Parity odd and time reversal odd NN interactions

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Particle Physics with Neutrons at the ESS

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Sakharov Criteria (JETP Lett. **5**, 32 (1967))

Particle Physics can produce matter/antimatter asymmetry in the early universe *IF* there is:

- Baryon Number Violation
- CP & C violation → **TRIV**
- Departure from Thermal Equilibrium

According to our hypothesis, the occurrence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions. This effect has not yet been observed experimentally, but its existence is theoretically undisputed (the first concrete example, Σ_+ and Σ_- decay, was pointed out by S. Okubo as early as in 1958) and should, in our opinion, have an important cosmological significance.

Observed:

$$(n_B - n_{\bar{B}})/n_\gamma \simeq 6\times 10^{-10}$$

(WMAP+COBE,2003)

SM prediction:

$$(n_B - n_{\bar{B}})/n_\gamma \sim 6\times 10^{-18}$$

Neutron transmission
(= "EDM quality")

P- and T-violation: $\vec{\sigma}_n \cdot [\vec{k} \times \vec{I}\,]$

P.K. Kabir, PR D25, (1982) 2013
L. Stodolsky, N.P. B197 (1982) 213

T-violation: $(\vec{\sigma}_n \cdot [\vec{k} \times \vec{I}\,])(\vec{k} \cdot \vec{I}\,)$

(for 5.9 *MeV*, on ^{165}Ho: $<1.2 \cdot 10^{-3}$, *P. R. Huffman et al.* , PRL 76, 4681 (1996))

P-violation: $(\vec{\sigma}_n \cdot \vec{k}) \sim 10^{-1} (not\ \ 10^{-7})$

Enhanced of about 10^6

$$\Delta\sigma_V = \frac{4\pi}{k} \mathrm{Im}\{\Delta f_V\}$$

$$\frac{d\psi}{dz} = \frac{2\pi N}{k} \mathrm{Re}\{\Delta f_V\}$$

O. P. Sushkov and V. V. Flambaum, JETP Pisma 32 (1980) 377
V. E. Bunakov and V.G., Z. Phys. A303 (1981) 285

Forward scattering amplitude

$$f = A' + B'(\vec{\sigma}\cdot\vec{I}) + C'(\vec{\sigma}\cdot\vec{k}) + D'(\vec{\sigma}\cdot[\vec{k}\times\vec{I}]) + H'(\vec{k}\cdot\vec{I})$$
$$+E'\left((\vec{k}\cdot\vec{I})(\vec{k}\cdot\vec{I}) - \frac{1}{3}(\vec{k}\cdot\vec{k})(\vec{I}\cdot\vec{I})\right) + F'\left((\vec{\sigma}\cdot\vec{I})(\vec{k}\cdot\vec{I}) - \frac{1}{3}(\vec{\sigma}\cdot\vec{k})(\vec{I}\cdot\vec{I})\right)$$
$$+G'(\vec{\sigma}\cdot[\vec{k}\times\vec{I}])(\vec{k}\cdot\vec{I})$$

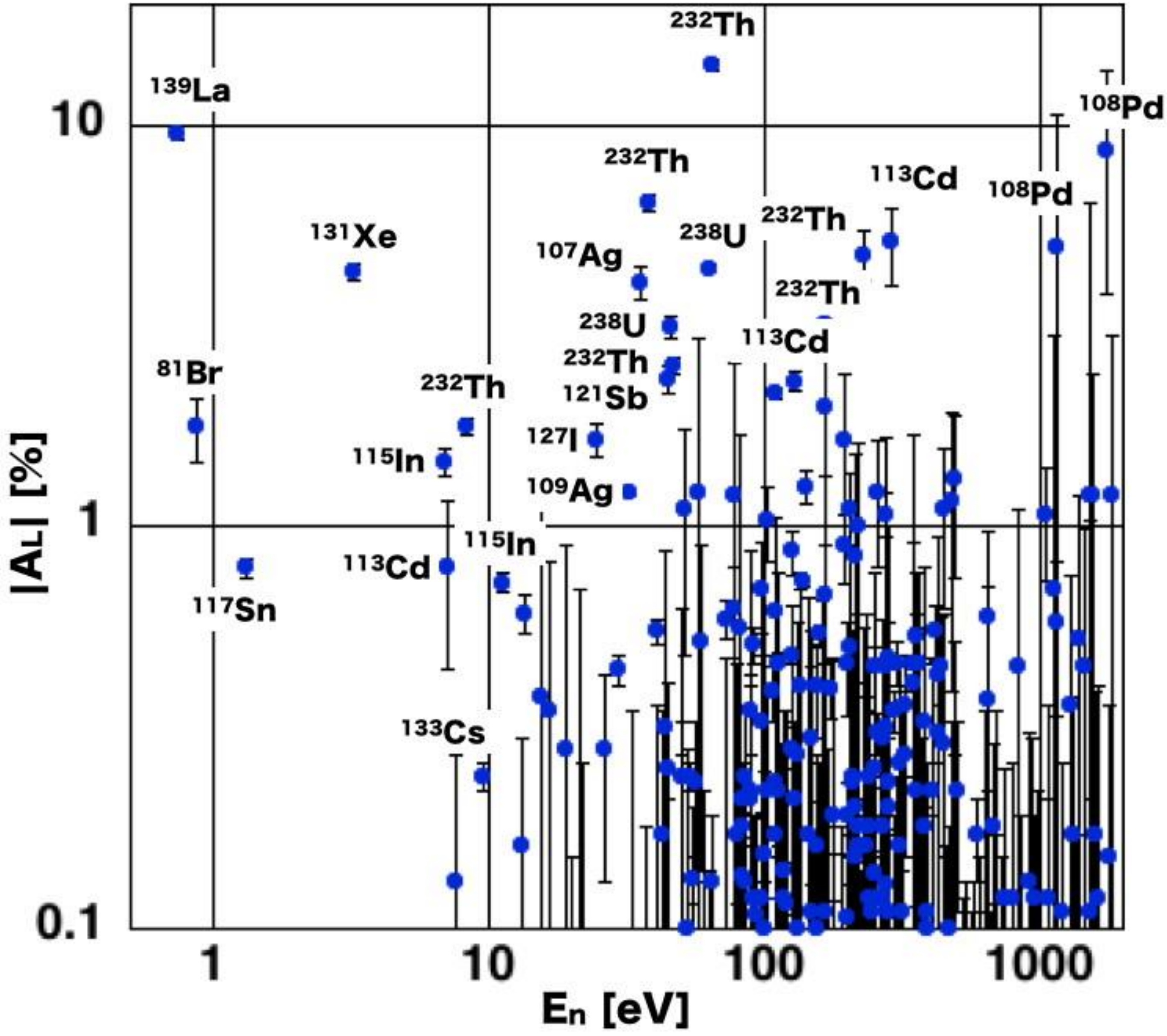
P-even, T-even: A', B', E'

P-odd, T-even: C', F', H'

P-odd, T-odd: D'

P-even, T-odd: G'

Tensor polarization: E', F', G'



G.E. MITCHELL, J.D. BOWMAN, S.I. PENTTILAG , E.I. SHARAPOV, Phys. Rep. 354 (2001) 157

Slide courtesy of H. Shimizu

General formalism

$$2\pi i\hat{T} = \hat{1} - \mathbb{S} = \hat{R}$$

$$\vec{S} = \vec{s} + \vec{I} \quad \text{and} \quad \vec{J} = \vec{l} + \vec{S}$$

$$2\pi i < \vec{k}\mu \,|\, T \,|\, \vec{k}\mu >= \sum_{JMlml'm'Sm_sS'm_s'} Y_{l'm'}(\theta,\phi) < s\mu IM_I \,|\, S'm_s' >< l'm'S'm_s' \,|\, JM >$$

$$\times < S'l'\alpha' \,|\, R^J \,|\, Sl\alpha >< JM \,|\, lmSm_s >< Sm_s \,|\, s\mu IM_I > Y_{lm}^*(\theta,\phi)$$

DWBA

$$T_{if} = <\Psi_f^- | W | \Psi_i^+>$$

$$\Psi_{i,f}^{\pm} = \sum_k a_{k(i,f)}^{\pm}(E)\phi_k + \sum_m \int b_{m(i,f)}^{\pm}(E,E')\chi_m^{\pm}(E')dE'$$

$$a_{k(i,f)}^{\pm}(E) = \frac{\exp(\pm i\delta_{i,f})}{\sqrt{2\pi}} \frac{(\Gamma_k^{i,f})^{1/2}}{E - E_k \pm i\Gamma_k / 2}$$

