Outline

- Defining the Goal.
- What is the Proper Energy to Measure at ?
- Recalling the Tools.
- The Experimental Setup
- 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

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.

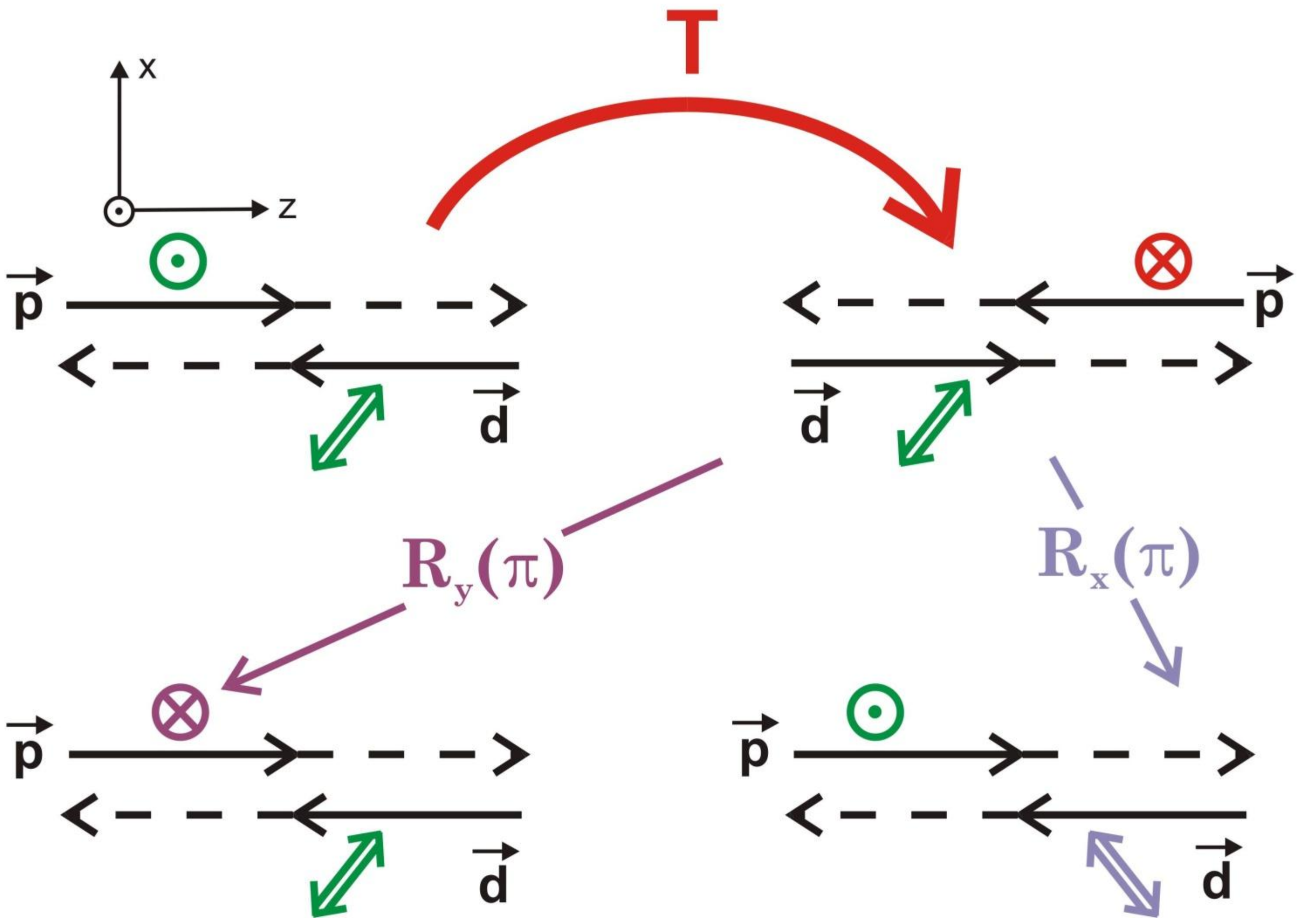
H.E. Conzett, „7th Int. Conf. on „Pol. Phen. Nucl. Phys.", Paris (1990) 2D

Measure forward scattering amplitude and thus total cross sections via the optical theorem

cf. talk by V. Gudkov

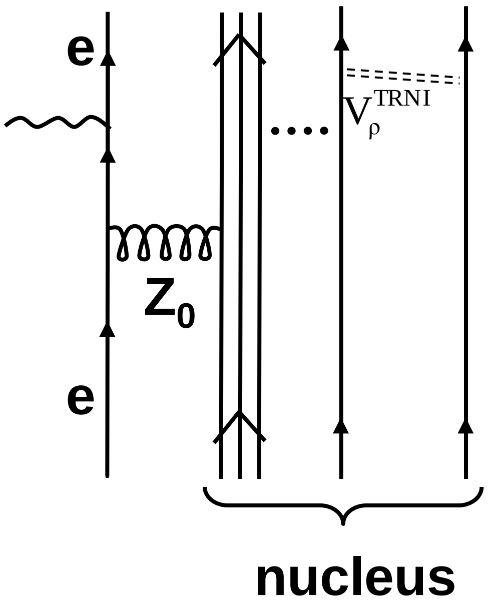
Measure total $A_{y,xz}$ in $\vec{p}$ - $\vec{\vec{d}}$ scattering

