

Time-Reversal Invariance Violating effects in neutron scattering

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Motivation

- CPT → CP $\sim T$
independent test (for the case of suppression/cancellation)
- CPT-violation:
T and CP are “independent”
problems with the standard field theory → even less trusted relations between different processes
- Search for New Physics
independent test (for the case of suppression/cancellation)
- High Intensity Neutron Facilities
SNS in Oak Ridge, JSNS at J-PARC, ESS in Lund

Criteria

- Unambiguous test
(no FSI)
- Reliability of calculations (to obtain a limit from zero-experiment)
(calculations of relative values)
- Relation to EDMs
(discovery potential)

PV (First order effects)

$$f = f_{PC} + \textcolor{red}{f}_{PV}$$

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

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

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

T-Reversal Invariance

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

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

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

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

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:

$$T^+ - T = \textcolor{red}{iT}T^+$$

in the first Born approximation T -is hermitian

$$\langle i | T | f \rangle = \langle i | T^* | f \rangle$$

⊕ T-invariance $\Rightarrow \langle f | T | i \rangle = \langle -f | T | -i \rangle^*$

$$\Rightarrow |\langle f | T | i \rangle|^2 = |\langle -f | T | -i \rangle|^2$$

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)

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 2 MeV, on ^{165}Ho : $<5 \cdot 10^{-3}$, J. E. Koster, 1991)

