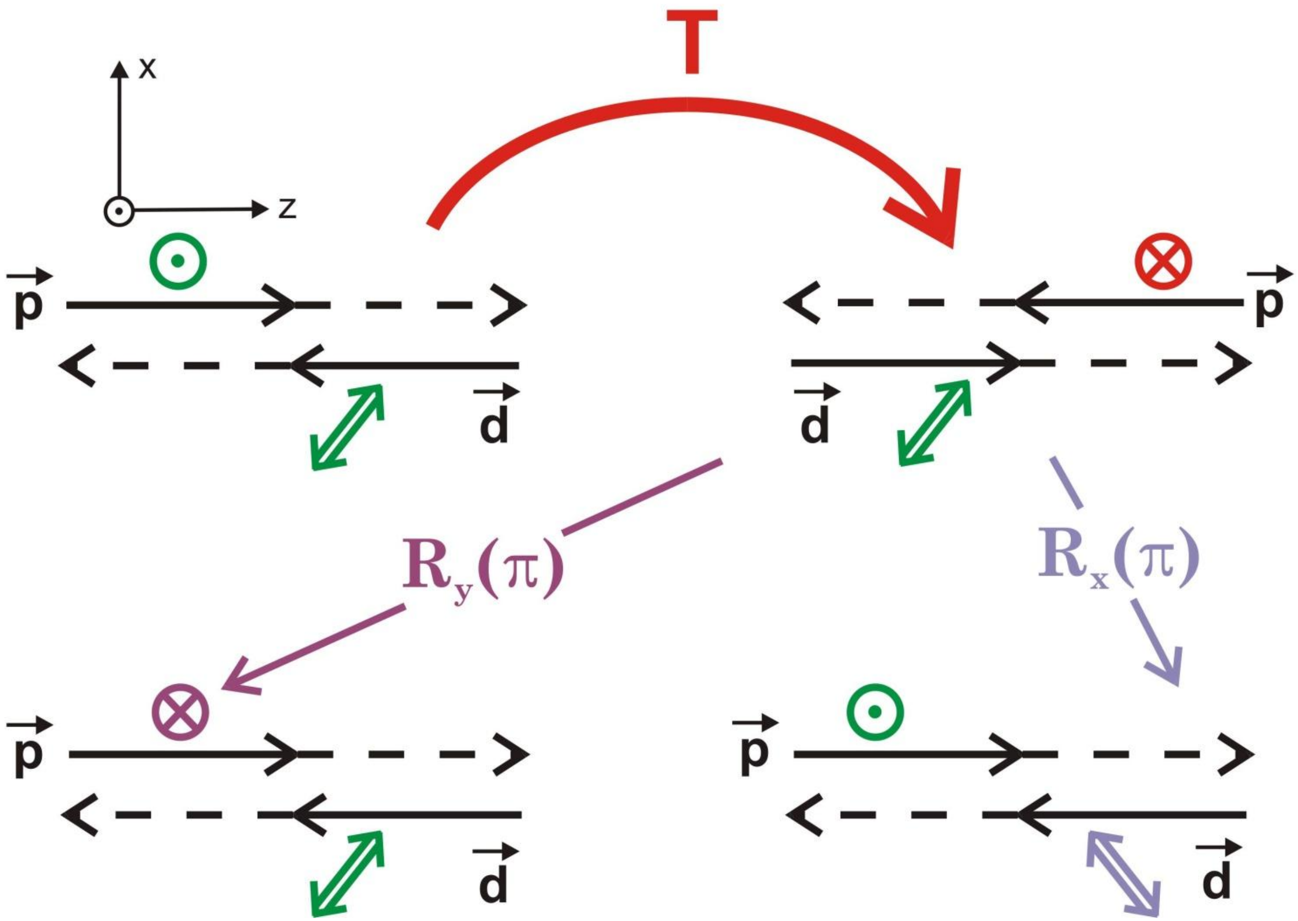
Loophole: **Proof holds for bilinear observables only.**