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

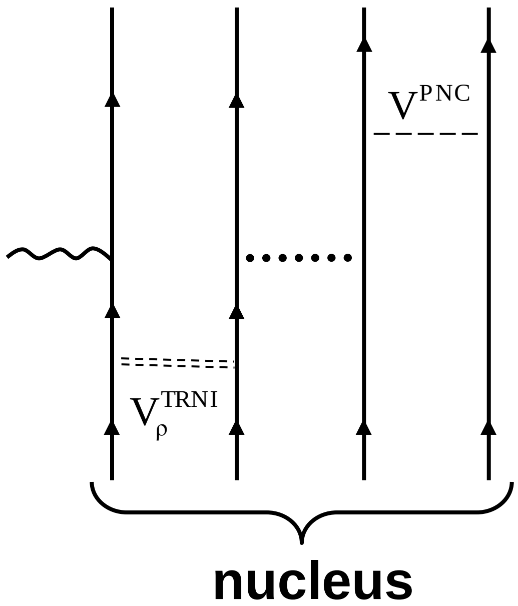


A P-even Time-Reversal Invariance Test at COSY
Defining the Goal

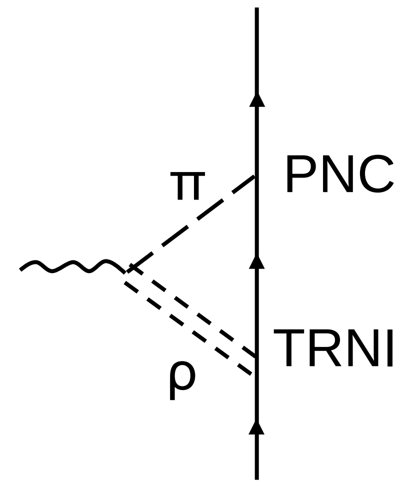
The atomic EDM



The nuclear EDM



The nucleon EDM



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

TRIC

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** : $\bar{g}_{\rho \not{T}} < 1.5 \cdot 10^{-3}$

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

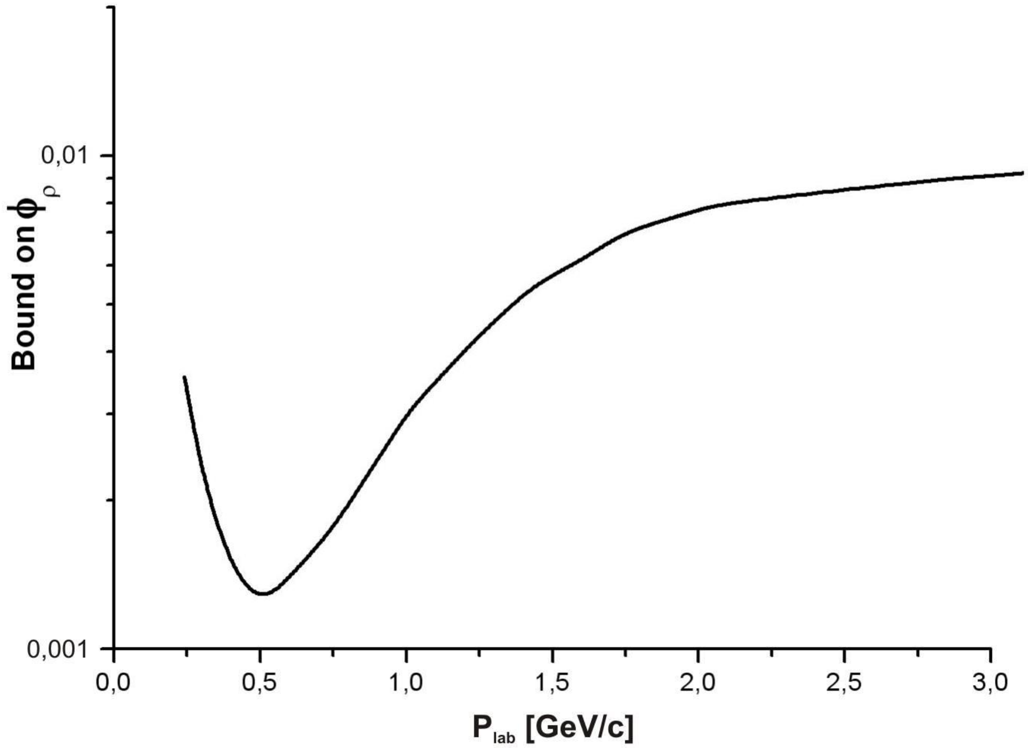
Experiment: From $A_5 = 8.6 \;\; 7.7 \cdot 10^{-6}$ gives: $\bar{g}_{\rho \not{T}} : 2.3 \pm 2.1 \cdot 10^{-2}$

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

A P-even Time-Reversal Invariance Test at COSY
What is the Proper Energy to Measure at ?

