Test of T-invariance in Double Polarized Scattering of ^{3}He Nuclei on Deuterons

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CONTENT

- Motivation (**BAU**)
  P-even Time-Reversal Invariance test (TIVOLI experiment) planned at COSY
  in pd at 135 MeV. Theory: Yu.N.U., A. Temerbayev ,PRC 92 (2015); Yu.U., Haidenbauer, PRC 94(2016)
  ^{3}He-d, d-d ? NICA SPD?
- Phenomenology of T-invariance Violating P-parity conserving (TVPC) NN interactions
- Null-test signal TVPC for ^{3}He-d scattering:
  model-independent formalism;
  Glauber spin-dependent theory for p^{3}He- , pd- and ^{3}He-d elastic scattering;
  numerical results at 0.1- 1 GeV
- Conclusion

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Why search for Time-invariance Violation?

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)

SM: Estimates of baryon excess much too small, $n_B / n_\gamma \approx 5 \times 10^{-19}$

☛ $(n_B - n_{\bar{B}})$ larger than expected → new sources of $\not{C}\not{P}$ needed

Sakharov: Three Requirements:

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

A. Sakharov; JETP Lett, 5, 24

There must be CP violation beyond the SM. (B.H.J. McKellar, AIP Conf. Proc. 1657 (2015) 030001)

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

Talks by Y. Semertzidis, Yu. Senichev, A. Aksentev, A. Melnikov , I. Obraztsov this conf.

is much less 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.

See S.N. Vergeles, N.N. Nikolaev, Yu.N. Obukhov, A.Yu. Silenko, O. Teryaev, UFN **66** (2023) 109

Why search for Time-invariance Violating P-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: $\mathbf{g \sim M^4 G_F^2} \sin\delta \sim \mathbf{10^{-10}}$

  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.**

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)

$$S^{J}_{a,b} = S^{J}_{b,a}$$

EDM and TVPC interactions

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

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

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

A.Kurylov, G.C. McLaughlin, M.Ramsey-Musolf , PRD 63(2001)076007:

EDM at energies below Λ_{TVPC}

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

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

TVPC scale and EDM

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)

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)

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

See S. N. Vergeles, N.N. Nikolaev, Yu.N. Obukhov, A.Yu. Silenko, O. Teryaev, UFN **66** (2023) 109

TIVOLI –exp. planned at COSY, T_p=135 MeV; P. Lenisa et al. EPJ Tech. Instr. (2019) 6

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

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 $A_{TVPC} \sim 10^{-6}$

pd TRANSMISSION experiment

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;
M.N. Platonova, V.I. Kukulin, Phys. Rev. C **81**, 014004 (2010)

Search for TVPC signal in double polarized pd and ^{3}He-d scattering

Phenomenology of the ^{3}Hed-^{3}Hed *transition*

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

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

TVPC NN interactions

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 $I^G(J^{PC}) = 0^-(1^{+-})$ ...

On-shell TVPC NN interaction potentials

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

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

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

$$T: \vec{p}_i \to -\vec{p}_f, \vec{p}_f \to -\vec{p}_i \Rightarrow \vec{p} \to -\vec{p}, \vec{q} \to \vec{q}$$

$$\vec{n} = [\vec{q} \times \vec{p}] \to -\vec{n}, \vec{\sigma} \to -\vec{\sigma};$$

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, $M^{str}_{pn\to np} = M^{str}_{np\to pn}$.

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

^3Hed

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

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:

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

Total polarized cross sections pd or ^{3}He-d scattering

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

with

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

/Yu.N. Uzikov, J. Haidenbauer, PRC **87** (2013) 054003/

$$\widetilde{\sigma}_{tvpc} = -\frac{4\pi}{k} Im \frac{2}{3} \widetilde{g}_5 \qquad (7)$$

/Yu.N. Uzikov, A.A. Temerbayev, Phys. Rev. C **92** (2015)/

TVPC-amplitude $\widetilde{g}_5$.

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

where $\mathbf{h_N}$, $\mathbf{g_n}$ **are TVPC constants**,

Deuteron form factors

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

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

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

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

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

Measurement of total $\widetilde{\sigma}_{tvpc}$ in $\vec{p}-\vec{d}$ scattering: and in ^{3}He-d:

- independent on dynamics
- 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 pro...

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*

TVPC signal in double polarized ^{3}He-d scattering

- ^{3}He – d has the ½+ 1 spin structure as in pd.
- Polarization of ^{3}He in S-wave approximation caused solely by the polarization of the neutron.
- ^{3}He –d scattering within the Glauber model can be considered like p-d with replacement of the pN-amplitudes by the p^{3}He ones.
- Does g' –term of TVPC nonvanishing contribution to the null-test signal in ^{3}He-d?

$$p^3He \to p^3He:$$

$$F = A_1 + A_2\boldsymbol{\sigma}(p)\hat{\mathbf{n}} + A_3\boldsymbol{\sigma}(\tau)\hat{\mathbf{n}} + A_4(\boldsymbol{\sigma}(p)\cdot\hat{\mathbf{k}})(\boldsymbol{\sigma}(\tau)\cdot\hat{\mathbf{k}})$$
$$+(A_5 + A_6)(\boldsymbol{\sigma}(p)\cdot\hat{\mathbf{q}})(\boldsymbol{\sigma}(\tau)\cdot\hat{\mathbf{q}}) + (A_5 - A_6)(\boldsymbol{\sigma}(p)\cdot\hat{\mathbf{n}})(\boldsymbol{\sigma}(\tau)\cdot\hat{\mathbf{n}})$$
$$\underline{+h_{\tau N}[(\boldsymbol{\sigma}(p)\cdot\hat{\mathbf{k}})(\boldsymbol{\sigma}(\tau)\cdot\hat{\mathbf{q}}) + (\boldsymbol{\sigma}(\tau)\cdot\hat{\mathbf{q}})(\boldsymbol{\sigma}(p)\cdot\hat{\mathbf{k}}) - \frac{2}{3}(\boldsymbol{\sigma}(\tau)\cdot\sigma(p))(\mathbf{q}\cdot\hat{\mathbf{k}})]}$$
$$+\underline{g_{\tau N}[\boldsymbol{\sigma}(p)\times\boldsymbol{\sigma}(\tau)]\cdot[\hat{\mathbf{q}}\times\hat{\mathbf{k}}]}$$
$$+\underline{g'_{\tau N}(\boldsymbol{\sigma}(p) - \boldsymbol{\sigma}(\tau)\cdot i[\hat{\mathbf{q}}\times\hat{\mathbf{k}}][\boldsymbol{\tau}(p)\times\tau(\tau)]_z}$$

$$\hat{\mathbf{k}} = \frac{\mathbf{p}+\mathbf{p}'}{|\mathbf{p}+\mathbf{p}'|}, \hat{\mathbf{q}} = \frac{\mathbf{p}'-\mathbf{p}}{|\mathbf{p}'-\mathbf{p}|}, \hat{\mathbf{n}} = [\hat{\mathbf{k}}\times\hat{\mathbf{q}}]$$

Spin amplitudes: A_1,…, A_6,$h_{tau\ N,}$ $g_{tau\ N}$, $g'_{tau\ N}$

$$\frac{d\sigma}{d\Omega} = \frac{1}{4} TrFF^{+} = \Sigma,$$

$$\Sigma = |A_1|^2 + |A_2|2 + |A_3|^2 + |A_4|^2 + |A_5 + A_6|^2 + |A_5 - A_6|^2,$$

$$A_y = TrF\hat{\sigma}_y(p)F^{+}/TrFF^{+},$$

$$A_y^p = 2Re[A_1 A_2^* + (A_5 - A_6)A_3^*]\Sigma^{-1},$$

$$C_{y,y} = \frac{TrF\sigma_y(p)\sigma_y(\tau)F^{+}}{TrFF^{+}} = 2\{ReA_1(A_5^* - A_6^*) - A_4(A_5^* - A_6^*)\}\Sigma^{-1}.$$

Polarization of final proton: $P_y = \frac{TrFF^{+}\sigma_y(p)}{TrFF^{+}}$

T-invariance: $A_y^p = P_y^p$

Glauber theory for p^{3}He and n^{3}He elastic scattering

$$f(\vec{k}',\vec{k}) = \frac{ik}{2\pi}\int d^2b e^{i(\vec{k}-\vec{k}')\cdot\vec{b}}(1-e^{i\chi(\vec{b})}), (1)$$

$^3He:$

$$\chi(\vec{b},\vec{s}_1,\vec{s}_2,\vec{s}_3) = \chi(\vec{b}-\vec{s}_1)+\chi(\vec{b}-\vec{s}_2)+\chi(\vec{b}-\vec{s}_3); (2)$$

$$\Gamma = 1-e^{i\chi}, (3)$$

$$\Gamma = \Gamma_1+\Gamma_2+\Gamma_3-\Gamma_1\Gamma_2-\Gamma_1\Gamma_3-\Gamma_2\Gamma_3+\Gamma_1\Gamma_2\Gamma_3. (4)$$

$$\Gamma = \frac{1}{2\pi ik}\int e^{i\vec{q}(\vec{b}-\vec{s})}f(\vec{q})d^2q, (5)$$

$$\Psi^A = \psi_x{}^S \xi^a;$$

Antisymmetric full wave function of ^{3}He

$$\xi^a = \frac{1}{\sqrt{2}}(\chi'\rho'' - \chi''\rho') - spin - isospin$$

$$\chi' = \frac{1}{\sqrt{2}}\alpha_1(\alpha_2\beta_3 - \alpha_3\beta_2); \alpha = |+\frac{1}{2}>, \beta = |-\frac{1}{2}>$$

$S_{23}=0$

$$\chi'' = \frac{1}{\sqrt{6}}[\alpha_1(\alpha_2\beta_3 + \alpha_3\beta_2) - 2\beta_1\alpha_2\alpha_3];$$

$S_{23}=1$

$$\psi_x{}^S = Ne^{-c^2(r_1^2+r_2^2+r_3^2)};$$

Symmetic s^3

$$F^{(1)} = \frac{3k_{p\tau}}{k_{pN}} S(q) < \xi^a | f_1(\vec{q}) | \xi^a >;$$

Single scattering

$$F^{(2)} = -\frac{3k_{p\tau}}{2\pi i(k_{pN})^2} S(\frac{q}{2}) \int d^2q' S(\sqrt{3}q') < \xi^a | f_1(\vec{q}_1) f_2(\vec{q}_2) | \xi^a >;$$

Double scattering

$$F^{(3)} = -\frac{k_{p\tau}}{4\pi^2(k_{pN})^3} \int d^2q' \int d^2q'' S(\sqrt{3}q') S(\frac{3q''}{2}) < \xi^a | f_1(\vec{q}_1) f_2(\vec{q}_2) f_3(\vec{q}_3) | \xi^a >$$

Triple sc.

