COSY Proposal / Letter of Intent / Beam Request

For Lab. use

Exp. No.:	Session No.
215	40

Title of Experiment:

Test of Time-Reversal Invariance in Proton-Deuteron Scattering at COSY

Collaborators: see cover page

Spokespersons: P.D. Eversheim, B. Lorentz and Yu. Valdau

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Is support from the LSF program of the EC requested?
Yes

Date: 02.04.2012

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Total number of particles and type of beam (p,d,polarization)	Momentum range (MeV/c)	Intensity or internal reaction rate (particles per second)	
		minimum needed	maximum useful
Polarized protons	521	$>2\cdot10^9$ protons polarization >70%	-
Type of target	Safety aspects (if any)	Earliest date of installation	Total beam time (weeks)
Hydrogen and Deuterium polarised atomic gas target with storage cell	-	June 2012	2 weeks

What equipment, floorspace etc. is expected from Forschungszentrum Jülich/IKP?

Summary of experiment:

We propose to perform a novel (P-even, T-odd) null test of time-reversal invariance to an experimental accuracy of 10^{-6}. The parity conserving time-reversal violating observable is the total cross-section asymmetry $A_{y,xz}$. The measurement is planned as an internal target transmission experiment at the cooler synchrotron COSY. $A_{y,xz}$ is measured using a polarized proton beam with an energy of 135 MeV and a tensor polarized deuteron target.

To test time invariance symmetry to the precision of 10^{-6} in total **12 weeks of beam time** is needed. Since the experiment has to be staged, with the current request we ask for the **two weeks** of beam time **by the end of 2012** for studies of the bunched beam life time.

Test of Time-Reversal Invariance in Proton-Deuteron Scattering at COSY

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Abstract

We propose to perform a novel (P-even, T-odd) null test of time-reversal invariance to an experimental accuracy of 10^{-6}. The parity conserving time-reversal violating observable is the total cross-section asymmetry $A_{y,xz}$. The measurement is planned as an internal target transmission experiment at the cooler synchrotron COSY. $A_{y,xz}$ is measured using a polarized proton beam with an energy of 135 MeV and a tensor polarized deuteron target. Since the experiment has to be staged, with the current request we ask for the **two weeks** of beam time by the end of 2012 for studies of bunched beam life time.

Introduction

Everything that we can observe around us is build out of matter. Thus, there is no symmetry between matter and antimatter in the Universe, although it is predicted by the Theory of Big Bang. Antimatter can be produced, using standard techniques in particle accelerators, but in negligible amounts compared to matter. The Standard Model (SM), although very successful in many respects, can not explain the difference between matter and antimatter in the Universe, and in particular between the number of baryons and antibaryons (Baryon Asymmetry of the Universe). The CP violation, which is linked to T violation via the CPT theorem, is generally accepted as a plausible explanation for the baryon asymmetry in the universe.

Up to now, the CP violation has been discovered in the Kaon- [1] and B-system [2], while T violation only in the K^0 system [3]. All these effects can well be accommodated within the SM by a complex phase of the Kobayashi-Maskawa-matrix [4] or the θ-term [5] allowed by QCD (may be except recently discovered in LHCb difference in decay properties of D mesons [6]). There are of course also other explanations for the CP violation which go beyond the standard model, like for instance the extension of the Higgs sector [7], the superweak interaction [8], or the left-right symmetric models [9]. However, up to now CP or T violation was only discovered in meson systems. Therefore it is utmost important to search for such effects in the baryon system. Moreover, the observed amount of antimatter in the Universe can not be explained by found CP/T violating reactions. Therefore, there have to be more sources for the CP/T violation.

The search for the electric-dipole moment (EDM) of nuclei and of the elementary neutron [10] has a long standing history, but up to now no signal for the T violation in any baryonic system has been observed. In this experiment we intend to probe the time-reversal invariance (TRI) with parity being conserved in contrast to experiments which test parity and time reversal invariance simultaneously (cf. EDM).

Usually P-even TRI tests compare two observables (cf. tests of detailed balance or P-A tests). Since in these experiments two observables have to be compared, the experimental accuracy [11] was limited to 10^{-3} – 10^{-2}. The accuracy can be increased by orders of magnitude if a true null experiment is performed i.e. a non-vanishing value of one single observable proves that the symmetry involved is violated. An example of this kind of experiment is the measurement of the parity violating quantity A_z in $\vec{p}-p$ scattering [12], which has been measured to some 10^{-8} (cf. Table 1). In this context the term “true” stresses the concept that the intended test has to be completely independent from dynamical assumptions. Therefore, the interpretation of the result is neither restricted nor subject to: Final state interactions, special tensorial interactions or, Hamiltonians of a certain form. True null tests are based only on the structure of the scattering matrix as determined by general conservation laws [13].

It has been proven in Ref. [13] that there exists no true null test of TRI in a nuclear reaction with two particles in and two particles out, except for forward scattering[1]. Based on this exception, Conzett [14] could show that a transmission experiment can be performed, which constitutes a true TRI null test. He suggested to measure the total cross-section asymmetry $A_{y,xz}$ of vector polarized Spin ½ particles interacting with tensor polarized Spin 1 particles.