Theoretical bound on TRV by ρ exchange

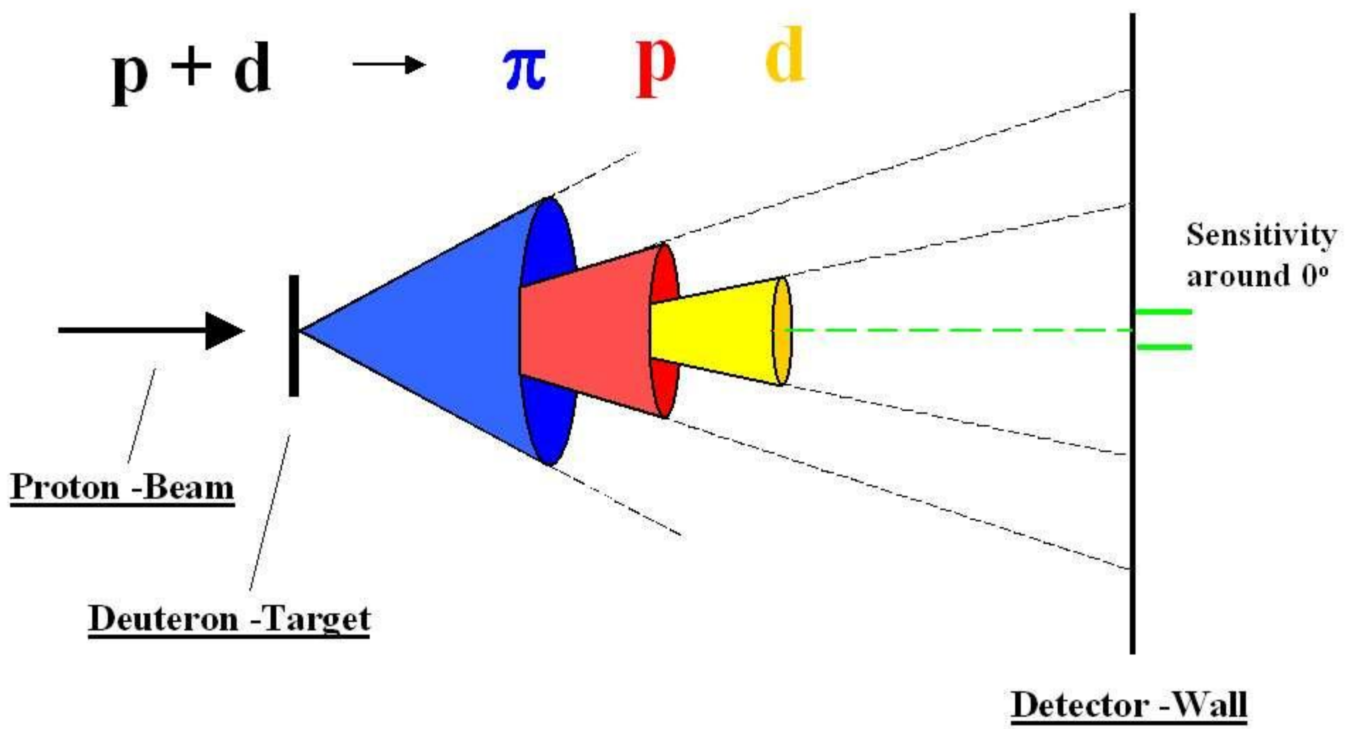
M. Beyer, Nucl. Phys. ***A560*** *(1993) 895*