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

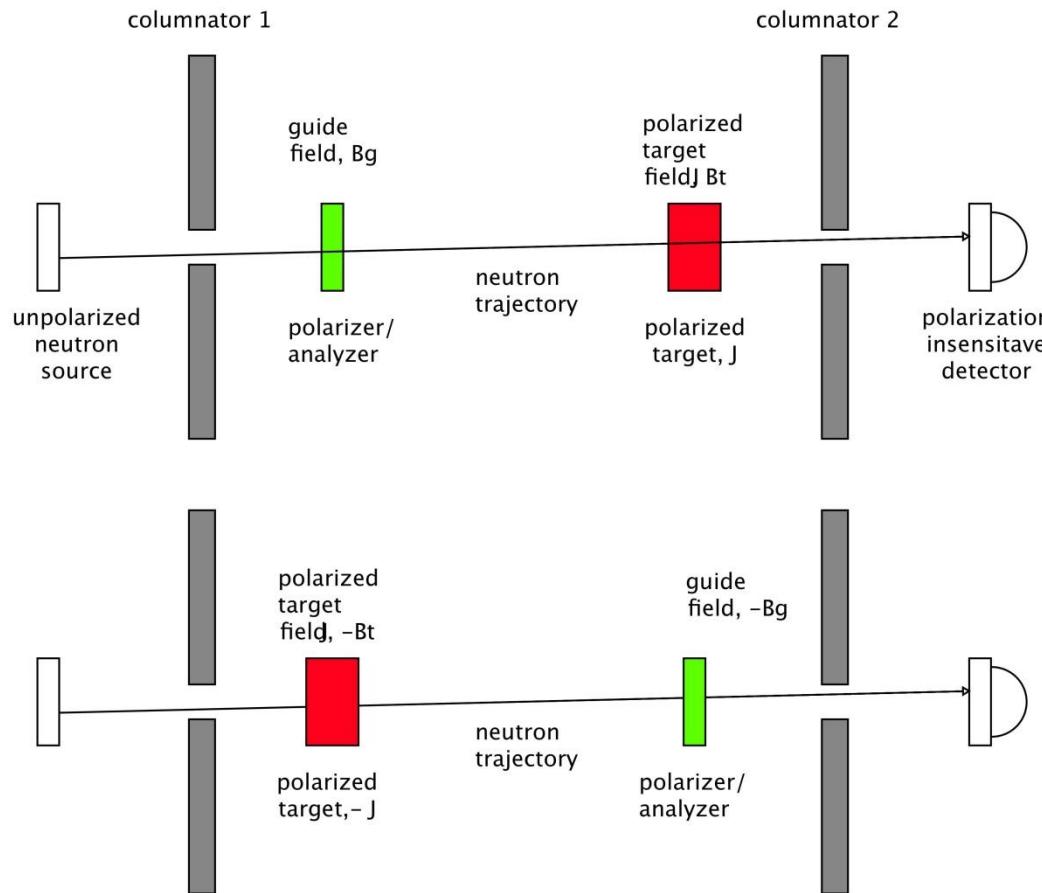
Enhanced of about 10^6

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

$$\Delta\sigma_v = \frac{4\pi}{k} \text{Im}\{\Delta f_v\}$$

$$\frac{d\psi}{dz} = \frac{2\pi N}{k} \text{Re}\{\Delta f_v\}$$

No Systematic



courtesy of J. D. Bowman

TRIV Transmission Theorem

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

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

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

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

TRIV effects in nuclei

- Is it **unambiguous** test? – **YES! (no FSI)**
- Could they be reliably **calculated?**
(calculations of relative values)
- How they are **related** to EDMs?
(discovery potential)

Neutron transmission

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DWBA

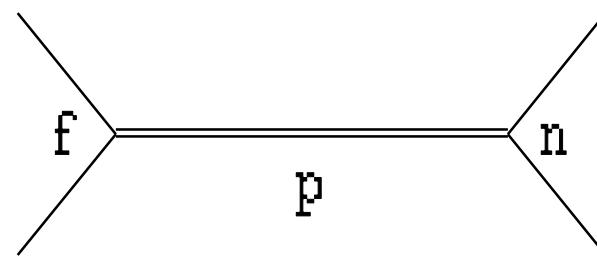
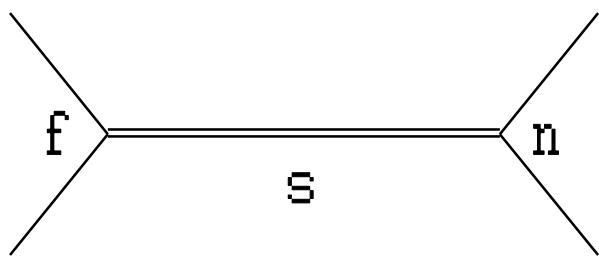
$$T_{if} = \langle \Psi_f^- | W | \Psi_i^+ \rangle$$

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

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

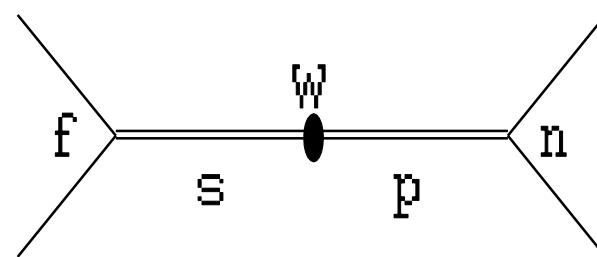
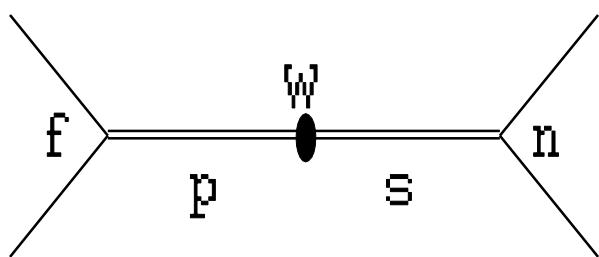
$$(\Gamma_k^i)^{1/2} = \sqrt{2\pi} \langle \chi_i(E') | V | \phi_k \rangle$$

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



c

L



C

L

^{117}Sn -case ($E_p=1.33\text{eV}$, $E_s=38.9\text{eV}$)

$$\sigma \approx \frac{\pi}{k^2} \frac{\Gamma_s^n \Gamma_s}{(E - E_s)^2 + \Gamma_s^2 / 4} + \frac{\pi}{k^2} \frac{\Gamma_p^n \Gamma_p}{(E - E_p)^2 + \Gamma_p^2 / 4}$$