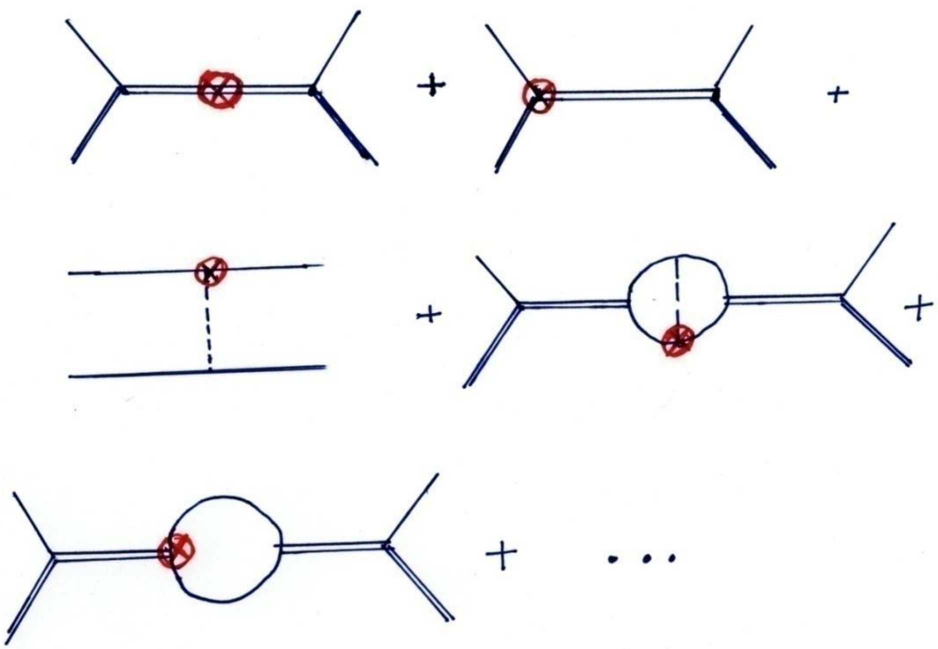
$$(\Gamma_k^i)^{1/2} = \sqrt{2\pi} < \chi_i(E') | V | \phi_k >$$

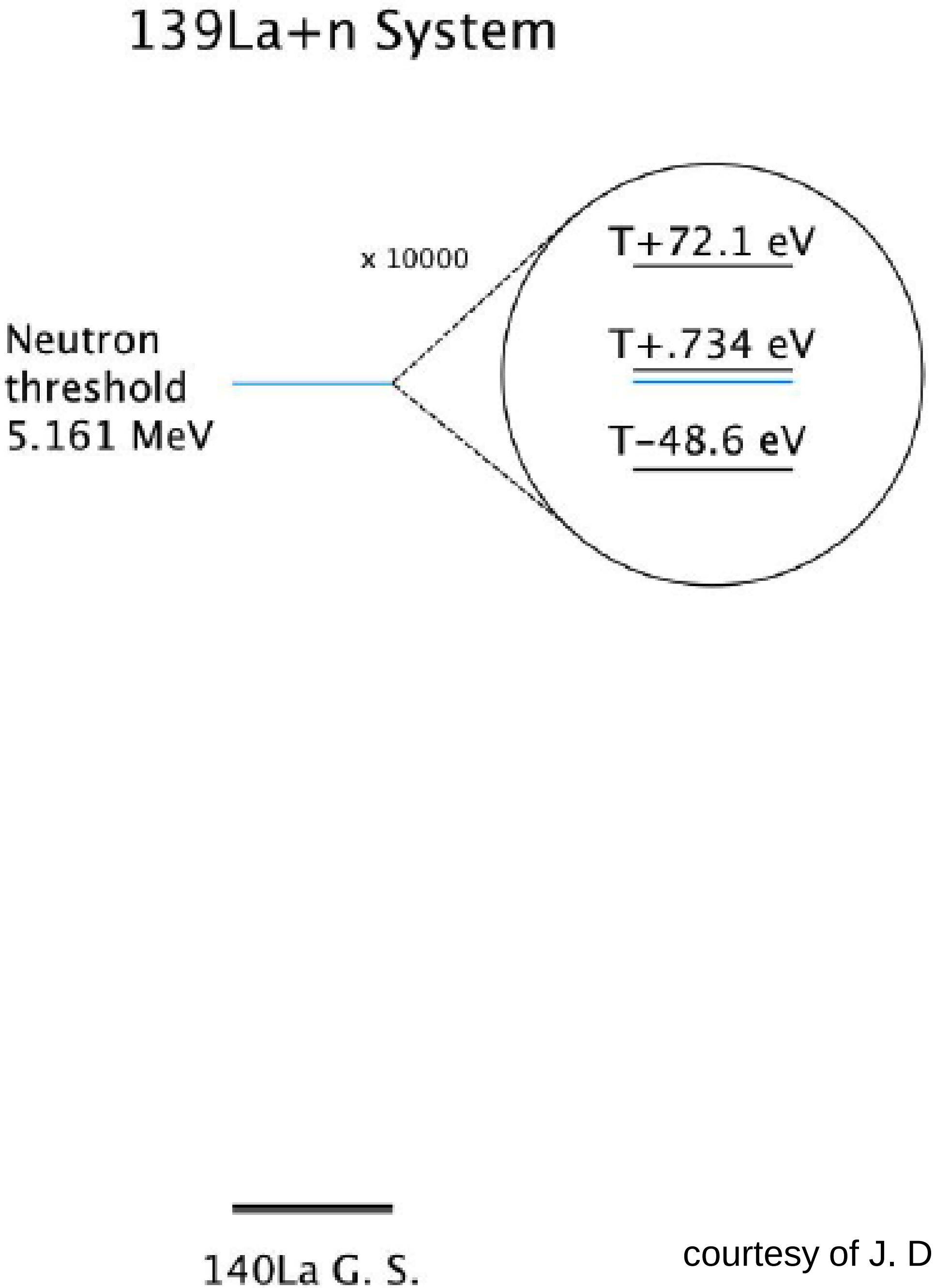
$$b_{m,\alpha}^{\pm}(E,E') = \exp(\pm i\delta_\alpha)\delta(E - E') + a_{k,\alpha}^{\pm} \frac{<\phi_k | V | \chi_m(E')>}{E - E' \pm i\varepsilon}$$

$$\Gamma / D << 1 \quad \Rightarrow$$

$$T_{PV} = a_{s,i}^{+} a_{p,f}^{+} < \phi_p | W | \phi_s > + a_{s,i}^{+} e^{i\delta_p^f} < \chi_{p,f}^{+} | W | \phi_s > +$$

$$+ e^{i(\delta_s^i + \delta_p^f)} < \chi_{p,f}^{+} | W | \chi_{s,i} > + \ldots$$

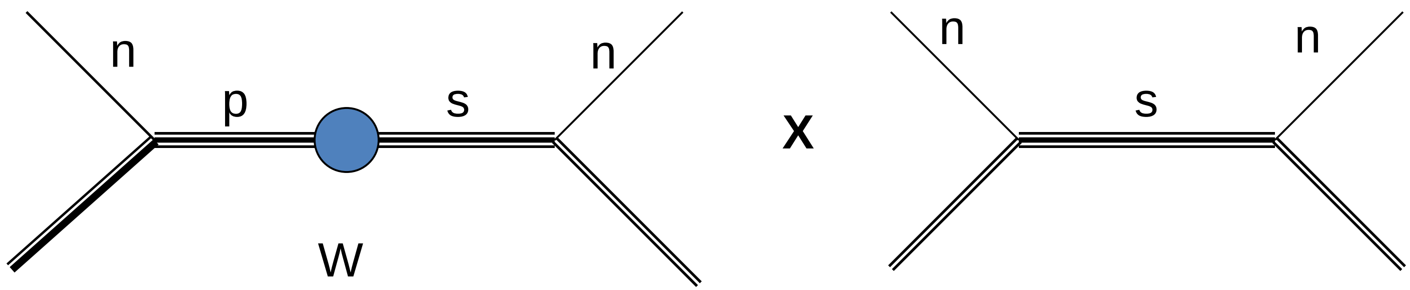




Compound-Nuclear States in ^{139}La+n system

courtesy of J. D. Bowman

P- and T-violation in a Relative measurement!!! & Enhancements



$$\Delta\sigma_T \sim \vec{\sigma}_n \cdot [\vec{k} \times \vec{I}\,] \sim \frac{W\sqrt{\Gamma_s^n \Gamma_p^n(s)}}{(E - E_s + i\Gamma_s/2)(E - E_p + i\Gamma_p/2)}[(E - E_s)\Gamma_p + (E - E_p)\Gamma_s]$$

$$\Delta\sigma_T / \Delta\sigma_P \sim \lambda = \frac{g_T}{g_P} \qquad [\sim \; - \; ?]$$

