SEARCH FOR T-REVERSAL INVARIANCE VIOLATION IN DOUBLE POLARIZED pd SCATTERING

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744. WE-Heraeus-Seminar:
Towards Storage Ring EDM measurements
(29-31 March, 2021, Bad Honnef)

Motivation

- TVPC and EDM
- NN(TVPC) phenomenology
- pd elastic scattering including TVPC in Glauber model
- Energy dependence of the null-test signal in pd
- TRIC/TIVOLI proposals.Static polarizations
- New approach with precessing spin

Conclusion

Baryon Asymmetry of the Universe (BAU) → today:

$$\eta = \left(\frac{n_B - n_{\bar{B}}}{n_\gamma}\right) \approx \left(\frac{n_B}{n_\gamma}\right) \approx 6 \times 10^{-10}$$

(WMAP + COBE, 2003; Steigman 2012)

Observed η is much too large vs. the SM expectation $n_B/n_\gamma \approx 5 \times 10^{-19}$:

$\Longrightarrow$ new sources of CP violation needed

Sakharov: Three Requirements:

- Baryon number violation
- Violation of C and CP symmetries
- Departure from thermodynamic equilibrium

A. Sakharov; JETP Lett, 5, 24

Planned experiments to search for CP violation beyond the SM

- Detecting a non-zero **EDM** of elementary fermion (neutron, atoms, charged particles). The current experimental limit

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst}) \times 10^{-26} e \cdot cm$$

C. Abel et al. (nEDM Coll.) PRL **8**, (2020) 081803

as compared the SM estimation (B.H.J. McKellar et al. PLB 197 (1987)

$1.4 \times 10^{-33} e\, cm \leq |d_n| \leq 1.6 \times 10^{-31} e\, cm$

- Search for CP violation in the **neutrino sector** ($\theta_{13} \neq 0$, then generation of lepton asymmetry and via $B - L$ conservation to get the BAU).

Thouse are T-violating and Parity violating (TVPV) effects.

Much less attention was paid to T-violating P-conserving (TVPC) flavor conserving effects.

- The T- violating, P-violating (TVPV) effects arise in SM through CP violating phase of CKM matrix and the QCD $\theta-$ term. **EDM**.

- T-violating P-conserving (TVPC) (flavor-conserving) effects first considered 1965: L.Okun; J.Prentki and M.Veltman; T.D.Lee and L.Wolfenstein, to explain CP violation physics of kaons, do not arise in SM as Fundamental interactions,

  although can be generated through weak corrections to TVPV interactions

  ⋆ Observed (in K^0, B^0, D^0) CP violation in SM leads to simultaneous violation of T- and P-invariance.
  Therefore, to produce T-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

  ⋆ ...much larger g is not excluded beyond the SM.

  ⋆ **Experimental limits on TVPC effects are much weaker than for EDM.**

J.Engel, P.H. Frampton, R.P. Springer, PRD 53 (1996) 5112

The reason the TVPC experiments [2] are interesting is that limits on the quantities they measure are still quite weak (much weaker than the limits on similar TVPV quantities), raising the possibility that TVPC effects could be relatively large.

The best published limit : $\bar{g}_\rho \sim 10^{-2}$

Is it possible that large T violation from outside the standard model is lurking just below current limits, that a TVPC effect could appear at 10^{-3} or 10^{-4} times the strong coupling g?

INDIRECT RESTRICTIONS

J.Engel, P.H. Framton, R.P. Springer, PRD **53** (1996) 5112:

$$\mathcal{L}_{NEW} = \mathcal{L}_4 + \frac{1}{\Lambda_{TVPC}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{TVPC}}\mathcal{L}_6 + \frac{1}{\Lambda^3_{TVPC}}\mathcal{L}_7 + \dots$$

The lowest-dimension flavor conserving TVPC interactions have $d = 7$
/R.S. Conti, I.B. Khriplovich, PRL 68 (1992)/.
These new TVPC can generate a permanent EDM in the presence of a PV SM radiative corrections.
J.Engel et al.: $\bar{g}_\rho \sim 10^{-8}$
M.J. Ramsey-Musolf, PRL 83 (1999): $\alpha_T \leq 10^{-15}$, $\Lambda_{TVPC} > 150$ TeV

$$\alpha_T = \frac{< M_{TVPC} >}{< M_{res.strong} >}$$

A.Kurylov, G.C. McLaughlin, M.Ramsey-Musolf , PRD 63(2001)076007:
EDM at energies below Λ_{TVPC}

$$d = \beta_5 C_5 \frac{1}{\Lambda_{TVPC}} + \beta_6 C_6 \frac{M}{\Lambda^2_{TVPC}} + \underbrace{\beta_7 C_7 \frac{M^2}{\Lambda^3_{TVPC}}}_{the\,first\,contrb.\,from\,TVPC}$$

C_d are *a priori* unknown coefficients , β_d calculable quantities from loops, $M < \Lambda_{TVPC}$ - dynamical degrees of freedom

Scenario "A":

P-parity invariance is restored at some scale $\mu \leq \Lambda_{TVPC}$

C_5, C_6 (both TVPV) vanish at tree level in EFT. The first contributions to the EDM arise from C_7 operator

$$\alpha_T \leq 10^{-15}$$

$\Lambda_{TVPC} > 150$ TeV

"Scenario "B":

P-parity invariance is restored at $\mu \geq \Lambda_{TVPC}$

C_5, C_6 (are both TVPV) do not vanish at tree level in EFT.

The EDM results do not provide direct constraint on the $d = 7$ operator, i.e. on the TVPC effects.

No constraints on TVPC within the "B"-scenario

(see also B.K. El-Menoufi, M.J. Ramsey-Musolf, C.-Y. Seng, PLB **765** (2017) 62; right-handed neutrino and β-decay of polarized n)

NN TVPC phenomenology

TVPC ($\equiv$ T-odd P-even) interactions

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

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 $/I^G(J^{PC}) = 1^+(1^{--})/$
Natural parity exchange ($P = (-1)^J$) must be charged

The TVPC Born NN-amplitude

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

C-odd (hence T-odd), only charged ρ's. No contribution to the nn or pp.

$\vec{q} = \vec{p}_f - \vec{p}_i$ dissappeares at $\vec{q} = 0$

$\star$ Axial $h_1(1170)$-meson exchange $I^G(J^{PC}) = 0^-(1^{+-})$ ...

$$t_{pN} = \underbrace{h[(\boldsymbol{\sigma}_1\cdot\mathbf{p})(\boldsymbol{\sigma}_2\cdot\mathbf{q}) + (\boldsymbol{\sigma}_2\cdot\mathbf{p})(\boldsymbol{\sigma}_1\cdot\mathbf{q}) - (\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)(\mathbf{p}\cdot\mathbf{q})]}_{h1-meson} +$$

$$+\underbrace{g[\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2]\cdot[\mathbf{q}\times\mathbf{p}](\boldsymbol{\tau}_1-\boldsymbol{\tau}_2)_z}_{abnormal\,parity\,OBE\,exchanges} + \underbrace{g'(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot i\,[\mathbf{q}\times\mathbf{p}][\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2]_z}_{\rho-meson}$$

$\mathbf{p} = \mathbf{p}_f + \mathbf{p}_i$, $\mathbf{q} = \mathbf{p}_f - \mathbf{p}_i$

g'-term is T-odd due to:

$$< n,p|[\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2]_z|p,n >= -i2,\; < p,n|[\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2]_z|n,p >= i2,$$

in contrast to strong interaction, $M^{str}_{pn\to np} = M^{str}_{np\to pn}$.