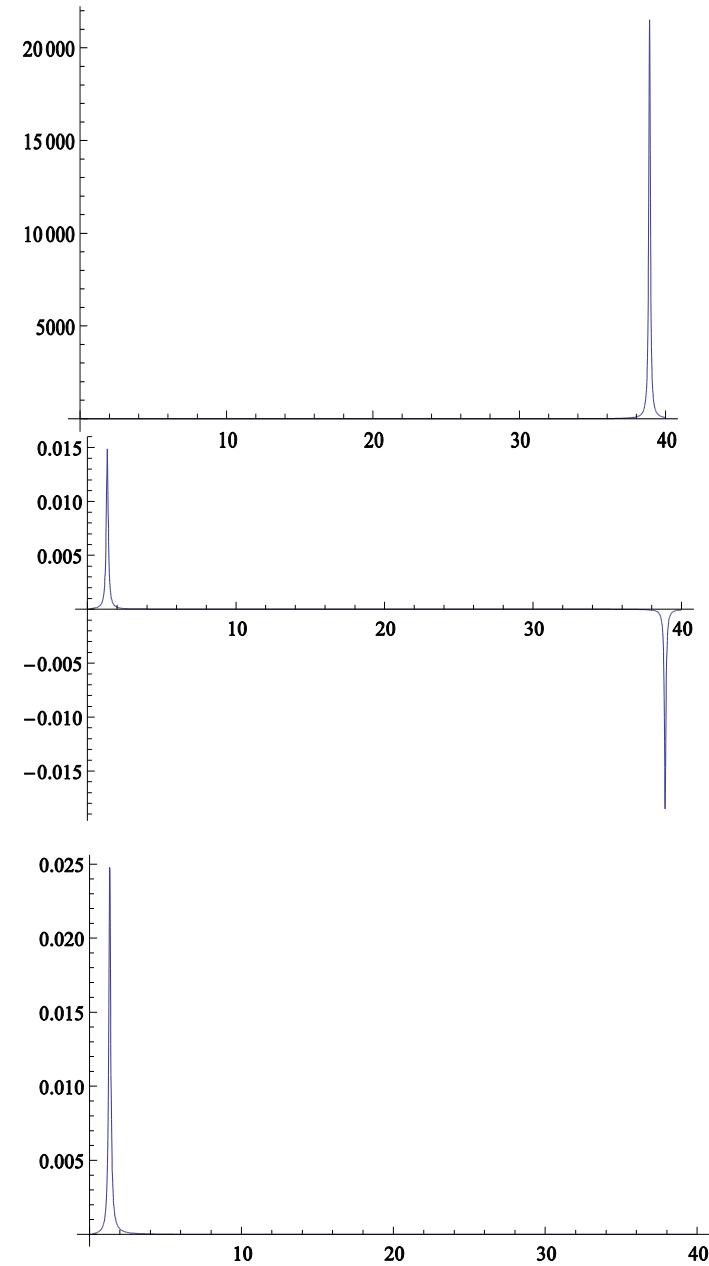
$$\sigma_- - \sigma_+ \simeq \frac{4\pi}{k^2} \Im m \frac{(\Gamma_s^n)^{1/2} w(\Gamma_p^n)^{1/2}}{(E - E_s + i\Gamma_s / 2)(E - E_p + i\Gamma_p / 2)}$$

$$P = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+}$$

$$\begin{aligned} P(E_p) &\sim 8 \frac{w}{D} \sqrt{\frac{\Gamma_p^n}{\Gamma_s^n}} \left(\frac{D^2}{\Gamma_s \Gamma_p} \right) \left[1 + \frac{\sigma_p(E_p) + \sigma_{pot}(E_p)}{\sigma_s(E_p)} \right]^{-1} \sim \\ &\sim \frac{w}{E_+ - E_-} (kR) \left(\frac{D}{\Gamma} \right)^2 \quad (\tau \sim 1/D \quad \& \quad \tau_R \sim 1/\Gamma) \end{aligned}$$

$$\text{if } \sigma_p(E_p) = \sigma_s(E_p) \Rightarrow \Gamma_s^n / \Gamma_p^n = 4D^2 / \Gamma^2$$

$$\text{then } P_{\max} \simeq \frac{w}{D} \sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}} = \frac{w}{D} \left(\frac{D}{\Gamma} \right) = \frac{w}{\Gamma}$$