V. E. Bunakov and V.G., Z. Phys. A308 (1982) 363
V.G., Phys. Lett.B243 (1990) 319

One-particle potential

$$V_P = c_w\{\vec{\sigma}\cdot\vec{p}, \rho(\vec{r})\}_+ \qquad V_{CP} = i\lambda c_w\{\vec{\sigma}\cdot\vec{p}, \rho(\vec{r})\}_-$$

$$\langle\lambda\rangle = \frac{\langle\varphi_p | V_{CP} | \varphi_s\rangle}{\langle\varphi_p | V_P | \varphi_s\rangle} = \frac{\lambda}{1+2\xi}$$

$$\text{where} \quad \xi = \frac{\langle\varphi_p | \rho(\vec{r})\vec{\sigma}\cdot\vec{p} | \varphi_s\rangle}{\langle\varphi_p | \vec{\sigma}\cdot\vec{p}\rho(\vec{r}) | \varphi_s\rangle} = \frac{1}{4}MD_{sp}R^2 = \frac{1}{4}\pi(KR) \sim 1$$

$$2\vec{p} = iM[H, r] \quad \Rightarrow \quad \langle\varphi_p | \rho(\vec{r})\vec{\sigma}\cdot\vec{p} | \varphi_s\rangle \simeq \frac{i}{2}\bar{\rho}MD_{sp}\langle\varphi_p | \vec{\sigma}\cdot\vec{r} | \varphi_s\rangle$$

$$\langle\varphi_p | \vec{\sigma}\cdot\vec{p}\rho(\vec{r}) | \varphi_s\rangle = -\left\langle\varphi_p \left| \vec{\sigma}\cdot\vec{r}\,\frac{1}{r}\frac{\partial\rho}{\partial r} \right| \varphi_s\right\rangle = \frac{2i\bar{\rho}}{R^2}\langle\varphi_p | \vec{\sigma}\cdot\vec{r} | \varphi_s\rangle$$

$$D_{sp} = \frac{1}{MR^2}\pi KR$$

- F. C. Mitchel, PR 113, 329B (1964); O.P. Sushkov et al.ZhETF 87, 1521 (1987);
- V.G., Phys. Lett. B243, 319 (1990)

$$-i\frac{\langle a'|V^{P,T}|a\rangle}{\langle a'|V^{P}|a\rangle} = \kappa^{(1)}\frac{\overline{g}^{(1)\prime}_{\pi NN}}{g^{(0)\prime}_{\rho NN}}$$

TABLE II. Isovector π-exchange, $V_{P,T}$, and isoscalar ρ-exchange, V_P, matrix elements evaluated for a closed-shell-plus-one configuration for six choices of the closed-shell core. The weak interaction coupling constants are $\overline{g}^{(1)\prime}_{\pi NN} = 1.0 \times 10^{-11}$ and $g^{(0)\prime}_{\rho NN} = -11.4 \times 10^{-7}$. Matrix elements were calculated with harmonic oscillator wave functions with $\hbar\omega = 45A^{-1/3} - 25A^{-2/3}$ MeV. The Miller-Spencer [14] short-range correlation function was used. The ratio, $\kappa^{(1)}$, is defined in Eq. (6).

	^{16}O N=8 Z=8	^{40}Ca N=20 Z=20	^{90}Zr N=50 Z=40	^{138}Ba N=82 Z=56	^{208}Pb N=126 Z=82	^{232}Th N=142 Z=90
	$0p$-$0s$	$1p$-$1s$	$2p$-$2s$	$2p$-$2s$	$3p$-$3s$	$3p$-$3s$
$\langle V_{P,T}\rangle$ in 10^{-4} eV	1.084	0.875	0.708	0.779	0.608	0.633
$i\langle V_P\rangle$ in eV	1.513	1.550	1.535	1.576	1.581	1.600
$\kappa^{(1)}$	−8.2	−6.4	−5.3	−5.6	−4.4	−4.5
	$0p$-$1s$	$1p$-$2s$	$2p$-$3s$	$2p$-$3s$	$3p$-$4s$	$3p$-$4s$
$\langle V_{P,T}\rangle$ in 10^{-4} eV	−0.400	−0.378	−0.388	−0.465	−0.376	−0.409
$i\langle V_P\rangle$ in eV	1.294	1.435	1.441	1.485	1.508	1.527
$\kappa^{(1)}$	3.5	3.0	3.1	3.6	2.8	3.0

I. S. Towner and A. C. Hayes, PR C49, 2391 (1994)

Consistent with statistical estimates of compound matrix elements by V.V. Flambaum and O. K. Vorov (Phys. Rev C51, 1521 (1995); C51, 2914 (1995); C49, 1827 (1994))

PHYSICAL REVIEW C, VOLUME 62, 054607

Statistical theory of parity nonconservation in compound nuclei

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(Received 22 November 1999; published 10 October 2000)

Comparison of experimental CN matrix elements with Tomsovic theory using DDH "best" meson-nucleon couplings: agreement within a factor of 2

TABLE IV. Theoretical values of M for the effective parity-violating interaction. Contributions are shown separately for the standard (Std) and doorway (Dwy) pieces of the two-body interaction. A comparison of the experimental value of M given in Table III is also shown.

Nucleus	M_{Std} (meV)	M_{Dwy} (meV)	$M_{Std+Dwy}$ (meV)	M_{expt} (meV)
^{239}U	0.116	0.177	0.218	$0.67^{+0.24}_{-0.16}$
^{105}Pd	0.70	0.79	1.03	$2.2^{+2.4}_{-0.9}$
^{106}Pd	0.304	0.357	0.44	$0.20^{+0.10}_{-0.07}$
^{107}Pd	0.698	0.728	0.968	$0.79^{+0.88}_{-0.36}$
^{109}Pd	0.73	0.72	0.97	$1.6^{+2.0}_{-0.7}$

PV (First order effects)

$$f = f_{PC} + f_{PV}$$

$$w \sim | f_{PC} + f_{PV} |^2 = | f_{PC} |^2 + 2\Re e(f_{PC} f_{PV}^*) + | f_{PV} |^2$$

$$\alpha \sim \frac{\Re e(f_{PC} f_{PV}^*)}{| f_{PC} |^2} \sim \frac{| f_{PV} |}{| f_{PC} |}$$

$$\alpha \sim G_F m_\pi^2 \sim 2 \cdot 10^{-7}$$

T-Reversal Invariance

$$a + A \rightarrow b + B$$

$$a + A \leftarrow b + B$$

$$\vec{k}_{i,f} \rightarrow -\vec{k}_{f,i} \quad \text{and} \quad \vec{s} \rightarrow -\vec{s}$$

$$< \vec{k}_f, m_b, m_B \,|\, \hat{T} \,|\, \vec{k}_i, m_a, m_A >= (-1)^{\sum_i s_i - m_i} < -\vec{k}_i, -m_a, -m_A \,|\, \hat{T} \,|\, -\vec{k}_f, -m_b, -m_B >$$

Detailed Balance Principle (DBP):

$$\frac{(2s_a+1)(2s_A+1)}{(2s_b+1)(2s_B+1)} \frac{k_i^2}{k_f^2} \frac{(d\sigma/d\Omega)_{if}}{(d\sigma/d\Omega)_{fi}} = 1$$

FSI:

$$T^{+} - T = iTT^{+}$$

in the first Born approximation T-is hermitian

$$<i|T|f>=<i|T^{*}|f>$$

$\oplus$ T-invariance $\Rightarrow$ $<f|T|i>=<-f|T|-i>^{*}$

$$\Rightarrow |<f|T|i>|^{2}=|<-f|T|-i>|^{2}$$

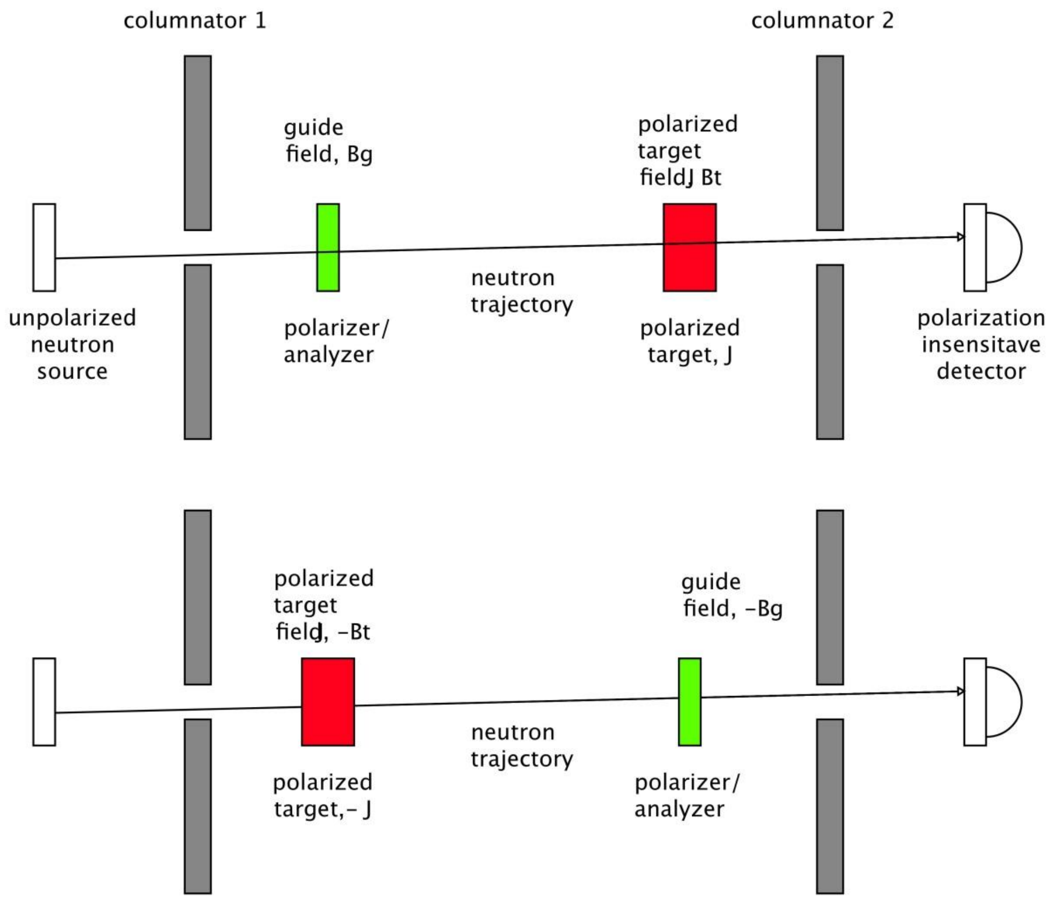
then the probability is even function of time.