Direct experimental constraints on TVPC

- 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). Numerous statistical analyses including nuclear energy-level fluctuations are required to relate to the NN T-odd P-even interaction (J.B. French et al. PRL **54** (1985) 2313) $\alpha_T < 2 \times 10^{-3}$ ($\bar{g}_\rho \leq 1.7 \times 10^{-1}$).

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

$$\Delta = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-) \leq 1.2 \times 10^{-5}$$

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

- 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)

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

• TRIC: a unique experiment for $\vec{p}(p_y^p) + d(P_{xz})$ transmission.
COSY proposal N 215 (2012),D. Eversheim, B.Lorentz, Yu. Valdau:

$$A_{TVPC} = (T^+ - T^-)/(T^+ + T^-),$$

T^+ (T^-) – transmission factor for $p_y^p P_{xz} > 0$ ($p_y^p P_{xz} < 0$).
The goal is to improve the direct upper bound on TVPC by one order of magnitude up to $A_{TVPC} \sim 10^{-6}$

Previous Theory:

M. Beyer, Nucl.Phys. A 560 (1993) 895;
d-breakup channel only, 135 MeV;
Y.-Ho Song, R. Lazauskas, V.Gudkov, PRC 84 (2011) 025501; Faddeev eqs., nd-scattering at 100 keV; pd at 2 MeV

We use the Glauber theory:

A.A. Temerbayev, Yu.N. Uzikov, Yad. Fiz. **78** (2015) 38;

PHENOMENOLOGY OF pd-ELASTIC SCATTERING

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

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

P-parity $\Longrightarrow$ 18 independent amplitudes

T-invariance $\Longrightarrow$ 12 independent amplitudes

At $\theta_{cm} = 0 \Longrightarrow$ 4 (for T-inv. P-inv.) + 1 (T- viol. P-inv.)

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

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

– –

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

$A_1 \div A_{12}$ 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

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

$$C_{y,y} = Tr M S_y \sigma_y M^+ / Tr M M^+, \quad \dots \quad (3)$$

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

$$e'^{*}_{\beta}\hat{M}_{\alpha\beta}(0)e_{\alpha} = g_1[\mathbf{e}\,\mathbf{e}'^{*} - (\hat{\mathbf{k}}\mathbf{e})(\hat{\mathbf{k}}\mathbf{e}'^{*})] + g_2(\hat{\mathbf{k}}\mathbf{e})(\hat{\mathbf{k}}\mathbf{e}'^{*}) +$$
$$ig_3\{\boldsymbol{\sigma}[\mathbf{e}\times\mathbf{e}'^{*}] - (\boldsymbol{\sigma}\hat{\mathbf{k}})(\hat{\mathbf{k}}\cdot[\mathbf{e}\times\mathbf{e}'^{*}])\} + ig_4(\boldsymbol{\sigma}\hat{\mathbf{k}})(\hat{\mathbf{k}}\cdot[\mathbf{e}\times\mathbf{e}'^{*}]) + \quad (3)$$

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

. . . and plus **T-odd P-even (TVPC) term**

$$\cdots + \widetilde{g}_5\{(\boldsymbol{\sigma}\cdot[\hat{\mathbf{k}}\times\mathbf{e}])(\mathbf{k}\cdot\mathbf{e}'^{*}) + (\boldsymbol{\sigma}\cdot[\hat{\mathbf{k}}\times\mathbf{e}'^{*}])(\mathbf{k}\cdot\mathbf{e})\}; \quad (4)$$

Non-diagonal:

$$< \mu' = \frac{1}{2}, \lambda' = 0|M^{TVPC}|\mu = -\frac{1}{2}, \lambda = 1 >= i\sqrt{2}\widetilde{g}_5. \quad (5)$$

Generalized Optical theorem:

$$Im\frac{Tr(\hat{\rho}_i\hat{M}(0))}{Tr\hat{\rho}_i} = \frac{k}{4\pi}\sigma_i \quad (6)$$

Null-test of T-reversal invariance

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

- FSI $\&$ ISI are yet included into $F(0)$
- a true null-test for TVPC, like EDM is a null-test for TVPV.

Comments to "Nonexistence proof":

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*

GLAUBER THEORY

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**)

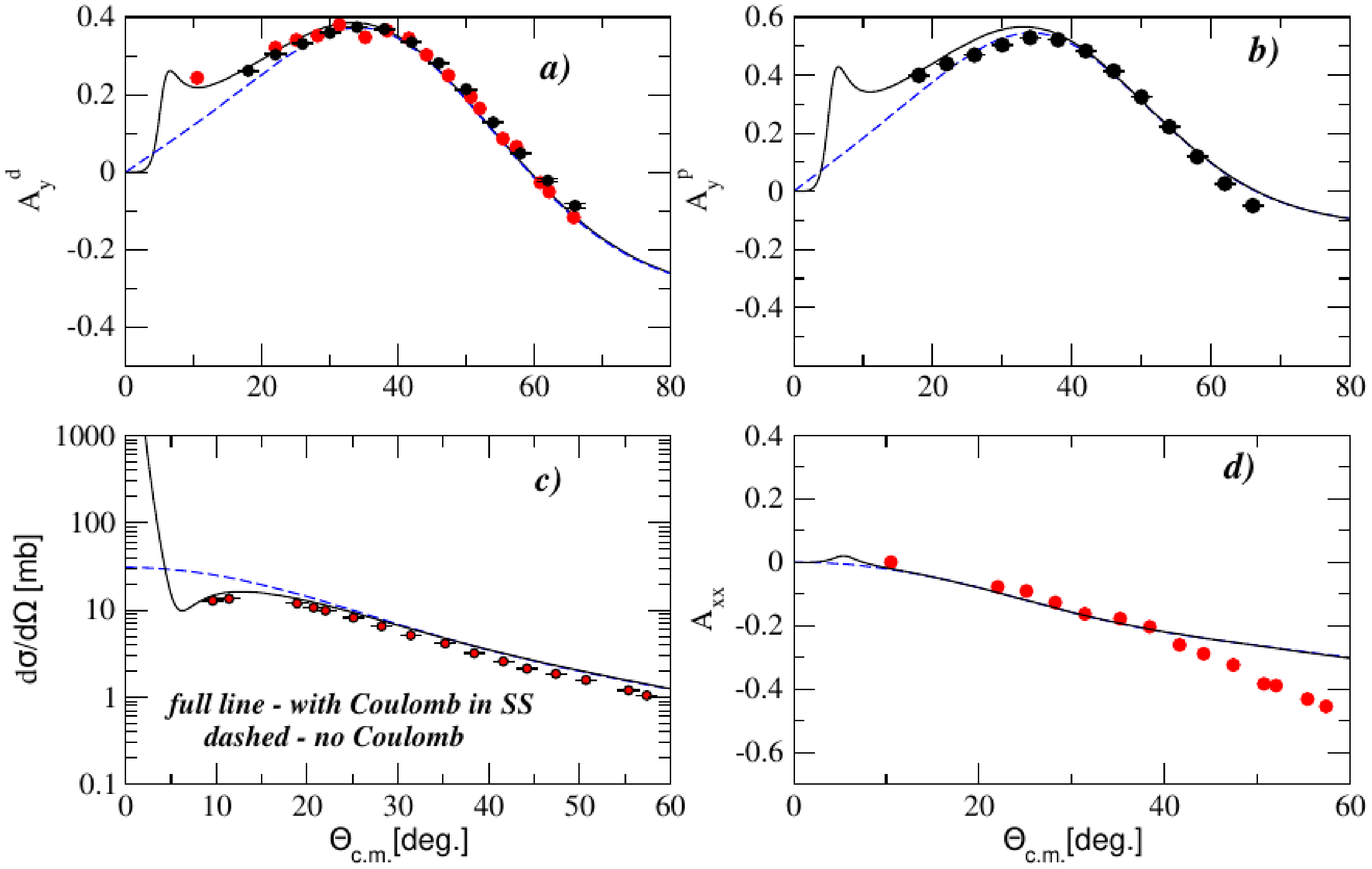
$$\begin{aligned} M_{pN} &= A_N + (C_N\boldsymbol{\sigma}_1 + C'_N\boldsymbol{\sigma}_2)\cdot\hat{\mathbf{n}} + B_N(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{k}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{k}}) + \\ &+ (G_N - H_N)(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{n}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{n}})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