We intend to study this observable $A_{y,xz}$ in the proton-deuteron system with the proton polarization P_y along the y direction and the deuteron tensor polarization P_{xz} aligned along the x-z direction. The proton-deuteron system has the advantage of being a particularly simple system allowing still a direct analysis in terms of time-reversal violating (TRV) nucleon-nucleon potentials based e.g. on one meson exchange. In addition, the proton-deuteron system offers the opportunity to test simultaneously the p–p and the p–n interaction. According to a theorem of Simonius [15], the n-p system is favoured over the p-p system as a TRI testing ground in view of the symmetry restrictions on possible TRV meson exchange processes. In principle, both systems can be tested with the intended experiment.

Table 1. Comparison of accuracies of TRI and parity-violation tests. The g_T and $g_{\rho T}$ are the strengths of T_{odd} N-N and ρM-N potential respectively, α_T is the strength of an effective T_{odd} N-core potential

Measurement	Remarks	Violated	Ref
Electric Dipole Moment of neutron	$g_{PT}<10^{-11}$ $g_{\rho T}<1.5\cdot 10^{-3}$	PT	[16]
Γ-γ correlations in ^{57}Fe	$\alpha_T<5\cdot 10^{-6}$	T	[17]
P-A in p-p scattering	$g_T<3\cdot 10^{-2}$	T	[18]
Detailed balance in $p+{}^{27}Al \leftrightarrow {}^{4}He+{}^{24}Mg$	$\alpha_T\sim 10^{-3}$	T	[19]
$\vec{n}$ transmission through ^{165}Ho	$g_{\rho T}<2.3\cdot 10^{-2}$ $\alpha_T<2.8\cdot 10^{-4}$	T	[20]
CSB ΔA for $\vec{n}-p$ and $\vec{p}-n$ scattering	$g_{\rho T}<6.7\cdot 10^{-3}$	T	[21]
A_z in $\vec{p}-p$ scattering	Error $\delta A_z\sim 2\cdot 10^{-8}$	P	[12]
$A_{y,xz}$ in $\vec{p}-\vec{d}$ scattering	Aim on $\delta A_{y,xz}\sim 10^{-6}$	T	This work

[1] The total cross-section can be calculated via the optical theorem. In contrast to usual cross-sections, which are calculated from bilinear products of scattering amplitudes, the total cross-section depends via the optical theorem only linearly on the forward scattering amplitude.

The most precise experiment measuring $A_{y,xz}$ at present is the neutron transmission through ^{165}Ho [20]. Since the tensor polarization in ^{165}Ho is generated by one valence nucleon only, the effect is diluted by the other 164 nucleons. This dilution can be avoided if the experiment is restricted to a most simple Spin ½ - Spin 1 system, i.e. $\vec{p}-\vec{d}$ scattering at COSY (as an internal transmission experiment).

The TRI test can be performed at any beam energy; but since the TRV processes are of short-range nature - the relatively long range contributions for these processes may be parameterized by a ρ vector meson or a f_1 axial-vector meson exchange [22]. The experiment is intended to be performed at 135 MeV (~521 MeV/c), since at this energy the sensitivity with respect to a possible TRV force is considered maximal. In addition, this low energy has the advantage that only (at most) one depolarizing resonance has to be considered and the experiment can be carried out with a permanently electron cooled beam. This fact, the substantially increased beam intensity and target density, the installed low-β section at the PAX-target location and the possibility to measure an eventually bunched beam intensity with improved accuracy compared to the situation with a coasting beam in the past, constitute the essential differences to the first TRIC-proposal (proposal #22).

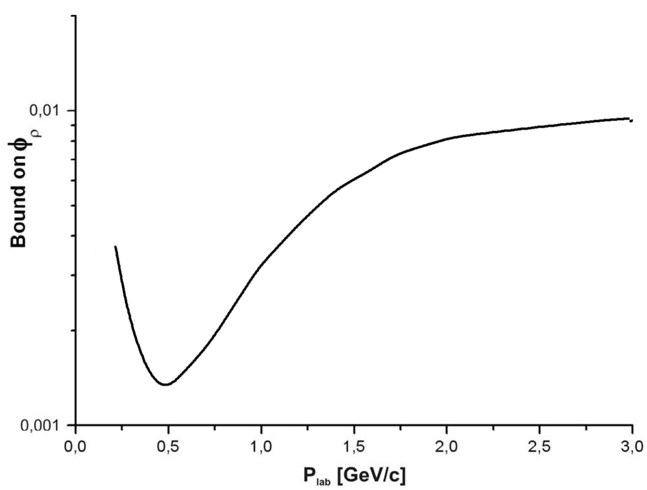

Fig. 1. The achievable upper bound of the dominating T-odd strength parameter Φ_ρ, is given as the ratio of the parity conserving T-odd over the T-even ρM-N coupling constants, mediated by the ρ-meson (derived from Fig. 2 in [22]). For this plot it is assumed that the error of the observable $\delta A_{y,xz}=10^{-6}$.

We plan to study the TRV quantity $A_{y,xz}$ in a transmission experiment using the internal PAX deuteron target with an openable cell in the cooler synchrotron COSY. The transmission losses of the circulating polarized proton beam are measured with high precision as a function of the vector- and tensor-polarization P_y and P_{xz}, respectively. Thus, in this experiment the COSY facility will not only be used as an accelerator, but also as an ideal forward spectrometer and detector.

