

Search for T-invariance Violation in the Proton-Deuteron Scattering

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- Motivation:
P-even **T**-**R**eversal **I**nvariance test planned at **COSY**
(TRIC)
- Null-test for T-odd P-even effects in pd interaction
- Sources for some false effects
- Capability of the Glauber model at ~ 100 - 200 MeV
- Total polarized pd cross sections

*Yu.N. Uzikov, J. Haidenbauer, PRC 79 (2009) 024617;
PRC 87 (2013) 054003; PRC 88 (2013) 027001*

Motivation

- CP-violation in K- and B-meson physics \implies T-violation \implies BA
- These T-odd, P-odd effects arise in SM through CP violating phase of CKM matrix and through the QCD θ - term
- Fundamental time-reversal-noninvariant parity-conserving (T-odd P-even) (flavor-conserving) interactions do not arise in SM but could be generated through weak corrections to T-odd P-odd interactions
 - ★ I.B. Khriplovich Nucl.Phys. B **352** (1991) 385: relative strength of the T-odd, P-even nuclear force does not exceed $\alpha_T \sim 2 \times 10^{-6}$
 - ★ CP violation in SM leads to simultaneous violation of CP and P-invariance. Therefore, to produce CP-odd P-even term one should have one additional P-odd term in the effective interaction: $g \sim M^4 G_F^2 \sin \delta \sim 10^{-10}$
V.P. Gudkov, Phys. Rep. **212**(1992)77
 - ★ ... much larger g is not excluded as the low energy limit of some unknown interaction beyond the SM (!?)

TVPC (T-odd P-even) interactions in terms of boson exchanges :

M.Simonius, Phys. Lett. 58B (1975) 147; PRL 78 (1997) 4161

- ★ $J \geq 1$
- ★ π, σ -exchanges do not contribute
- ★ The lowest mass meson allowed is the ρ -meson
- ★ Natural parity exchange ($P = (-1)^J$) must be charged

The TVPC Born NN-amplitude

$$\begin{aligned} \tilde{V}_{\rho}^{TVPC} &= \bar{g}_{\rho} \frac{g_{\rho} \kappa}{2M} [\vec{\tau}_1 \times \vec{\tau}_2]^z \frac{1}{m_{\rho}^2 + |\vec{q}|^2} \\ &\quad \times i[(\vec{p}_f + \vec{p}_i) \times \vec{q}] \cdot (\vec{\sigma}_1 - \vec{\sigma}_2) \end{aligned} \quad (1)$$

C-odd, only charged ρ 's. Cannot contribute to the *nn or pp*.

$$\vec{q} = \vec{p}_f - \vec{p}_i \quad \text{disappears at } \vec{q} = 0$$

Axial a_1 -meson exchange ...

The most general structure contains 18 terms *P. Herczeg, Nucl.Phys. 75 (1966) 655*

Experimental constraints (direct and indirect)

- Test of the detailed balance $^{27}\text{Al}(p, \alpha)^{24}\text{Mg}$ and $^{24}\text{Mg}(\alpha, p)^{27}\text{Al}$,
 $\Delta = (\sigma_{dir} - \sigma_{inv}) / (\sigma_{dir} + \sigma_{inv}) \leq 5.1 \times 10^{-3}$ (E.Blanke et al. PRL **51** (1983) 355) is not simply related to the NN T-odd P-even interaction
Numerous statistical analyses including nuclear energy-level fluctuations (J.B. French et al. PRL **54** (1985) 2313)

$$\alpha_T < 2 \times 10^{-3}$$

- \vec{n} transmission through ^{165}Ho (P.R. Huffman et al. PRC **55** (1997) 2684)

$$\alpha_T \leq 7.1 \times 10^{-4} \quad (\text{or } \bar{g}_\rho \leq 5.9 \times 10^{-2})$$

- Elastic $\vec{p}n$ and $\vec{n}p$ scattering, A^p, P^p, A^n, P^n ; CSB ($A = A^n - A^p$) (M. Simonius, PRL **78** (1997) 4161)

$$\alpha_T \leq 8 \times 10^{-5} \quad (\text{or } \bar{g}_\rho < 6.7 \times 10^{-3})$$