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

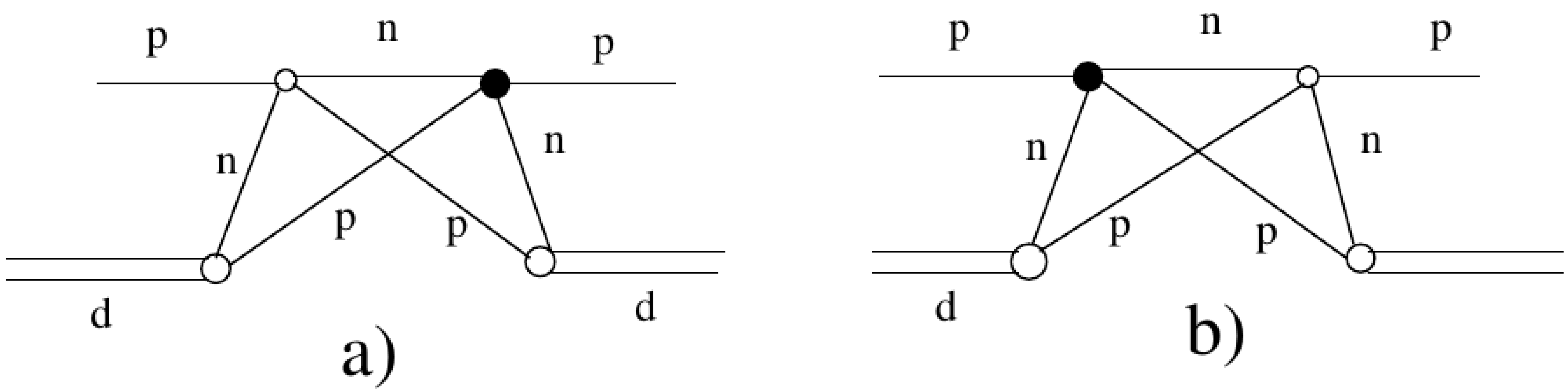
Test calculations: pd elastic scattering at 135 MeV

A.A. Temerbayev, Yu.N.Uzikov, Yad. Fiz. **78** (2015) 38

GLAUBER THEORY CAN BE APPLIED for TVPC X-section



Data: K. Sekiguchi et al. PRC (2002); B. von Przewoski et al. PRC (2006)
See also Faddeev calculations: A.Deltuva, A.C. Fonseca, P.U. Sauer, PRC 71 (2005) 054005.



However, for g'-term the sum is zero due to

$$< n, p|[\boldsymbol{\tau} \times \boldsymbol{\tau}_N]_z|p, n >= -i2, \;\; < p, n|[\boldsymbol{\tau} \times \boldsymbol{\tau}_N]_z|n, p >= i2,$$

ρ-meson does not contribute!

(Single scattering mechanism gives zero contribution to $\widetilde{\sigma}$, $\mathbf{q} = 0$.)

T-ODD P-ODD MODULATING FACTOR FOR TVPC SIGNAL

$$\widetilde{g}_5 = \frac{i}{4\pi m_p}\int_0^\infty dq q^2 \left[S_0^{(0)}(q) - \sqrt{8}S_2^{(1)}(q) - 4S_0^{(2)}(q) + \sqrt{2}\frac{4}{3}S_2^{(2)}(q) + 9S_1^{(2)}(q)\right] \times[-C_n'(q)\, h_p + C_p'(q)(g_n - h_n)],$$

where

$$S_0^{(0)}(q) = \int_0^\infty dr\, u^2(r) j_0(qr), S_0^{(2)}(q) = \int_0^\infty dr\, w^2(r) j_0(qr),$$

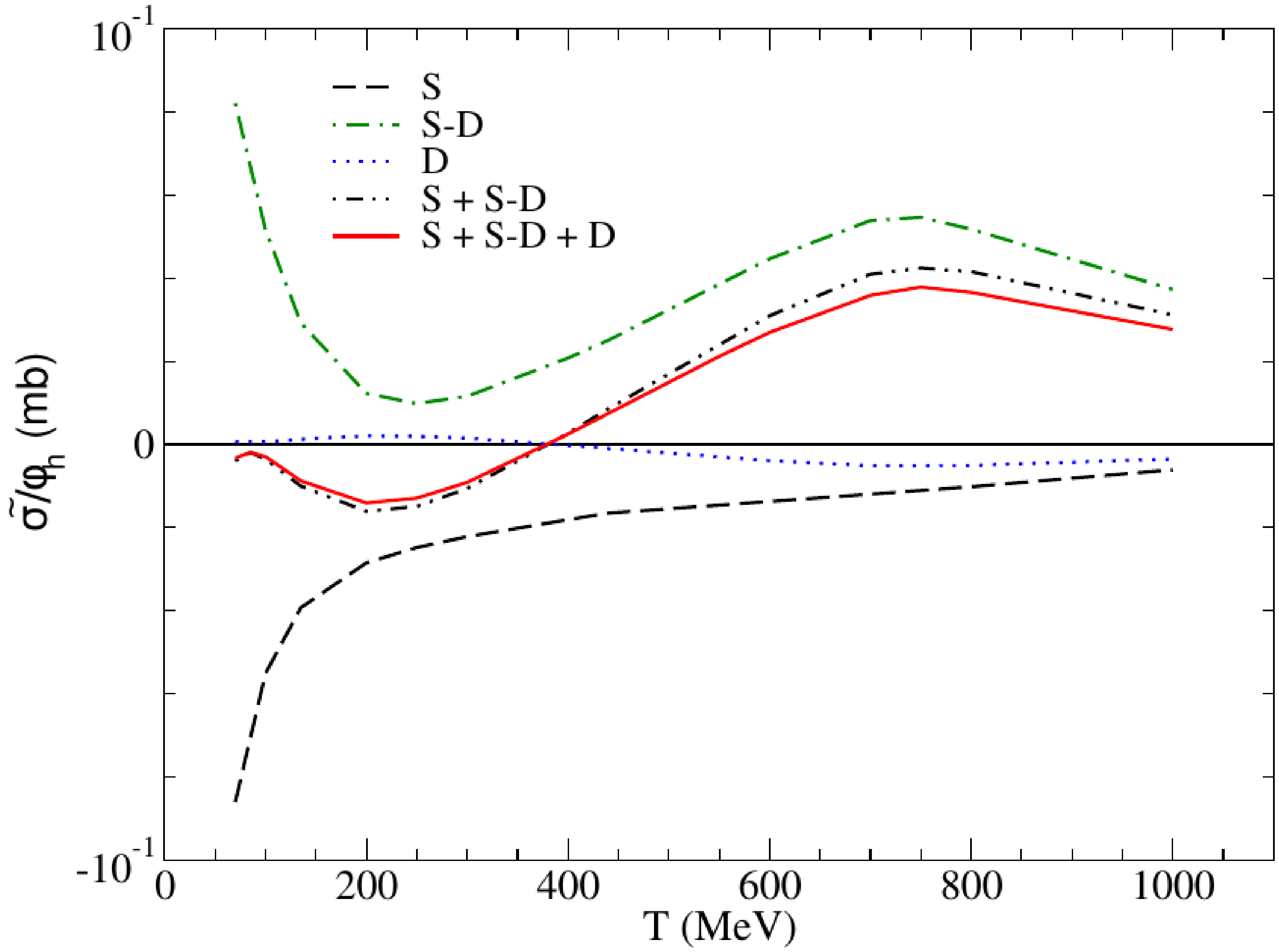
$$S_2^{(1)}(q) = 2\int_0^\infty dr\, u(r) w(r) j_2(qr),$$