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

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

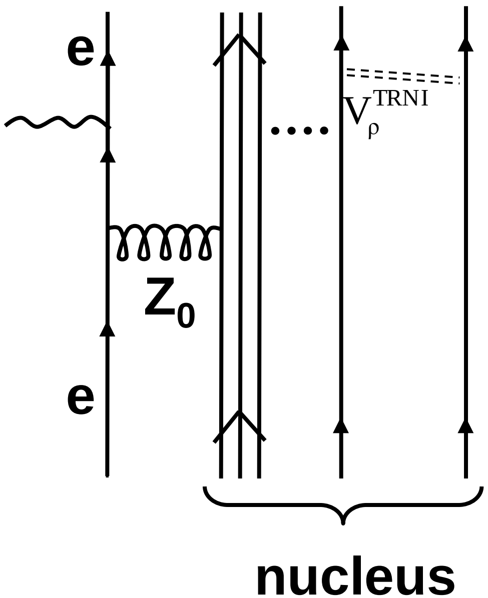
Measure total $A_{y,xz}$ in $\vec{p}$ - $\vec{d}$ scattering

The Principle of the Time Reversal Invariance test at COSY (TRIC)

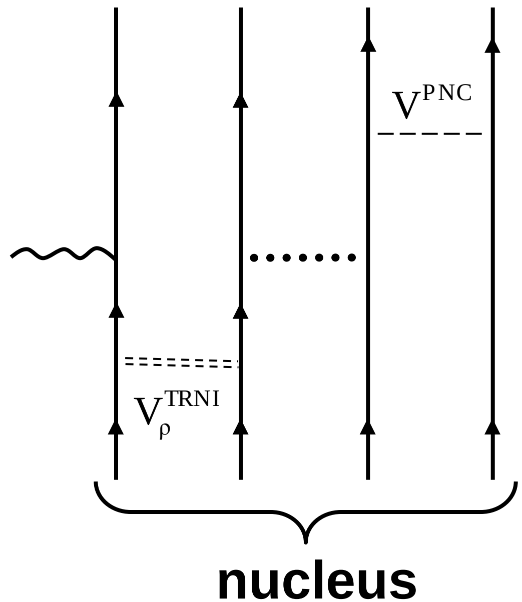


Defining the Goal

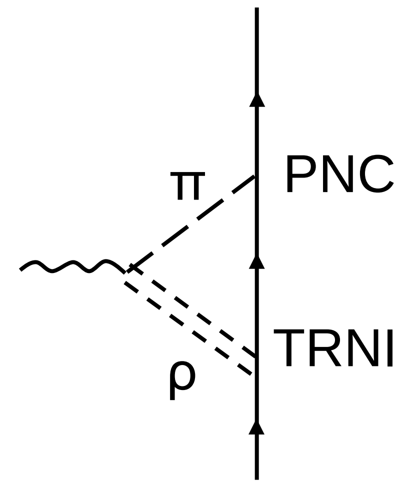
The atomic EDM



The nuclear EDM



The nucleon EDM



W.C.Haxton. Antje Höring and M.J. Musolf, Phys.Rev. ***D50*** *(1994) 3422*

EDM of an elementary particle :

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

P-odd/T-odd experiment

Upper limit from n-EDM

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

W.C.Haxton. Antje Höring and M.J. Musolf, Phys.Rev. ***D50*** *(1994) 3422*

Experiment: $\vec{n} + {}^{165}\vec{H}o$ From $A_5 = 8.6 \;\; 7.7 \cdot 10^{-6}$ gives: $\bar{g}_{\rho\cancel{T}} : 2.3 \pm 2.1 \cdot 10^{-2}$

