Spin Observables of pd Scattering and Null-Test for T-invariance Violation

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" Baldin XXII ISHEPP"
September, 15-20, 2014

- Motivation:
  P-even **T**ime-**R**eversal **I**nvariance test planned at **C**OSY (TRIC)
- Null-test for T-odd P-even effects in pd interaction
- Sorces 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*

- CP-violation in K- and B-meson physics $\Longrightarrow$ T-violation $\Longrightarrow$ BAU
- These T-odd, P-odd effects arise in SM through CP violating phase of CKM matrix and through the QCD $\theta-$ 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

$\star$ I.B. Khriplovich Nucl.Phys. B **352** (1991) 385: relative strength of the T-odd, P-even nuclear force does not exceed $\alpha_T \sim 2 \times 10^{-6}$

$\star$ 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: $\mathbf{g} \sim \mathbf{M^4 G_F^2} \sin\delta \sim \mathbf{10^{-10}}$

V.P. Gudkov, Phys. Rep. **212**(1992)77

$\star$ ...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*

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

The TVPC Born NN-amplitude

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

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

$\vec{q} = \vec{p}_f - \vec{p}_i$ dissappeares 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 $^{27}Al(p,\alpha)^{24}Mg$ and $^{24}Mg(\alpha,p)^{27}Al$,

$\Delta=(\sigma_{dir}-\sigma_{inv})/(\sigma_{dir}+\sigma_{inv})\leq 5.1\times 10^{-3}$ (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)

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

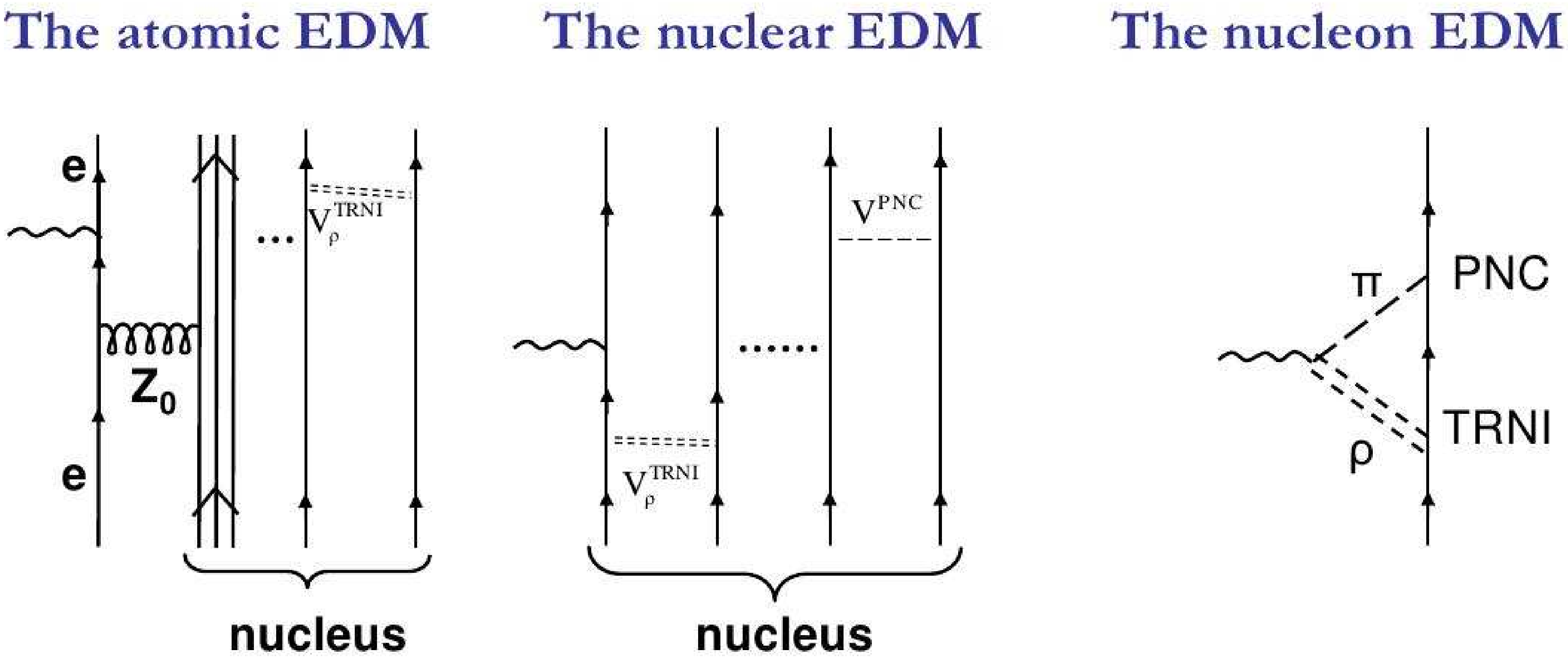
- Mössbauer test, ^{171}Yb, V.G. Tsinoev et al. PRC 76 (2007)