Recalling the Tools

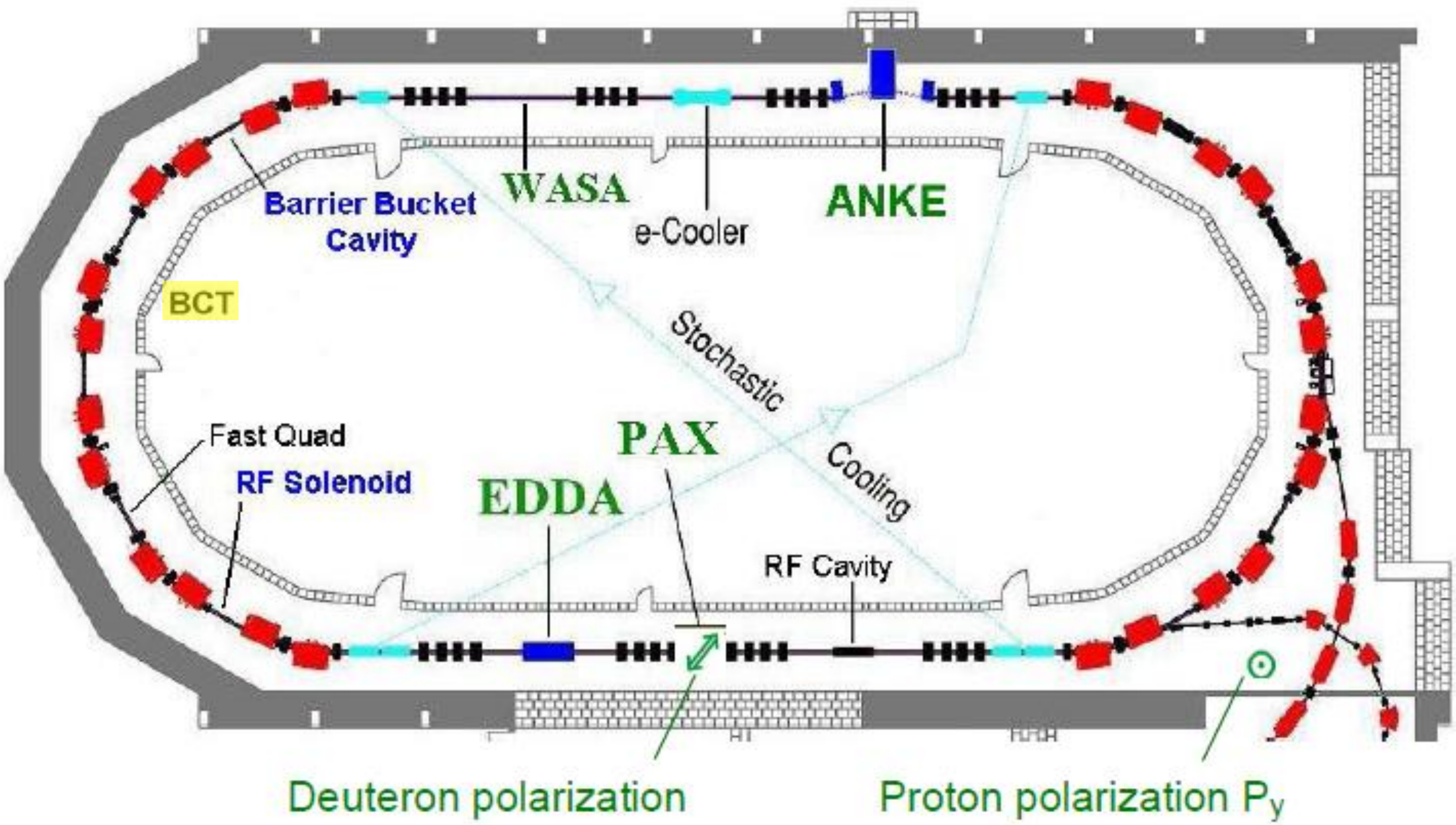
External Fixed Target

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

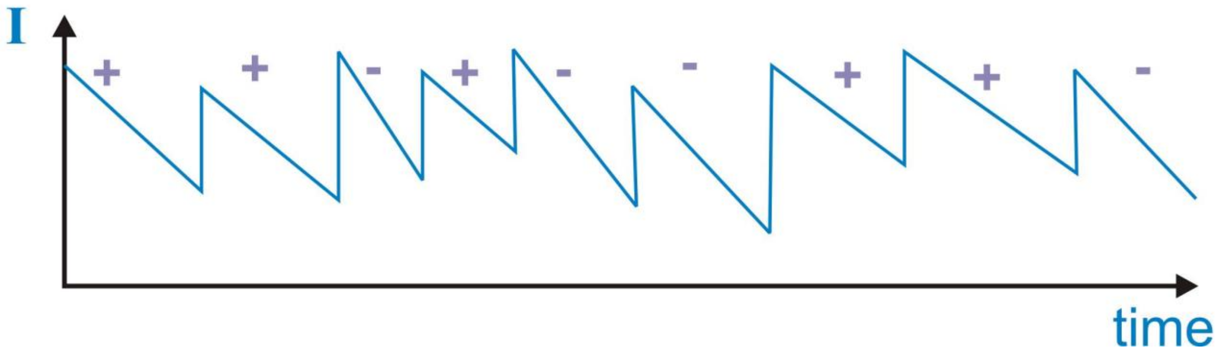
TRIC

The total pol. correlation $A_{y,\,xz}$ 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

$A_{y,\,xz}$ 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.