For an elastic scattering at the zero angle: $"i" \equiv "f"$,

then always "T-odd correlations" = "T-violation"

(R. M. Ryndin)

No Systematics



courtesy of J. D. Bowman

TRIV Transmission Theorem

$$H = a + b(\vec{\sigma} \cdot \vec{I}) + c(\vec{\sigma} \cdot \vec{k}) + d(\vec{\sigma} \cdot [\vec{k} \times \vec{I}])$$

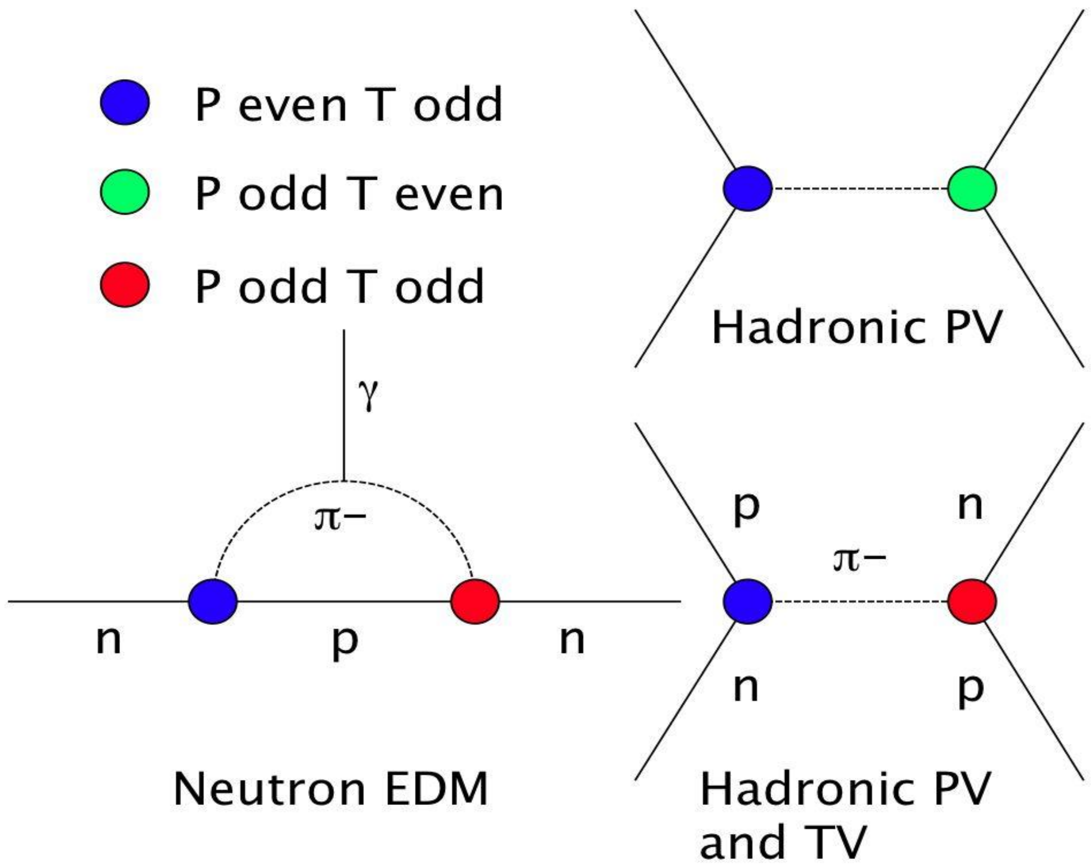
$$U_F = \prod_{j=1}^{m} \exp\left(-i \frac{\Delta t_j}{\hbar} H_j^F\right) = \alpha + (\vec{\beta} \cdot \vec{\sigma})$$

$$U_R = \prod_{j=m}^{1} \exp\left(-i \frac{\Delta t_j}{\hbar} H_j^R\right) = \alpha - (\vec{\beta} \cdot \vec{\sigma}).$$

$$T_F = \frac{1}{2} Tr(U_F^\dagger U_F) = \alpha^* \alpha + (\vec{\beta}^* \vec{\beta}) = \frac{1}{2} Tr(U_R^\dagger U_R) = T_R$$

J. D. Bowman and V.G., Phys. Rev. C90, 065503 (2014)

Meson exchange potentials for PV and TVPV interactions



Slide courtesy of D. Bowman

TVPV vs PV vs TVPC

PV

$$h_{\pi}^{(1)},\ \ h_{\rho}^{(0)},\ h_{\rho}^{(1)},\ h_{\rho}^{(2)},\ h_{\omega}^{(0)},\ h_{\omega}^{(1)}$$

TVPV

$$\bar{g}_{\pi}^{(0)}, \bar{g}_{\pi}^{(1)}, \bar{g}_{\pi}^{(2)},\ \bar{g}_{\eta}^{(0)},\ \bar{g}_{\eta}^{(1)},\ \bar{g}_{\rho}^{(0)},\ \bar{g}_{\rho}^{(1)},\ \bar{g}_{\rho}^{(2)},\ \bar{g}_{\omega}^{(0)},\ \bar{g}_{\omega}^{(1)}$$

TVPC

$$\rho(770)\ \ I^{G}(J^{PC}) = 1^{+}(1^{--})\ \ \&\ \ h_{1}(1170)\ \ I^{G}(J^{PC}) = 0^{-}(1^{+-})$$

EDM

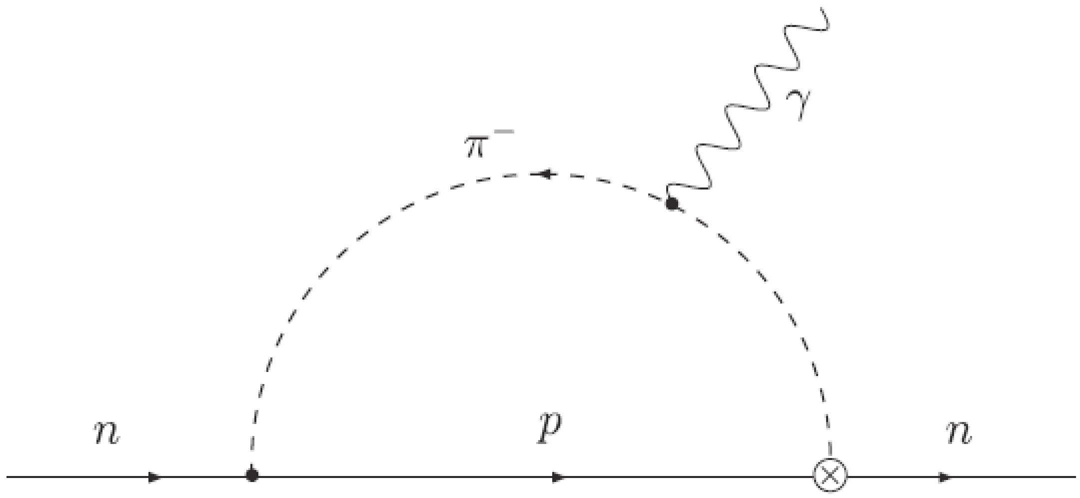
$$< p' | J_\mu^{em} | p >= e\bar{u}(p')\left\{\gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M}F_2(q^2) - G(q^2)\sigma_{\mu\nu}\gamma_5 q^\nu + \ldots\right\}u(p)$$

$$q^\nu = (p' - p)^\nu; \qquad \sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]; \qquad \gamma_5 = \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix}$$

$$G(0) = d$$

$$H_{EDM} = i\frac{d}{2}\bar{u}\sigma_{\mu\nu}\gamma_5 u F^{\mu\nu} \to -(\vec{d} \cdot \vec{E})$$