THE MOST CUMBERSOME TASK:
spin matrix elements of products of pN spin-operators and extraction of invariant spin amplitudes of N-^{3}He scattering

$$M_N(\mathbf{p},\mathbf{q};\boldsymbol{\sigma},\boldsymbol{\sigma}_N) = A_N + C_N\boldsymbol{\sigma}\hat{\mathbf{n}} + C'_N\boldsymbol{\sigma}_N\hat{\mathbf{n}} + B_N(\boldsymbol{\sigma}\hat{\mathbf{k}})(\boldsymbol{\sigma}_N\hat{\mathbf{k}}) + (G_N + H_N)(\boldsymbol{\sigma}\hat{\mathbf{q}})(\boldsymbol{\sigma}_N\hat{\mathbf{q}}) + (G_N - H_N)(\boldsymbol{\sigma}\hat{\mathbf{n}})(\boldsymbol{\sigma}_N\hat{\mathbf{n}})$$

T-even P-even TCPC pN amplitudes

$$\mathbf{q} = (\mathbf{p} - \mathbf{p}'),\ \ \mathbf{k} = (\mathbf{p} + \mathbf{p}')\ \ \text{and}\ \ \mathbf{n} = [\mathbf{k}\times\mathbf{q}]$$

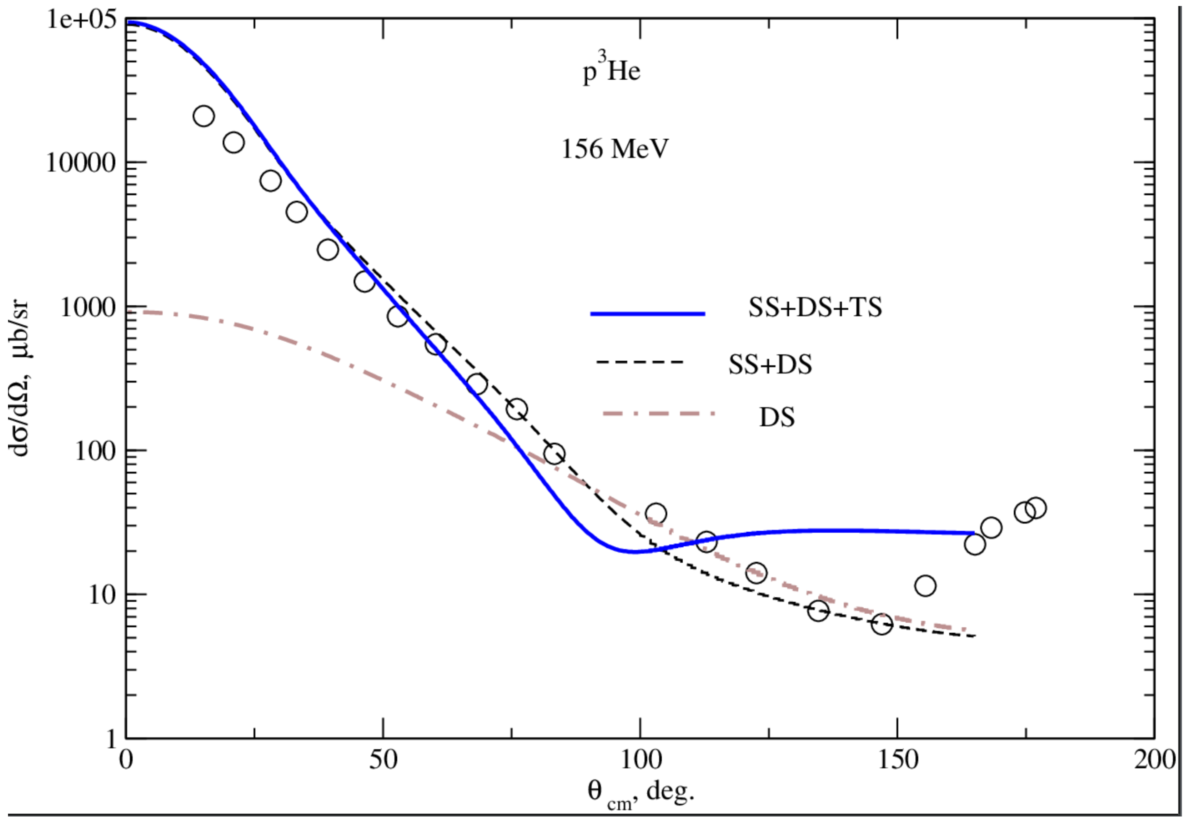
Double scattering ~$M_N(q_1)M_N(q_2)$

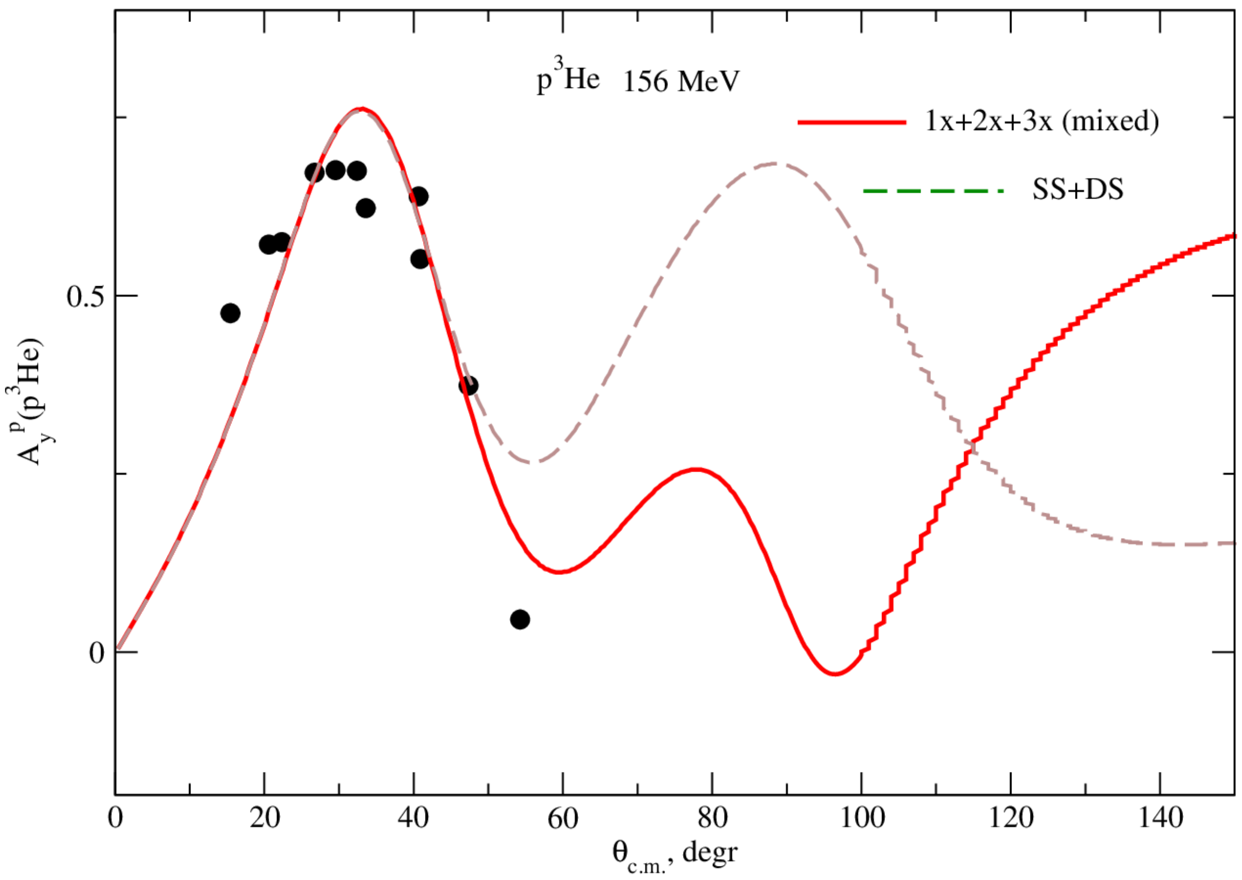
Triple scattering ~$M_N(q_1)M_N(q_2)M_N(q_3)$

$$t_{pN} = h_N[(\boldsymbol{\sigma}\cdot\mathbf{k})(\boldsymbol{\sigma}_N\cdot\mathbf{q}) + (\boldsymbol{\sigma}_N\cdot\mathbf{k})(\boldsymbol{\sigma}\cdot\mathbf{q}) - \tfrac{2}{3}(\boldsymbol{\sigma}_N\cdot\boldsymbol{\sigma})(\mathbf{k}\cdot\mathbf{q})]/m_p^2 + g_N[\boldsymbol{\sigma}\times\boldsymbol{\sigma}_N]\cdot[\mathbf{q}\times\mathbf{k}][\boldsymbol{\tau}-\boldsymbol{\tau}_N]_z/m_p^2 + g'_N(\boldsymbol{\sigma}-\boldsymbol{\sigma}_N)\cdot i\,[\mathbf{q}\times\mathbf{k}][\boldsymbol{\tau}\times\boldsymbol{\tau}_N]_z/m_p^2.$$