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~~

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

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

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

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

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, gives with $\nu = 8 \cdot 10^5$ Hz
	P_y, P_{xz}	- 0.8
	Δt	- 1 s

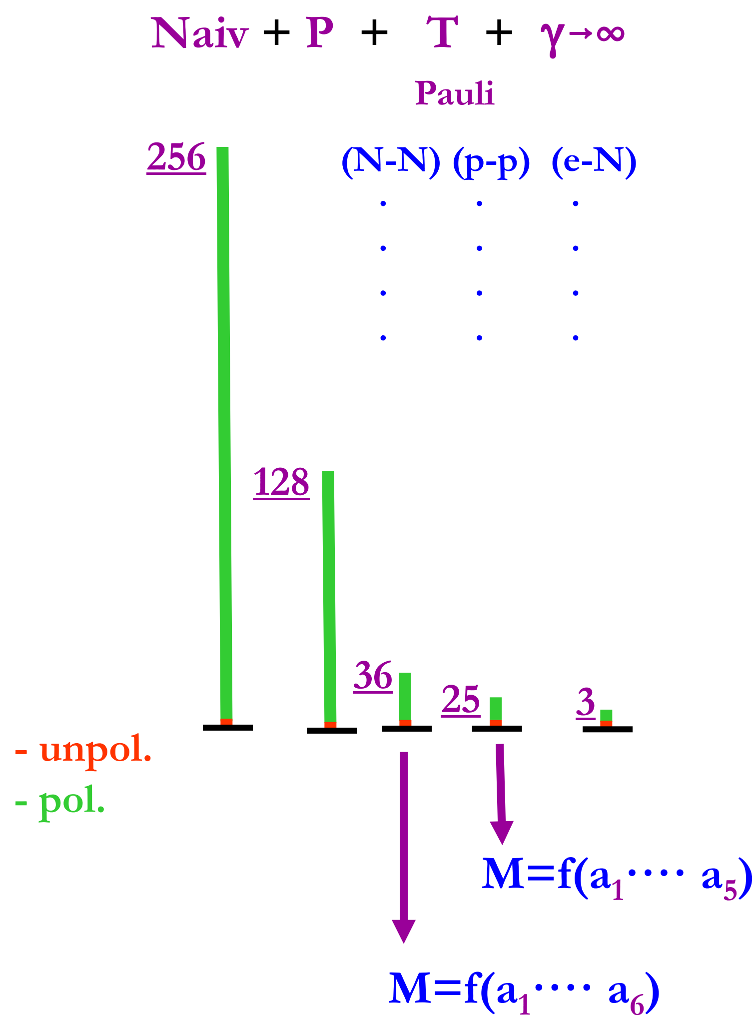
Summary

- 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

TRIC

Thank You

Number of Spin½ + Spin½ Observables



Example:

$$\sigma_0 = \sum_i a_i a_i^*$$

$$\sigma_{pol} = \sum_{i,j} \pm a_i a_j^*$$

Recalling the Tools

TRIC

25 Observables for Identical Particles (Spin 1/2 + Spin 1/2)

$$\sigma \equiv I_{0000} = \sigma C_{nnnn} = \frac{1}{2}\{|a|^2 + |b|^2 + |c|^2 + |d|^2 + |e|^2\}$$

$$\sigma C_{nn00} = \sigma A_{00nn} = \frac{1}{2}\{|a|^2 - |b|^2 - |c|^2 + |d|^2 + |e|^2\}$$

$$\sigma D_{n0n0} = \sigma D_{0n0n} = \frac{1}{2}\{|a|^2 + |b|^2 - |c|^2 - |d|^2 + |e|^2\}$$

$$\sigma K_{0nn0} = \sigma K_{n00n} = \frac{1}{2}\{|a|^2 - |b|^2 + |c|^2 - |d|^2 + |e|^2\}$$

$$\sigma C_{llll} = \sigma C_{mmmm} = \frac{1}{2}\{|a|^2 + |b|^2 + |c|^2 + |d|^2 - |e|^2\}$$

$$\sigma P \equiv \sigma P_{n000} = \sigma P_{0n00} = \sigma A_{00n0} = \sigma A_{000n} = \sigma C_{nnn0} = \sigma C_{nn0n} = \sigma M_{n0nn} = \sigma N_{0nnn} = \mathrm{Re}\, a^* e$$

$$\sigma C_{lllm} = \sigma C_{llml} = -\sigma C_{lmll} = -\sigma C_{mlll} = \sigma C_{lmmm} = \sigma C_{mlmm} = -\sigma C_{mmlm} = -\sigma C_{mmml} = \mathrm{Im}\, a^* e$$

$$\sigma C_{lnl0} = \sigma C_{mnm0} = \sigma C_{nl0l} = \sigma C_{nm0m} = \sigma M_{l0ln} = \sigma M_{m0mn} = \sigma N_{0lnl} = \sigma N_{0mnm} = \mathrm{Re}\, b^* e$$

$$\sigma D_{l0n0} = \sigma D_{0l0m} = -\sigma D_{m0l0} = -\sigma D_{0m0l} = \sigma C_{nlnm} = \sigma C_{lnmn} = -\sigma C_{mnln} = -\sigma C_{nmnl} = \mathrm{Im}\, b^* e$$