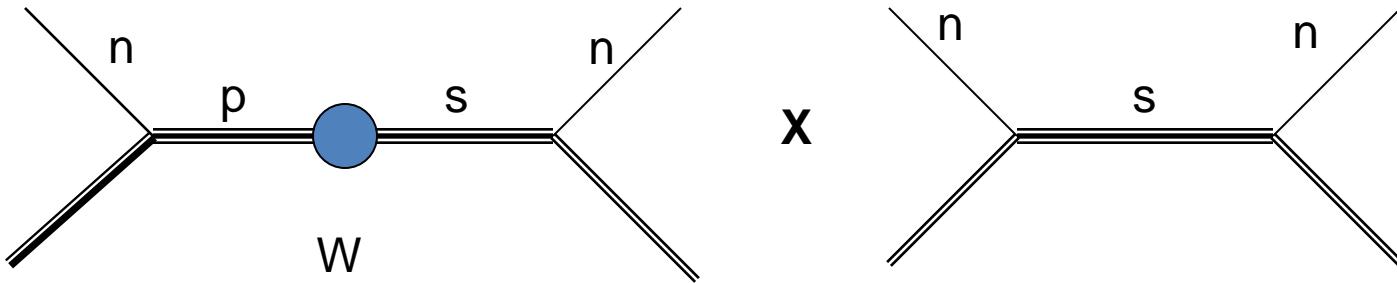


Dynamical Enhancement

$$\phi = \sum_{i=1}^N c_i \psi_i \quad \Rightarrow \quad w = \langle \phi_s | W | \phi_p \rangle = \overline{\langle \psi_i | W | \psi_k \rangle} N^{-1/2}$$

$$N \approx \overline{D_0} / \bar{D} \quad \Rightarrow \quad \frac{w}{D} \simeq \frac{\overline{\langle \psi_i | W | \psi_k \rangle}}{\overline{D_0}} \sqrt{N}$$

P- and T-violation in Neutron transmission



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

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

One-particle potential

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

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

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

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

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

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

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

TVPV potential

P. Herczeg (1966)

$$\begin{aligned} V_{T\#} = & \left[-\frac{\bar{g}_\eta^{(0)} g_\eta}{2m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) + \frac{\bar{g}_\omega^{(0)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \boldsymbol{\sigma}_- \cdot \hat{r} \\ & + \left[-\frac{\bar{g}_\pi^{(0)} g_\pi}{2m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\rho^{(0)} g_\rho}{2m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) \right] \tau_1 \cdot \tau_2 \boldsymbol{\sigma}_- \cdot \hat{r} \\ & + \left[-\frac{\bar{g}_\pi^{(2)} g_\pi}{2m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\rho^{(2)} g_\rho}{2m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) \right] T_{12}^z \boldsymbol{\sigma}_- \cdot \hat{r} \\ & + \left[-\frac{\bar{g}_\pi^{(1)} g_\pi}{4m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\eta^{(1)} g_\eta}{4m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) + \frac{\bar{g}_\rho^{(1)} g_\rho}{4m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) + \frac{\bar{g}_\omega^{(1)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \tau_+ \boldsymbol{\sigma}_- \cdot \hat{r} \\ & + \left[-\frac{\bar{g}_\pi^{(1)} g_\pi}{4m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) - \frac{\bar{g}_\eta^{(1)} g_\eta}{4m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) - \frac{\bar{g}_\rho^{(1)} g_\rho}{4m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) + \frac{\bar{g}_\omega^{(1)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \tau_- \boldsymbol{\sigma}_+ \cdot \hat{r} \end{aligned}$$