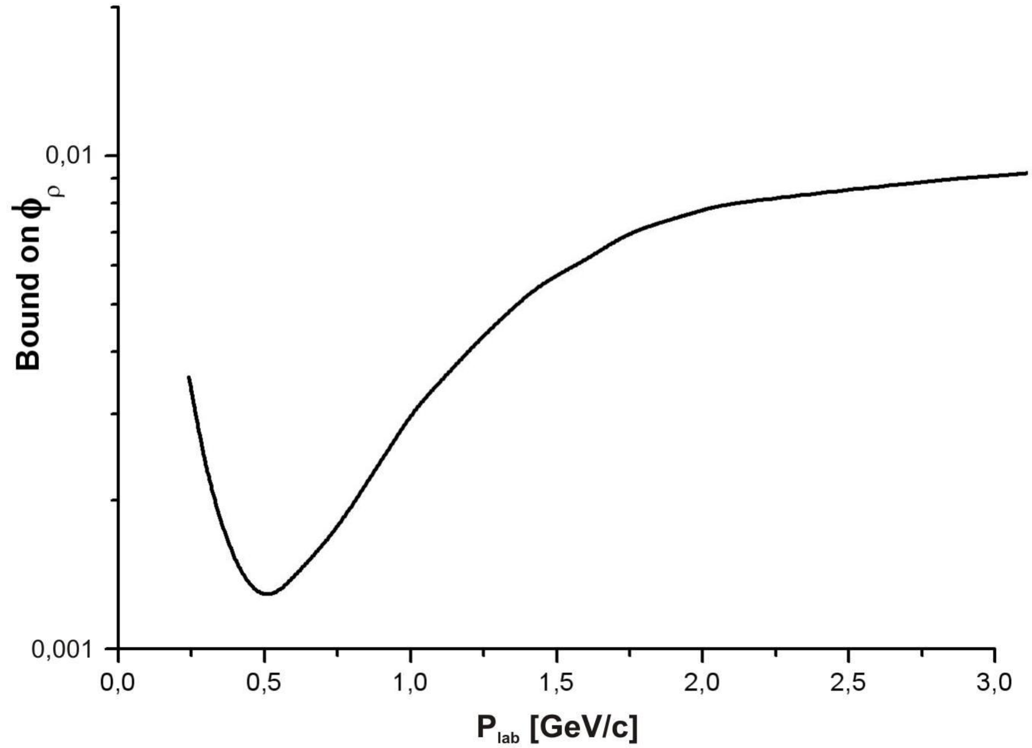
P.R. Huffmann et al., Phys.Rev. ***C55*** *(1997) 2684*