$$S_2^{(2)}(q) = -\frac{1}{\sqrt{2}}\int_0^\infty dr\, w^2(r) j_2(qr),$$

$$S_1^{(2)}(q) = \int_0^\infty dr\, w^2(r) j_1(qr)/(qr).$$

Yu.N. U., A.A.Temerbayev, PRC **92**, 014002 (2015),
Yu.N. U., J.Haidenbauer, PRC 94, 035501 (2016)

ENERGY DEPENDENCE OF THE NULL-TEST SIGNAL



Yu.N. Uzikov, J.Haidenbauer, PRC 94 (2016) 035501

TRIC: HOW TO MEASURE ?

This process is described by the transmission factor T(n):

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

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:

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

with: σ_o - Unpolarized total cross-section

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

TVPC ASYMMETRY

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

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:

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

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

$$A_{y,xz} \sim 10^{-6}$$

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

Possible source of false effect. Total polarized T-even P-even pd cross sections.

$$\sigma_{tot} = \sigma_0 + \sigma_1 \mathbf{p}^p \cdot \mathbf{P}^d + \sigma_2 (\mathbf{p}^p \cdot \hat{\mathbf{k}})(\mathbf{P}^d \cdot \hat{\mathbf{k}}) + \sigma_3 P_{zz} + \widetilde{\sigma} p_y^p P_{xz}^d \qquad (8)$$

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

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

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

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

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

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

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

Differential pd-pd polarization observables for T-invariance test

$$A_y^p = P_y^p, \;\; A_y^d = P_y^d \tag{9}$$

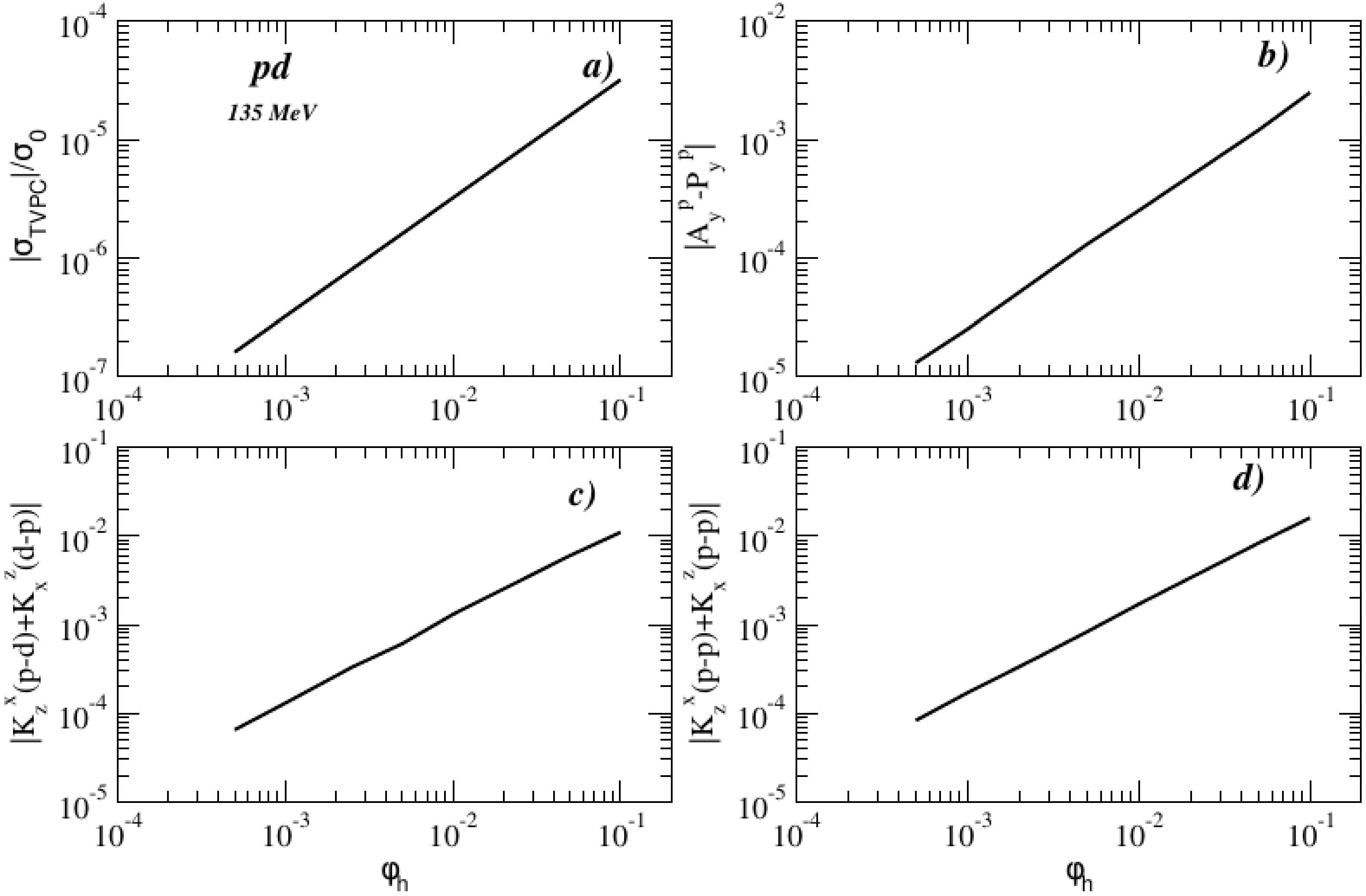
In Madison frame:

$$\begin{aligned} K_z^{x'} &= K_z^x \cos\theta - K_z^z \sin\theta, \\ K_x^{z'} &= K_x^z \cos\theta + K_x^x \sin\theta; \end{aligned} \tag{10}$$

$$K_z^x(p \to p) = \frac{TrM\sigma_z M^+\sigma_x}{TrMM^+}, \; K_z^x(p \to d) = \frac{TrM\sigma_z M^+ S_x}{TrMM^+},$$
$$K_z^x(d \to p) = \frac{TrMS_z M^+\sigma_x}{TrMM^+}, \; K_z^x(d \to d) = \frac{TrMS_z M^+ S_x}{TrMM^+}.$$

$$\begin{aligned} K_x^{z'}(p \to p) &= -K_z^{x'}(p \to p), \\ K_x^{z'}(p \to d) &= -K_z^{x'}(d \to p), \\ K_x^{z'}(d \to p) &= -K_z^{x'}(p \to d), \\ K_x^{z'}(d \to d) &= -K_z^{x'}(d \to d), \end{aligned} \tag{11}$$