Chiral Limit



$$d_n = -d_p = \frac{e}{m_N} \frac{g_\pi \left(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)}\right)}{4\pi^2} \ln \frac{m_N}{m_\pi} \simeq 0.14\left(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)}\right)$$

R. Crewther, P. Di Vecchia, G. Veneziano, and E. Witten (1979)

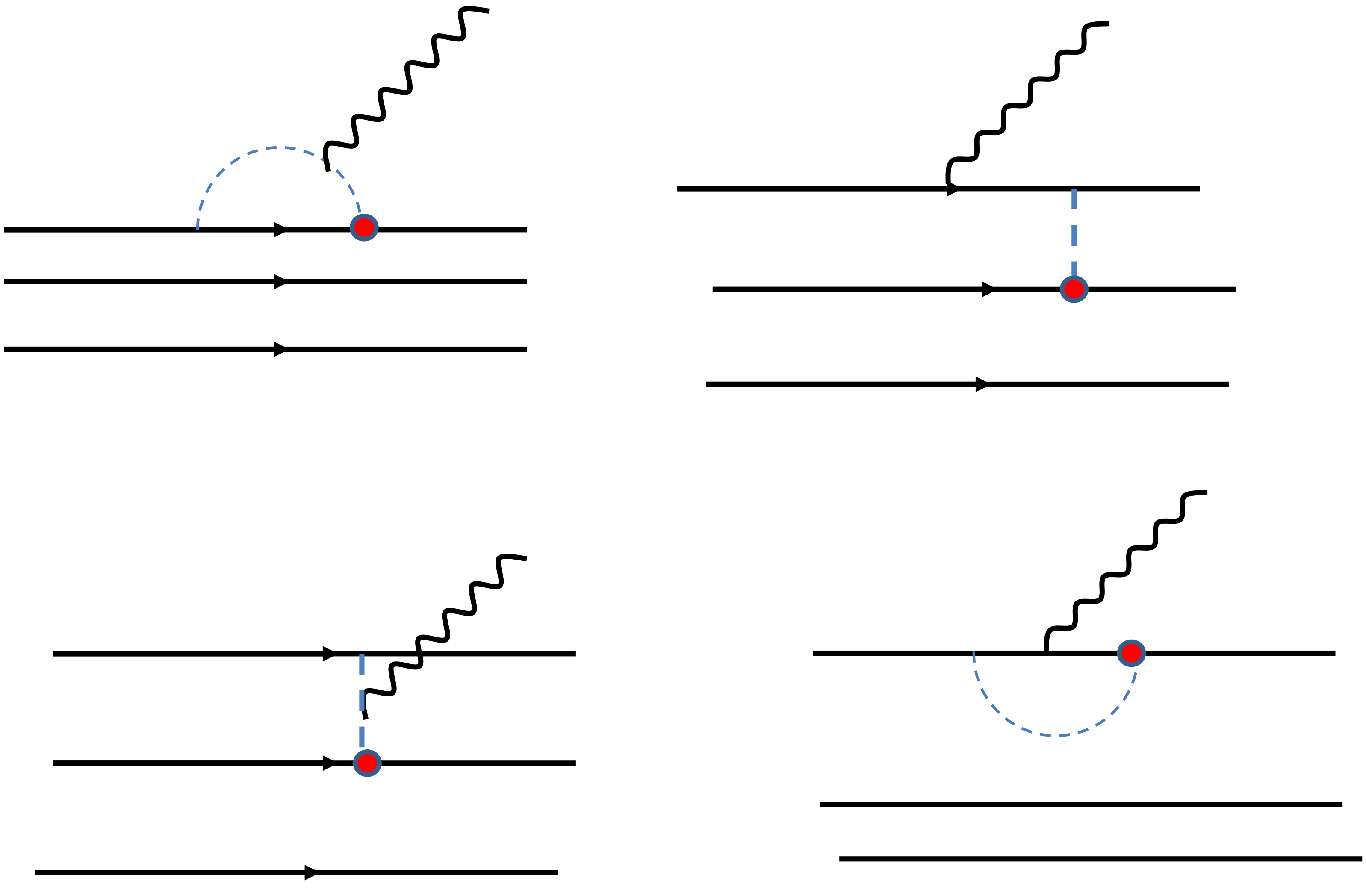
With more details…

$$d_n = 0.14(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)}) - 0.02(\bar{g}_\rho^{(0)} - \bar{g}_\rho^{(1)} + 2\bar{g}_\rho^{(2)}) + 0.006(\bar{g}_\omega^{(0)} - \bar{g}_\omega^{(1)})$$

$$d_p = -0.08(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)}) + 0.03(\bar{g}_\pi^{(0)} + \bar{g}_\pi^{(1)} + 2\bar{g}_\pi^{(2)}) + 0.003(\bar{g}_\eta^{(0)} + \bar{g}_\eta^{(1)})$$
$$+ 0.02(\bar{g}_\rho^{(0)} + \bar{g}_\rho^{(1)} + 2\bar{g}_\rho^{(2)}) + 0.006(\bar{g}_\omega^{(0)} + \bar{g}_\omega^{(1)})$$

C.-P. Liu and R. G. E. Timmermans, Phys. Rev. C **70**, 055501 (2004)

Many Body system EDMs



^{3}He and ^{3}H

$$d_{^3\mathrm{He}} = (-0.0542 d_p + 0.868 d_n) + 0.072\big[\bar{g}_\pi^{(0)} + 1.92\bar{g}_\pi^{(1)} + 1.21\bar{g}_\pi^{(2)} - 0.015\bar{g}_\eta^{(0)} + 0.03\bar{g}_\eta^{(1)} - 0.010\bar{g}_\rho^{(0)} + 0.015\bar{g}_\rho^{(1)} - 0.012\bar{g}_\rho^{(2)} + 0.021\bar{g}_\omega^{(0)} - 0.06\bar{g}_\omega^{(1)}\big] e\mathrm{fm}$$

$$d_{^3\mathrm{H}} = (0.868 d_p - 0.0552 d_n) - 0.072\big[\bar{g}_\pi^{(0)} - 1.97\bar{g}_\pi^{(1)} + 1.26\bar{g}_\pi^{(2)} - 0.015\bar{g}_\eta^{(0)} - 0.030\bar{g}_\eta^{(1)} - 0.010\bar{g}_\rho^{(0)} - 0.015\bar{g}_\rho^{(1)} - 0.012\bar{g}_\rho^{(2)} + 0.022\bar{g}_\omega^{(0)} + 0.061\bar{g}_\omega^{(1)}\big] e\mathrm{fm}.$$

PV nucleon Potential

$$
\begin{aligned}
V^{\mathrm{PV}}_{\mathrm{DDH}}(\vec{r}) = & \; i\frac{h^1_\pi g_A m_N}{\sqrt{2}F_\pi}\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\pi(r)\right] \\
& - g_\rho\left(h^0_\rho\tau_1\cdot\tau_2 + h^1_\rho\left(\frac{\tau_1+\tau_2}{2}\right)_3 + h^2_\rho\frac{(3\tau^3_1\tau^3_2-\tau_1\cdot\tau_2)}{2\sqrt{6}}\right) \\
& \times\left((\vec{\sigma}_1-\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right\}\right. \\
& \left. + \, i(1+\chi_\rho)\vec{\sigma}_1\times\vec{\sigma}_2\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right]\right) \\
& - g_\omega\left(h^0_\omega + h^1_\omega\left(\frac{\tau_1+\tau_2}{2}\right)_3\right) \\
& \times\left((\vec{\sigma}_1-\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\omega(r)\right\}\right. \\
& \left. + \, i(1+\chi_\omega)\vec{\sigma}_1\times\vec{\sigma}_2\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\omega(r)\right]\right) \\
& - \left(g_\omega h^1_\omega - g_\rho h^1_\rho\right)\left(\frac{\tau_1-\tau_2}{2}\right)_3(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right\} \\
& - g_\rho h'^1_\rho i\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right].
\end{aligned}
$$