TVPC pN

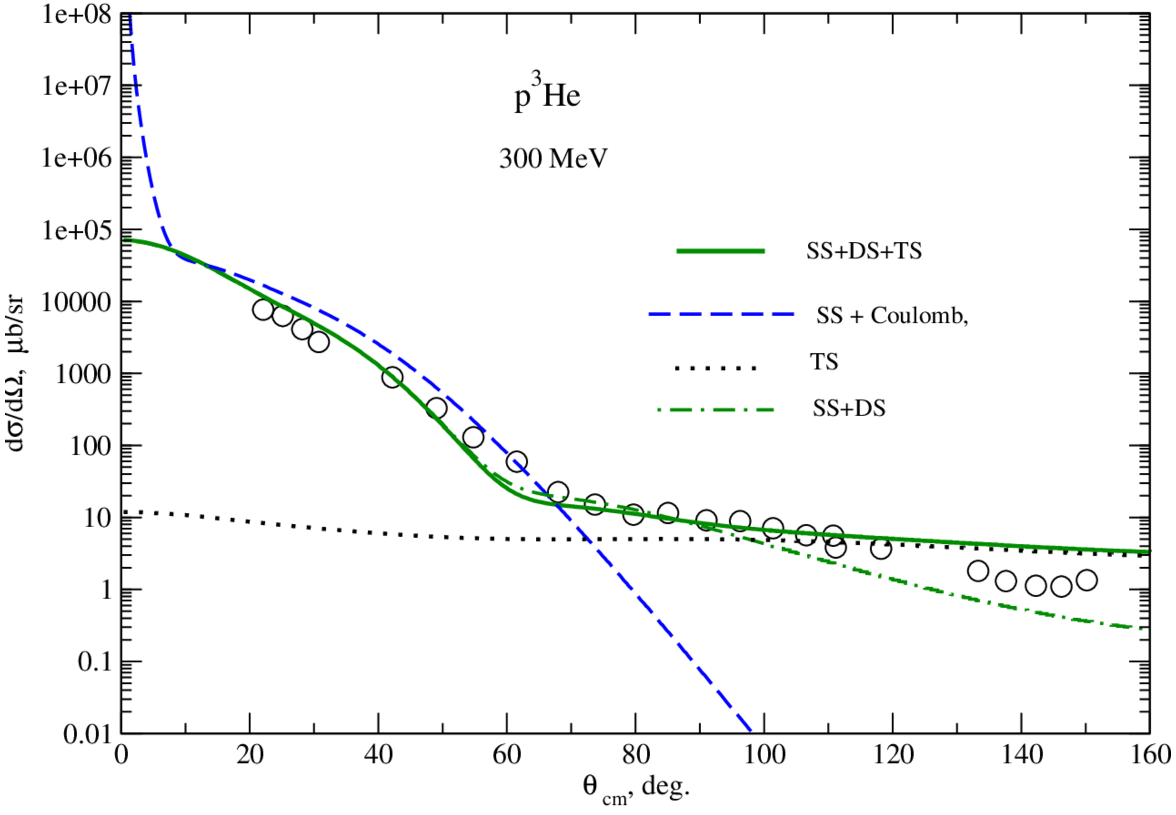
NUMERICAL RESLUTS for p^{3}He

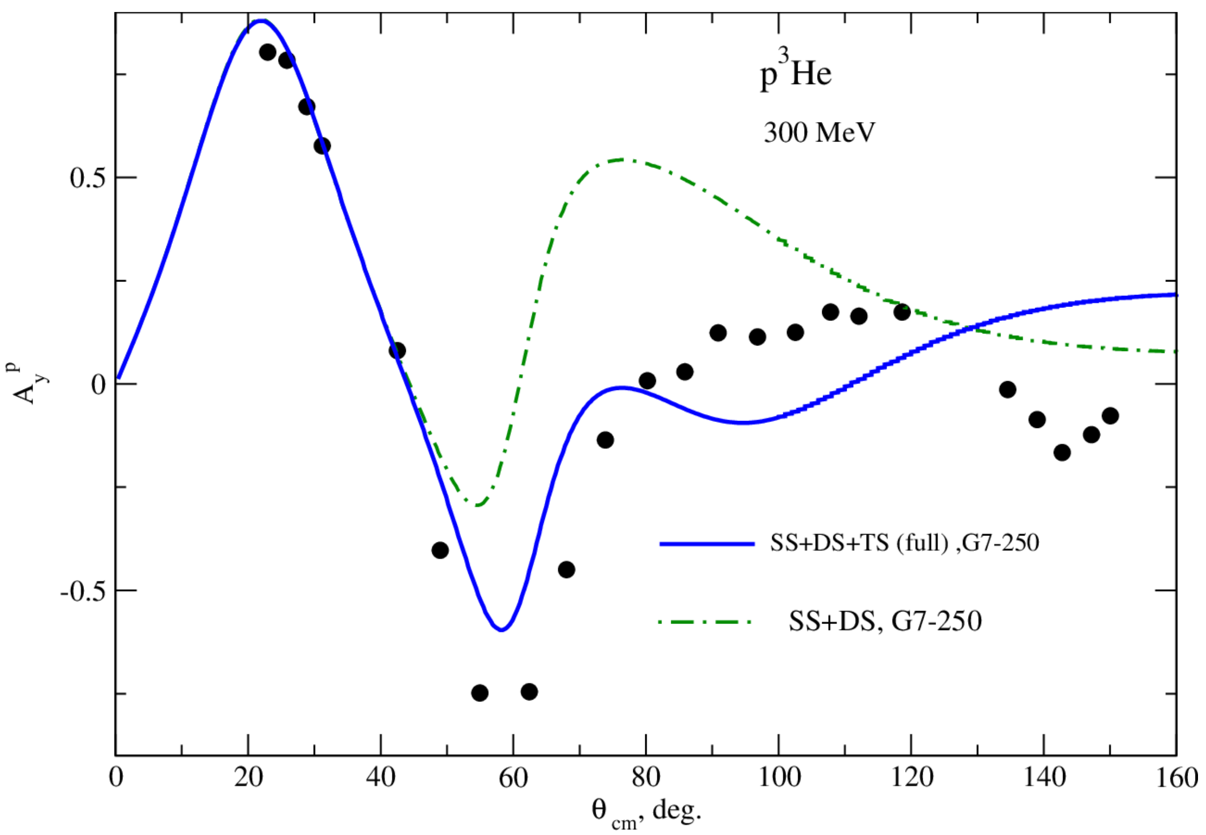




Exp. data : D.K. Hasell et al., Phys.Rev. C34 (1986) 236

NUMERICAL RESULTS p^3He