$$\sigma C_{nll0} = \sigma C_{nmm0} = \sigma C_{ln0l} = \sigma C_{mn0m} = \sigma M_{l0nl} = \sigma M_{m0nm} = \sigma N_{0lln} = \sigma N_{0mmn} = \mathrm{Re}\, c^* e$$

$$\sigma K_{0lm0} = \sigma K_{l00m} = -\sigma K_{m00l} = -\sigma K_{0ml0} = \sigma C_{nlmn} = \sigma C_{lnnm} = -\sigma C_{mnnl} = -\sigma C_{nmln} = \mathrm{Im}\, c^* e$$

$$\sigma C_{lln0} = -\sigma C_{mmn0} = \sigma C_{ll0n} = -\sigma C_{mm0n} = \sigma M_{n0ll} = -\sigma M_{n0mm} = \sigma N_{0nll} = -\sigma N_{0nmm} = -\mathrm{Re}\, d^* e$$

$$\sigma C_{lm00} = \sigma C_{ml00} = -\sigma A_{00lm} = -\sigma A_{00ml} = -\sigma C_{nnml} = -\sigma C_{nnlm} = \sigma C_{mlnn} = \sigma C_{lmnn} = \mathrm{Im}\, d^* e$$

$$\sigma D_{m0m0} = \sigma D_{0m0m} = \sigma C_{nlnl} = \sigma C_{lnln} = \mathrm{Re}\,(a^* b + c^* d)$$

$$\sigma C_{mnl0} = \sigma C_{nm0l} = -\sigma M_{l0mn} = -\sigma N_{0lnm} = \mathrm{Im}\,(a^* b + c^* d)$$

$$\sigma D_{l0l0} = \sigma D_{0l0l} = \sigma C_{nmnm} = \sigma C_{mnmn} = \mathrm{Re}\,(a^* b - c^* d)$$

$$\sigma C_{lnm0} = \sigma C_{nl0m} = -\sigma M_{m0ln} = -\sigma N_{0mnl} = -\mathrm{Im}\,(a^* b - c^* d)$$

$$\sigma K_{0mm0} = \sigma K_{m00m} = \sigma C_{nlln} = \sigma C_{lnnl} = \mathrm{Re}\,(a^* c + b^* d)$$

$$\sigma C_{nml0} = \sigma C_{mn0l} = -\sigma M_{l0nm} = -\sigma N_{0lmn} = \mathrm{Im}\,(a^* c + b^* d)$$

$$\sigma K_{0ll0} = \sigma K_{l00l} = \sigma C_{mnnm} = \sigma C_{nmmn} = \mathrm{Re}\,(a^* c - b^* d)$$

$$\sigma C_{nlm0} = \sigma C_{ln0m} = -\sigma M_{m0nl} = -\sigma N_{0mln} = -\mathrm{Im}\,(a^* c - b^* d)$$

$$\sigma C_{mm00} = \sigma A_{00mm} = -\sigma C_{nnll} = -\sigma C_{llnn} = \mathrm{Re}\,(a^* d + b^* c)$$

$$\sigma C_{lmn0} = \sigma C_{ml0n} = -\sigma M_{n0lm} = -\sigma N_{0nml} = -\mathrm{Im}\,(a^* d + b^* c)$$

$$\sigma C_{ll00} = \sigma A_{00ll} = -\sigma C_{mmnn} = -\sigma C_{nnmm} = -\mathrm{Re}\,(a^* d - b^* c)$$

$$\sigma C_{mln0} = \sigma C_{lm0n} = -\sigma M_{n0ml} = -\sigma N_{0nlm} = -\mathrm{Im}\,(a^* d - b^* c)$$

$$C_{lmlm} = C_{mlml} = -1 + D_{n0n0} + C_{llll}$$

$$C_{llmm} = C_{mmll} = 1 - A_{00nn} - C_{llll}$$

$$C_{lmml} = C_{mllm} = -1 + K_{0nn0} + C_{llll}\,.$$

Bistricky et al, J. de Phys. 39

High accuracy is achieved by:

- Extracting the quantity of interest from ratios, rather from absolute measurements.
  - All polarization observables are calculated from relative differences.
  - Polarization observables allow for correlations in the time domain (reduces drift effects, systematics)
- Performing Null-Experiments (reduces systematics by orders of magnitude).