TVPV Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\not T \not P} = & \bar{N}\big[\bar{g}_\pi^{(0)}\tau^a\pi^a + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}(3\tau^z\pi^0 - \tau^a\pi^a)\big]N \\
& +\bar{N}\big[\bar{g}_\eta^{(0)}\eta + \bar{g}_\eta^{(1)}\tau^z\eta\big]N \\
& +\bar{N}\frac{1}{2m_N}\big[\bar{g}_\rho^{(0)}\tau^a\rho_\mu^a + \bar{g}_\rho^{(1)}\rho_\mu^0 + \bar{g}^{(2)} \\
& \times(3\tau^z\rho_\mu^0 - \tau^a\rho_\mu^a)\big]\sigma^{\mu\nu}q_\nu\gamma_5 N \\
& +\bar{N}\frac{1}{2m_N}\big[\bar{g}_\omega^{(0)}\omega_\mu + \bar{g}_\omega^{(1)}\tau^z\omega_\mu\big]\sigma^{\mu\nu}q_\nu\gamma_5 N, \qquad (
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}^{st} = & g_\pi\bar{N}i\gamma_5\tau^a\pi^a N + g_\eta\bar{N}i\gamma_5\eta N \\
& -g_\rho\bar{N}\left(\gamma^\mu - i\frac{\chi_V}{2m_N}\sigma^{\mu\nu}q_\nu\right)\tau^a\rho_\mu^a N \\
& -g_\omega\bar{N}\left(\gamma^\mu - i\frac{\chi_S}{2m_N}\sigma^{\mu\nu}q_\nu\right)\omega_\mu N,
\end{aligned}
$$

P. Herczeg (1987); C. P. Liu and R. G. E. Timmermans (2004)

TVPV potential

P. Herczeg (1966)

$$
\begin{aligned}
V_{\not{T}\not{P}} = & \left[-\frac{\bar{g}_\eta^{(0)} g_\eta}{2m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) + \frac{\bar{g}_\omega^{(0)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \boldsymbol{\sigma}_- \cdot \hat{r} \\
& + \left[-\frac{\bar{g}_\pi^{(0)} g_\pi}{2m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\rho^{(0)} g_\rho}{2m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) \right] \tau_1 \cdot \tau_2 \boldsymbol{\sigma}_- \cdot \hat{r} \\
& + \left[-\frac{\bar{g}_\pi^{(2)} g_\pi}{2m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\rho^{(2)} g_\rho}{2m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) \right] T_{12}^z \boldsymbol{\sigma}_- \cdot \hat{r} \\
& + \left[-\frac{\bar{g}_\pi^{(1)} g_\pi}{4m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\eta^{(1)} g_\eta}{4m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) + \frac{\bar{g}_\rho^{(1)} g_\rho}{4m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) + \frac{\bar{g}_\omega^{(1)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \tau_+ \boldsymbol{\sigma}_- \cdot \hat{r} \\
& + \left[-\frac{\bar{g}_\pi^{(1)} g_\pi}{4m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) - \frac{\bar{g}_\eta^{(1)} g_\eta}{4m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) - \frac{\bar{g}_\rho^{(1)} g_\rho}{4m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) + \frac{\bar{g}_\omega^{(1)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \tau_- \boldsymbol{\sigma}_+ \cdot \hat{r}
\end{aligned}
$$

- Y.-H. Song, R. Lazauskas and V. G, Phys. Rev. C83, 065503 (2011).

PV nucleon Potential

n	$c_n^{\rm DDH}$	$f_n^{\rm DDH}(r)$	$c_n^{\not\pi}$	$f_n^{\not\pi}(r)$	c_n^{π}	$f_n^{\pi}(r)$	$O_{ij}^{(n)}$
1	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}C_6^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$(\tau_i\times\tau_j)^z(\sigma_i+\sigma_j)\cdot X_{ij,-}^{(1)}$
2	$-\frac{g_\rho}{m_N}h_\rho^0$	$f_\rho(r)$	0	0	0	0	$(\tau_i\cdot\tau_j)(\sigma_i-\sigma_j)\cdot X_{ij,+}^{(2)}$
3	$-\frac{g_\rho(1+\kappa_\rho)}{m_N}h_\rho^0$	$f_\rho(r)$	0	0	0	0	$(\tau_i\cdot\tau_j)(\sigma_i\times\sigma_j)\cdot X_{ij,-}^{(3)}$
4	$-\frac{g_\rho}{2m_N}h_\rho^1$	$f_\rho(r)$	$\frac{\mu^2}{\Lambda_\chi^3}(C_2^{\not\pi}+C_4^{\not\pi})$	$f_\mu^{\not\pi}(r)$	$\frac{\Lambda^2}{\Lambda_\chi^3}(C_2^{\pi}+C_4^{\pi})$	$f_\Lambda(r)$	$(\tau_i+\tau_j)^z(\sigma_i-\sigma_j)\cdot X_{ij,+}^{(4)}$
5	$-\frac{g_\rho(1+\kappa_\rho)}{2m_N}h_\rho^1$	$f_\rho(r)$	0	0	$\frac{2\sqrt{2}\pi g_A^3\Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$L_\Lambda(r)$	$(\tau_i+\tau_j)^z(\sigma_i\times\sigma_j)\cdot X_{ij,-}^{(5)}$
6	$-\frac{g_\rho}{2\sqrt{6}m_N}h_\rho^2$	$f_\rho(r)$	$-\frac{2\mu^2}{\Lambda_\chi^3}C_5^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$-\frac{2\Lambda^2}{\Lambda_\chi^3}C_5^{\pi}$	$f_\Lambda(r)$	$\mathcal{T}_{ij}(\sigma_i-\sigma_j)\cdot X_{ij,+}^{(6)}$
7	$-\frac{g_\rho(1+\kappa_\rho)}{2\sqrt{6}m_N}h_\rho^2$	$f_\rho(r)$	0	0	0	0	$\mathcal{T}_{ij}(\sigma_i\times\sigma_j)\cdot X_{ij,-}^{(7)}$
8	$-\frac{g_\omega}{m_N}h_\omega^0$	$f_\omega(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}C_1^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$\frac{2\Lambda^2}{\Lambda_\chi^3}C_1^{\pi}$	$f_\Lambda(r)$	$(\sigma_i-\sigma_j)\cdot X_{ij,+}^{(8)}$
9	$-\frac{g_\omega(1+\kappa_\omega)}{m_N}h_\omega^0$	$f_\omega(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}\tilde{C}_1^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$\frac{2\Lambda^2}{\Lambda_\chi^3}\tilde{C}_1^{\pi}$	$f_\Lambda(r)$	$(\sigma_i\times\sigma_j)\cdot X_{ij,-}^{(9)}$
10	$-\frac{g_\omega}{2m_N}h_\omega^1$	$f_\omega(r)$	0	0	0	0	$(\tau_i+\tau_j)^z(\sigma_i-\sigma_j)\cdot X_{ij,+}^{(10)}$
11	$-\frac{g_\omega(1+\kappa_\omega)}{2m_N}h_\omega^1$	$f_\omega(r)$	0	0	0	0	$(\tau_i+\tau_j)^z(\sigma_i\times\sigma_j)\cdot X_{ij,-}^{(11)}$
12	$-\frac{g_\omega h_\omega^1-g_\rho h_\rho^1}{2m_N}$	$f_\rho(r)$	0	0	0	0	$(\tau_i-\tau_j)^z(\sigma_i+\sigma_j)\cdot X_{ij,+}^{(12)}$
13	$-\frac{g_\rho}{2m_N}h_\rho'^1$	$f_\rho(r)$	0	0	$-\frac{\sqrt{2}\pi g_A\Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$L_\Lambda(r)$	$(\tau_i\times\tau_j)^z(\sigma_i+\sigma_j)\cdot X_{ij,-}^{(13)}$
14	0	0	0	0	$\frac{2\Lambda^2}{\Lambda_\chi^3}C_6^{\pi}$	$f_\Lambda(r)$	$(\tau_i\times\tau_j)^z(\sigma_i+\sigma_j)\cdot X_{ij,-}^{(14)}$
15	0	0	0	0	$\frac{\sqrt{2}\pi g_A^3\Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$\tilde{L}_\Lambda(r)$	$(\tau_i\times\tau_j)^z(\sigma_i+\sigma_j)\cdot X_{ij,-}^{(15)}$

$$V_{ij}=\sum_\alpha c_n^\alpha O_{ij}^{(n)};\qquad X_{ij,+}^{(n)}=[\vec{p}_{ij},f_n(r_{ij})]_+\rightarrow\ X_{ij,-}^{(n)}=i[\vec{p}_{ij},f_n(r_{ij})]_-$$

- TVPV interactions are “simpler” than PV ones

- All TVPV operators are presented in PV potential

- If one can calculate PV effects, TVPV can be calculated with even better accuracy

Enhancements:

- **“Weak” structure**

$$\frac{\Delta\sigma^{T\not P}}{\Delta\sigma^{\not P}} \sim \left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + (0.26)\frac{\bar{g}_\pi^{(1)}}{h_\pi^1} \right)$$

$h_\pi^1 \sim 4.6 \cdot 10^{-7}$ "best" DDH

or 10 - 100 Enhancement!!!