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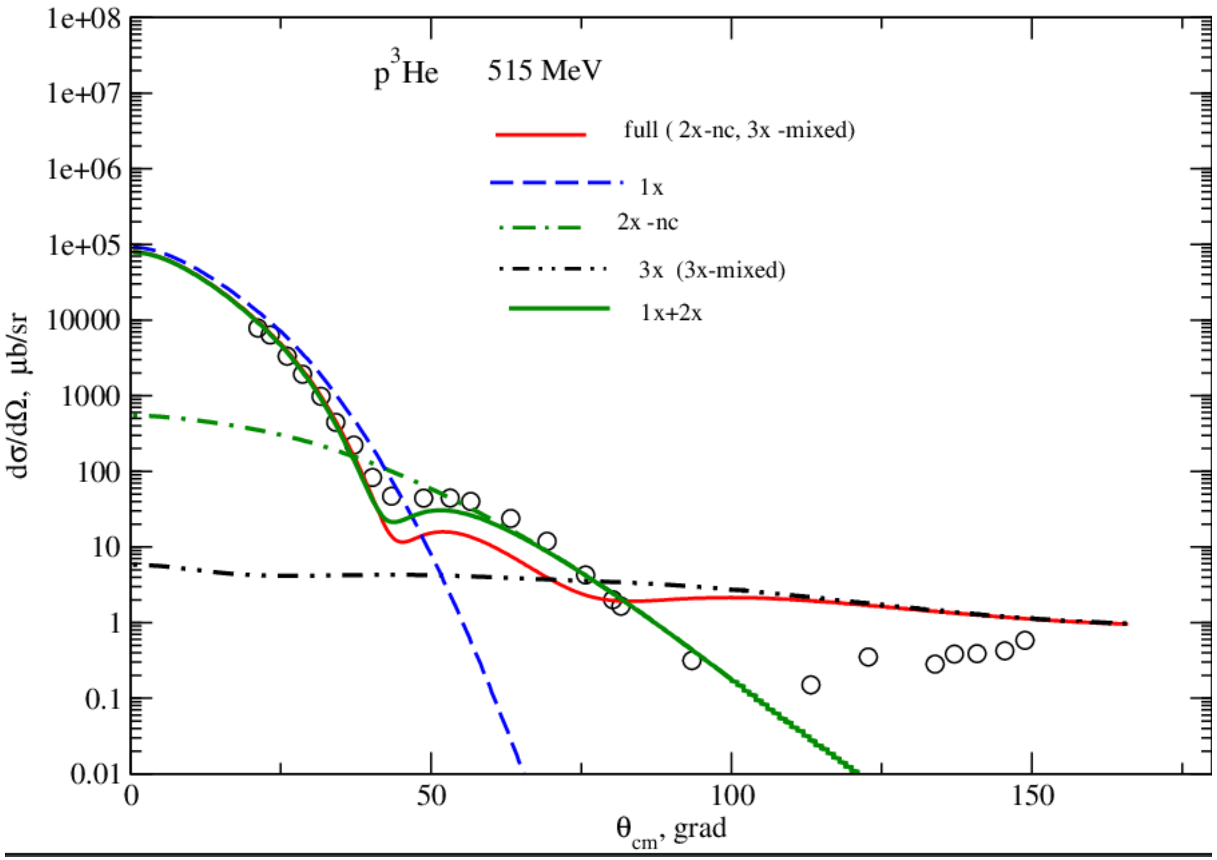
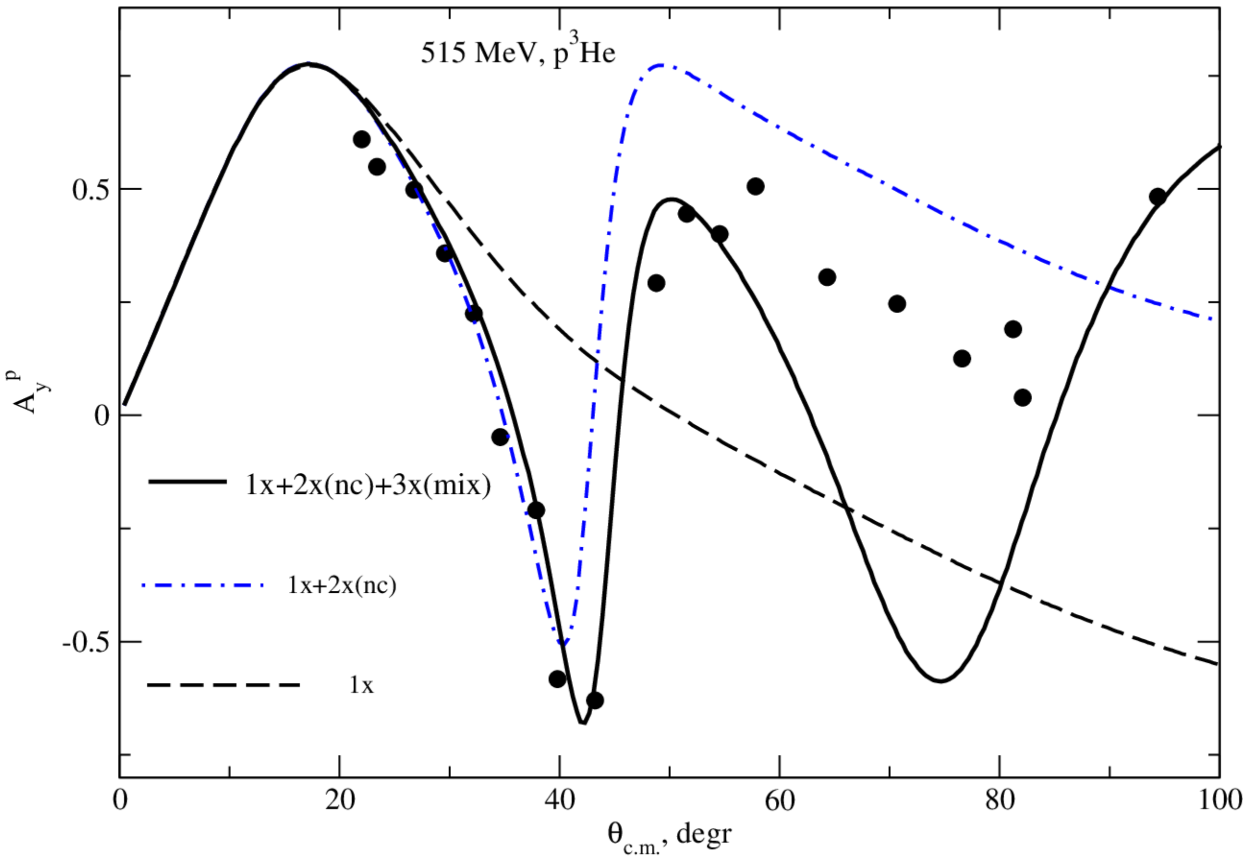
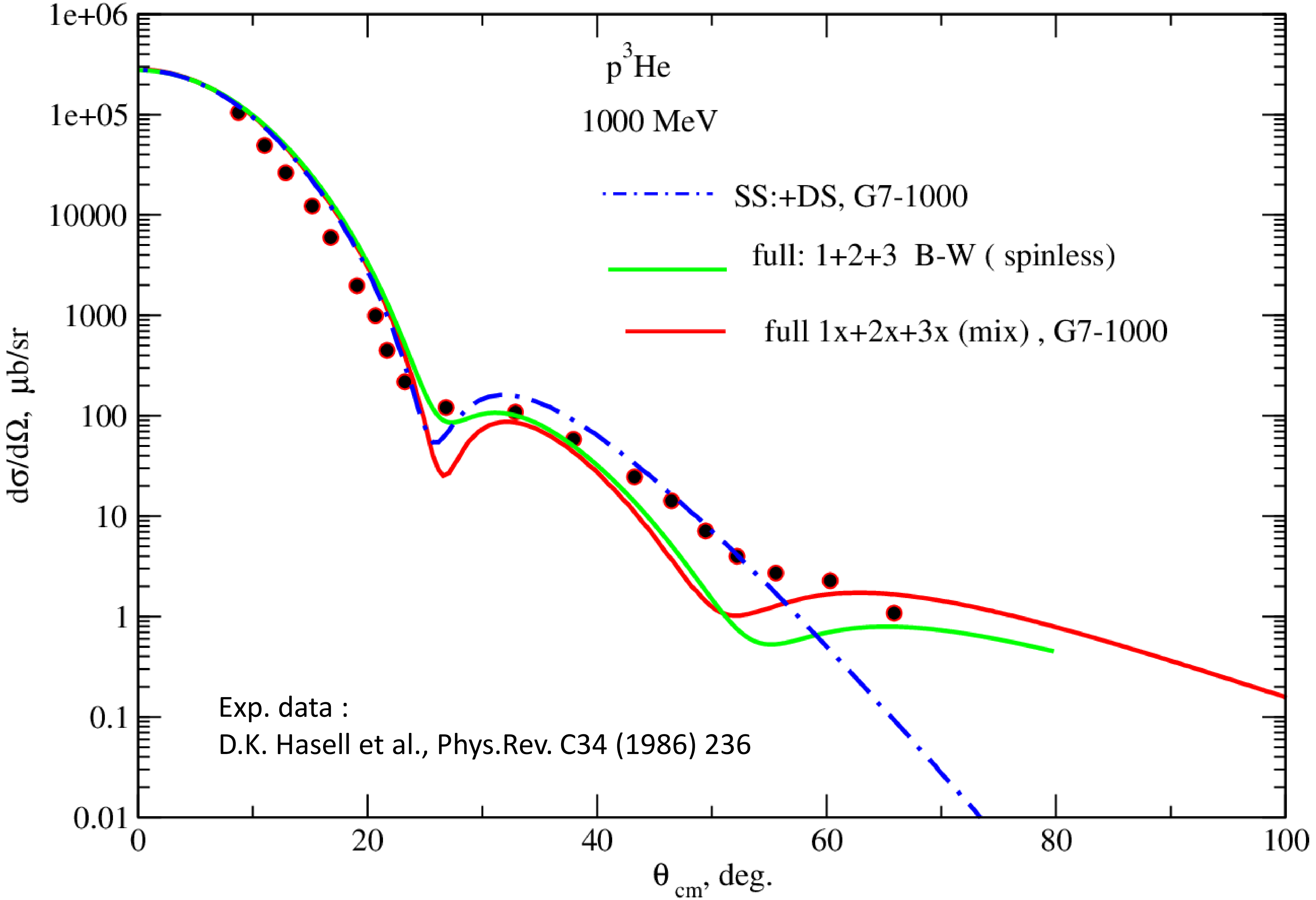
NUMERICAL RESULTS p^3He