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

TVPV n-D

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

$$P^{T\phi} = \frac{\Delta\sigma^{T\phi}}{2\sigma_{tot}} = \frac{(-0.185 \text{ b})}{2\sigma_{tot}} [\bar{g}_{\pi}^{(0)} + 0.26\bar{g}_{\pi}^{(1)} - 0.0012\bar{g}_{\eta}^{(0)} + 0.0034\bar{g}_{\eta}^{(1)} \\ - 0.0071\bar{g}_{\rho}^{(0)} + 0.0035\bar{g}_{\rho}^{(1)} + 0.0019\bar{g}_{\omega}^{(0)} - 0.00063\bar{g}_{\omega}^{(1)}]$$

$$P^{\phi} = \frac{\Delta\sigma^{\phi}}{2\sigma_{tot}} = \frac{(0.395 \text{ b})}{2\sigma_{tot}} [h_{\pi}^1 + h_{\rho}^0(0.021) + h_{\rho}^1(0.0027) + h_{\omega}^0(0.022) + h_{\omega}^1(-0.043) + h_{\rho}'^1(-0.012)]$$

$$\frac{\Delta\sigma^{T\phi}}{\Delta\sigma^{\phi}} \simeq (-0.47) \left(\frac{\bar{g}_{\pi}^{(0)}}{h_{\pi}^1} + (0.26) \frac{\bar{g}_{\pi}^{(1)}}{h_{\pi}^1} \right)$$

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

EDM limits

From n EDM ⁽¹⁾

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

From ${}^{199}Hg$ EDM ⁽²⁾

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

$\Rightarrow \frac{\cancel{T}\cancel{P}}{\cancel{P}} \sim 10^{-3}$ 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)

Enhancements:

- "Weak" structure

$$\frac{\Delta\sigma^{TP}}{\Delta\sigma^P} \sim \left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + (0.26) \frac{\bar{g}_\pi^{(1)}}{h_\pi^1} \right)$$

$h_\pi^1 \sim 4.6 \cdot 10^{-7}$ "best" DDH
or 10 - 100 Enhancement!!!

- "Strong" structure

P-violation:

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

Enhanced of about $\sim 10^6$

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Nuclear dependent factor

$$\Delta\sigma_{CP} = \kappa(J)(w/v) \Delta\sigma_P ,$$

$$\kappa(I + \frac{1}{2}) = - \frac{3}{2^{3/2}} \left(\frac{2I+1}{2I+3} \right)^{3/2} \left(\frac{3}{\sqrt{2I+3}} \gamma - \sqrt{I} \right)^{-1} ,$$

$$\kappa(I - \frac{1}{2}) = - \frac{3}{2^{3/2}} \left(\frac{2I+1}{2I-1} \right) \left(\frac{I}{I+1} \right)^{1/2} \left(- \frac{I-1}{\sqrt{2I-1}} \frac{1}{\gamma} + \sqrt{I+1} \right)^{-1} .$$

$\gamma = [\Gamma_p^n(I + 1/2)/\Gamma_p^n(I - 1/2)]^{1/2}$. Here γ is the ratio of the neutron width amplitudes channel spins. In general the parameter v may be obtained from the angular correlation

$$\vec{J} = \vec{s}_n + \vec{l} + \vec{I} = (\vec{s}_n + \vec{l}) + \vec{I} = \vec{j} + \vec{I}$$

$$\vec{J} = \vec{s} + \vec{l} + \vec{I} = (\vec{s}_n + \vec{I}) + \vec{l} = \vec{S} + \vec{l}$$

$$j=1\pm 1/2 \quad \Rightarrow \quad x=\left(\Gamma_p^n(1/2)\right)^{1/2}/\left(\Gamma_p^n\right)^{1/2} \text{ and } y=\left(\Gamma_p^n(3/2)\right)^{1/2}/\left(\Gamma_p^n\right)^{1/2}$$

$$S=I\pm 1/2 \quad \Rightarrow \quad x_s=\left(\Gamma_p^n(I-1/2)\right)^{1/2}/\left(\Gamma_p^n\right)^{1/2} \text{ and } y_s=\left(\Gamma_p^n(I+1/2)\right)^{1/2}/\left(\Gamma_p^n\right)^{1/2}$$