The Quantity of Interest

In this chapter it is argued why in a $p-d$ scattering experiment the observable that is sensitive to TRV is the total cross-section asymmetry $A_{y,xz}$. The time-mirrored situation can be created experimentally either by reversing the vector polarization P_y of the proton beam, or by changing the alignment of the tensor polarization of the deuteron. As a consequence, depending on the polarizations any TRV results in different transmissions through the internal tensor polarized deuteron target. The different transmissions cause different slopes of the decreasing proton beam as it passes turn after turn through the target. This current decrease can be measured to the very high precision. It is shown i) that the slopes do not depend on any losses (σ_{Loss}) in the ring as long as these losses do not depend on P_y, and ii) that the sensitivity by which $A_{y,xz}$ can be measured increases with the number n of turns the proton beam takes through the target.

A total cross-section experiment involving polarized particles is described by the generalized optical theorem [22]:

$$\sigma_{tot} = 4\pi/k \, \mathrm{Im}(\mathrm{Tr}(\rho)\cdot F(0)) \qquad (1)$$

with:

σ_{tot}	Total cross-section
k	Wave number
Δ	Density Matrix
$F(\theta)$	Scattering amplitude matrix for scattering at angle θ

The density matrix ρ reflects the experimental set-up, whereas the scattering matrix F(0) of the forward scattering amplitudes contains the physics, which is to be tested. In the following it is shown which observable conserves parity but violates time-reversal and that the time reversed situation is tested by flipping the spin.

The discussion of parity conserving (P-even) TRV (T-odd) observable follows the arguments of Ohlsen [23]. It is discussed in the projectile helicity frame i.e.:

$$\vec{e}_z = \vec{e}_{kin}$$
$$\vec{e}_y = \vec{e}_{kin} \times \vec{e}_{kout} \qquad (2)$$
$$\vec{e}_x = \vec{e}_y \times \vec{e}_z$$

with: $\vec{e}$ is a unit vector pointing in the direction of $\vec{x}, \vec{y}, \vec{z}$ and $\vec{kin}$ and $\vec{kout}$

Since for a transmission experiment $\vec{e}_{kout}$ is parallel to $\vec{e}_{kin}$, the direction of $\vec{e}_y$ can be chosen at will. A convenient choice is to have $\vec{e}_y$ parallel to the proton polarization P_y.

In general a polarization observable describing a process of two particles having tensor polarizations of ranks *r* and *r'* is characterized by a quantity with a number n_r of indices with: $n_r = r_{in} + r'_{in} + r_{out} + r_{out}'$. Each index specifies whether the polarization is observed in x, y, z-direction or not at all (index=0).

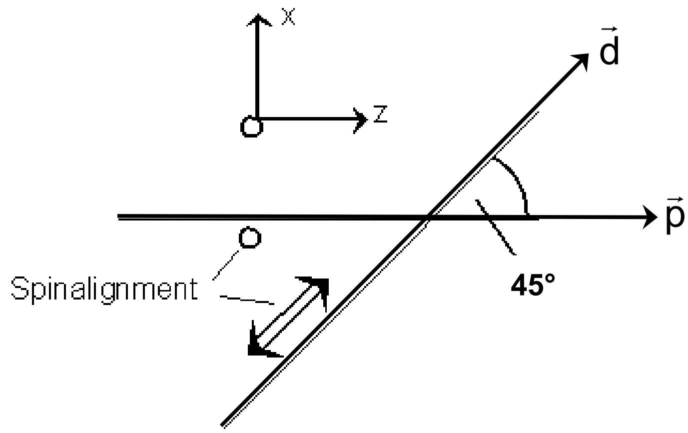

Fig. 2. Beam and target spin-alignment in the laboratory projectile helicity frame

For the intended transmission experiment only the initial states are of interest, thus: $n_r = r_{in} + r'_{in}$. Furthermore, the quantity of interest has to be invariant under the rotation about the z-axis (R_z-even). R_z invariance means to have an observable that behaves odd or even as a function of the scattering angle η. Equivalent to this condition behaves the sum of the indices n_x+n_y, which is odd or even, respectively. All "odd" quantities with this respect rule out to the degree that the acceptance angle of the detector (i.e. COSY) is small. Since COSY can be tuned to have a small acceptance angle without a significant loss in luminosity, a decisive advantage over an external (spectrometer) experiment is given.

According to Ohlsen [23], the symmetry character of a polarization amplitude with $n_r = n_x+n_y+n_z$ indices can be determined by "counting rules". n_x, n_y, and n_z are the numbers of x, y, and z indices of the observable in question.