Exp. data : D.K. Hasell et al., Phys.Rev. C34 (1986) 236



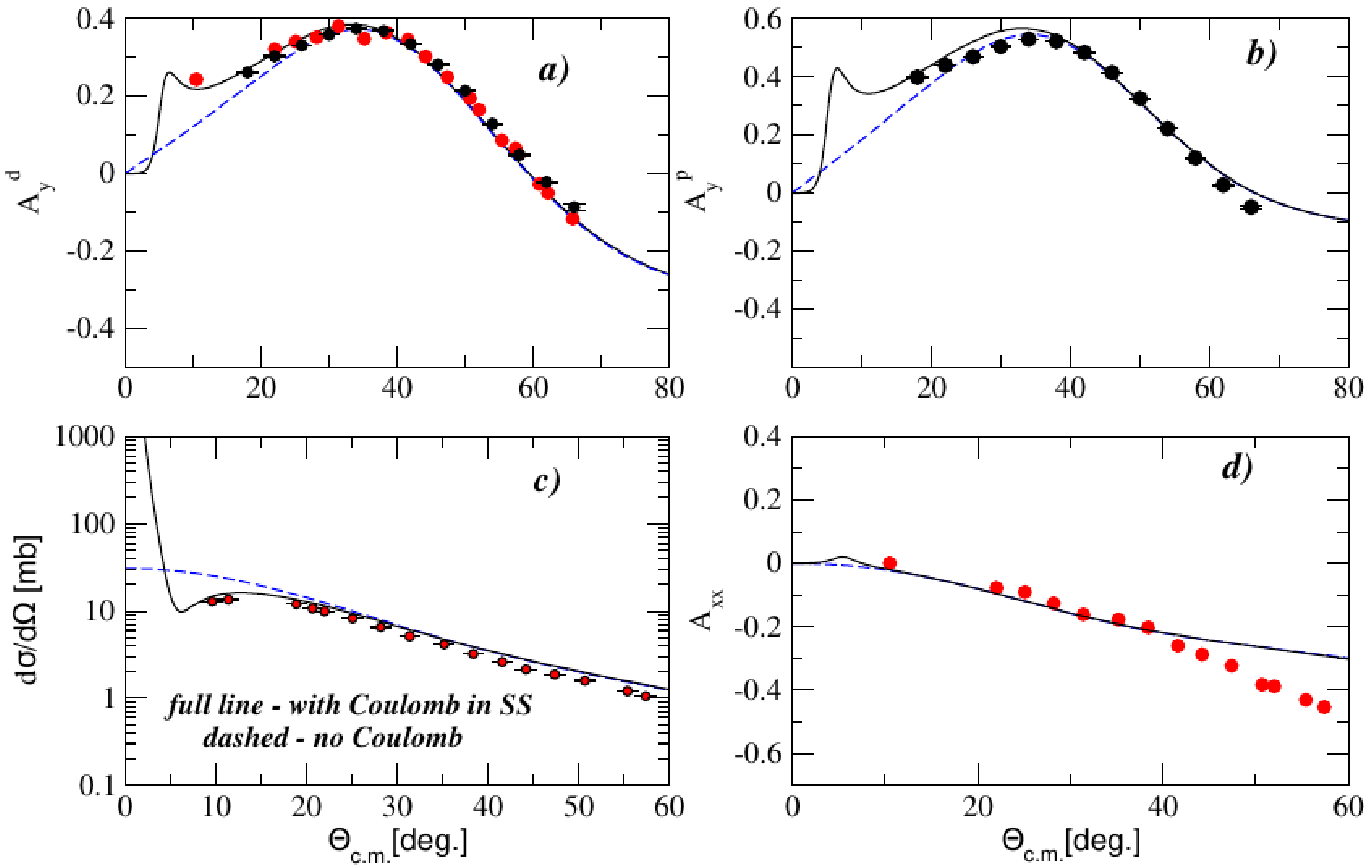



p^{3}He
1000 MeV
SS:+DS, G7-1000
full: 1+2+3 B-W (spinless)
full 1x+2x+3x (mix) , G7-1000
Exp. data :
D.K. Hasell et al., Phys.Rev. C34 (1986) 236
dσ/dΩ, μb/sr
θ cm, deg.
1e+06
1e+05
10000
1000
100
10
1
0.1
0.01
0
20
40
60
80
100

- pd elastic scattering within the spin-dependent Glauber theory
- Extension to ^{3}Hed elastic scattering via replacement of pN by the ^{3}HeN amplitudes

Test calculations: pd elastic scattering at 135 MeV

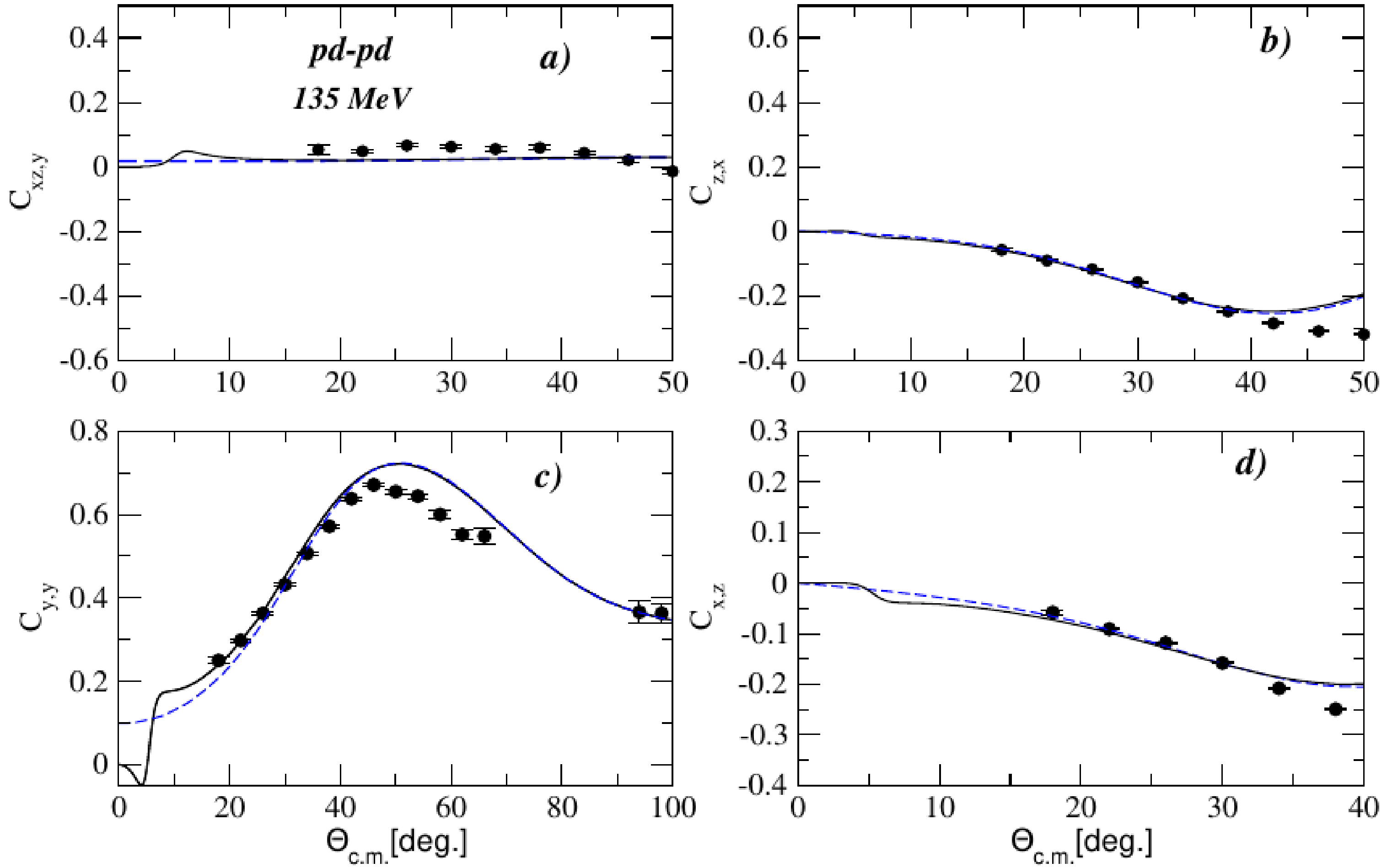
A.A. Temerbayev, Yu.N.Uzikov, Yad. Fiz. **78** (2015) 38



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.

Test calculations-II: pd elastic scattering at 135 MeV

Double polarized scattering



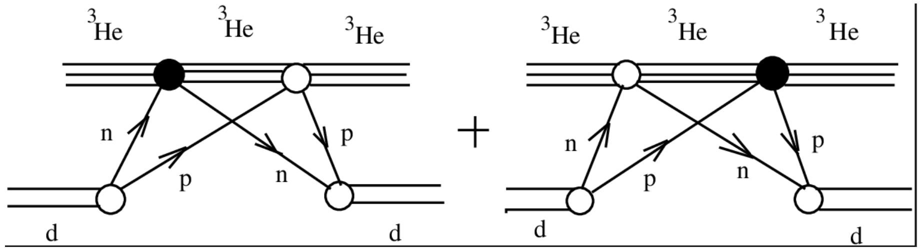
Curves: the modified Glauber model; A.A. Temerbayev, Yu.N.Uzikov, Yad. Fiz. **78** (2015) 38

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

TVPC Null-test signal in ^{3}He-d scattering

pd : Yu.N. U., J. Haidenbauer, PRC, 94 (2016)

$$\tilde{g} = \frac{i}{4\pi m_p}\int_0^\infty dq q^2\Big[S_0^{(0)}(q) - \sqrt{8}S_2^{(1)}(q) - 4S_0^{(2)}(q) + \sqrt{2}\frac{4}{3}S_2^{(2)}(q) + 9S_1^{(2)}(q)\Big][-C'_n(q)h_p + C'_p(q)(g_n - h_n)]$$