A P-even Time-Reversal Invariance Test at COSY

Defining the Goal

Theoretical bound on TRV by ρ exchange

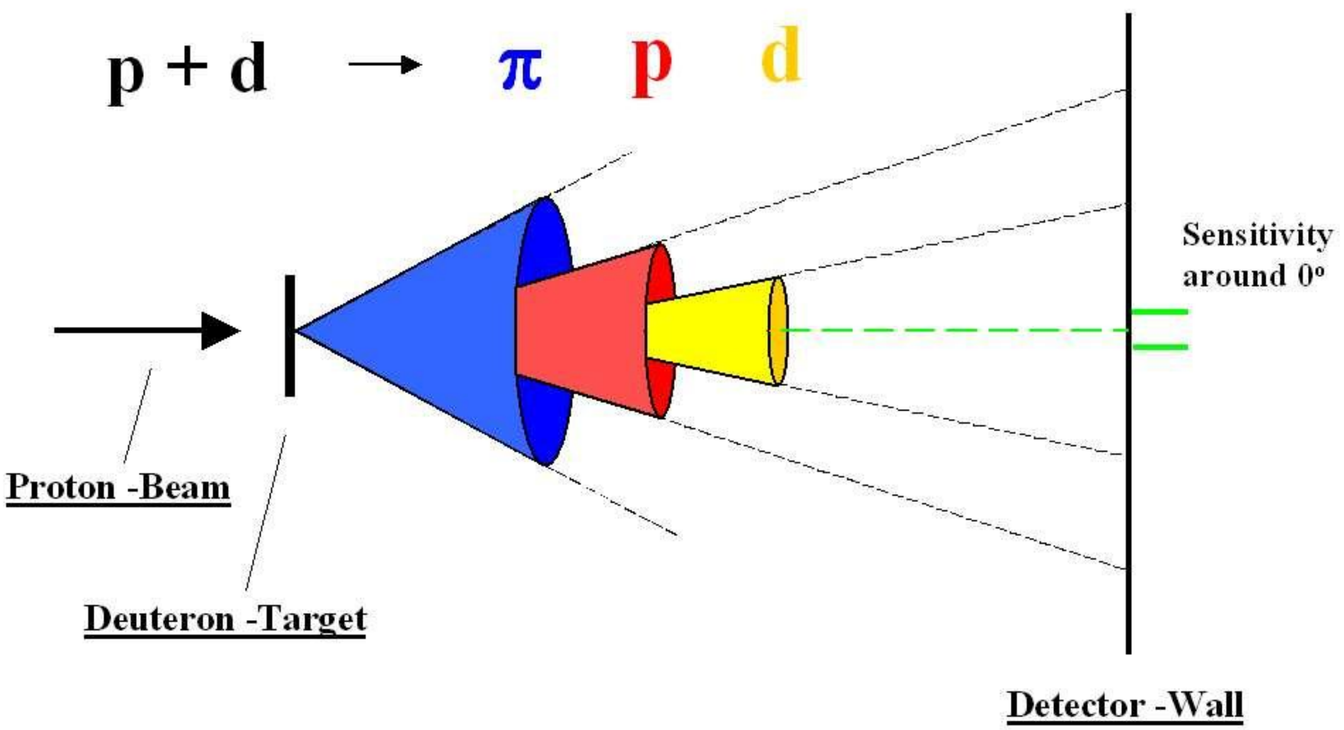
M. Beyer, Nucl. Phys. ***A560*** *(1993) 895*