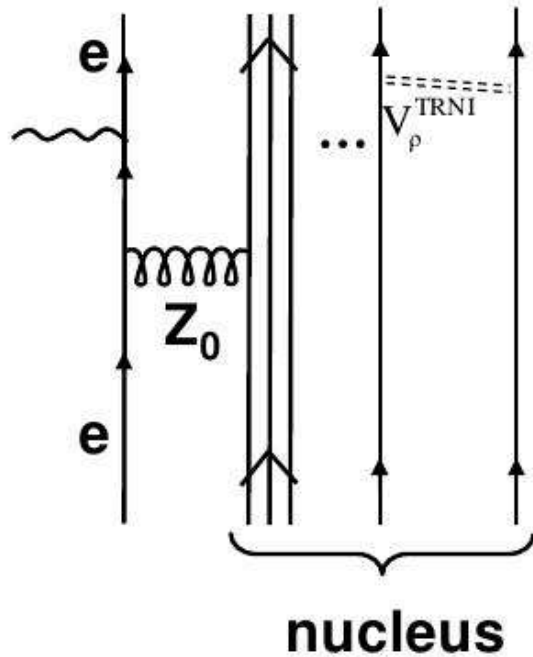
- Mössbauer test, ^{171}Yb , V.G. Tsinoev et al. PRC **76** (2007)
 $\Delta\eta = 1.1 \times 10^{-4}$, $E2/M1$

- indirect from T-odd P-odd (EDM)

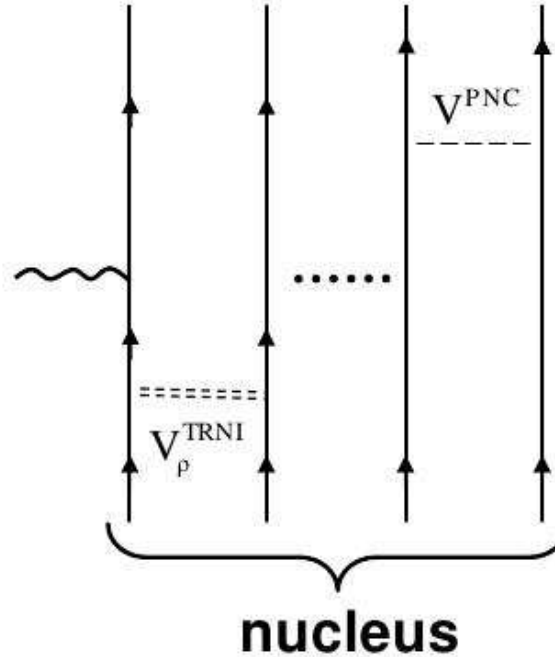
$$\alpha_T \leq 1.1 \times 10^{-5} \quad (\text{or } \bar{g}_\rho \leq \times 10^{-3})$$

- (W.C. Haxton, A. Höring, M.J. Musolf, PRD **50** (1994) 3422)

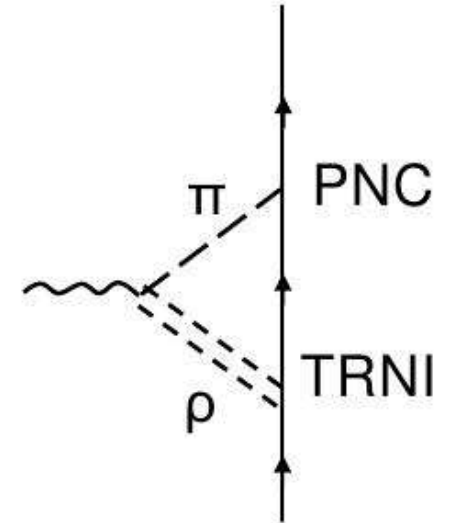
The atomic EDM



The nuclear EDM



The nucleon EDM



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

But Kurylov A., McLaughlin G.C., Ramsey-Musolf M., PRD
63(2001)076007: **no constraints within the "B"-scenario**

Motivation

- TRIC (D. Eversheim, B. Lorentz, Yu. Valdau. COSY proposal N 215):
 $\vec{p}(p_y^p) + d(P_{xz})$ transmission in the COSY ring

The goal is to improve the **direct** upper bound on **TVPC** by one order of magnitude.