- **“Strong” structure**

P-violation:

$$(\vec{\sigma}_n \cdot \vec{k}) \sim 10^{-1} (not \ \ 10^{-7})$$

Enhanced of about ~10^6

O. P. Sushkov and V. V. Flambaum, JETP Pisma 32 (1980) 377
V. E. Bunakov and V.G., Z. Phys. A303 (1981) 285

Large N_C expansion

Hierarchy of couplings:

$$\bar{g}_\pi^{(1)} \sim N_C^{1/2} > \bar{g}_\pi^{(0)} \sim \bar{g}_\pi^{(2)} \sim N_C^{-1/2}$$

$$h_\pi^{(1)} \sim N_C^{-1/2}$$

Strong-interaction enhancement of TVPV compared to PV one-pion exchange

D. Samart, C. Schat, M. R. Schindler, D. R. Phillips (2016)

EDM limits

From n EDM [1]

$$\bar{g}_{\pi}^{(0)} < 2.5 \cdot 10^{-10}$$

From ^{199}Hg EDM [2]

$$\bar{g}_{\pi}^{(1)} < 0.5 \cdot 10^{-10}$$

$\Rightarrow \quad \dfrac{\not{T}\not{P}}{\not{P}} \sim 10^{-3}$ from the current EDMs

$\equiv$ "discovery potential" 10^2 (nucl) -- 10^4 (nucl & "weak")

- M. Pospelov and A. Ritz (2005)
- V. Dmitriev and I. Khriplovich (2004)

Ranking

$\bar{g}_{\pi}^{(0)}: \quad \Rightarrow \quad Scattering, \quad {}^{3}He, \quad n$

$\bar{g}_{\pi}^{(1)}: \quad \Rightarrow \quad Scattering, \quad D, {}^{3}He$

Dominant

$\bar{g}_{\pi}^{(2)}: \quad \Rightarrow \quad {}^{3}H, \quad p, \quad n$

$\bar{g}_{\eta}^{(0)}: \quad \Rightarrow \quad p, \quad D$

$\bar{g}_{\eta}^{(1)}: \quad \Rightarrow \quad D, \quad Scattering$

$\bar{g}_{\rho}^{(0)}: \quad \Rightarrow \quad n, \quad p, \quad {}^{3}He, \quad {}^{3}H$

Sub-Dominant

$\bar{g}_{\rho}^{(1)}: \quad \Rightarrow \quad D, \quad n, \quad p$

$\bar{g}_{\rho}^{(2)}: \quad \Rightarrow n, \quad p, \quad {}^{3}He, \quad {}^{3}H$

$\bar{g}_{\omega}^{(0)}: \quad \Rightarrow D$

$\bar{g}_{\omega}^{(1)}: \quad \Rightarrow \quad {}^{3}H, \; n, \quad p, \; Scattering$

Conclusions

- No FSI = like "EDM"
- Relative values → cancelations of "unknowns"
- Reasonably simple theoretical description
- A possibility for an additional enhancement
- Sensitive to a variety of TRIV couplings
- New facilities with high neutron fluxes

→

The possibility to improve limits on TRIV

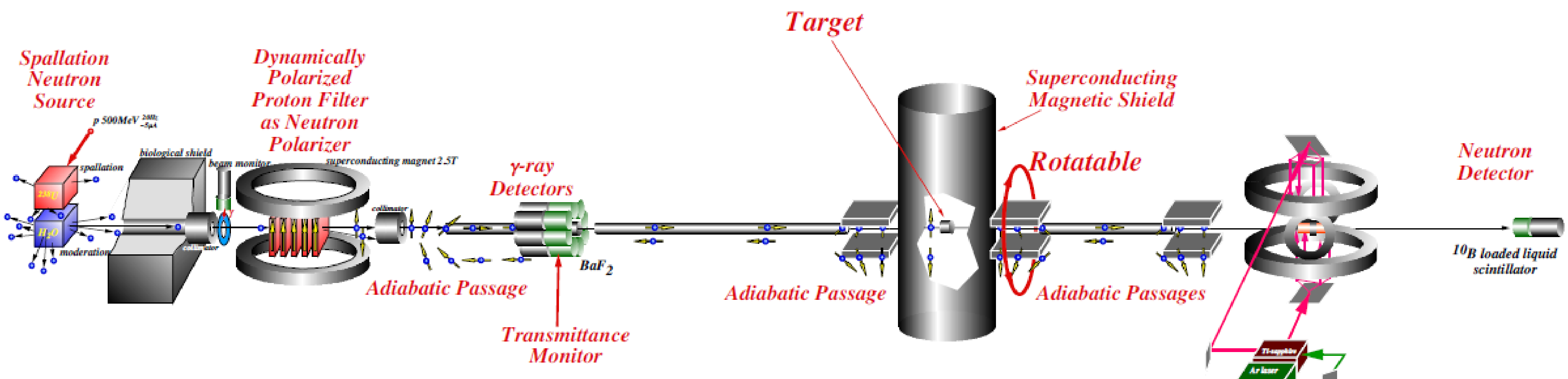
(or to discover new physics) by $10^2 – 10^4$

Thank you!

KEK 2018S12

Neutron Optics for Parity and Time Reversal EXperiment

NOPTREX Collaboration



epithermal neutron polarizer

polarized target

spin control

epithermal neutron spin analyzer

← *Polarized Neutron Source* → ← *Target station* → ← *Neutron Spin Analyzer* →

$\overrightarrow{^3\mathrm{He}}$ $\vec{\mathrm{p}}$

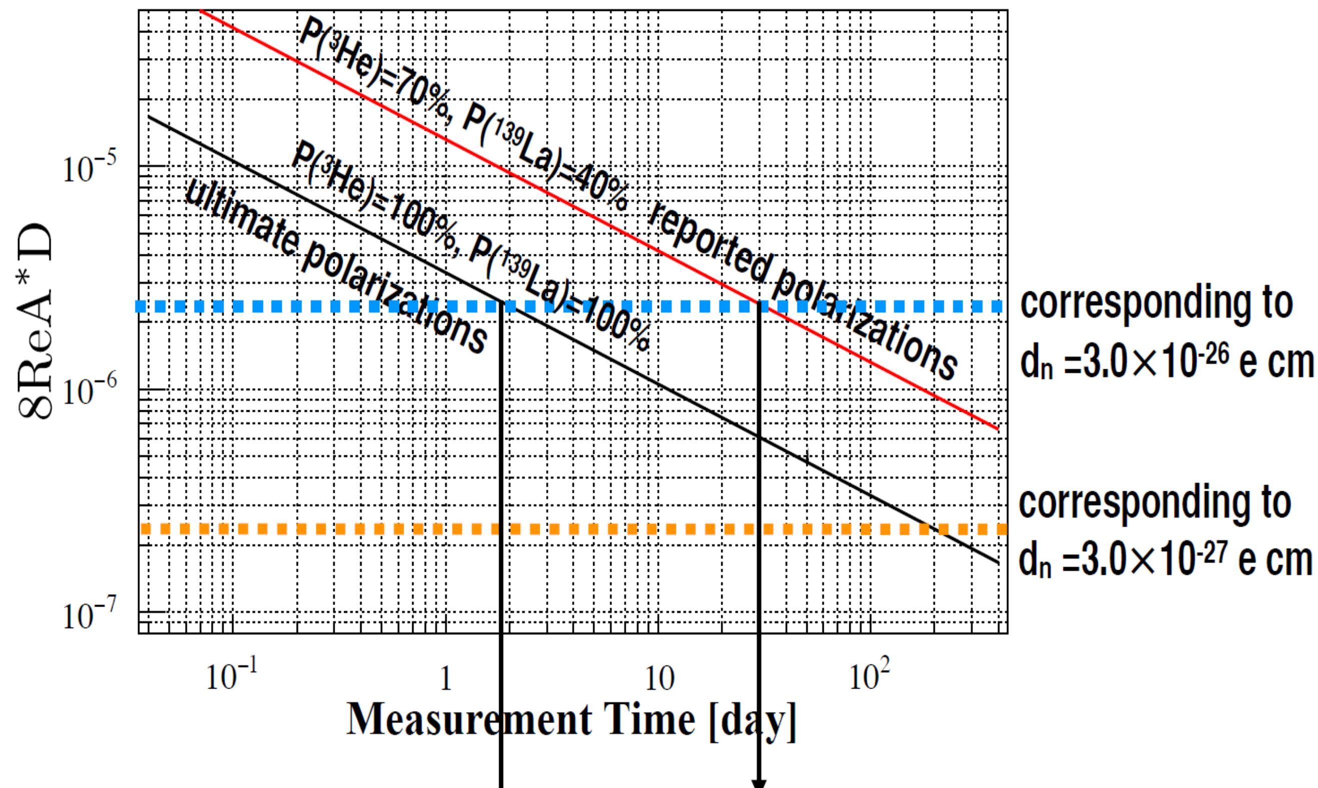
$\overrightarrow{^{139}\mathrm{La}}$ $\overrightarrow{^{131}\mathrm{Xe}}$

$\overrightarrow{^{81}\mathrm{Br}}, \overrightarrow{^{117}\mathrm{Sn}}, \overrightarrow{^{115}\mathrm{In}}, \overrightarrow{^{127}\mathrm{I}}, \overrightarrow{^{133}\mathrm{Cs}}, \overrightarrow{^{81}\mathrm{Br}}, \ldots$