TRI and Parity Tests

γ – γ	correlation in ^{57}Fe	$\bar{\alpha}_{\not T} \leq 5\cdot 10^{-6}$	
Detailed Bal.	in p + ^{27}Al ↔ ^{4}He + ^{24}Mg	$\bar{\alpha}_{\not T} \leq 10^{-3}$	
P – A	in $\vec{p}$ - p scattering	$\bar{g}_{\not T} \leq 3\cdot 10^{-2}$	
Neutron EDM		$\bar{g}_{\not T \not P} \leq 10^{-11}$	$\bar{g}_{\rho \not T} \leq 1.5\cdot 10^{-3}$
Atomic EDM	in ^{199}Hg		$\bar{g}_{\rho \not T} \leq 1\cdot 10^{-2}$
CSB	ΔA for $\vec{n}$ - p and $\vec{p}$ - n scatt.		$\bar{g}_{\rho \not T} \leq 6.7\cdot 10^{-3}$
$\vec{n}$ - transm.	through $^{165}\vec{\mathrm{Ho}}$	$\bar{g}_{\not T} \leq 2.8\cdot 10^{-4}$	$\bar{g}_{\rho \not T} \leq 2.3\cdot 10^{-2}$

Null-tests

A_L in $\vec{p}$ - p scattering (δA ~ 2·10^{-8})

$A_{y,xz}$ in $\vec{p}$ - $\vec{d}$ scattering (potentially **0.1** · $\bar{g}_{\rho \not T}$ of $^{165}\vec{\mathrm{Ho}}$

$\bar{\alpha}_{\not T}$ Strength of eff. T-violating N-core potential

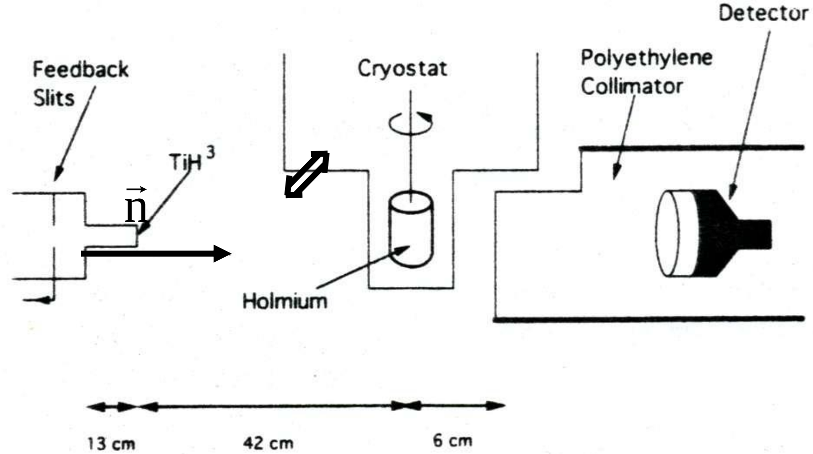
$\bar{g}_{\not T / \not T \not P}$ Strength of T-violating / TP-violating NN potential

$\bar{g}_{\rho \not T}$ Strength of T-violating ρ-MN coupling constant

5.9 MeV Neutron Transmission Experiment through ^{165}Ho

Observable (A_5): $\vec{p}\cdot(\vec{\sigma}_1\times\vec{\sigma}_2)(\vec{p}\cdot\vec{\sigma}_2)$

Result : $g_{\rho T}$: $\lesssim 2{,}3 \cdot 10^{-2}$



J.E.Koster et al., Phys. Rev. C ***49*** *(1994) 710*

- 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 Spin1-Spin½ system, i.e. $\vec{p}$ - $\vec{d}$ scattering at COSY (as an internal experiment)