$(A_y - P_y,\, K_x^{z'} + K_z^{x'})$: A.A. Temerbaeyv, Yu.N.U., Izv.RAN, Ser. Fiz. **80** (2016)



NEW METHOD TO SEARCH FOR NULL-TEST TVPC SIGNAL in pd

N.N. Nikolaev, F. Rathmann, A.J. Silenko, Yu.N. Uzikov, PLB 811 (2020) 135983

JEDI Revolution-2015: the Fourier analyisis makes the in-plane precessing spin as good as the static one

PRL 115, 094801 (2015) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

New Method for a Continuous Determination of the Spin Tune in Storage Rings and Implications for Precision Experiments

JEDI technique: put the polarization in the ring plane and monitor oscillating $P_{x,z}$ by time-stamped up-down asymmetry

Forerunners:

I.B.Vasserman et al., Phys. Lett. B 187 (1987) 172 (High precision comparison of (g-2) in e+e- by comparison of the concurrent in-plane precession of e+ & e- spins)

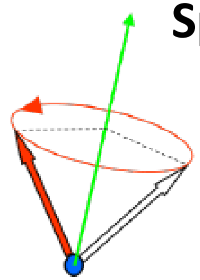
I.M. Sitnik et al., PEPAN Letters No. 2 [111] (2002) (Suggestion to accelarte the in-plane polarized deuterons in Nuclotron)

Spin coherence

Most polarization experiments don't care about coherence of spins along $\vec{n}_s$

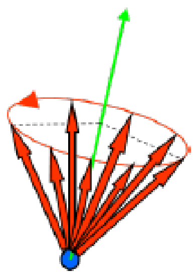
Spins aligned:

Ensemble *coherent*



Spins out of phase:

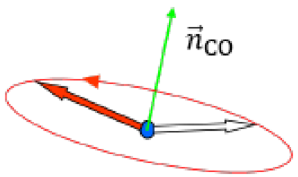
Ensemble *decoherent*



$\Rightarrow$ **Polarization components along $\vec{n}_s$ not affected**

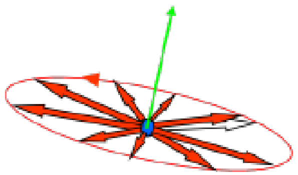
With in-plane spins: $\vec{S} \perp \vec{n}_s$:

Ensemble *coherent*



Over time:

Spins out of phase in horizontal plane



$\Rightarrow$ **In-plane polarization vanishes**

TRIC/TIVOLI:

The conventional method: search for TVPC asymmetry in total X-section with vertical vector polarized protons in the ring and tensor polarized deuterons in the ABS target:

Potential of $A_{TVPC} < 10^{-6}$

Beautiful Appendix in JEDI: Phys.Rev.ST Accel.Beams 17 (2014) no.5, 052803 for precessing in-plane polarization

Need to suppress false signal from vector polarization of deuterons to $< 10^{-6}$

Alternative approach: antilaboratory setting with deuterons in the ring and protons in the ABS

The major issues are:

- What is the tensor polarization of deuterons in the ring?
- Is separation of the TVPC asymmetry possible?
- What is the systematic background? **None !?**

Decomposition of the pd total X-section

$$\sigma_{\rm tot} = \sigma_0 + \sigma_{\rm TT}\left[\left(\mathbf{P}^{\rm d}\cdot\mathbf{P}^{\rm p}\right) - \left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right)\right]$$ PC TT

PC LL $$+\,\sigma_{\rm LL}\left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) + \sigma_{\rm T} T_{mn}k_m k_n$$ PC tensor

$$+\,\sigma^{\rm p}_{\rm PV}\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) + \sigma^{\rm d}_{\rm PV}\left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)$$ PV single spin

$$+\,\sigma^{\rm T}_{\rm PV}\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) T_{mn}k_m k_n$$ PV tensor

$$+\,\sigma_{\rm TVPV}\left(\mathbf{k}\cdot\left[\mathbf{P}^{\rm d}\times\mathbf{P}^{\rm p}\right]\right)$$ TVPV

$$+\,\sigma_{\rm TVPC} k_m T_{mn}\epsilon_{nlr}P^{\rm p}_l k_r \,.$$ TVPC

$$k_m T_{mn}\epsilon_{nlr}P^{\rm p}_l k_r = T_{xz}P^{\rm p}_y - T_{yz}P^{\rm p}_x$$

Ring with RF solenoid as a rotator

$$\vec{S}(n) = \mathbf{R}_{evol}(n)\vec{S}(0)$$

$$\mathbf{R}_{evol}(n) = \mathbf{R}_{idle}(n)\mathbf{R}_{env}(n) = \begin{pmatrix} \cos\theta_s n \cos\epsilon n & \cos\theta_s n \sin\epsilon n & \sin\theta_s n \\ -\sin\epsilon n & \cos\epsilon n & 0 \\ -\sin\theta_s n \cos\epsilon n & -\sin\theta_s n \sin\epsilon n 0 & \cos\theta_s n \end{pmatrix}$$

$$\theta_s = 2\pi\nu_s \qquad \nu_s = G\gamma \qquad \epsilon = \frac{1}{2}\psi_{RF} \qquad \nu_{res} = \frac{\epsilon}{2\pi}$$

$$\vec{S}(n) = S_y(0)[\vec{e}_y \cos\epsilon n + \sin\epsilon n(\vec{e}_x \cos\theta_s n - \vec{e}_z \sin\theta_s n)]$$

$\cos\epsilon n$, $\sin\epsilon n$ -- the envelopes of polarization. Freezing point $\varepsilon n^* = \dfrac{\pi}{2}$

Tensor polarization is entirely driven by evolution of the vector polarization

$$\mathbf{Q}(n) = \mathbf{R}_{evol}(n)\mathbf{Q}(0)\mathbf{R}^T_{evol}(n)$$

$$\langle S_{x,z}(0)\rangle = 0 \rightarrow \langle Q_{yx}(0)\rangle, \quad \langle Q_{yz}(0)\rangle, \quad \langle Q_{xz}(0)\rangle = 0$$

$$\langle Q_{yy}(n)\rangle = \tfrac{1}{2}\langle Q_{yy}(0)\rangle[-1 + 3\cos^2 \epsilon n]\,,$$

$$\langle Q_{xx}(n)\rangle = \tfrac{1}{2}\langle Q_{yy}(0)\rangle[-1 + 3\sin^2 \epsilon n \cos^2 \theta_s n]\,,$$

$$\langle Q_{zz}(n)\rangle = \tfrac{1}{2}\langle Q_{yy}(0)\rangle[-1 + 3\sin^2 \epsilon n \sin^2 \theta_s n]\,,$$ ← $P^P{}_y$ even

$$\langle Q_{yx}(n)\rangle = \tfrac{3}{4}\langle Q_{yy}(0)\rangle \sin 2\epsilon n \cos \theta_s n\,,$$ ← freezes at 0

$$\langle Q_{yz}(n)\rangle = -\tfrac{3}{4}\langle Q_{yy}(0)\rangle \sin 2\epsilon n \sin \theta_s n\,,$$ ← freezes at 0

Unique TVPC → $$\langle Q_{xz}(n)\rangle = -\tfrac{3}{4}\langle Q_{yy}(0)\rangle \sin^2 \epsilon n \sin 2\theta_s n\,,$$ ← $P^P{}_y$ odd

Freeze the RF driven rotation at $\epsilon n = \dfrac{\pi}{2}$ → the idle precession shall continue unimpeded, the vertical vector polarization freezes at 0