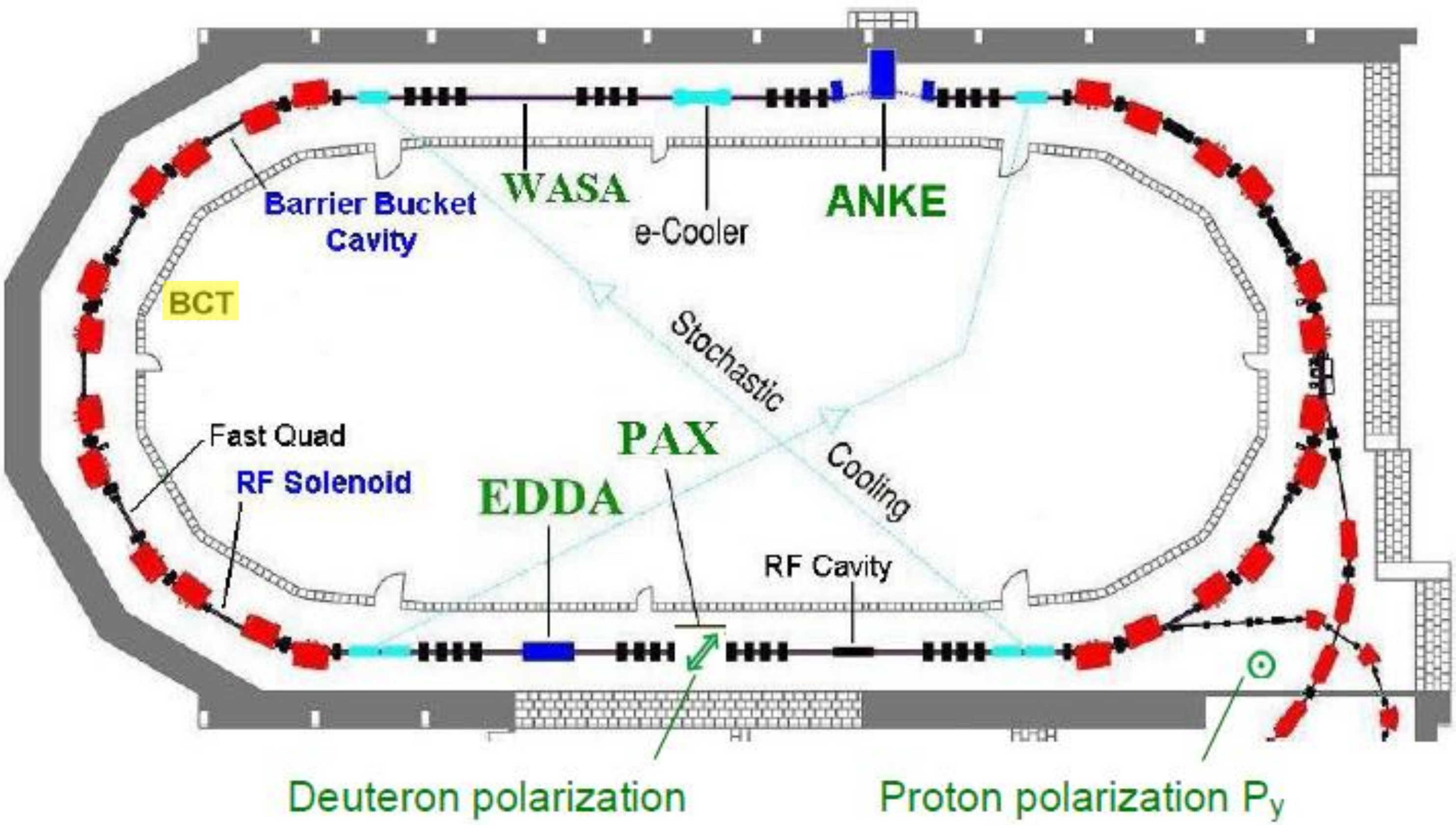
The Experimental Setup

External Fixed Target

Scattering-Cones and Detector-Sensitivity



A P-even Time-Reversal Invariance Test at COSY
The Experimental Setup



A P-even Time-Reversal Invariance Test at COSY
The Principle Idea of the Experimental Setup

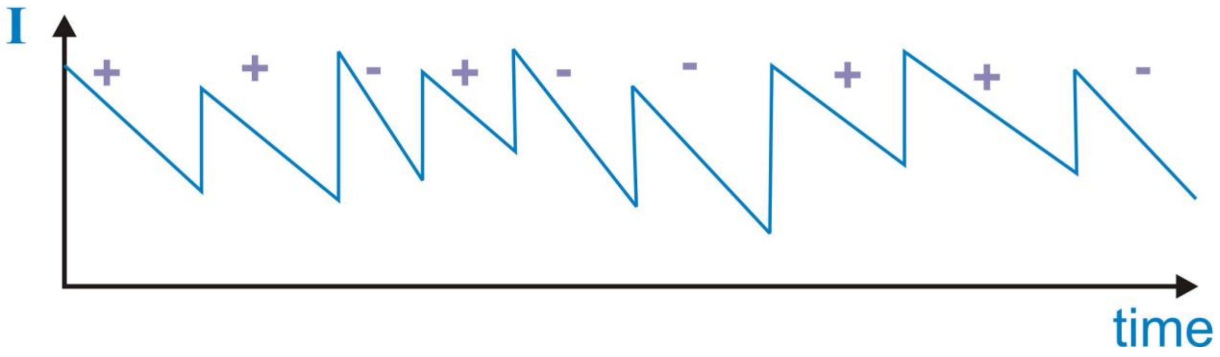
TRIC

The total pol. correlation $\mathbf{A}_{y,\,xz}$ is measured via the forward scatt. amplitude $\mathcal{F}(0)$

$$\sigma_{tot} = \frac{4\pi}{k}\, Im\, F(0) \quad \longrightarrow \quad \frac{4\pi}{k}\, Im\, tr(\,\rho\ \mathcal{F}(0)\,)$$

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

$\mathbf{A}_{y,\,xz}$ 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.