$\Delta\eta = 1.1\times 10^{-4}$, $\quad E2/M1$

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

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

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



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**

- 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*

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

$(2+1)^2(2\frac{1}{2}+1)^2 = 36$ transition amplitudes
P-parity $\Longrightarrow$ 18 independent amplitudes
T-invariance for $pd \to pd \Longrightarrow$ 12 independent amplitudes

Transition matrix element

$$M_{fi} =< \mu'\lambda'|M|\mu\lambda > \tag{2}$$

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

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

$$- -$$

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

$A_1 \div A_{12}$ T-even P-even:
M. Platonova, V.I. Kukulin,PRC **81** (2010) 014004

$\mathbf{T_{13} \div T_{18}}$ **: TVPC**

The polarized elastic differential pd cross section

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

$$C_{y,y} = TrMS_y\sigma_y M^+/TrMM^+, \quad \dots \quad (4)$$

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**

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

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

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

whith

$$\sigma_0 = \frac{4\pi}{k} Im \frac{2g_1 + g_2}{3}, \sigma_1 = -\frac{4\pi}{k} Im g_3,$$
$$\sigma_2 = -\frac{4\pi}{k} Im(g_4 - g_3), \sigma_3 = \frac{4\pi}{k} Im \frac{g_1 - g_2}{6}.$$

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

$$\widetilde{\sigma}_{tvpc} = -\frac{4\pi}{k} c\, Im g_5 \qquad (8)$$

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

Measurement of total $\widetilde{\sigma}_{tvpc}$ 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