Theory: M. Beyer, Nucl.Phys. A 560 (1993) 895

d-breakup channel only, 135 MeV

Faddeev eqs., 100 keV, *nd*-scattering: Y.-Ho Song, R. Lazauskas, V.Gudkov, PRC 84 (2011) 025501

Phenomenology of the $pd \rightarrow pd$ transition

$$\frac{1}{2} + 1 \rightarrow \frac{1}{2} + 1$$

$(2 + 1)^2(2\frac{1}{2} + 1)^2 = 36$ transition amplitudes

P-parity \implies 18 independent amplitudes

T-invariance for $pd \rightarrow pd \implies$ 12 independent amplitudes

Transition matrix element

$$M_{fi} = \langle \mu' \lambda' | M | \mu \lambda \rangle \quad (2)$$

Phenomenology of the $pd \rightarrow pd$ transition

$$\hat{\mathbf{q}} = (\mathbf{p} - \mathbf{p}'), \quad \hat{\mathbf{k}} = (\mathbf{p} + \mathbf{p}')/, \quad \hat{\mathbf{n}} = [\mathbf{k} \times \mathbf{q}] - \text{unit vect.} \quad (Z \uparrow\uparrow \hat{\mathbf{k}}, X \uparrow\uparrow \hat{\mathbf{q}}, Y \uparrow\uparrow \hat{\mathbf{n}})$$

$$M = (A_1 + A_2 \boldsymbol{\sigma} \hat{\mathbf{n}}) + (A_3 + A_4 \boldsymbol{\sigma} \hat{\mathbf{n}})(\mathbf{S} \hat{\mathbf{q}})^2 + (A_5 + A_6 \boldsymbol{\sigma} \hat{\mathbf{n}})(\mathbf{S} \hat{\mathbf{n}})^2 + A_7(\boldsymbol{\sigma} \hat{\mathbf{k}})(\mathbf{S} \hat{\mathbf{k}}) + \\ A_8(\boldsymbol{\sigma} \hat{\mathbf{q}}) [(\mathbf{S} \hat{\mathbf{q}})(\mathbf{S} \hat{\mathbf{n}}) + (\mathbf{S} \hat{\mathbf{n}})(\mathbf{S} \hat{\mathbf{q}})] + (A_9 + A_{10} \boldsymbol{\sigma} \hat{\mathbf{n}})(\mathbf{S} \hat{\mathbf{n}}) + A_{11}(\boldsymbol{\sigma} \hat{\mathbf{q}})(\mathbf{S} \hat{\mathbf{q}}) + \\ A_{12}(\boldsymbol{\sigma} \hat{\mathbf{k}}) [(\mathbf{S} \hat{\mathbf{k}})(\mathbf{S} \hat{\mathbf{n}}) + (\mathbf{S} \hat{\mathbf{n}})(\mathbf{S} \hat{\mathbf{k}})]$$

$$+(T_{13} + T_{14} \boldsymbol{\sigma} \hat{\mathbf{n}}) [(\mathbf{S} \hat{\mathbf{k}})(\mathbf{S} \hat{\mathbf{q}}) + (\mathbf{S} \hat{\mathbf{q}})(\mathbf{S} \hat{\mathbf{k}})] + T_{15}(\boldsymbol{\sigma} \hat{\mathbf{q}})(\mathbf{S} \hat{\mathbf{k}}) + T_{16}(\boldsymbol{\sigma} \hat{\mathbf{k}})(\mathbf{S} \hat{\mathbf{q}}) + \\ T_{17}(\boldsymbol{\sigma} \hat{\mathbf{k}}) [(\mathbf{S} \hat{\mathbf{q}})(\mathbf{S} \hat{\mathbf{n}}) + (\mathbf{S} \hat{\mathbf{n}})(\mathbf{S} \hat{\mathbf{q}})] + T_{18}(\boldsymbol{\sigma} \hat{\mathbf{q}}) [(\mathbf{S} \hat{\mathbf{k}})(\mathbf{S} \hat{\mathbf{n}}) + (\mathbf{S} \hat{\mathbf{n}})(\mathbf{S} \hat{\mathbf{k}})]$$

$A_1 \div A_{12}$ **T-even P-even:**

M. Platonova, V.I. Kukulín, PRC **81** (2010) 014004

$T_{13} \div T_{18} : \text{TVPC}$

The polarized elastic differential pd cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{pol} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left[1 + \frac{3}{2} p_j^p p_i^d C_{j,i} + \frac{1}{3} P_{ij}^d A_{ij} + \dots\right]. \quad (3)$$

$$C_{y,y} = \text{Tr} M S_y \sigma_y M^+ / \text{Tr} M M^+, \quad \dots \quad (4)$$