Final State Interaction

TRIC

Concerning FSI :

Reading the Optical Theorem carefully: $\frac{4\pi}{k} \operatorname{Im} F^{el}(0°) = \sigma_{tot}^{el} + \sigma_{tot}^{inel}$

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,*

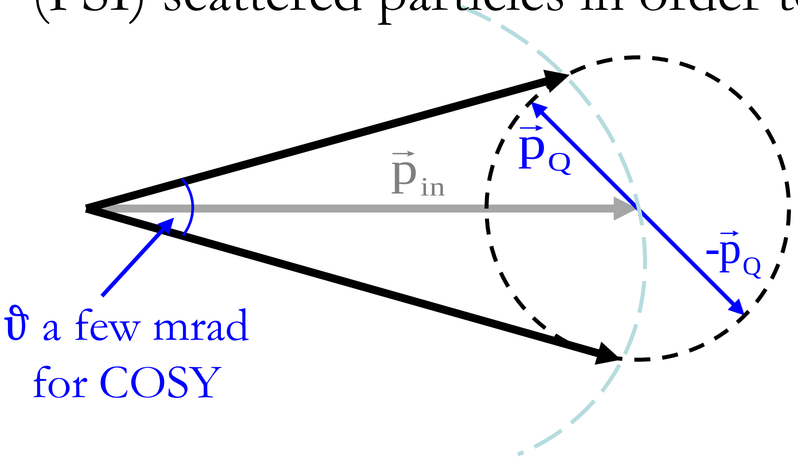
arXiv:1110.1279vl [nucl-th] 6Oct 2011

Unitarity ⟶ Optical Theorem ⟶ $F_i(0°) = F_f(0°)$ ⟶ Unitarity

Final State Interaction

$$\frac{4\pi}{k}\,\mathrm{Im}\,F^{el}(0°) = \sigma_{tot}^{el} + \sigma_{tot}^{inel}$$

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 ϑ must not exceed a few mrad

The phase space is considered to be virtually Zero

Most Basic Error Analysis

TRIC

Involved Spins: ½ + 1 → ½ + 1

$I_{0,0}$	$A_{0,X}$	$A_{0,Y}$	$A_{0,Z}$
$A_{X,0}$	$A_{X,X}$	$A_{X,Y}$	$A_{X,Z}$
$A_{Y,0}$	$A_{Y,X}$	$A_{Y,Y}$	$A_{Y,Z}$
$A_{Z,0}$	$A_{Z,X}$	$A_{Z,Y}$	$A_{Z,Z}$

$A_{0,XX}$	$A_{0,YY}$	$A_{0,ZZ}$	$A_{0,XY}$	$A_{0,YZ}$	$A_{0,XZ}$
$A_{X,XX}$	$A_{X,YY}$	$A_{X,ZZ}$	$A_{X,XY}$	$A_{X,YZ}$	$A_{X,XZ}$
$A_{Y,XX}$	$A_{Y,YY}$	$A_{Y,ZZ}$	$A_{Y,XY}$	$A_{Y,YZ}$	$A_{Y,XZ}$
$A_{Z,XX}$	$A_{Z,YY}$	$A_{Z,ZZ}$	$A_{Z,XY}$	$A_{Z,YZ}$	$A_{Z,XZ}$

Line cancels because of : Protonspinflip
p_x, p_z negligible for protons

Quantity cancels because of : ~~R~~, ~~P~~

A P-even Time-Reversal Invariance Test at COSY

Some Experimental Details

TRIC

- 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 $(\sigma_{tot} \cdot \varrho d \cdot n)$ with respect to the proton-deuteron spin-alignment

$$\boxed{\Delta T_{y,xz} = -\sigma_o \, \varrho d \, n \, P_y \, P_{xz} \, A_{y,xz} =: - S \, A_{y,xz}}$$

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

n - Number of turns the beam takes through the target

Some Experimental Details

$$\delta A_{y,xz}^{meas} = \frac{8 \cdot 10^{-6}}{I_0\, \sigma_0\, \rho d\, \nu\, P_y\, P_{xz}} \frac{\sqrt{\Delta t}}{h\sqrt{H}} \delta I$$

with: I_0	is the initial circulating proton current in COSY at the start of a slope measurement [A]
σ_0	is the total unpolarized cross-section [cm^2]
ρd	is the areal target density [atoms/cm^2]
ν	is the revolving frequency of the COSY beam [Hz]
P_y and P_{xz}	are the polarizations of beam and target, respectively
Δt	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]
δI	is the error of the current measurement in the interval Δt [A]