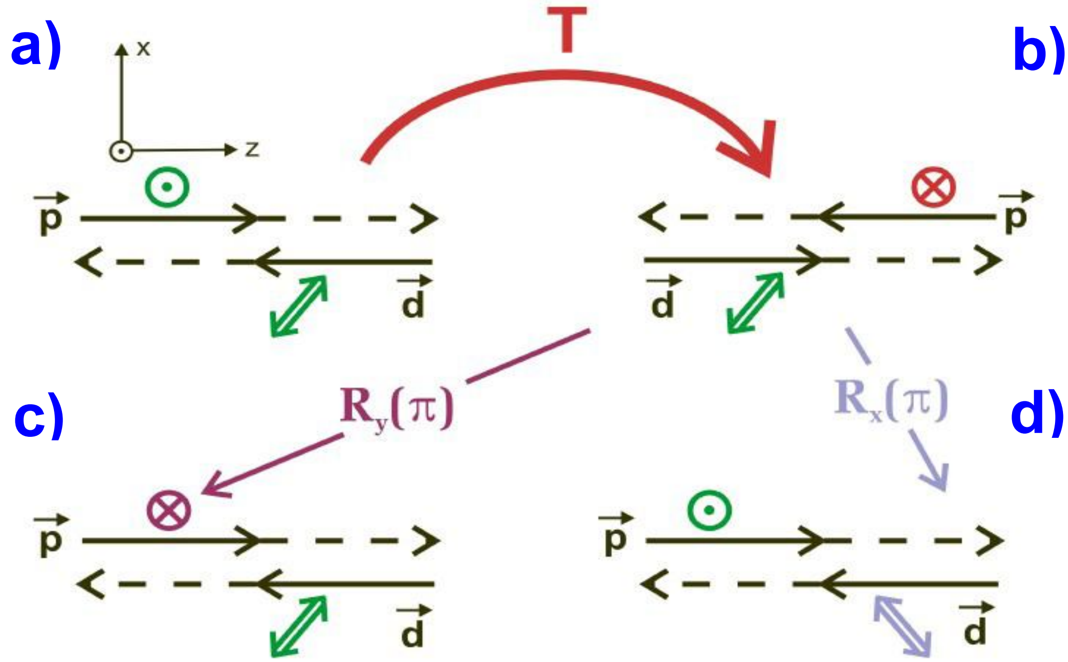

Fig. 3. Principal demonstration that a time-reversed situation is prepared by either a proton or a deuteron spin-flip. a) The basic system is shown. b) The time reversal operation is applied (momenta and spins are reversed and the particles are exchanged). In order to have a direct comparison between situation a) and b), two rotations $R_y(\pi)$ or $R_x(\pi)$ by 180° about the y- or x-axis are applied, leading to the situations c) and d), respectively. This is allowed, since the scattering process is invariant under rotations.

$\odot$	Proton spin up (y-direction)
$\otimes$	Proton spin down
<=>	Deuteron tensor polarization

In detail, the following counting rules apply for a P-even, T-odd, and R_z-even quantity:

$$
\begin{array}{llll}
\text{Time-reversal} & : n_x & \text{has to be} & \text{odd} \\
\text{Parity conservation} & : n_x+n_z & \text{has to be} & \text{even} \\
R_z \text{ invariance} & : n_x+n_y & \text{has to be} & \text{even}
\end{array} \tag{3}
$$

The minimal configuration fulfilling these conditions gives:

$$n_x = n_y = n_z = 1 \tag{4}$$

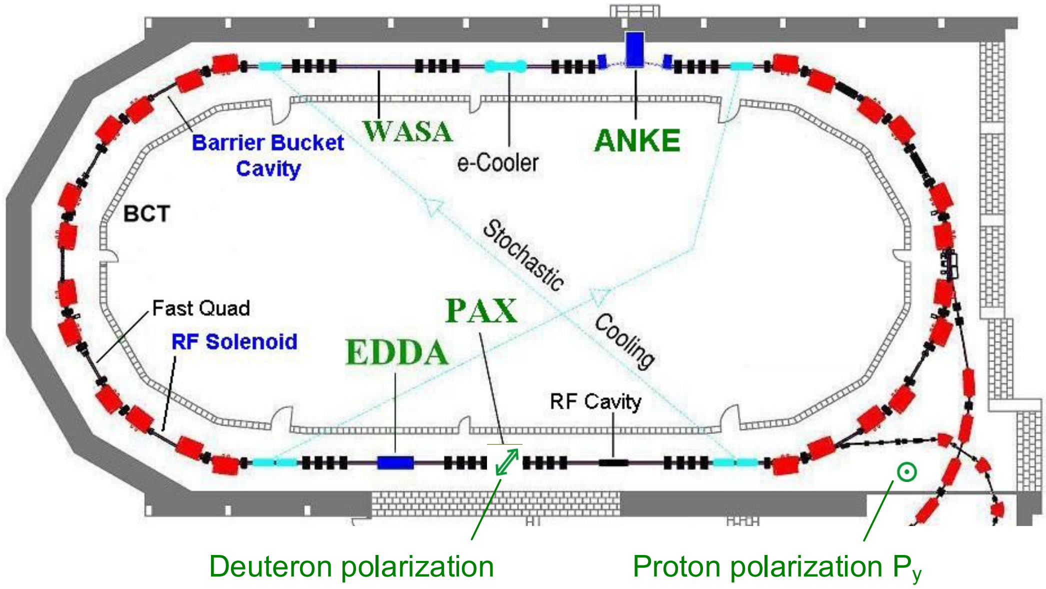

Fig. 4. The scheme at COSY.