Forward elastic pd scattering amplitude (P-even, T-even):

$$e'_{\beta}{}^* \hat{F}_{\alpha\beta}(0) e_{\alpha} = g_1[\mathbf{e} \mathbf{e}'^* - (\hat{\mathbf{k}}\mathbf{e})(\hat{\mathbf{k}}\mathbf{e}'^*)] + g_2(\hat{\mathbf{k}}\mathbf{e})(\hat{\mathbf{k}}\mathbf{e}'^*) + ig_3\{\boldsymbol{\sigma}[\mathbf{e} \times \mathbf{e}'^*] - (\boldsymbol{\sigma}\hat{\mathbf{k}})(\hat{\mathbf{k}} \cdot [\mathbf{e} \times \mathbf{e}'^*])\} + ig_4(\boldsymbol{\sigma}\hat{\mathbf{k}})(\hat{\mathbf{k}} \cdot [\mathbf{e} \times \mathbf{e}'^*]) + \quad (5)$$

M.P. Rekalo et al., Few-Body Syst. 23, 187 (1998)

... and plus **T-odd P-even term**

$$\dots + g_5\{(\boldsymbol{\sigma} \cdot [\hat{\mathbf{k}} \times \mathbf{e}])(\mathbf{k} \cdot \mathbf{e}'^*) + (\boldsymbol{\sigma} \cdot [\hat{\mathbf{k}} \times \mathbf{e}'^*])(\mathbf{k} \cdot \mathbf{e})\} \quad (6)$$

Generalized Optical theorem:

$$Im \frac{Tr(\hat{\rho}_i \hat{F}(0))}{Tr \hat{\rho}_i} = \frac{k}{4\pi} \sigma_i \quad (7)$$

Total polarized cross sections pd

$$\sigma_{tot} = \underbrace{\sigma_0 + \sigma_1 \mathbf{p}^p \cdot \mathbf{P}^d + \sigma_2 (\mathbf{p}^p \cdot \hat{\mathbf{k}}) (\mathbf{P}^d \cdot \hat{\mathbf{k}})}_{T\text{-even}, P\text{-even}} + \underbrace{\sigma_3 P_{zz} + \tilde{\sigma}_{tvp} p_y^p P_{xz}^d}_{T\text{-odd}, P\text{-even}}$$

whith

$$\sigma_0 = \frac{4\pi}{k} \text{Im} \frac{2g_1 + g_2}{3}, \quad \sigma_1 = -\frac{4\pi}{k} \text{Im} g_3,$$

$$\sigma_2 = -\frac{4\pi}{k} \text{Im} (g_4 - g_3), \quad \sigma_3 = \frac{4\pi}{k} \text{Im} \frac{g_1 - g_2}{6}.$$

/Yu.N. Uzikov, J. Haidenbauer, *PRC* **79** (2009) 024617; *PRC* **87** (2013) 054003/

$$\tilde{\sigma}_{tvp} = -\frac{4\pi}{k} c \text{Im} g_5 \quad (8)$$

/A.A. Temerbaev, Yu.N. Uzikov, *DSPIN-2013* (Dubna, 2014) p.151/

Measurement of total $\tilde{\sigma}_{tvp\bar{c}}$ in $\vec{p} - \vec{d}$ scattering:

- a true null-test for T-invariance
- independent on dynamics
- FSI is yet included into "exact" $F(0)$

"Nonexistence" proof,

"It is impossible to construct, in any reaction in atomic, nuclear, or particle physics, a null experiment that would unambiguously test the time-reversal invariance independently of dynamical assumptions"