COSY Parameters at p_d=0.97 GeV/c:

$$\frac{d\vec{s}}{dt} = \vec{s} \times \vec{\Omega}_s;$$

$$\vec{\Omega}_s = \vec{\Omega} - \vec{\Omega}_{cyc};$$

$$\Omega_{cyc} = \frac{qB}{M\gamma};$$

$$\nu_s = \Omega_s / \Omega_{cyc}$$

$$\theta_s = 2\pi\nu_s$$

$$\nu_s = G\gamma; G = -0.142980;$$

$$resonance \cdot frequency \cdot for \cdot RF \cdot solenoid:$$

$$f_{rf} = (k + \nu_s) f_{COSY}; | f_{rf} = 873 kHz$$

D.Eversmann et al.(JEDI Coll.) PRL 115(2015) 094801

$$\nu_s = -0.16.... \pm 0.97 \times 10^{-8}$$

TVPC asymmetry: signal and backgrounds

$$A_{\mathrm{TVPC}}(n) = -\frac{3}{4} \cdot \frac{\sigma_{\mathrm{TVPC}}}{\sigma_0} T_{yy}(0) P_y^{\mathrm{p}} \cdot \sin^2 \epsilon n^* \cdot \sin 2\theta_s n$$

$\sigma_T T_{zz}(n) \sim \sin^2 \varepsilon n^* \cos 2\theta_s n$ $\quad p_y^p$ - independent

Small departure of εn^* from pi/2 $\quad \Rightarrow p_y^d : \sigma_{TT} p_y^p p_y^d(0) \cos \varepsilon n^*$ $\quad$ Fourier analysis

$p_x^p, p_z^p \Rightarrow: p_y^d(0) \sin \varepsilon n^* (\sigma_{TT} p_x^p \cos\theta_s n - \sigma_{LL} p_z^p \sin\theta_s n)$ $\quad$ Fourier analysis

$\sigma_{PV}^T p_z^p T_{zz}(n) \sim p_z^p \cos 2\theta_s n \cdot \sin^2 \varepsilon n^*$ $\quad$ P_z and PV suppression

In contrast to TRIC:
TVPC and TVPV asymmetries can be extracted simultaneously

Beyond SM T-violating, P-violating & flavor conserving (TVPV) interaction

Enormous theoretical activity: J.de Vries, E.Epelbaum, L.Girlanda, A.Gnech, E.Mereghetti and M.Viviani, Frontiers in Physics, vol.8 (2020) artcle 218; arXiv:2001.09050 [nucl-th], 68 p., 239 refs.

TVPV: crossed proton and deuteron vector polarizations

$$\sigma_{\rm TVPV} \mathbf{k}\cdot\left[\mathbf{P}^{\rm d}\times\mathbf{P}^{\rm p}\right]$$

Oscillating horizontal deuteron polarization, vertical proton polarization

$$\mathbf{k}\cdot\left[\mathbf{P}^{\rm d}\times\mathbf{P}^{\rm p}\right] = P_x^{\rm d}(n)\,P_y^{\rm p} \propto P_y^{\rm p}\,\sin\epsilon n^* \cdot\cos\theta_s n$$

Vertical deuteron polarization, radial proton polarization

$$\sigma_{\rm TVPV} \mathbf{k}\cdot\left[\mathbf{P}^{\rm d}\times\mathbf{P}^{\rm p}\right] \propto P_y^{\rm d}(0)\,P_x^{\rm p}\cos\epsilon n\,,$$

is P_x^p – odd, can be distinguished from oscillating $\sigma_{TT} p_x^d(n) p_x^p \sim \sin\varepsilon n^* \cdot \cos\theta_s n$

Invoke still another Fourier marker: longitudinal "guide" B-field → oscillating radial & vertical proton polarization ?

Are measurements of very small asymmetries feasible?

Counting 10^{15} -10^{16} events is a major challenge. Measure currents instead?

Valdau et al. (2016): test stand experiment with Bergoz Fast Current Transformer and Lock-in Amplifier --- the COSY bunches simulated by pulsed current in the wire

Optomistic conclusion: the cross section asymmetry of 10^{-6} (vector polarized protons in COSY impinging on xz tensor polarized deuterons in the ABS target) is within the reach of 1 month run with FCT already in the COSY ring.

Requires a comparison of attenuation of +/- polarized beams from different cycles

The reverse kinematics: precessing polarization measures the difference of +/- polarized beams concurrently in the same cycle.

Compared to Valdau et al case we need to isolate a signal of the time modulated attenuation of the bunch current. The feasibility analysis is in progress.

Repeat the Valdau et al. test stand expt with RF modulated pulses .

Summary:

- σ_{TVPC} is a true null-test TVPC observable. Not affected by ISI & FSI.
  Analog of EDM being a null-test signal for TVPV.
- Tp dependence of σ_{TVPC} is predicted within the Glauber theory of pd-pd.
  "Unexpected" zeros.

- Search for TVPC can be done at any beam energy (COSY, NICA…), but at Tp<1.3 GeV the modulation factor can be eliminated using NN data and Glauber theory

- Simple description of the RF driven evolution of the tensor polarization of injected vertically polarized deuterons

- No background to the oscillating TVPC-like signal from the static vector polarization of deuterons

- Fourier analysis of oscillation spin asymmetries in conjunction with the reversal of the p^p_y provides an unique determination of TVPC and simultaneously TVPV signals. As a by product, measurement in the same setup of the whole family of single and double spin observables

THANK YOU FOR YOUR ATTENTION!

$$i\frac{\partial\psi(t)}{\partial t} = \mathcal{H}\psi(t)$$

$t \to -t$ and $\psi(-t) \to \psi^*(-t)$,
if $H = H^*$ then $\psi'(t) = \psi^*(-t)$ is a solution of Eq. (1).

In general case, the T-transformation $t \to t = -t$:

$$\psi'(t') = T\psi(-t), Q' = TQT^{-1}$$

T-inversion: $\mathbf{x}' = \mathbf{x}$, $\mathbf{p}' = -\mathbf{p}$,
$\mathbf{L} = [\mathbf{r} \times \mathbf{p}] \to -\mathbf{L}$, and, therefore, $\boldsymbol{\sigma} \to -\boldsymbol{\sigma}$
Then $[p_i, x_j] = -i\delta_{ij}$ requires

$$TiT^{-1} = -i$$

Thus, T is an antilinear operator.
The operator T must have the properties:
$T = UK,\ KzK^{-1} = z^*,\ \ UU^+ = 1$,
K is the operator for complex congugation
$K^2 = 1$, $K^{-1} = K$, $T^{-1} = KU^+$
$T\psi = U\psi^*$