Backround conditions for TRIC? Elastic $pd \to pd$ transitions

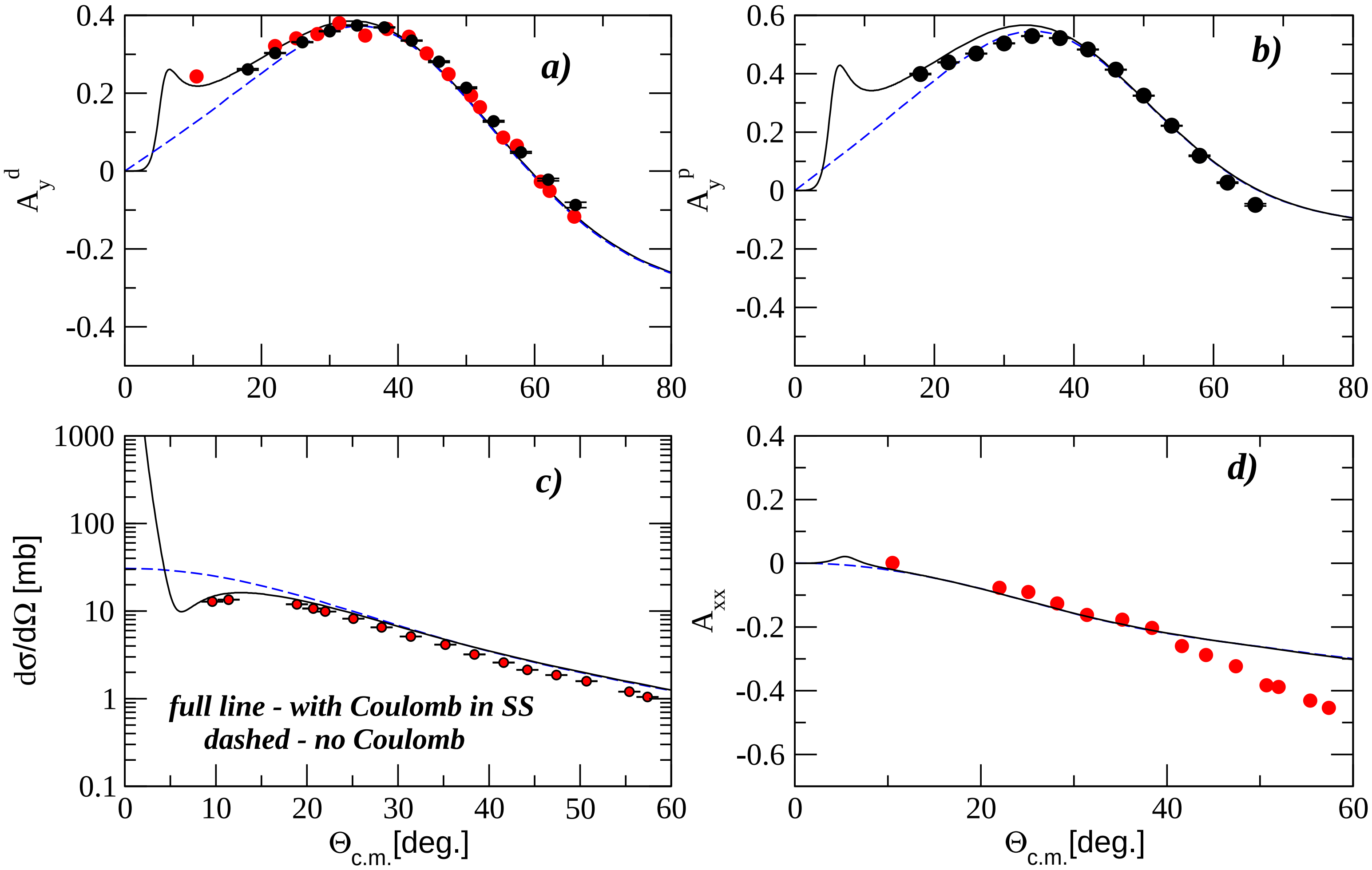
$$\hat{M}(\mathbf{q},\mathbf{s}) =$$
$$\exp\left(\frac{1}{2}i\mathbf{q}\cdot\mathbf{s}\right)M_{pp}(\mathbf{q}) + \exp\left(-\frac{1}{2}i\mathbf{q}\cdot\mathbf{s}\right)M_{pn}(\mathbf{q}) +$$
$$+\frac{i}{2\pi^{3/2}}\int \exp\left(i\mathbf{q}'\cdot\mathbf{s}\right)\Big[M_{pp}(\mathbf{q}_1)M_{pn}(\mathbf{q}_2)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