$\overrightarrow{^3\mathrm{He}}$ $\vec{\mathrm{p}}$

Slide courtesy of H. Shimizu

$\overrightarrow{^{139}La}$ $LaAlO_3$ $P(^{139}La) \geq 0.4$, $V \geq 4cm \times 4cm \times 6cm$
$B_0 \leq 0.1T$



with reported polarizations
reaches to the discovery potential in 30 days

with ultimate polarizations
reaches the discovery potential in 45 hours

Slide courtesy of H. Shimizu

TVPV n-D

$\vec{\sigma}_n \cdot [\vec{k} \times \vec{I}]$

$$P^{\not T \not P} = \frac{\Delta\sigma^{\not T \not P}}{2\sigma_{tot}} = \frac{(-0.185\ \text{b})}{2\sigma_{tot}}[\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)} - 0.0012\bar{g}_\eta^{(0)} + 0.0034\bar{g}_\eta^{(1)} - 0.0071\bar{g}_\rho^{(0)} + 0.0035\bar{g}_\rho^{(1)} + 0.0019\bar{g}_\omega^{(0)} - 0.00063\bar{g}_\omega^{(1)}]$$

$$P^{\not P} = \frac{\Delta\sigma^{\not P}}{2\sigma_{tot}} = \frac{(0.395\ \text{b})}{2\sigma_{tot}}\left[h_\pi^1 + h_\rho^0(0.021) + h_\rho^1(0.0027) + h_\omega^0(0.022) + h_\omega^1(-0.043) + h_\rho'^1(-0.012)\right]$$

$$\frac{\Delta\sigma^{\not T \not P}}{\Delta\sigma^{\not P}} \simeq (-0.47)\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + (0.26)\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right)$$

- Y.-H. Song, R. Lazauskas and V. G., Phys. Rev. C83, 065503 (2011).

Sensitivity to CP-odd sources

$$d_n \sim 0.14(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})$$

$$d_p \sim 0.14\bar{g}_\pi^{(2)}$$

$$d_d \sim 0.22\bar{g}_\pi^{(1)}$$

$$d_{^3He} \sim 0.2\bar{g}_\pi^{(0)} + 0.14\bar{g}_\pi^{(1)}$$

$$d_{^3H} \sim 0.22\bar{g}_\pi^{(0)} - 0.14\bar{g}_\pi^{(1)}$$

$$P \sim \bar{g}_\pi^{(0)} + 0.3\bar{g}_\pi^{(1)}$$

Y.-H. Song, R. Lazauskas, V. G., Phys. Rev. C83, 065503 (2011), Phys. Rev. C87, 015501 (2013).

Simple systems: n-d

$$(\vec{\sigma}_n \cdot [\vec{k} \times \vec{I}\,])(\vec{k} \cdot \vec{I}\,)$$

$$\left\{ {}^3S_1(T=0) \leftrightarrow {}^3D_1(T=0), \quad {}^3P_1(T=1) \leftrightarrow {}^1P_1(T=0) \right\}$$

$$\Delta\sigma_T = \frac{4\pi}{k}\,\mathrm{Im}\{\Delta f_T\} \quad \text{and} \quad \frac{d\psi}{dz} = \frac{2\pi N}{k}\,\mathrm{Re}\{\Delta f_T\}$$

$$\Delta\sigma_T = -\frac{40\pi}{3} g_A g_T \frac{(\alpha_s + \alpha_t)\alpha_t k^2}{(\alpha_t^2 + k^2)^2(\alpha_s^2 + k^2)} \sim -3.5\times10^{-4} g_T E_{eV}\,(barn)$$

$$\frac{d\psi}{dz} = \frac{8\pi N}{3} g_A g_T \frac{(\alpha_s + \alpha_t)\alpha_s\alpha_t k^2}{(\alpha_t^2 + k^2)^2(\alpha_s^2 + k^2)} \sim 10^{-3} g_T \sqrt{E_{eV}} \left(\frac{rad}{cm}\right)$$

V.G., Z. Phys. A337 (1990) 247

TVPC potential

P. Herczeg (1966)

$$
\begin{aligned}
H^{\not{T}\not{P}} = & \left(g_1(r) + g_2(r)\tau_1\cdot\tau_2 + g_3(r)T_{12}^z + g_4(r)\tau_+\right)\hat{r}\cdot\frac{\boldsymbol{p}}{m_N} \\
& + \left(g_5(r) + g_6(r)\tau_1\cdot\tau_2 + g_7(r)T_{12}^z + g_8(r)\tau_+\right)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\hat{r}\cdot\frac{\bar{\boldsymbol{p}}}{m_N} \\
& + \left(g_9(r) + g_{10}(r)\tau_1\cdot\tau_2 + g_{11}(r)T_{12}^z + g_{12}(r)\tau_+\right) \\
& \quad \times\left(\hat{r}\cdot\boldsymbol{\sigma}_1\frac{\bar{\boldsymbol{p}}}{m_N}\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_2\frac{\bar{\boldsymbol{p}}}{m_N}\cdot\boldsymbol{\sigma}_1 - \frac{2}{3}\hat{r}\cdot\frac{\bar{\boldsymbol{p}}}{m_N}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right) \\
& + \left(g_{13}(r) + g_{14}(r)\tau_1\cdot\tau_2 + g_{15}(r)T_{12}^z + g_{16}(r)\tau_+\right) \\
& \quad \times\left(\hat{r}\cdot\boldsymbol{\sigma}_1\hat{r}\cdot\boldsymbol{\sigma}_2\hat{r}\cdot\frac{\bar{\boldsymbol{p}}}{m_N} - \frac{1}{5}\left(\hat{r}\cdot\frac{\bar{\boldsymbol{p}}}{m_N}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_1\frac{\bar{\boldsymbol{p}}}{m_N}\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_2\frac{\bar{\boldsymbol{p}}}{m_N}\cdot\boldsymbol{\sigma}_1\right)\right) \\
& + g_{17}(r)\tau_-\hat{r}\cdot\left(\boldsymbol{\sigma}_\times\times\frac{\bar{\boldsymbol{p}}}{m_N}\right) + g_{18}(r)\tau_\times^z\hat{r}\cdot\left(\boldsymbol{\sigma}_-\times\frac{\bar{\boldsymbol{p}}}{m_N}\right),
\end{aligned}
$$

TVPC potential

$$\mathcal{L}^{st} = -g_\rho \bar{N}(\gamma_\mu \rho^{\mu,a} - \frac{\kappa_V}{2M}\sigma_{\mu\nu}\partial^\nu \rho^{\mu,a})\tau^a N - g_h \bar{N}\gamma^\mu \gamma_5 h_\mu N,$$

$$\mathcal{L}^{\not{T}P} = -\frac{\bar{g}_\rho}{2m_N}\bar{N}\sigma^{\mu\nu}\epsilon^{3ab}\tau^a \partial_\nu \rho^b_\mu N + i\frac{\bar{g}_h}{2m_N}\bar{N}\sigma^{\mu\nu}\gamma_5 \partial_\nu h_\mu N,$$

$$g_5^{ME}(r) = \left(-\frac{4g_h\bar{g}_h}{3m_N}\right)\left(\frac{m_h^2}{4\pi}Y_1(m_h r)\right) = C^{\not{T}P}_{5,h} f^{\not{T}P}_{5,h}(r, \mu = m_h),$$

$$g_9^{ME}(r) = \left(-\frac{2g_h\bar{g}_h}{m_N}\right)\left(\frac{m_h^2}{4\pi}Y_1(m_h r)\right) = C^{\not{T}P}_{9,h} f^{\not{T}P}_{9,h}(r, \mu = m_h),$$

$$g_{18}^{ME}(r) = \left(\frac{g_\rho\bar{g}_\rho}{2m_N}\right)\left(\frac{m_\rho^2}{4\pi}Y_1(m_\rho r)\right) = C^{\not{T}P}_{18,\rho} f^{\not{T}P}_{18,\rho}(r, \mu = m_\rho),$$

- Y.-H. Song, R. Lazauskas and V. G, Phys. Rev. C84, 025501 (2011).

N-D TVPC

$$\Delta\sigma^{TP} = 10^{-6}[g_h\bar{g}_h(-1.09) + g_\rho\bar{g}_\rho(4.20\cdot 10^{-3})]\ \text{b},$$

$$\frac{1}{N}\frac{d\phi^{TP}}{dz} = -10^{-3}[g_h\bar{g}_h(1.24) - g_\rho\bar{g}_\rho(5.81\cdot 10^{-3})]\ \text{rad fm}^2$$

Heavy nuclei:

$$\Delta\sigma_T / \sigma_{tot} \sim 10\cdot g_T$$

"discovery potential" $10^2 - 10^3$

- Y.-H. Song, R. Lazauskas and V. G, Phys. Rev. C84, 025501 (2011)