$$C'_{\tau N}, h_{\tau N}, g_{\tau N}$$

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

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

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

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

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

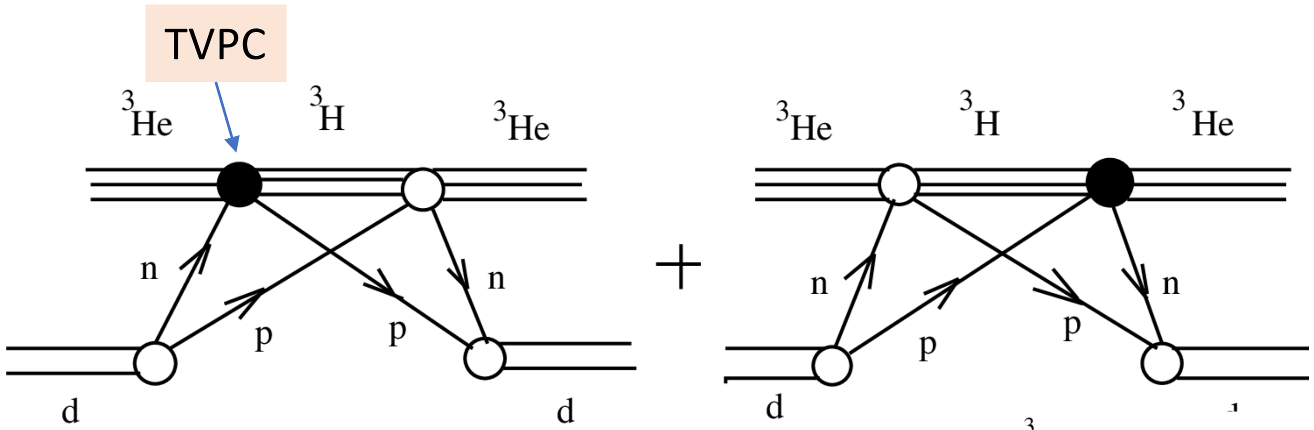
p^{3}He-, n^{3}He- elastic

h_N, g_{N}- terms- only

$$\tilde{\sigma} = -4\sqrt{\pi}\frac{2}{3}\mathrm{Im}\,\tilde{g}.$$

g' –term of TVPC in ^{3}He-d. Charge-exchange pn->np

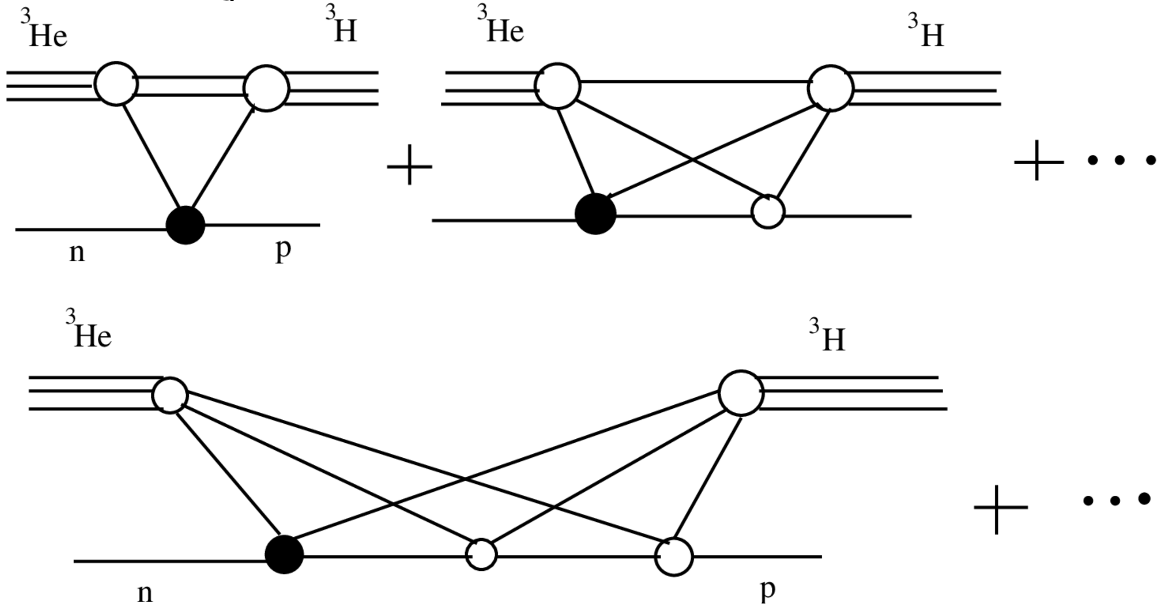
$$\langle n,p|[\boldsymbol{\tau} \times \boldsymbol{\tau}_N]_z|p,n\rangle = -i2, \quad \langle p,n|[\boldsymbol{\tau} \times \boldsymbol{\tau}_N]_z|n,p\rangle = i2.$$



= 0

$$< 3Hen\,|\,\hat{g}'\,|\,3Hp >= - < 3Hp\,|\,\hat{g}'\,|\,3Hen >$$

$F_{TCPC}(n^3He \rightarrow p^3H) = F_{TCPC}(p^3H \rightarrow n^3He)$



g'-term in ^{3}He-d vanishes like in pd

TVPC p^{3}He amplitudes
h_N type

$$F_{p\tau}^{TV} = F_{p\tau}^{TV(1)} + F_{p\tau}^{TV(2)} + F_{p\tau}^{TV(3)},$$

$$h_{p\tau}^{(1)} = \frac{k_{p\tau}}{k_{pN}} S(q) h_n(q),$$

$$h_{p\tau}^{(2)} = \frac{k_{p\tau}}{2\pi i k_{pN}^2} S(q/2) 2 \int d^2q' S(\sqrt{3}q') A_p(q_1) h_n(q_2),$$

$$h_{p\tau}^{(3)} = -\tilde{S}/3 \frac{k_{p\tau}}{4\pi^2 i k_{pN}^3}$$

$$\times \{\Sigma_p g_n + \frac{1}{2}(B_p + G_p + H_h) h_p (B_n - G_n - H_n)$$

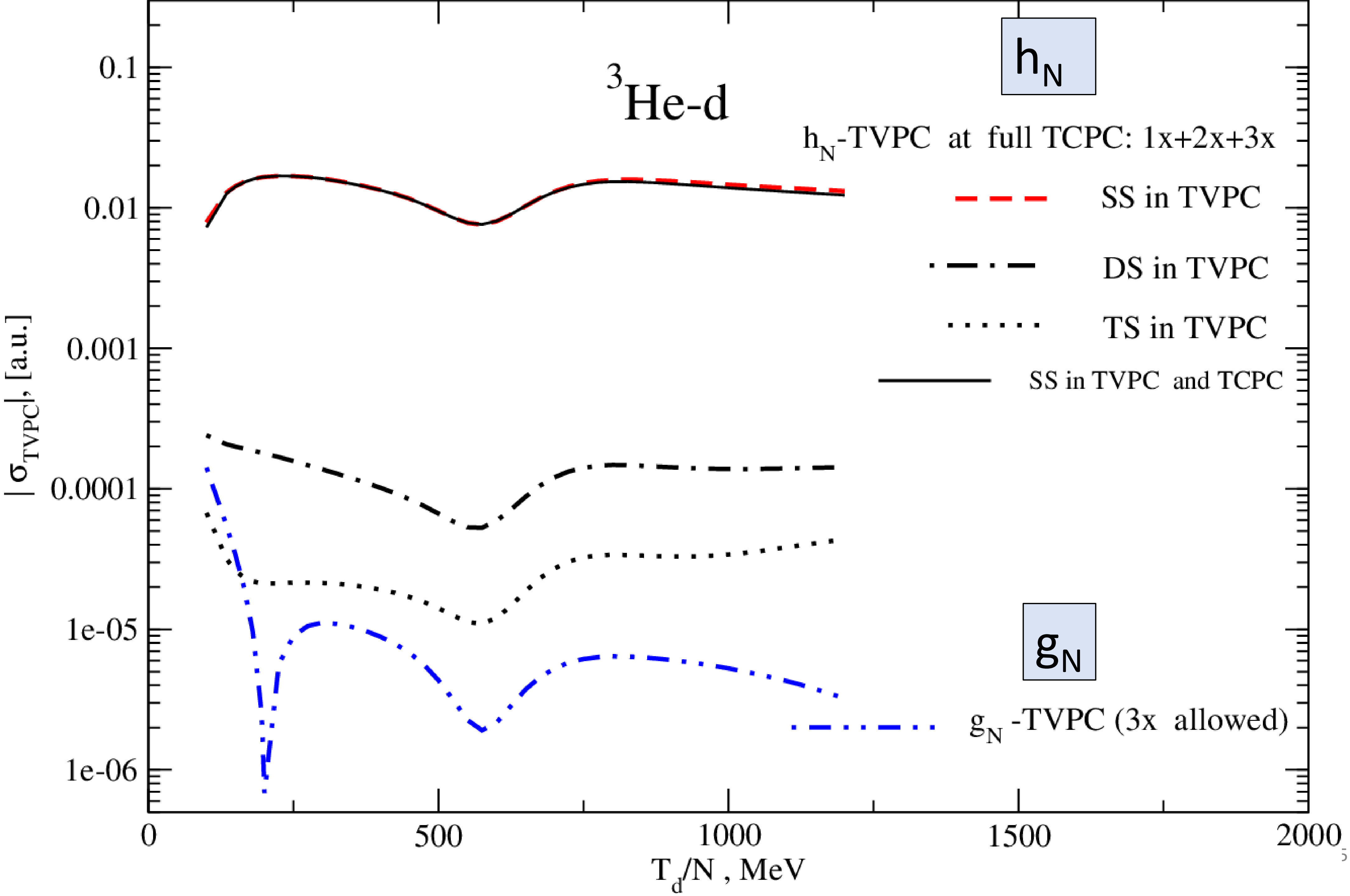
$$+\frac{1}{2}[B_P^2 - (G_p + H_p)^2] h_p\}$$