F.Arash, M.J. Moravcsik, G.R. Goldstein, Phys.Rev.Lett. 54(1985) 2649

Proof holds for bilinear ($\sim |F_{if}|^2$) observables only

H.E. Conzett, Phys.Rev. C 48 (1993) 423

Transmission experiments are not included into that proof

Background conditions for TRIC? Elastic $pd \rightarrow pd$ transitions

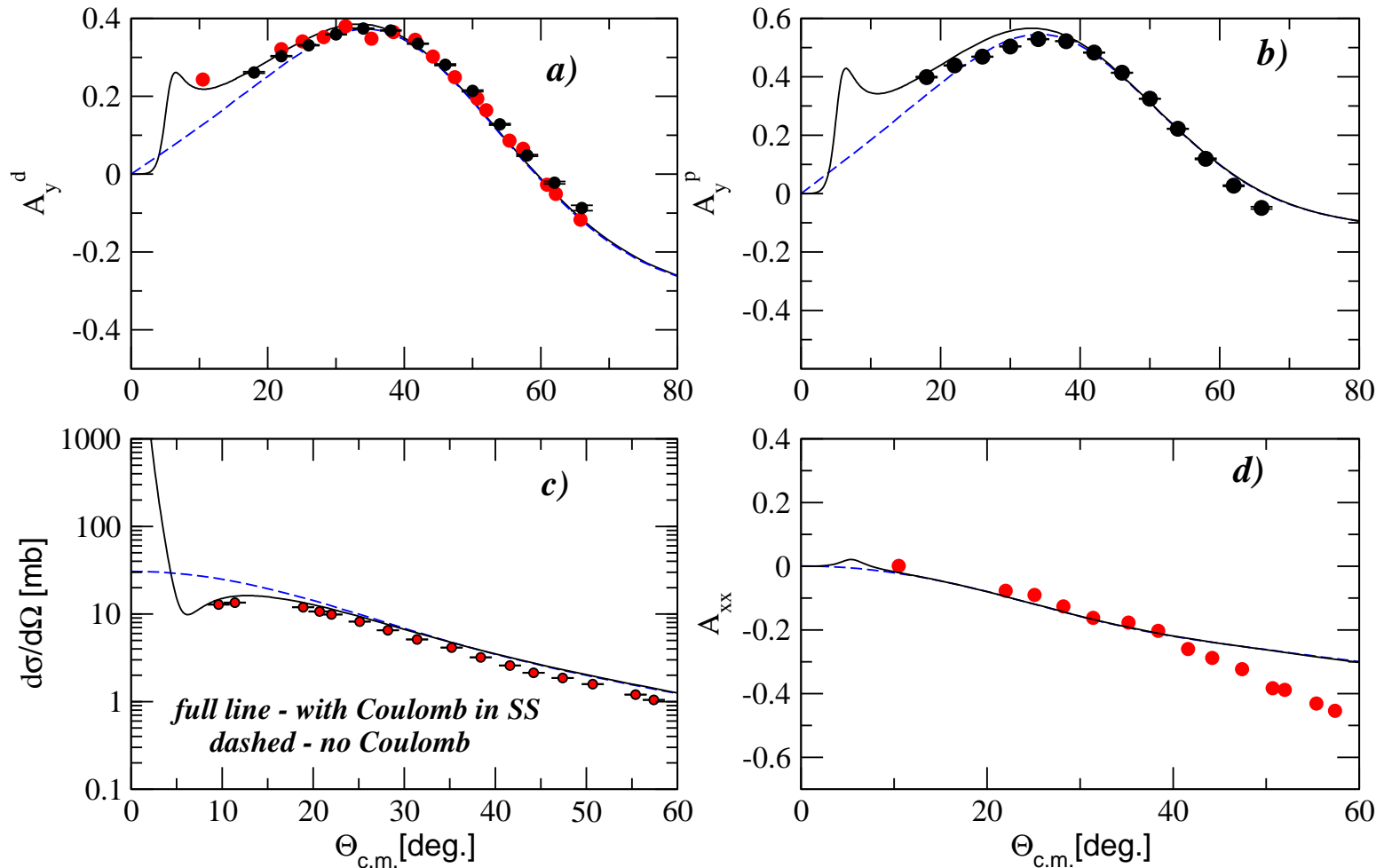
$$\hat{M}(\mathbf{q}, \mathbf{s}) = \exp\left(\frac{1}{2}i\mathbf{q} \cdot \mathbf{s}\right) M_{pp}(\mathbf{q}) + \exp\left(-\frac{1}{2}i\mathbf{q} \cdot \mathbf{s}\right) M_{pn}(\mathbf{q}) + \frac{i}{2\pi^{3/2}} \int \exp(i\mathbf{q}' \cdot \mathbf{s}) \left[M_{pp}(\mathbf{q}_1) M_{pn}(\mathbf{q}_2) + p \leftrightarrow n \right] d^2\mathbf{q}'.$$

On-shell elastic pN scattering amplitude (**T-even, P-even**)

$$M_{pN} = A_N + (C_N \boldsymbol{\sigma}_1 + C'_N \boldsymbol{\sigma}_2) \cdot \hat{\mathbf{n}} + B_N (\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{k}}) (\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{k}}) + (G_N - H_N) (\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{n}}) (\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{n}}) + (G_N + H_N) (\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{q}}) (\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{q}})$$