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

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

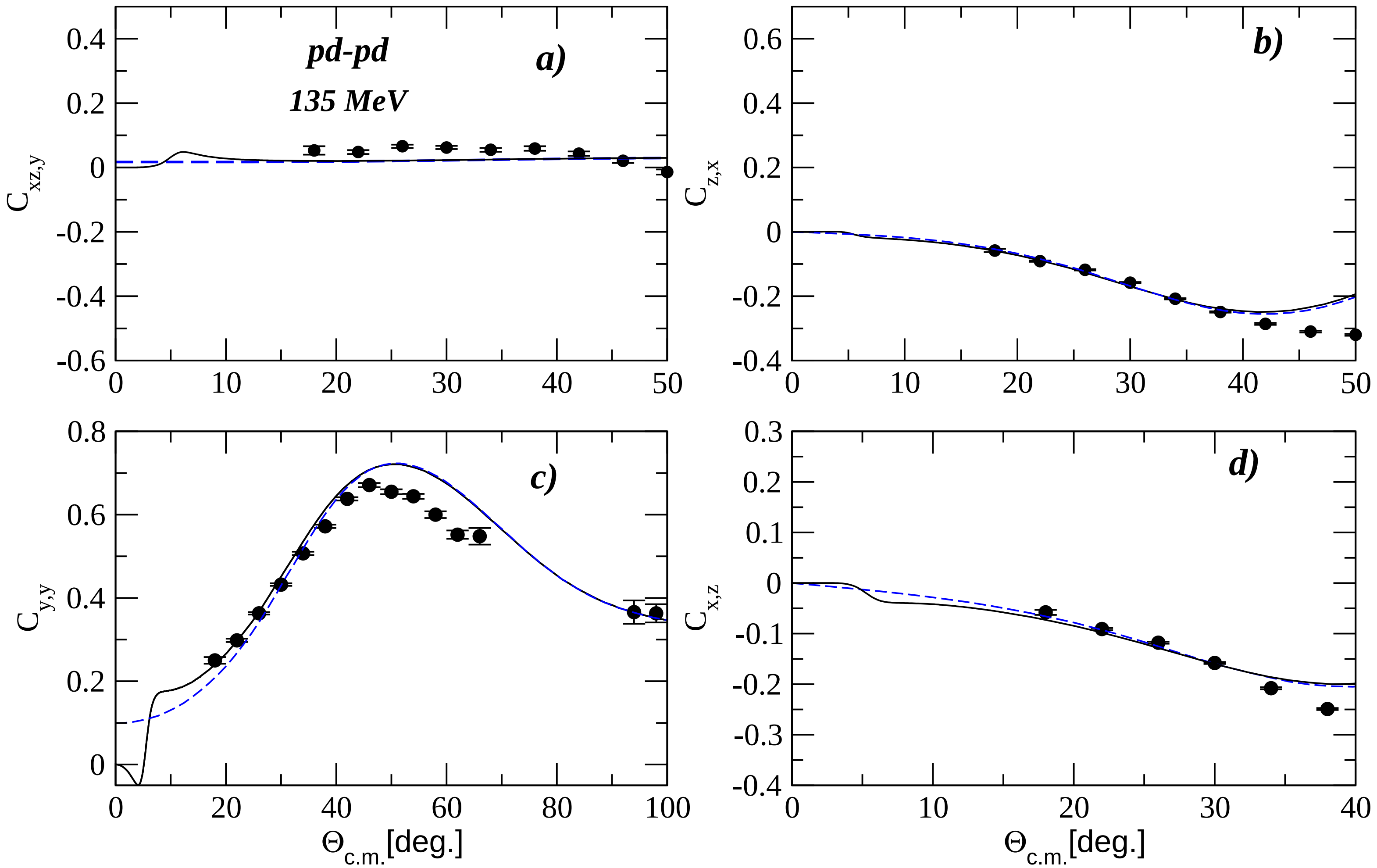
M. Platonova, V. Kukulin, PRC **81** (2010) 014004:

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: pd 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

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

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

$\sigma_0 = 78.5\, mb$, $\sigma_1 = 3.7\, mb$, $\sigma_2 = 12.4\, mb$, $\sigma_3 = -1.1\, mb$