Some Experimental Details

TRIC

When are these accuracies equal ? $\delta A_{y,xz}^{meas} = \delta A_{y,xz}^{shot}$

$$h_{min} = \frac{1.1 \cdot 10^{19}}{\nu^{3/2} \cdot \sqrt{\sigma_0 \, \rho d \, N_0}} \cdot \frac{1}{P_y P_{xz}} \cdot \delta I$$

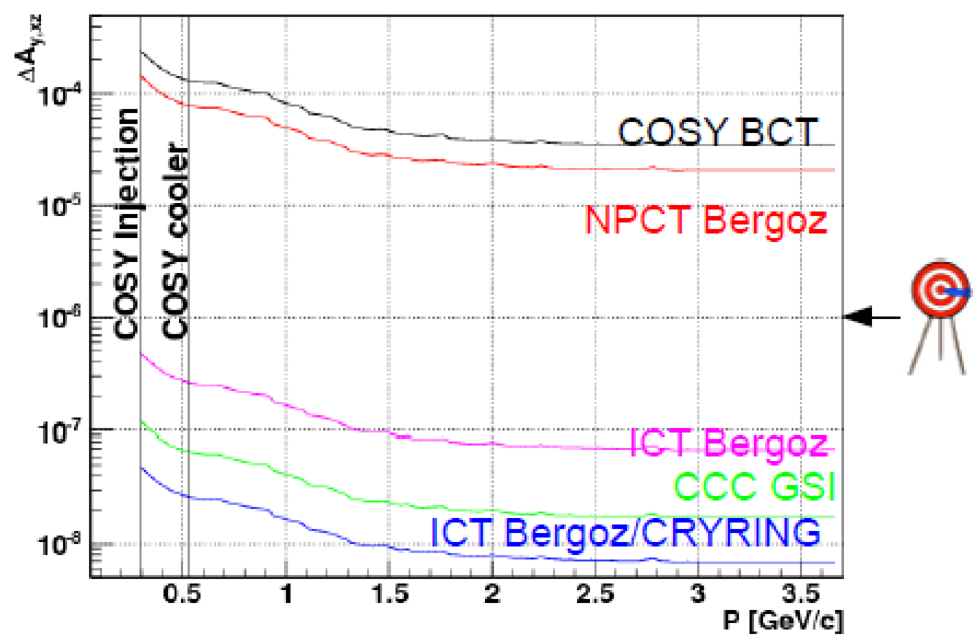
Given:	H	- 720 h (30 days)
	h	- 1/6 h
	σ_0	- 80 mb
	ϱd	- $8 \cdot 10^{13}$ atoms/cm^2 (PAX target with openable cell)
	ν	- $8 \cdot 10^5$ Hz (@ 135 MeV)
	N_0	- $3 \cdot 10^9$ protons
	P_y, P_{xz}	- 0.8
	Δt	- 1 s

Beam time estimation

Five options for σ_I :

1) COSY BCT σ_I=0.5μA/√Hz
2) NPCT Bergoz σ_I=0.3μA/√Hz
3) CCC GSI σ_I=0.25nA/√Hz
4) ICT Bergoz σ_I=1nA/√Hz
5) ICT Bergoz σ_I=0.1nA/√Hz

Precission after 30 days of beam-time



Summary

- The TRIC experiment at COSY constitutes a T-odd, P-even True TRI Null-Test
- The TRIC experiment has the ability to probe the lower bound of a T-odd, P-even test of TRI as derived from n-EDM
- For the TRIC experiment COSY serves as accelerator, ideal foreward spectrometer and detector

“Go right to the frontiers of science and you will learn soon what is missing”

Georg Christoph Lichtenberg (1742-1799)

Thank You