$$\tilde{S} = \frac{1}{3} 64\pi^2 c^4,$$

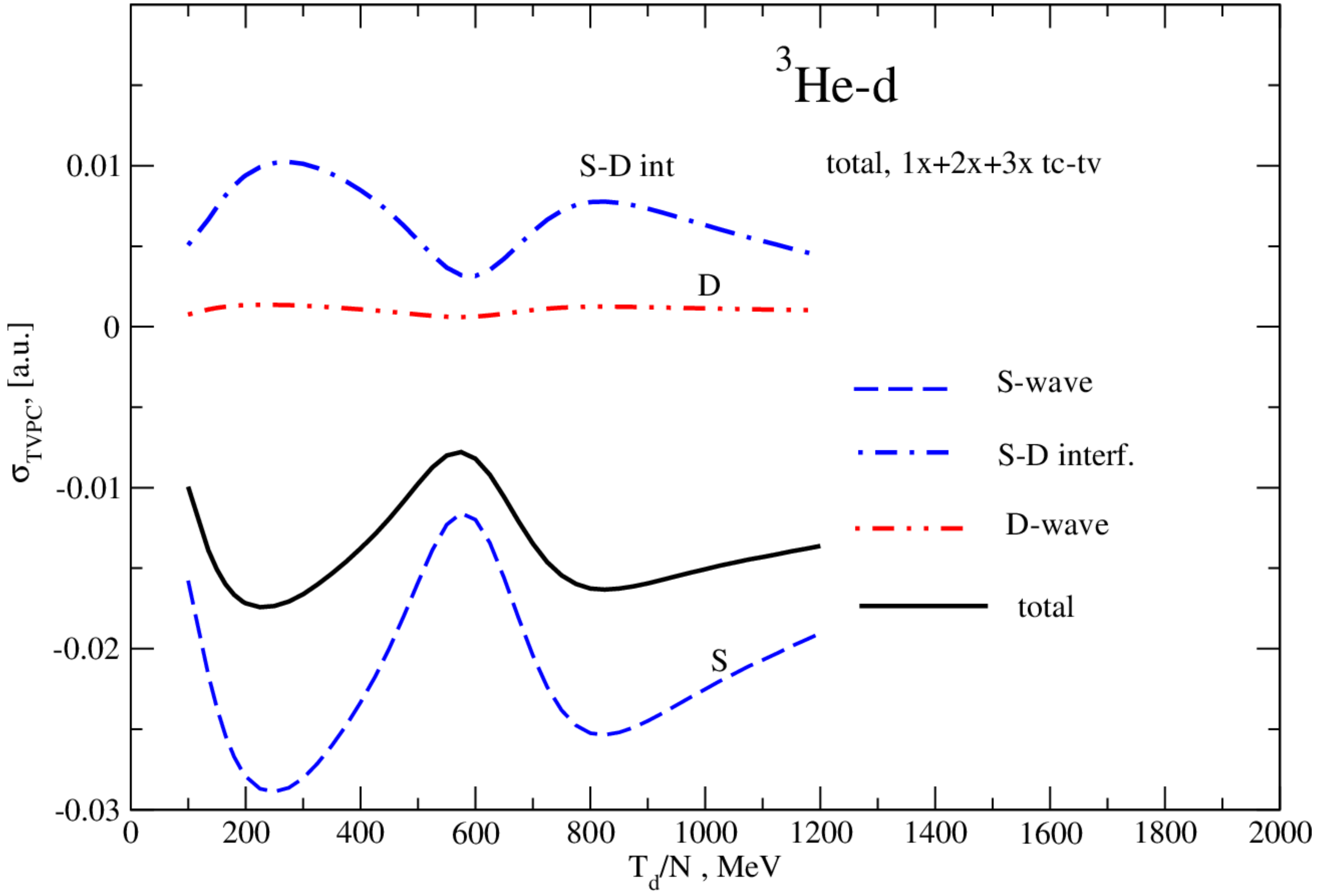
$$\Sigma_p^2 = 3A_p^2 + C_p^2 - 3C_p'^2 - 2B_p^2 - 3G_p^2 - 3H_p^2 - 2G_p H_p$$

in $q_1 = q_2 = q_3 = q/3$ approximation

NUMERICAL RESULTS FOR ENERGY DEPENDENCE OF THE TVPC NULL-TEST SIGNAL IN ^{3}He-d SCATTERING



^{3}He-d
h_N
h_N-TVPC at full TCPC: 1x+2x+3x
SS in TVPC
DS in TVPC
TS in TVPC
SS in TVPC and TCPC
g_N
g_N -TVPC (3x allowed)
$|\sigma_{TVPC}|$, [a.u.]
0.1
0.01
0.001
0.0001
1e-05
1e-06
0
500
1000
1500
2000
T_d/N , MeV



Contribution of the S- and D- components of the deuteron w.f.

S-D interference is destructive

CONCLUSION:

- 1x – scattering dominates in the null-test TVPC of ^{3}He-d .

- mixing of h_N and g_N terms in the null-test appears only in 3x- scattering, which is suppressed by 3 orders of magnitude as compared to the 1x.

- g_N -type of TVPC contribution is negligible as compared to the h_N term.

- g'-term is excluded by symmetry.

In total, a very simple SS- calculation will allow one to extract h_N –type of TVPC constants from the ^{3}He-d data

Next Step: TVPC signal in double polarized dd- scattering

- d-d has the 1+ 1 spin structure, that differs from pd and ^{3}Hed
- dd-scattering within the Glauber model was considered (G. Goggi et al., Nucl. Phys. B 149, (1979)) neglecting spin-dependence of pN amplitudes.
- Detailed study of the $d^{\uparrow}d^{\uparrow}$ elastic will be usefull for application at SPD NICA
- Does g' –term of TVPC nonvanishing contribution to the null-test signal in d-d?
- Helicty pN amplitudes at SPD energies will be constructed in a theoretical model by O. Selugin (BLTF)

Work is planned by RSCF grant for 2024 …

σ_{TVPC}

OUTLOOK

- Is a true null-test observable, not generated by ISI&FSI, analog of EDM (=null-test signal for TVPV).

- T_p –dependence of the σ_{TVPC} is calculated at 0.1-1 GeV within the Glauber theory. The T-even modulation factor can be eliminated.

- ^{3}He-d is an ideal process for clear elimination of h_N- type of TVPC.

- How to measure at SPD?

  Precessing polarization of the beam & Fourier analysis

  N. Nikolaev, F. Rathman, A. Silenko, Yu. U., PLB 811 (2020) 135983)

The basic question:

"How did it happen that there is enough matter left in the universe to be able to create galaxies, stars, planet and us ?"

Bruce H.J. McKellar, AIP Conf. 2015

"It is important not to miss the opportunity to significantly expand the horizons of spin physics research at the NICA facility"

(See V. Abramov et al., Phys. Part. Nucl. 52 (2021) 1044; Sect. 17, I. Koop et al .)

THANK YOU FOR ATTENTION!

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: $\delta R_T \leq 10^{-6}$, 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

Decomposition of the pd total X-section (k = collision axis)

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

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

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

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

TVPC $$+ \sigma_{\rm TVPC} k_m T_{mn} \epsilon_{nlr} P^{\rm p}_l k_r \,.$$ (TRIC Proposal in Juelich)

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

13

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

The main idea: precessing polarization of the beam in horizontal plane & Fourier analysis

Time-Reversal Violation in the Kaon and B^0 Meson Systems

- CP-violation in K- and B-meson physics (under CPT) $\Longrightarrow$ T-violation
- T violation in the K-system:

$K^0 \to \bar{K}^0$ and $\bar{K}^0 \to K^0$

Difference between probabilities was observed

A.Angelopoulos et al. (CPLEAR Collaboration) Phys. Lett. **B 444** (1998) 43.

These channels are connected both by T- and CP- transformation!

- Direct observation of T-violation in

$\bar{B}^0 \to B_- $ and $B_- \to \bar{B}^0$ $\qquad B\_ = c\bar{c}K_S^0$

connected only by T-symmetry transformation

(There are three other independet pairs)

J.P. Lees et al. (BABAR Collaboration) PRL **109** (2012) 211801

The results are consistent with current CP-violating measurements obtained invoking CPT-invariance

We will focus on TVPC flavor conserving effects.

T-INVARIANCE P-INVARIANCE in pd- elastic

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

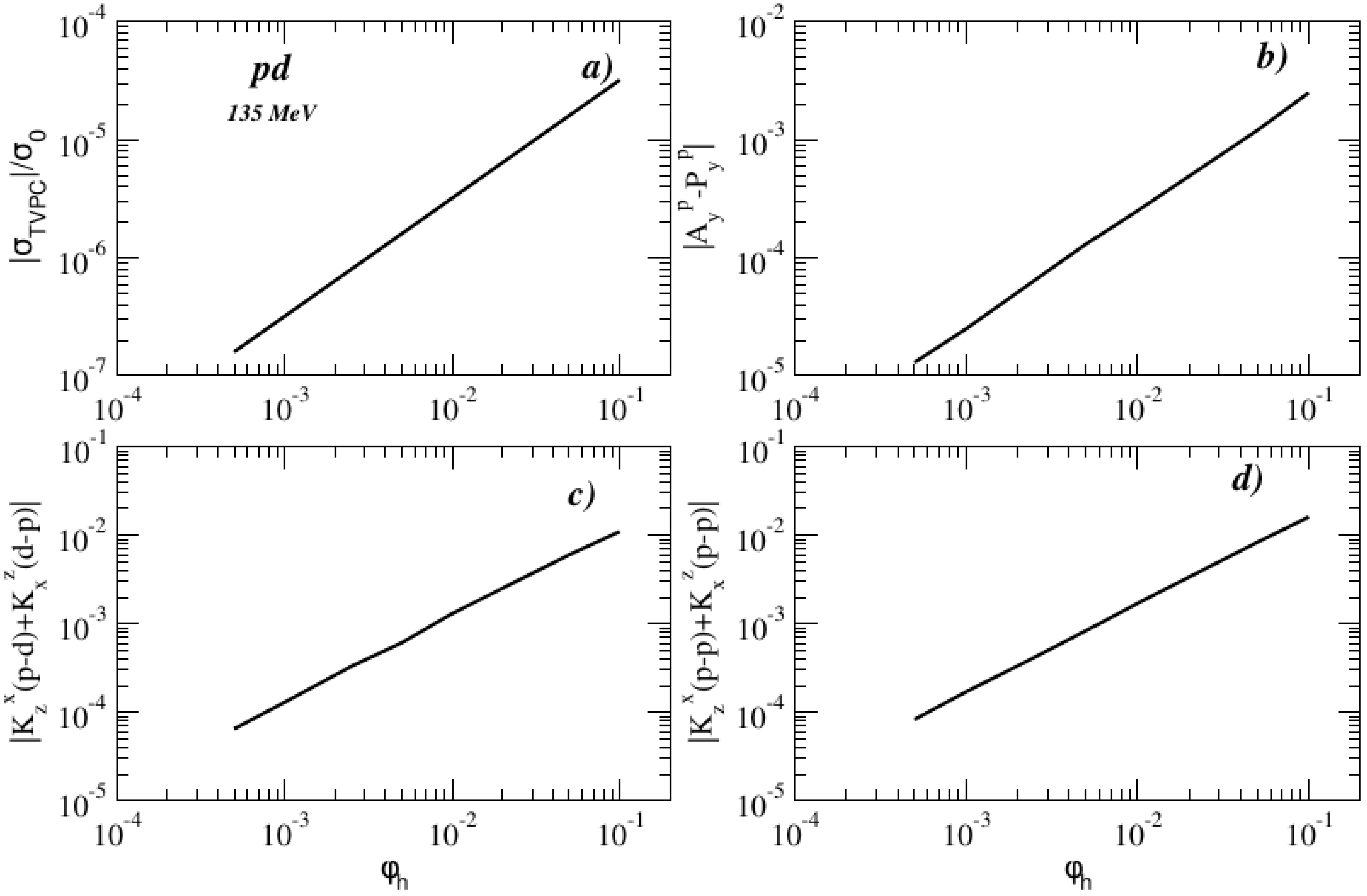
In Madison frame:

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

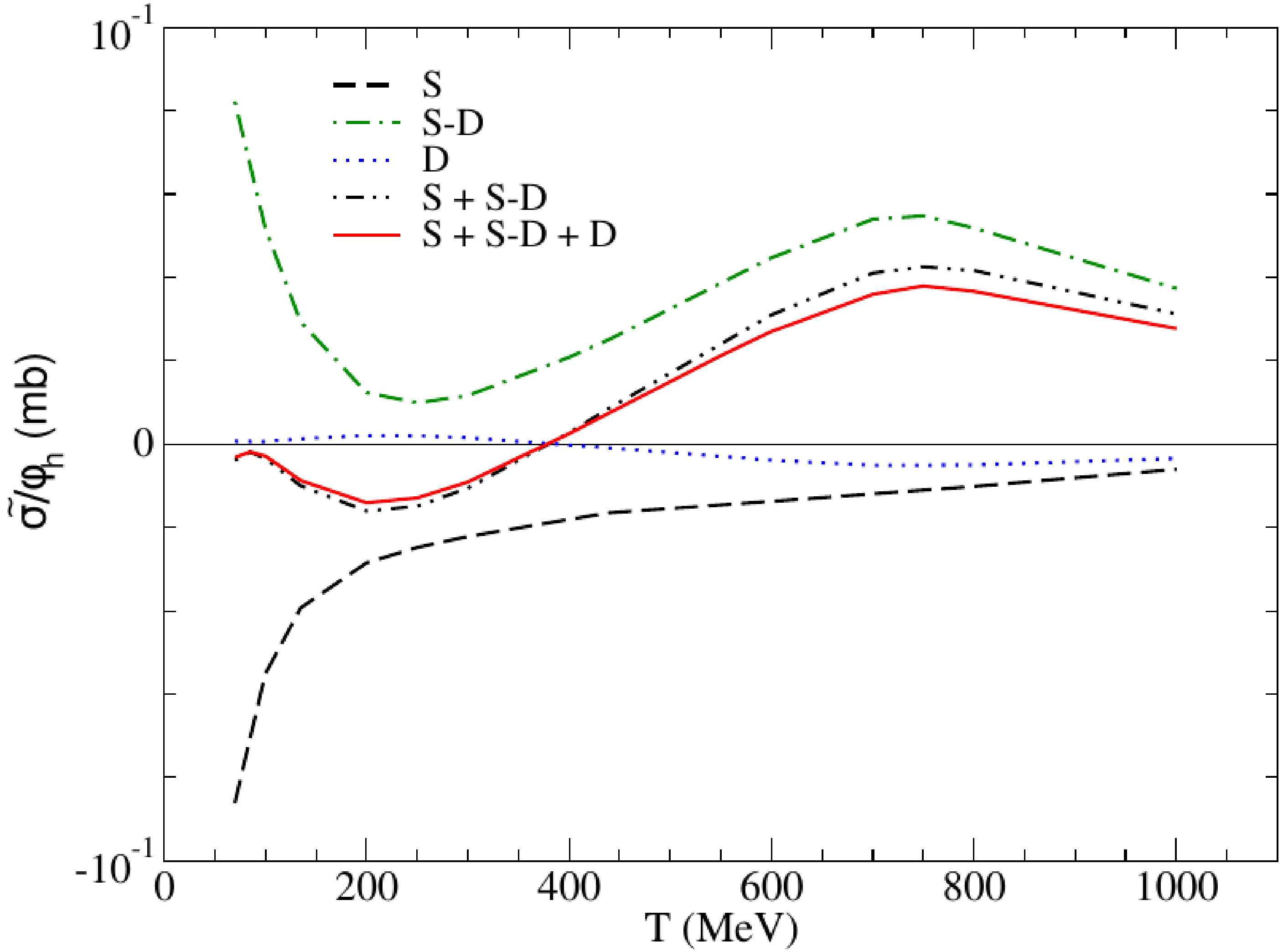
$$K_z^x(p \to p) = \frac{TrM\sigma_z M^+\sigma_x}{TrMM^+},\ K_z^x(p \to d) = \frac{TrM\sigma_z M^+ S_x}{TrMM^+},$$
$$K_z^x(d \to p) = \frac{TrMS_z M^+\sigma_x}{TrMM^+},\ K_z^x(d \to d) = \frac{TrMS_z M^+ S_x}{TrMM^+}.$$

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

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



Null-test signal in units of ϕ_h = TVPC constant. The S- and D- wave included.



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

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

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

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:

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

Search for T-violation in other processes

- Search for T-violation in decays

A.G. Beda, V.P. Skoy, Elem.Chat. At. Yadr. **37** (2007) 1477

$\vec{n} \to p\, e \tilde{\nu}$ or triple nuclear fussion

$$W_{if} \sim X \mathbf{s_n}[\mathbf{k}_n \times \mathbf{k}_\nu] + R \mathbf{s}_n[\mathbf{k}_n \times \mathbf{s}_e]$$

i) FSI with Coulomb

ii) Not all T-odd correlations are related to the true T-invariance violation

- Total cross section of the nA interaction from forward nA scattering amplitude

$$f = \underbrace{A + p_n p_T B(\mathbf{s}\cdot\mathbf{I})}_{strong} + \underbrace{p_n C(\mathbf{s}\cdot\mathbf{k})}_{PV} + \underbrace{p_n p_T D(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])}_{TV\,PV} + \underbrace{p_T E(\mathbf{k}\cdot\mathbf{I})}_{PV} + \underbrace{p_n p_T F(\mathbf{k}\cdot\mathbf{I})(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])}_{TV\,PC}$$

T-odd correlations in forward elastic scattering (=in total cross section):

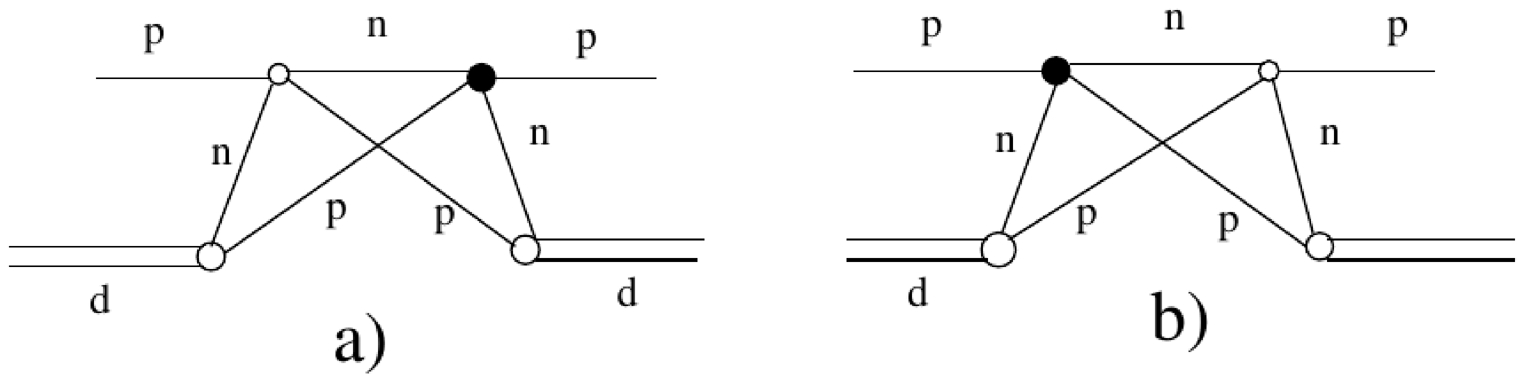
Three-fold $(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])$ – TVPV

five-fold $(\mathbf{k}\cdot\mathbf{I})(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])$ – TVPC

V. Baryshevsky, Yad.Fiz. 38 (1983) 699

TRANSMISSION experiment!

*T*VPC. *Double scattering mechanism with charge-exchange*



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 $\widetilde{\sigma}$, $\mathbf{q} = 0$.)