M. Platonova, V. Kukulín, PRC **81** (2010) 014004:

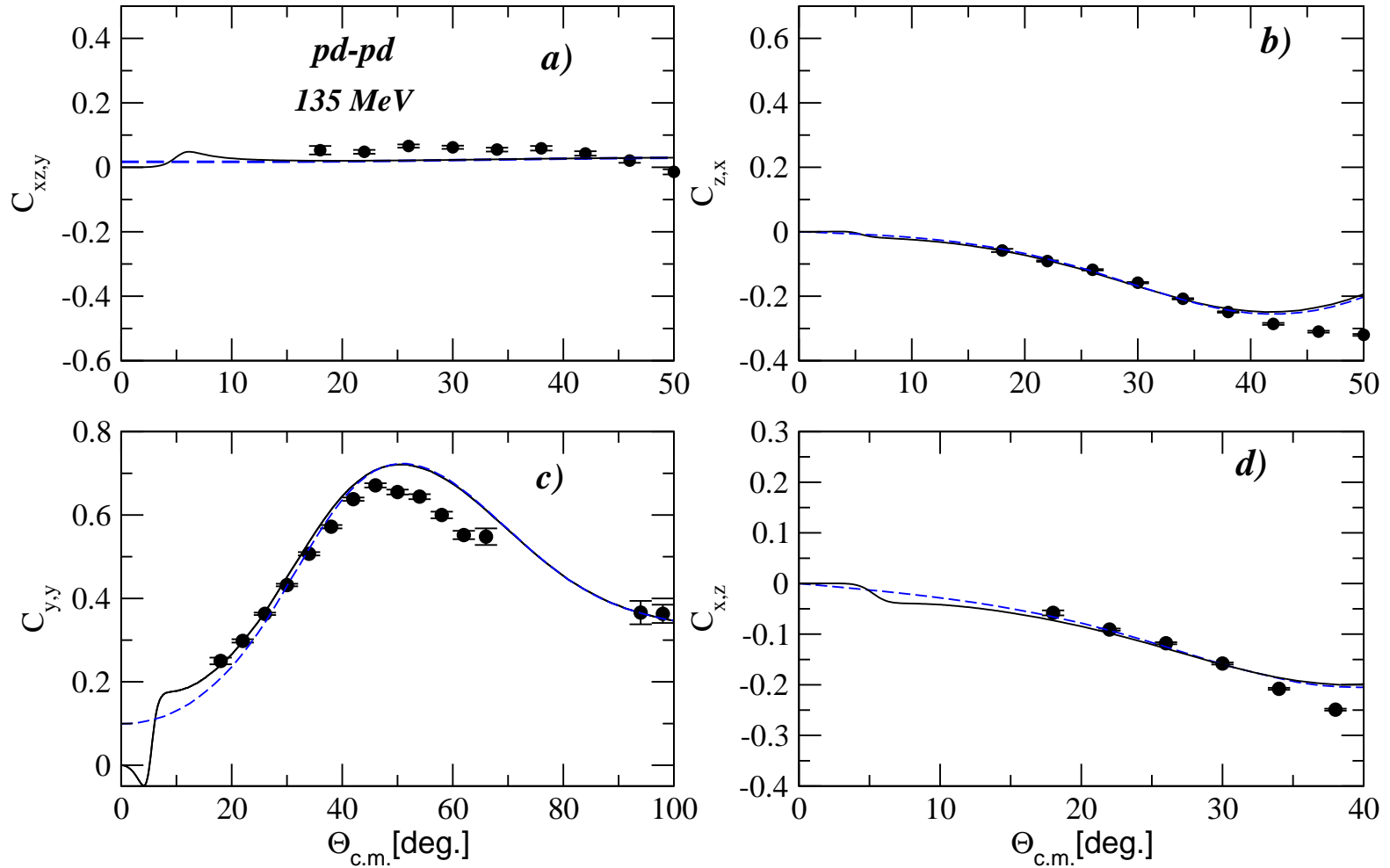
Test calculations: pd elastic scattering at 135 MeV



Data: K. Sekiguchi et al. PRC (2002); B. von Przewoski et al. PRC (2006)

See also Coulomb in Faddeev eqs.: A.Deltuva, A.C. Fonseca, P.U. Sauer, PRC 71 (2005) 054005.