A P-even Time-Reversal Invariance Test at COSY

First Test of a Novel Measuring Method for Total Cross-Sections

TRIC

Ay,y
in p-p scattering

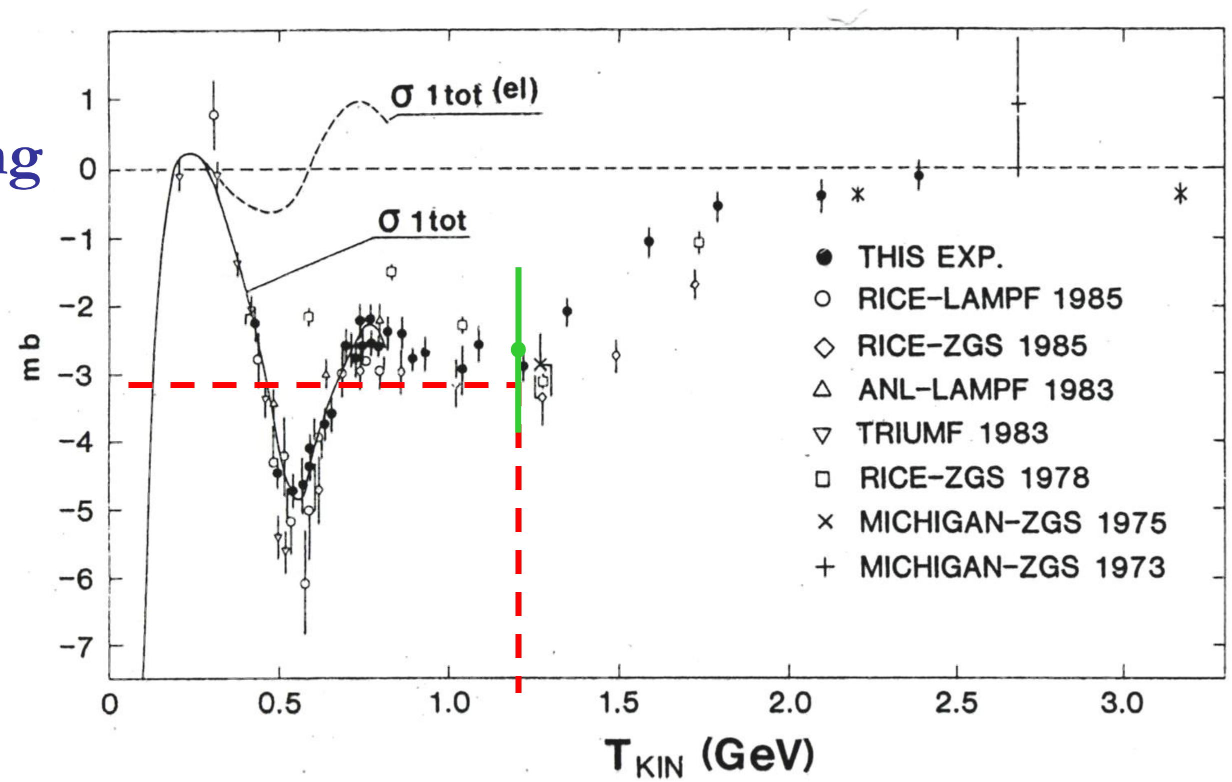
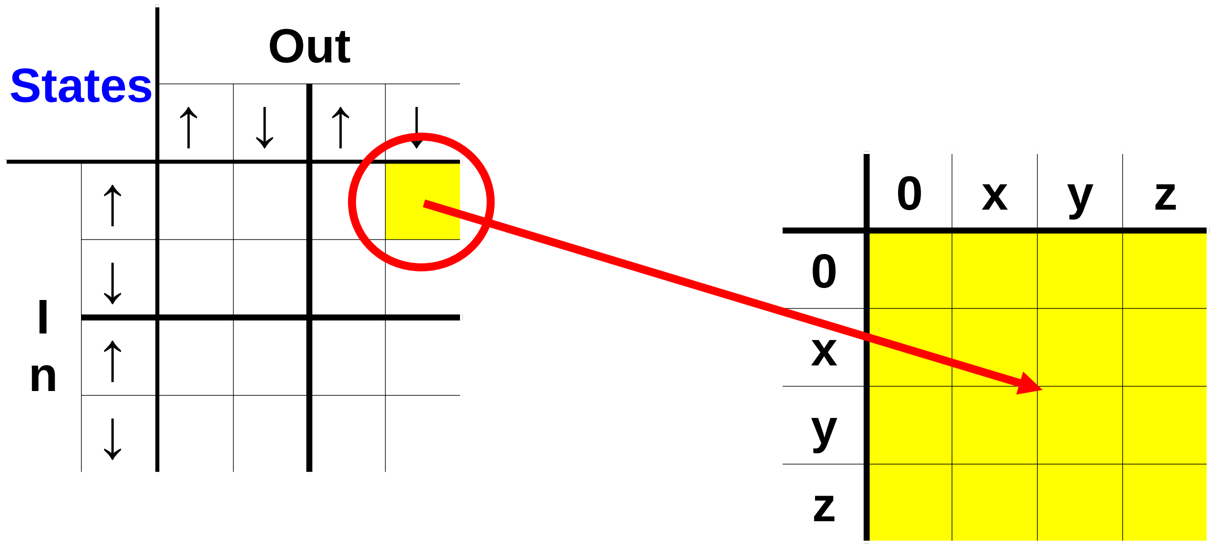


Fig. 6. Existing results of $\sigma_{1\text{tot}} = -\frac{1}{2}\Delta\sigma_T$. The full line is the fit of the Saclay-Geneva PSA [17] where our data below 0.8 GeV were included. The dashed line is the energy dependence of the elastic part of $\sigma_{1\text{tot}}$.

F. Perrot et al., Nucl. Phys. B ***278*** *(1986) 881*

Number of Spin½ + Spin½ Observables

TRIC



Partitioning of #256 (4-indexed Observables: $A_{\text{Beam, Target, Ejectile, Recoil}}$)

$$\sum_{n=0}^{4}\binom{4}{n}\cdot 3^{n} = 1\cdot 1+4\cdot 3+6\cdot 9+4\cdot 27+1\cdot 81 = 1+12+54+108+81 = 256$$

- 4 indexed observable
- 3 indexed observable
- 2 indexed observable
- 1 indexed observable
- unpolarized cross-section

A P-even Time-Reversal Invariance Test at COSY