Assuming a proton beam with normal polarization P_y, the target has to be at least a spin 1 particle, in order to be able to offer a tensor polarization P_{xz} aligned in the x-z (cf. Fig. 2) direction. Deuterons fulfil this requirement. Thus, the quantity of interest is the total cross-section asymmetry $A_{y,xz}$ for proton-deuteron scattering. $A_{y,xz}$ is measured by flipping the spins of the interacting particles. By flipping the spins in this particular system the time reversed situation is prepared too. This is shown in Fig. 3a-c by reversing all momenta and spins and exchanging the in- and out-going particles. The experimental situation is depicted in Fig. 4.

The total cross-section asymmetry $A_{y,xz}$ is measured in a transmission experiment. This process is described by the transmission factor T(n):

$$T(n) = I(n) / I(0) = \exp(-(\sigma_T \rho d\, n)) \tag{5}$$

with: $I(0)$ - Intensity of the primary beam

$I(n)$ - Intensity of the beam having passed n times the internal target with density ρ and thickness d

σ_T - Total cross-section

ρd - The areal target density

For the case of polarized particles σ_T has to be replaced by:

$$\sigma_T = \sigma_{y,xz} + \sigma_{Loss} = \sigma_o (1 + P_y\, P_{xz}\, A_{y,xz}) + \sigma_{Loss} \tag{6}$$

with: σ_o - Unpolarized total cross-section

σ_{Loss} - Loss cross-section, taking account of beam losses outside of the target

P_y - Proton vector polarization

P_{xz} - Deuteron tensor polarization

$A_{y,xz}$ - Total cross-section asymmetry

In order to measure $A_{y,xz}$ the transmission asymmetry)$T_{y,xz}$ is introduced:

$$\Delta T_{y,xz} = \frac{T^+ - T^-}{T^+ + T^-} = \frac{\exp\text{-}(\chi^+) - \exp\text{-}(\chi^-)}{\exp\text{-}(\chi^+) + \exp\text{-}(\chi^-)} \tag{7}$$

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 ($\sigma T \cdot \rho d \cdot n$) with respect to the proton-deuteron spin-alignment

this gives:

$$\Delta T_{y,xz} = -\tanh\left(\sigma_o \, \Delta d \; n \; P_y \; P_{xz} \; A_{y,xz}\right) \tag{8}$$

Is the argument of the tanh in equation (8) small, then:

$$\Delta T_{y,xz} = -\sigma_o \, \rho d \; n \; P_y \; P_{xz} \; A_{y,xz} =: -S \; A_{y,xz} \tag{9}$$

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

With the help of equation (9) the total cross-section asymmetry $A_{y,xz}$ can be determined.

Sources of Systematic Errors

Two obvious experimental effects are discussed: the loss of the beam intensity somewhere in the ring except in the target zone, and polarization observables faking a TRV.

i) The effect of beam losses in the ring cancels in equation (7), since it is not related to the proton- or deuteron-polarization (no effects are known). The dominating Coulomb scattering does not depend on the polarization; nuclear scattering is negligible due to the excellent vacuum quality.

ii) All possible polarization observables in proton-deuteron scattering for this type of experiment are listed in Table 2.

If $A_{y,xz}$ is calculated from changing the proton polarization each time the ring is filled, all observables of Table 2 in line 1 and 5 cancel. Since only the proton polarization P_y is an eigenvector in the ring, all observables with respect to the proton polarization P_x and

P_z cancel too (the average of P_x and P_z should be $< 10^{-8}$ in a 30 days run). This is true for lines 2, 4, 6, and 8 in Table 2.

Table 2. Polarization observables of the total cross-section in $\vec{p}-\vec{d}$ scattering. The first index refers to the proton polarization, the second and third index refers to the deuteron vector- and tensor-polarization. All quantities with a hat cancel, since they are R_z-odd (n_x+n_y has to be even). All quantities which are doubly underlined are P_z-odd (n_x+n_z has to be even)

Line	Observable						Line cancels because of:
1	$I_{o,o}$	$\underline{\underline{\hat{A}_{o,x}}}$	$A_{o,y}$	$\underline{\underline{\hat{A}_{o,z}}}$			protonspinflip
2	$\underline{\underline{\hat{A}_{x,o}}}$	$A_{x,x}$	$\underline{\underline{A_{x,y}}}$	$\hat{A}_{x,z}$			P_x negligible for protons
3	$\hat{A}_{y,o}$	$\underline{\underline{A_{y,x}}}$	$A_{y,y}$	$\underline{\underline{\hat{A}_{y,z}}}$			
4	$\underline{\underline{A_{z,o}}}$	$\hat{A}_{z,x}$	$\underline{\underline{\hat{A}_{z,y}}}$	$A_{z,z}$			P_z negligible for protons
5	$A_{o,xx}$	$A_{o,yy}$	$A_{o,zz}$	$\underline{\underline{A_{o,xy}}}$	$\underline{\underline{\hat{A}_{o,yz}}}$	$\hat{A}_{o,xz}$	protonspinflip
6	$\underline{\underline{\hat{A}_{x,xx}}}$	$\underline{\underline{\hat{A}_{x,yy}}}$	$\underline{\underline{\hat{A}_{x,zz}}}$	$\hat{A}_{x,xy}$	$A_{x,yz}$	$\underline{\underline{A_{x,xz}}}$	P_x negligible for protons
7	$\hat{A}_{y,xx}$	$\hat{A}_{y,yy}$	$\hat{A}_{y,zz}$	$\underline{\underline{\hat{A}_{y,xy}}}$	$\underline{\underline{A_{y,yz}}}$	$A_{y,xz}$	
8	$\underline{\underline{A_{z,xx}}}$	$\underline{\underline{A_{z,yy}}}$	$\underline{\underline{A_{z,zz}}}$	$A_{z,xy}$	$\hat{A}_{z,yz}$	$\underline{\underline{\hat{A}_{z,xz}}}$	P_z negligible for protons