Test calculations-II: *nd* elastic scattering at 135 MeV



Curves: the modified Glauber model

Data: von B.Przewoski et al. PRC 74 (2006) 064003

Total polarized T-even P-even pd cross sections and restrictions to P_y^d

$$\sigma_{tot} = \sigma_0 + \sigma_1 \mathbf{p}^p \cdot \mathbf{P}^d + \sigma_2 (\mathbf{p}^p \cdot \hat{\mathbf{k}})(\mathbf{P}^d \cdot \hat{\mathbf{k}}) + \sigma_3 P_{zz} + \tilde{\sigma} p_y^p P_{xz}^d \quad (9)$$

$$\underline{T_0 = 135 \text{ MeV:}}$$

$$\sigma_0 = 78.5 \text{ mb}, \quad \sigma_1 = 3.7 \text{ mb}, \quad \sigma_2 = 12.4 \text{ mb}, \quad \sigma_3 = -1.1 \text{ mb}$$

$$\frac{\sigma_1}{\sigma_0} = 0.047$$

The goal of TRIC: $\delta R_T \leq 10^{-6}$, where

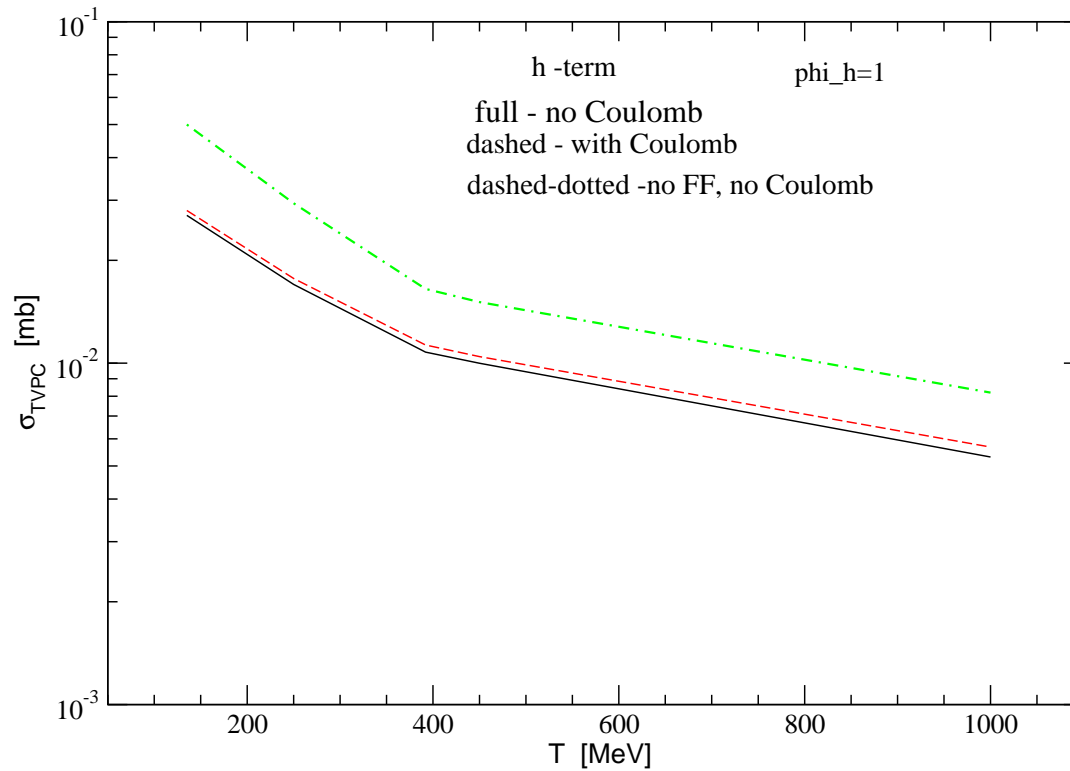
$$R_T = \frac{\tilde{\sigma}}{\sigma_0}$$

then from $\frac{P_y^d \sigma_1}{\tilde{\sigma}} \sim 10^{-1}$ and $R_T \leq 10^{-6} \implies P_y^d \leq 2 \times 10^{-6}$

The deuteron vector polarization has to be adjusted to be zero in the atomic beam source

T-odd P-even NN interactions and σ_{TVPC}

$$\begin{aligned}
 t_{pN} = & \underbrace{h_p [(\boldsymbol{\sigma} \cdot \mathbf{p})(\boldsymbol{\sigma}_p \cdot \mathbf{q}) + (\boldsymbol{\sigma}_p \cdot \mathbf{p})(\boldsymbol{\sigma} \cdot \mathbf{q}) - (\boldsymbol{\sigma}_p \cdot \boldsymbol{\sigma})(\mathbf{p} \cdot \mathbf{q})]}_{a1\text{-meson}} + \\
 & + g_p [\boldsymbol{\sigma} \times \boldsymbol{\sigma}_p] \cdot [\mathbf{q} \times \mathbf{p}] + \underbrace{g'_p (\boldsymbol{\sigma} - \boldsymbol{\sigma}_p) \cdot i [\mathbf{q} \times \mathbf{p}] [\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2]_z}_{\rho\text{-meson}} + (p \leftrightarrow n)
 \end{aligned}$$