The T-invariance:

$$T\mathcal{H}T^{-1} = \mathcal{H},$$

then the S-matrix

$$S = \lim_{t_1\to\infty} \lim_{t_2\to\infty} = \exp^{-i\mathcal{H}(t_2-t_1)},$$

transforms as

$$T\mathcal{S}T^{-1} = \mathcal{S}^+,$$

or $T^{-1}\mathcal{S}^+T = \mathcal{S}$. Therefore (T is antilinear)

$$< f, S\, i >=< f, T^{-1}S^+T\, i >=< Tf, S^+T\, i >^*=< f_T, S^+ i_T >^*$$

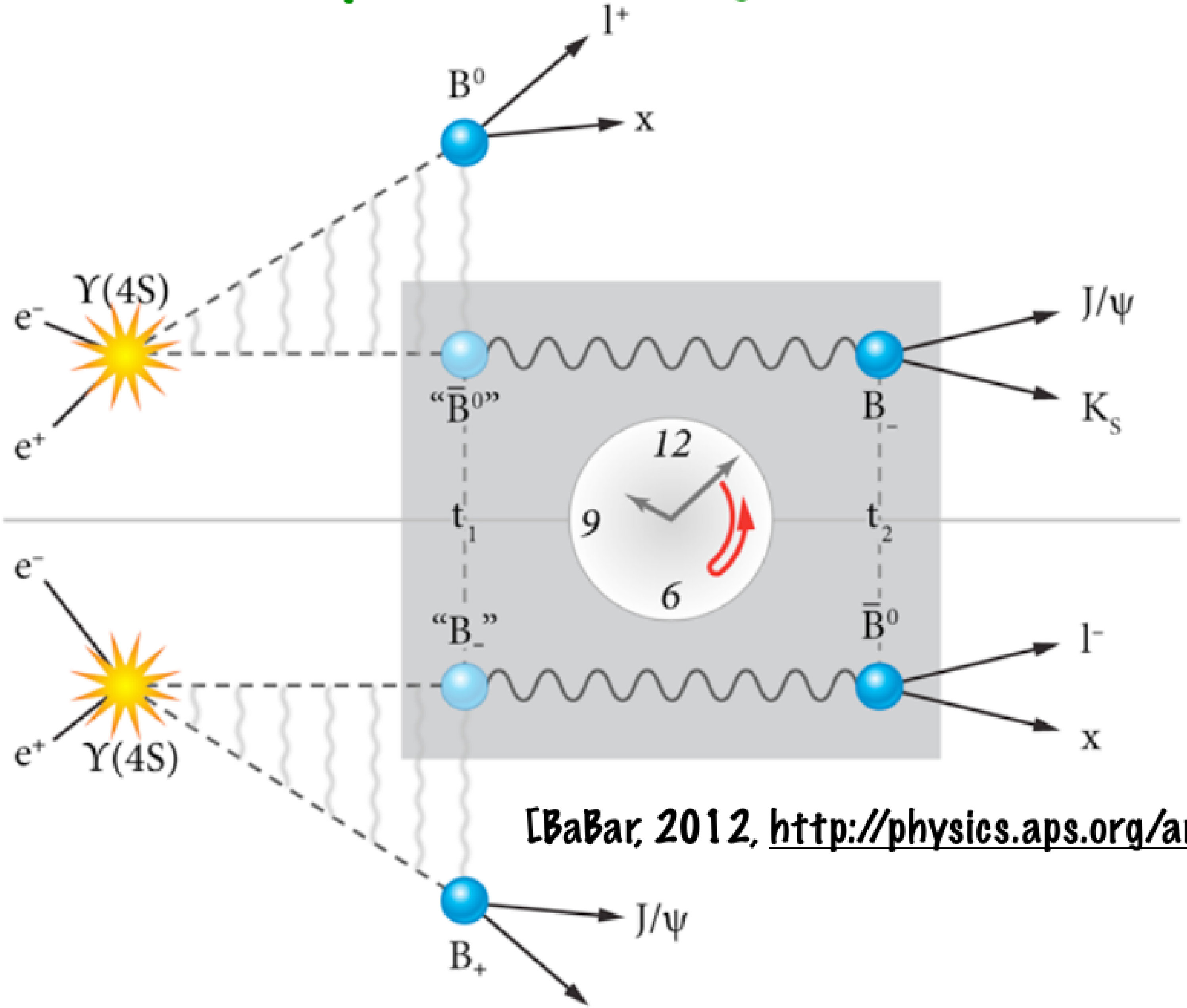
in other words, the T-invariance:

$$< f|\mathcal{S}|i >=< i_T|S|f_T >$$

(See, S.M. Bilen'kii, L.I. Lapidus, R.M. Ryndin, Usp. Phys. Nauk. 95 (1968) 489
J.R.Taylor, Sattering Theory. Quantum theory of Nonrelativistic collisions, N-Y, 1972)

$$S^J_{a,b} = S^J_{b,a}$$

Direct Observation of T violation in the B system via "quantum entanglement"



[BaBar, 2012, http://physics.aps.org/articles/v5/129]

Analysis Framework

Suppose new physics enters at an energy scale

$$E > \Lambda$$

Then for $E < \Lambda$ we can extend the SM as per

$$\mathcal{L}_{\rm SM} \Longrightarrow \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^D \,,$$

where the new operators have mass dimension D>4

and we impose $SU(2)_L \times U(1)$ gauge invariance

on the operator basis

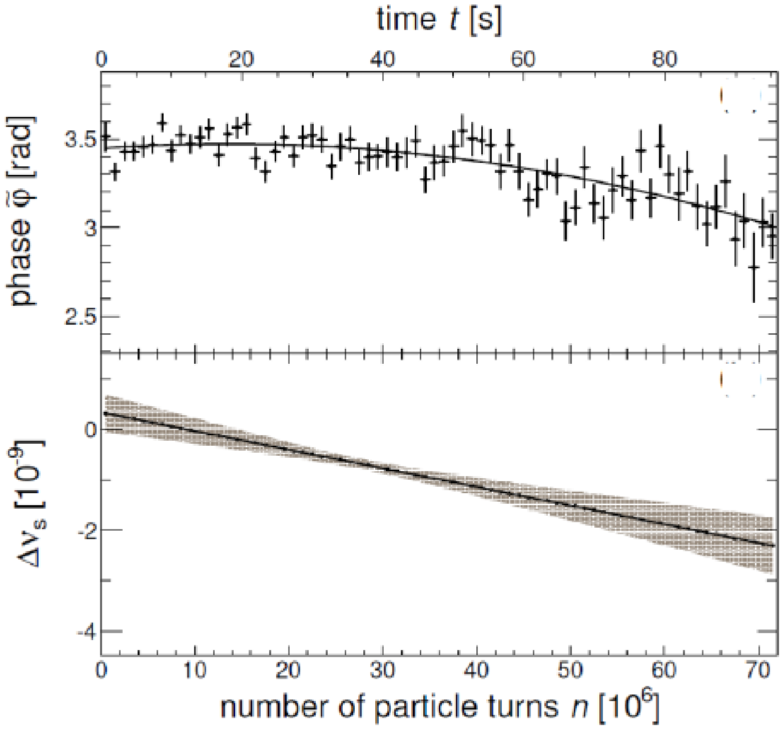
Determination of spin tune [15]

$\theta_S = 2\pi\nu_S$ is spin precession angle per turn,
ν_S is the spin tune

Analyze all time intervals:

- Monitor phase of measured asymmetry with assumed fixed spin tune ν_s^{fix} in a 100 s cycle:

$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} \qquad (6)$$
$$= \nu_s^{\text{fix}} + \Delta\nu_s(n)$$