In the remaining lines 3 and 7 of Table 2 all quantities with a hat cancel, because they are not R_z-even (n_x+n_y has to be even). $A_{y,x}$ and $A_{y,yz}$ violate parity conservation (n_x+n_z is odd for these quantities). Therefore, since $\vec{p}-\vec{d}$ scattering is an elementary process, these quantities are expected to be of the order of 10^{-7}, even if parity is violated. Thus, besides our quantity of interest $A_{y,xz}$, only $A_{y,y}$ "survives". Since $A_{y,y}$ in $\vec{p}-\vec{d}$ scattering is not known at 135 MeV it has to be determined in a dedicated measurement.

The effect of $A_{y,y}$ in $\vec{p}-\vec{d}$ scattering is small, because i) there must be a deuteron vector polarization in the first place, and ii) there must be a misalignment between the COSY beam direction and the deuteron beam, so that a deuteron vector polarization is able to generate a P_y deuteron vector polarization. The deuteron vector polarization can be adjusted to be zero in the atomic beam source, if this polarization is measured in the dump of the atomic beam source.

Assuming the deuteron vector polarization can be limited to 0.01, and the deuteron source and the proton beam can be aligned to better than 0.1°, then a false deuteron vector polarization $P_y < 2 \cdot 10^{-5}$. If $A_{y,y}$ in $\vec{p}-\vec{d}$ scattering is < 0.05 the error contribution is $< 10^{-6}$.

The Accuracy of the Experiment

The principle the experimental accuracy is limited by the precision of the beam current measurement system installed at COSY and the accumulated statistics. The expected statistics can be estimated on the basis of our knowledge about the intensity of the polarized proton beam at COSY and the pd total cross-section. An on-line current monitor [24] of high precision is needed for this experiment. The accuracy and especially the low frequency noise of the current monitor are crucial for the final error in $A_{y,xz}$ [25]. As pointed out above, only the slopes as a function of the set polarizations of beam and target enter the calculation of the error $\delta A_{y,xz}$ (cf. Fig. 5).

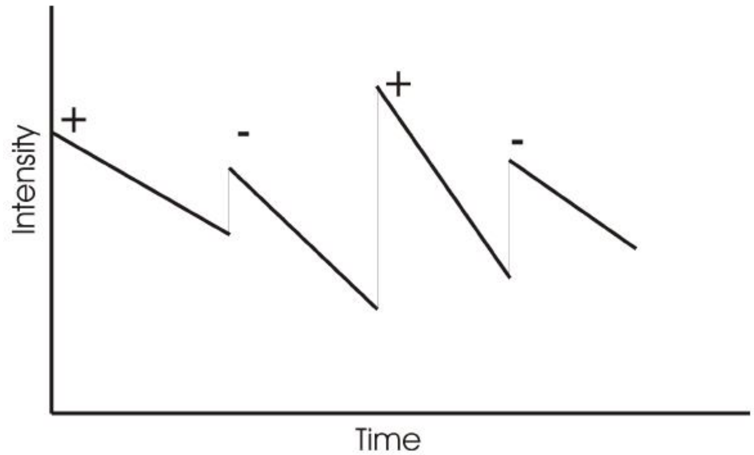

Fig. 5. $A_{y,xz}$ is calculated from the slopes for different polarizations of beam and target. It is not depending on the actual number of injected protons.

By D.Samuel [25] the error $\delta A_{y,xz}$ was calculated for handy units (Appendix C, equation (8)).

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

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 t [A]