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

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

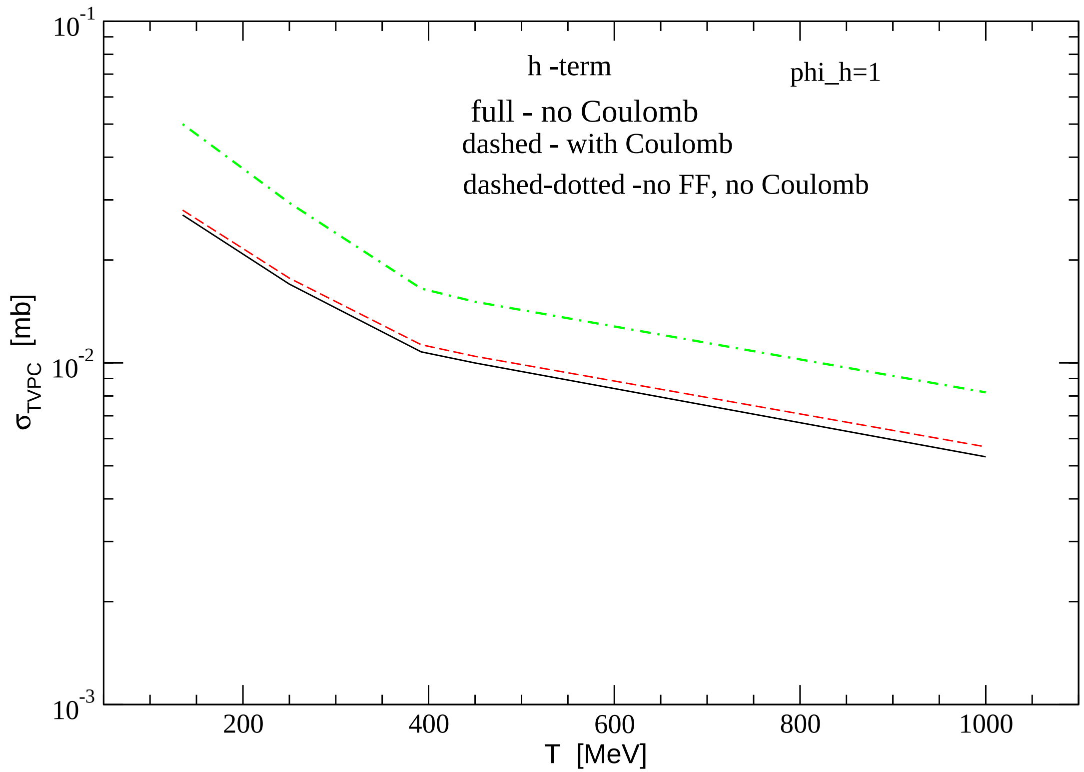
$$R_T = \frac{\widetilde{\sigma}}{\sigma_0}$$

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

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

$$t_{pN} = \underbrace{h_p[(\boldsymbol{\sigma}\cdot\mathbf{p})(\boldsymbol{\sigma}_p\cdot\mathbf{q}) + (\boldsymbol{\sigma}_p\cdot\mathbf{p})(\boldsymbol{\sigma}\cdot\mathbf{q}) - (\boldsymbol{\sigma}_p\cdot\boldsymbol{\sigma})(\mathbf{p}\cdot\mathbf{q})]}_{a1-meson} +$$

$$+g_p[\boldsymbol{\sigma}\times\boldsymbol{\sigma}_p]\cdot[\mathbf{q}\times\mathbf{p}] + \underbrace{g'_p(\boldsymbol{\sigma}-\boldsymbol{\sigma}_p)\cdot i\,[\mathbf{q}\times\mathbf{p}][\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2]_z}_{rho-meson} + (p\leftrightarrow n)$$