SUMMARY

- True null-test observable, which is not affected by FSI and does not depend on dynamics assumptions, will be measured by TRIC. Uncertainties can be reasonable estimated within the Glauber model:
- Agreement with the $pd \rightarrow pd$ data on $d\sigma/d\Omega$, A_y , $C_{y,y}$, $C_{xz,y}$ at **TRIC energy** is obtained in forward hemisphere within the Glauber model with full spin-dependence of the NN (T-even, P-even) and Coulomb included.
- The Glauber model is expected to provide a similar accuracy for the **TVPC** observable $\tilde{\sigma}_{tvpc}$
- Total polarized pd cross sections σ_1 , σ_2 , σ_3 are calculated \implies control of some experimental uncertainties, **essential restriction** on p_y^d .
- The Coulomb interaction does not lead to divergence of the null-test observable $\tilde{\sigma}_{tvpc}$!

THANK YOU FOR ATTENTION!

Sources for false effects

Involved Spins: $\frac{1}{2} + 1 \rightarrow \frac{1}{2} + 1$

<u>I_{0,0}</u>	<u>A_{0,X}</u>	<u>A_{0,Y}</u>	<u>A_{0,Z}</u>	A _{0,XX}	A _{0,YY}	A _{0,ZZ}	<u>A_{0,XY}</u>	<u>A_{0,YZ}</u>	<u>A_{0,XZ}</u>
<u>A_{X,0}</u>	A _{X,X}	<u>A_{X,Y}</u>	<u>A_{X,Z}</u>	<u>A_{X,XX}</u>	<u>A_{X,YY}</u>	<u>A_{X,ZZ}</u>	<u>A_{X,XY}</u>	A _{X,YZ}	<u>A_{X,XZ}</u>
<u>A_{Y,0}</u>	<u>A_{Y,X}</u>	A_{Y,Y}	<u>A_{Y,Z}</u>	<u>A_{Y,XX}</u>	<u>A_{Y,YY}</u>	<u>A_{Y,ZZ}</u>	<u>A_{Y,XY}</u>	<u>A_{Y,YZ}</u>	A_{Y,XZ}
<u>A_{Z,0}</u>	<u>A_{Z,X}</u>	<u>A_{Z,Y}</u>	A _{Z,Z}	<u>A_{Z,XX}</u>	<u>A_{Z,YY}</u>	<u>A_{Z,ZZ}</u>	<u>A_{Z,XY}</u>	<u>A_{Z,YZ}</u>	<u>A_{Z,XZ}</u>

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

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

From talk by D. Eversheim, ECT, (Trento, October, 2012)

The PK reference frame:

$$OZ' \uparrow\uparrow (\mathbf{p} + \mathbf{p}'), \quad OX' \uparrow\uparrow (\mathbf{p} - \mathbf{p}') \quad OY' \uparrow\uparrow [(\mathbf{p} + \mathbf{p}') \times (\mathbf{p} - \mathbf{p}')] \uparrow\uparrow [\mathbf{p}' \times \mathbf{p}]$$

$$M = (A_1 + A_2\sigma\hat{\mathbf{n}}) + (A_3 + A_4\sigma\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})^2 + (A_5 + A_6\sigma\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{n}})^2 + A_7(\sigma\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{k}}) + \\ A_8(\sigma\hat{\mathbf{q}}) [(\mathbf{S}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})] + (A_9 + A_{10}\sigma\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{n}}) + A_{11}(\sigma\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{q}}) + \\ A_{12}(\sigma\hat{\mathbf{k}}) [(\mathbf{S}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{k}})]$$

Madison reference frame:

$OZ \uparrow\uparrow \mathbf{p}$, $OY \uparrow\uparrow [\mathbf{p} \times \mathbf{p}']$, $OX \implies$ right-hand system

$XYZ \implies X'Y'Z'$:

i) rotation by $\theta/2$ around OY ,

θ is the angle between \mathbf{p} and \mathbf{p}'

ii) $OY \rightarrow -OY$ and $OX \rightarrow -OX$.

is related to $C_{xz,y}, C_{x,z}, C_{z,x} \dots$, but not for $A_y, C_{y,y}, \dots$