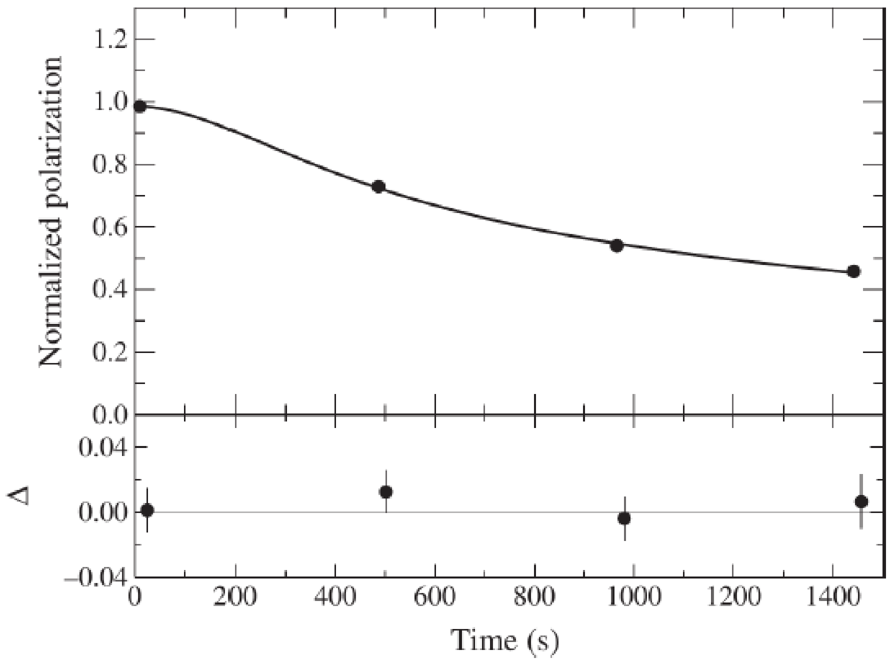
Experimental technique allows for:

- Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval.
- In a 100 s cycle at $t \approx 38$ s, interpolated spin tune amounts to $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$, *i.e.*, $\Delta\nu_s/\nu_s \approx 10^{-10}$.

$\Rightarrow$ **New precision tool to study systematic effects in a storage ring.**

Koop-Shatunov technique of tuning the chromaticity

Optimization of spin-coherence time [17]



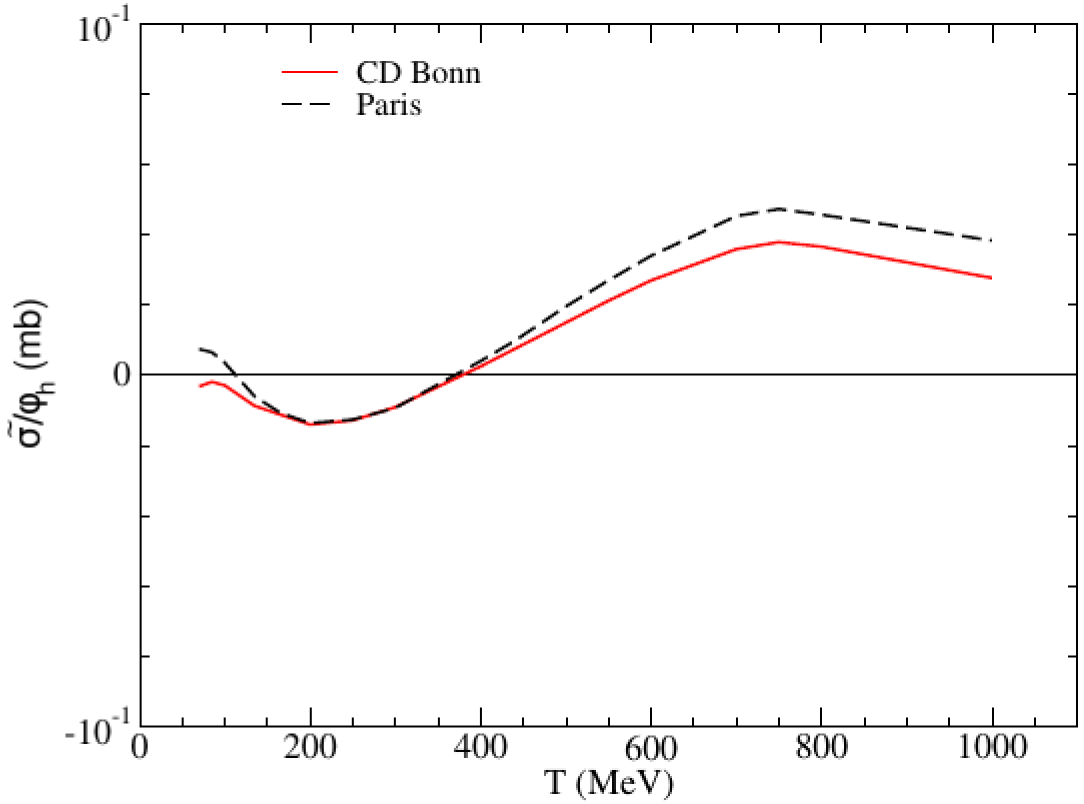
JEDI progress on τ_{SCT}:

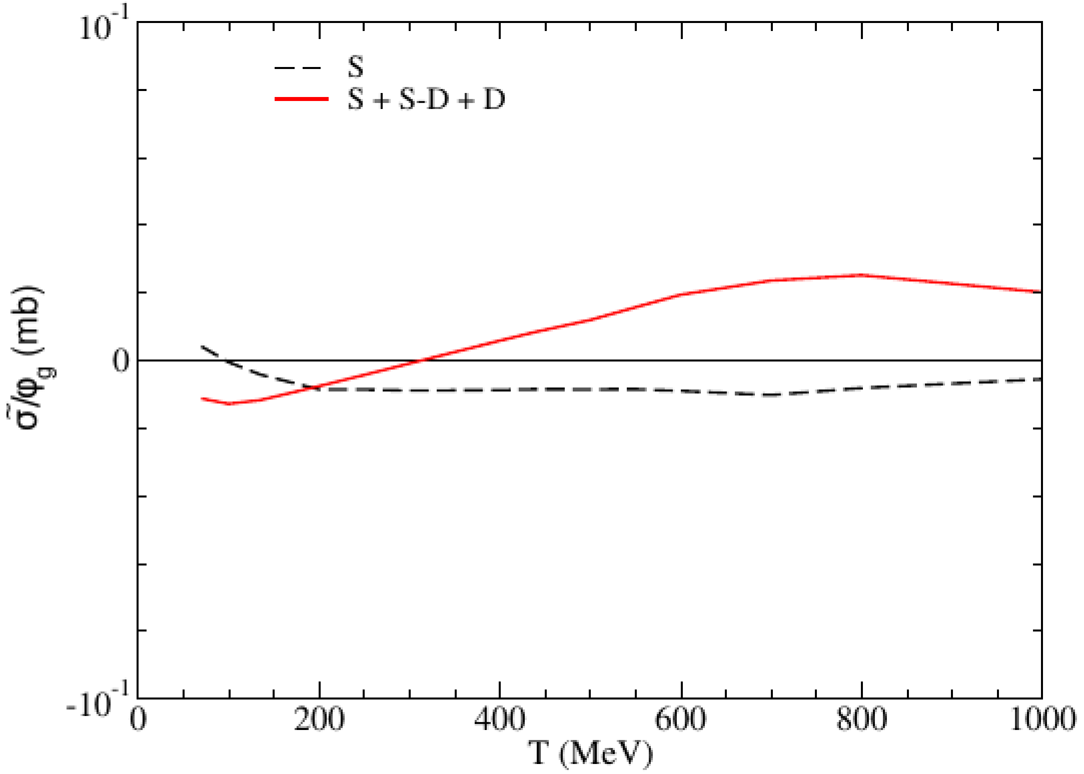
$$\tau_{SCT} = (\mathbf{782} \pm \mathbf{117})\,\text{s}$$

- Previous record: $\tau_{SCT}(\text{VEPP}) \approx 0.5\,\text{s}$ [16] ($\approx 10^7$ spin revolutions).

In 2015, way beyond expectation:

- With about 10^9 stored deuterons.
- Spin decoherence considered one main obstacle of srEDM experiments.





Yu.N. Uzikov, J.Haidenbauer, PRC 94 (2016) 035501