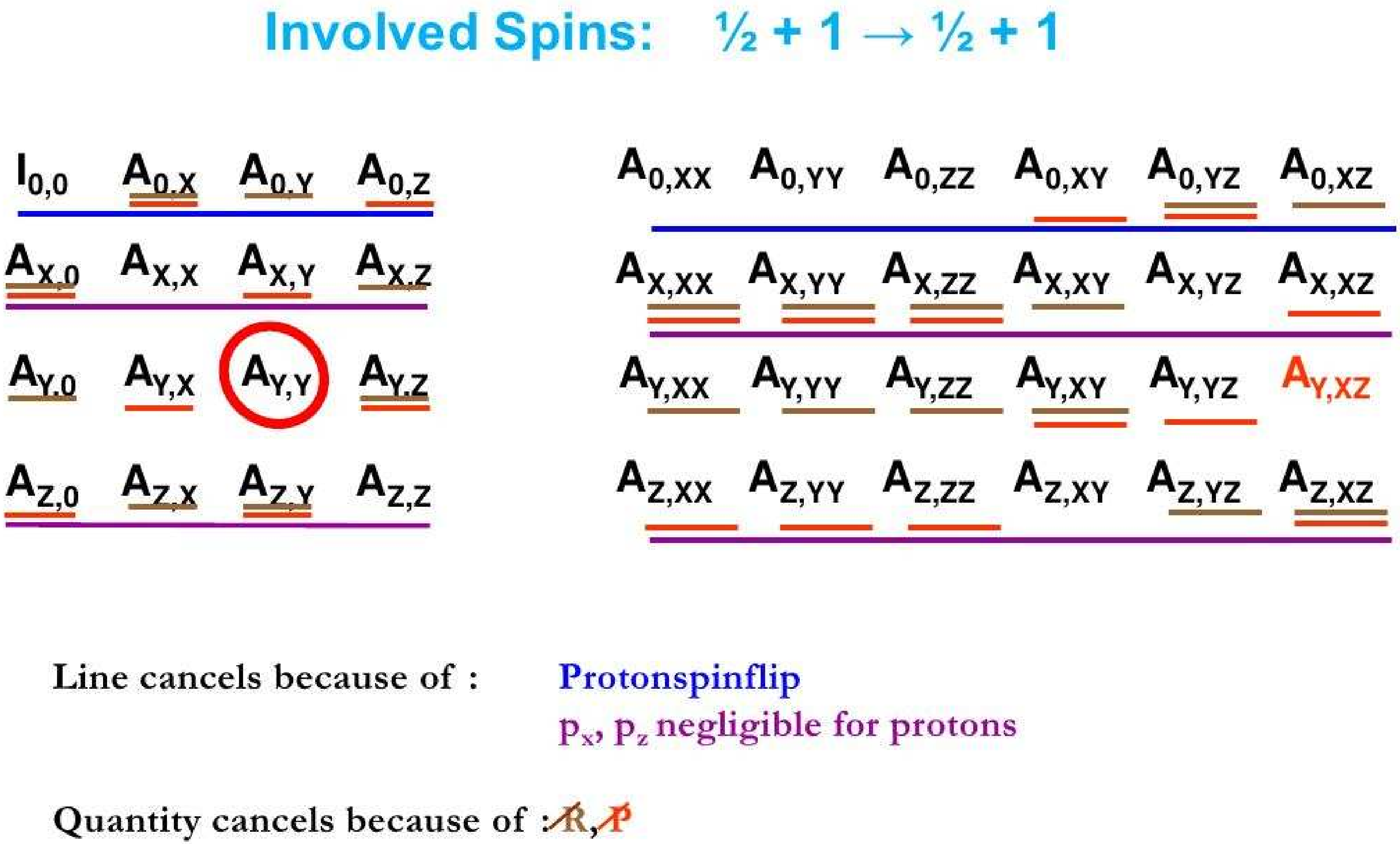


SUMMARY

- 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 $pd \to pd$ 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 $\widetilde{\sigma}_{tvpc}$
- Total polarized pd cross sections σ_1, σ_2, σ_3 are calculated $\Longrightarrow$ control of some experimental uncertainties, essential restriction on p_y^d.
- The Coulomb interaction does not lead to divergence of the null-test observable $\widetilde{\sigma}_{tvpc}$!

THANK YOU FOR ATTENTION!

Sources for false effects



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

From PK to Madison reference frame for $pd \to pd$

The PK reference frame:

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

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

Madison reference frame:

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

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

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

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

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

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