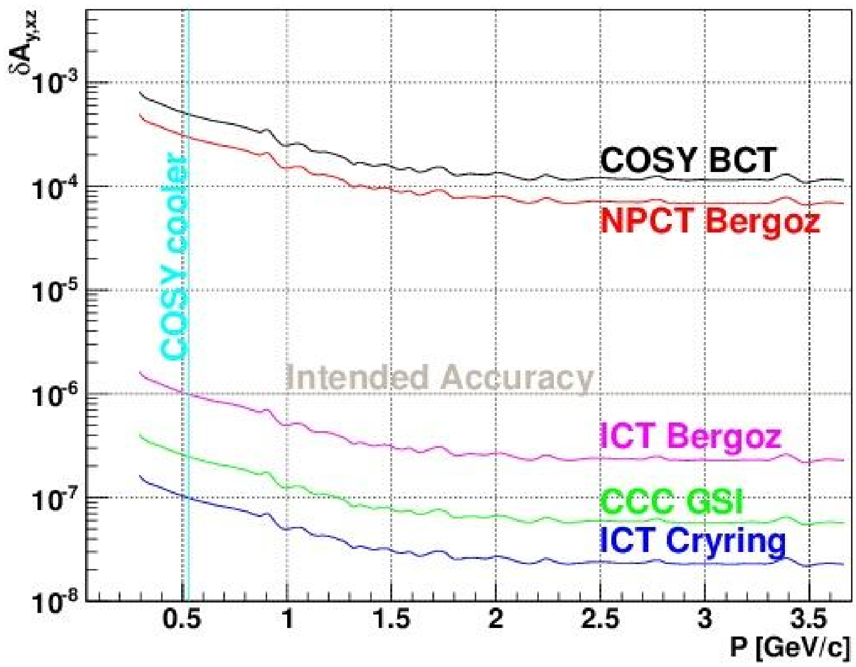

Fig. 6. Different current measuring devices with different errors δI result in different errors $\delta A_{y,xz}$ for a 30 days run.

Beam Current Transformer (BCT) at COSY	$\delta I =$	$0.5\mu A/\sqrt{Hz}$
New Parametric Current Transformer (NPCT)	$\delta I =$	$0.3\mu A/\sqrt{Hz}$
Integrating Current Transformers (ICT) from Bergoz	$\delta I =$	$1 nA/\sqrt{Hz}$
Cryogenic Current Comparator at GSI (CCC GSI)	$\delta I =$	$0.25nA/\sqrt{Hz}$
ICT from Bergoz at Cryring	$\delta I =$	$0.1nA/\sqrt{Hz}$

Be N_0 the number of protons at the start of a slope measurement, then the best achievable accuracy can be determined from the error due to the shot noise of the rate of the scattered particles $\dot{N}$:

$$\delta A_{y,xz}^{shot} = \frac{1}{\sqrt{\dot{N} \cdot H}} = \frac{1}{\sqrt{\sigma_0\, \rho d\, N_0 \nu \cdot H}} \tag{11}$$

From equation (10) and (11) the spin flip period h_{min} can be calculated, when the accuracy $\delta A_{y,xz}^{shot}$ equals $\delta A_{y,xz}^{meas}$:

$$h_{min} = \frac{1.1 \cdot 10^{19}}{\nu^{3/2} \cdot \sqrt{\sigma_0\, \rho d\, N_0}} \cdot \frac{1}{P_y P_{xz}} \cdot \delta I \tag{12}$$

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 - $3\cdot10^9$ protons, gives with < = $8\cdot10^5$ Hz

P_y, P_{xz} - 0.8

Δt - 1 s

Then, the achievable accuracy $\delta A_{y,xz}$ is only depending on δI, which shows Fig. 6 for different current measuring devices. For instance, the ICT Bergoz gives an h_{min} (equation 12) of ~200s.

From the simulation of Fig. 6 it becomes clear that for the intended error in $\delta A_{y,xz} < 10^{-6}$ and the assumed (realistic) target thickness and beam intensity the Beam Current Transformer (BCT) installed at COSY [24] and the New Parametric Current Transformer (NPCT) from Bergoz [26] are not sufficiently accurate. Only the Integrating Current Transformer (ICT) [28], which needs a bunched beam, or the Cryogenic Current Comparator (CCC) [27], which is based on SQUIDs, allow for the intended accuracy. Then, for an ICT with a $\delta I = 1\mathrm{nA}/\sqrt{\mathrm{Hz}}$ and the parameters from above equation (10) gives the error of the total cross-section asymmetry $\delta A_{y,xz} \sim 10^{-6}$.

Measurements of $A_{y,xz}$ at COSY

For the measurements of the transmission asymmetry $A_{y,xz}$ at COSY we need: a polarized proton beam of good quality at the energy of the experiment, a polarized atomic target with sufficient thickness, measure the polarization of beam and target, and measure the beam current to high precision.

Although, there is still room for improvement in polarized beam intensity, the quality of polarized proton beam (polarization ~80% and $3\cdot10^9$ protons), available now at COSY, is sufficient to perform measurements of the value of interest to the desired accuracy. Calculations for the expected accuracy, presented in the previous section, shows that the measurement of the beam intensity to the desired accuracy is only possible using an ICT, which requires the use of a bunched COSY beam. Up to now, there is not much experience accumulated at COSY concerning the preparation of a bunched beam with long life time. This is a topic for the dedicated machine development week which we would like to be approved by the PAC.

Nowadays, with the PAX installation a polarized atomic hydrogen gas target together with a storage cell are available. The low-β section conditions provided at the PAX location allows to perform experiments with target thicknesses not available at ANKE. The holding field system, available at PAX, is able to provide field strength and field direction necessary for the $A_{y,xz}$ measurements using a deuterium target. Thus, it is natural to use the PAX target for this experiment. Experiments with a polarized atomic deuterium gas target at the PAX location will only be possible after a major upgrade of the atomic beam source, which is scheduled for 2013.

An acceleration with the PAX low-β section up to the energy of this experiment (135 MeV) was also never done and is an important topic for the machine development week which should be connected to this experiment.

Measurements of target polarization and intensity at the PAX target location is done on-line using a Breit-Rabi polarimeter with sufficient accuracy. The proton beam polarization can be measured using the PAX detection system, when it is available in 2014, or at the ANKE target location using two silicon tracking telescopes (STT) and the cluster jet target. Alternatively, with the information from the Low Energy Polarimeter (LEP) in the transfer line to COSY an asymmetry can be measured with the EDDA internal polarimeter just below and above the first depolarizing resonance at 108 MeV. From these three measurements one can deduct the value of the proton beam polarization at 135 MeV.

During the first feasibility tests for TRIC [25] it became clear that this experiment is very sensitive to low frequency noise of the current measuring device due to the long spin-flip periods. The dominant noise source was identified as the Barkhausen noise in the ferrite-ring of the COSY beam current transformer. As this noise results from the random flipping of magnetic domains, a 1/f noise results. Usually the relevant corner frequencies and the 1/f dependence is not given in the manuals and is inherent to all ferrite loaded current measuring devices (BCT, NPCT, ICT and CCC). On the other hand, as equation (12) reveals, the spin flip period can be chosen shorter, the better the accuracy of the current measuring device is. Consequently, the sensitivity to the 1/f noise decreases. It is therefore very important to build and test a new beam current measurements system in the laboratory before implementing it in COSY. This is intended to be done during 2012-2013.

Provided that COSY can deliver a bunched beam with long life time, then it will be possible to reach the desired sensitivity in the current measurement using an ICT. This device is commercially available and only a precision readout and calibration scheme for this device must be developed for the TRI experiment. The sensitivity of the ICT can be further improved using techniques used at CRYRING (Sweden) [29]. In this case the noise of the $\delta A_{y,xz}$ measurement can be lowered to $0.1 \mathrm{nA}/\sqrt{\mathrm{Hz}}$.

In view of the options mentioned above, a typical measurement scenario may be

i) The e-cooler is switched on

ii) The bunched polarized proton beam is injected into the COSY ring, stacked and accelerated to 135 MeV

iii) The e-cooler is now operated at 73.5 KeV. The low-β section at the PAX target operates at 135 MeV

iv) The atomic beam source is switched on, to give pure deuteron tensor polarization P_{xz}

v) The PAX target cell is closed

vi) The loss rate is eliminated by flipping the deuteron tensor polarization and eventually the proton vector polarization P_y randomly. The slopes of the decreasing proton intensity is measured with an ICT

vii) While the proton beam is circulating, its polarization is measured by the PAX detector system or at the end of the cycle by the EDDA internal polarimeter

viii) The beam is decelerated and dumped. Until the next sequence starts, the polarimeter in the deuteron beam-dump is calibrated

Time line for the experiment

Aside from this scenario there exist time constraints for the PAX target, which in turn demands for a staged development of the TRI experiment. The PAX target will not provide polarized deuterium before 2014 after a major external rebuild in 2013. In parallel to this the PAX detector system will be developed. Therefore, we propose:

i) To use the period until end of 2012 to develop a bunched beam and to measure $A_{y,y}$ in $\vec{p}-\vec{p}$ scattering and manifest the potential of the novel measuring method for total cross-sections via internal target experiments. Simultaneously, operation of the low-β section at the PAX target station at 135 MeV should be established and the e-cooler should run at 73.5 keV. Allocation of this beam time in 2012 will allow to use the complete PAX installation, as it was used for the filtering experiment in September 2011, without additional commissioning of its systems.

ii) In 2013 the beam handling can be further improved. In parallel: a high precision beam current measurement system, using an ICT will be prepared in the laboratory, the PAX atomic beam source will be prepared to operate with polarized deuterium gas, and a new PAX multipurpose detector together with an openable storage cell will be constructed.

iii) From 2014 on, the openable storage cell and PAX detector system will be available. As the first step, the "false" observable $A_{y,y}$ in $\vec{p}-\vec{d}$ scattering at 135 MeV should be measured. Approximate beam time, needed for this experiment, is 5 weeks.

iv) The total cross-section asymmetry $A_{y,xz}$ can be studied as an internal target transmission experiment utilizing a novel method according the scenario from above. A different amount of beam time will be requested depending on the parameters of the beam current measurement system constructed for COSY. Conservative estimates for the required beam time amount to approximately 5 weeks.

v) The accuracy of the experiment can be further improved by approximately one order of magnitude using the technique developed and applied at the CRYRING [29]. This extension of the TRI experiment will require detailed studies of the sensitivity of COSY beam position monitors with respect to the beam current.

Beam request

In order to test time reversal invariance to an accuracy of 10^{-6} by the cross-section asymmetry $A_{y,xz}$ measured in $\vec{p}-\vec{d}$ scattering, in total approximately **~12 weeks** of beam time is needed. Within the next beam-time allocation period (2012-2013) we would like to perform a **2 weeks** beam time for the **bunched beam life time studies**. Due to the time constrains from the PAX target development we would like to ask for the allocation of this experiment by the end of 2012. During this experiment we would like to:

1. Prepare a permanently e-cooled beam of polarized protons at 135 MeV which is accelerated with the low-β section and storage cell in the PAX experimental place
2. Study the bunched beam life time
3. Study the bunched beam polarization life time using the EDDA polarimeter
4. Measure $A_{y,y}$ in $\vec{p}-\vec{p}$ scattering, to an accuracy of $\sim 10^{-3}$, and manifest the potential of the novel measuring method for total cross-sections via internal target experiments.

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