$$x_s = \frac{1}{\sqrt{3}}x + \sqrt{\frac{2}{3}}y$$

$$y_s = -\sqrt{\frac{2}{3}}x + \frac{1}{\sqrt{3}}y$$

$$\gamma = \left(\frac{\Gamma_p^n(I+1/2)}{\Gamma_p^n(I-1/2)} \right)^{1/2} = \frac{y_s}{x_s} = \frac{-\sqrt{2}x+y}{x+\sqrt{2}y} = \frac{-\sqrt{2}\left(\Gamma_p^n(1/2)\right)^{1/2}+\left(\Gamma_p^n(3/2)\right)^{1/2}}{\left(\Gamma_p^n(1/2)\right)^{1/2}+\sqrt{2}\left(\Gamma_p^n(3/2)\right)^{1/2}}$$

TRIV effects in nuclei

- Is it **unambiguous** test? – **YES!** (no FSI)
- Could they be reliably **calculated**? – **YES!**
(calculations of relative values)
- How they are **related** to EDMs?
- **(discovery potential)**

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

$$d_d^{(pol)} = 18.95 \times 10^{-2} \bar{g}_\pi^1 + 3.52 \times 10^{-3} \bar{g}_\eta^1 + 17.13 \times 10^{-4} \bar{g}_\rho^1 - 49.09 \times 10^{-4} \bar{g}_\omega^1$$

$$\begin{aligned} d_3\text{He} = & (-0.0542d_p + 0.868d_n) + 0.072[\bar{g}_\pi^{(0)} + 1.92\bar{g}_\pi^{(1)} + 1.21\bar{g}_\pi^{(2)} - 0.015\bar{g}_\eta^{(0)} + 0.03\bar{g}_\eta^{(1)} \\ & - 0.010\bar{g}_\rho^{(0)} + 0.015\bar{g}_\rho^{(1)} - 0.012\bar{g}_\rho^{(2)} + 0.021\bar{g}_\omega^{(0)} - 0.06\bar{g}_\omega^{(1)}]e \cdot fm \end{aligned} \quad (1)$$

$$\begin{aligned} d_3\text{H} = & (0.868d_p - 0.0552d_n) - 0.072[\bar{g}_\pi^{(0)} - 1.97\bar{g}_\pi^{(1)} + 1.26\bar{g}_\pi^{(2)} - 0.015\bar{g}_\eta^{(0)} - 0.030\bar{g}_\eta^{(1)} \\ & - 0.010\bar{g}_\rho^{(0)} - 0.015\bar{g}_\rho^{(1)} - 0.012\bar{g}_\rho^{(2)} + 0.022\bar{g}_\omega^{(0)} + 0.061\bar{g}_\omega^{(1)}]e \cdot fm. \end{aligned} \quad (1)$$

TRIV:

$$\begin{aligned} \frac{1}{N} \frac{d\phi^{TP}}{dz} = & (-65 \text{ rad} \cdot \text{ fm}^2)[\bar{g}_\pi^{(0)} + 0.12\bar{g}_\pi^{(1)} + 0.0072\bar{g}_\eta^{(0)} + 0.0042\bar{g}_\eta^{(1)} \\ & - 0.0084\bar{g}_\rho^{(0)} + 0.0044\bar{g}_\rho^{(1)} - 0.0099\bar{g}_\omega^{(0)} + 0.00064\bar{g}_\omega^{(1)}] \end{aligned}$$

$$\begin{aligned} P^{TP} = \frac{\Delta\sigma^{TP}}{2\sigma_{tot}} = & \frac{(-0.185 \text{ b})}{2\sigma_{tot}} [\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)} - 0.0012\bar{g}_\eta^{(0)} + 0.0034\bar{g}_\eta^{(1)} \\ & - 0.0071\bar{g}_\rho^{(0)} + 0.0035\bar{g}_\rho^{(1)} + 0.0019\bar{g}_\omega^{(0)} - 0.00063\bar{g}_\omega^{(1)}]. \end{aligned}$$

Major Contributions

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

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

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

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

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

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

Ranking

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

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

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

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

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

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

Sub-Dominant

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

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

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

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

Correlations

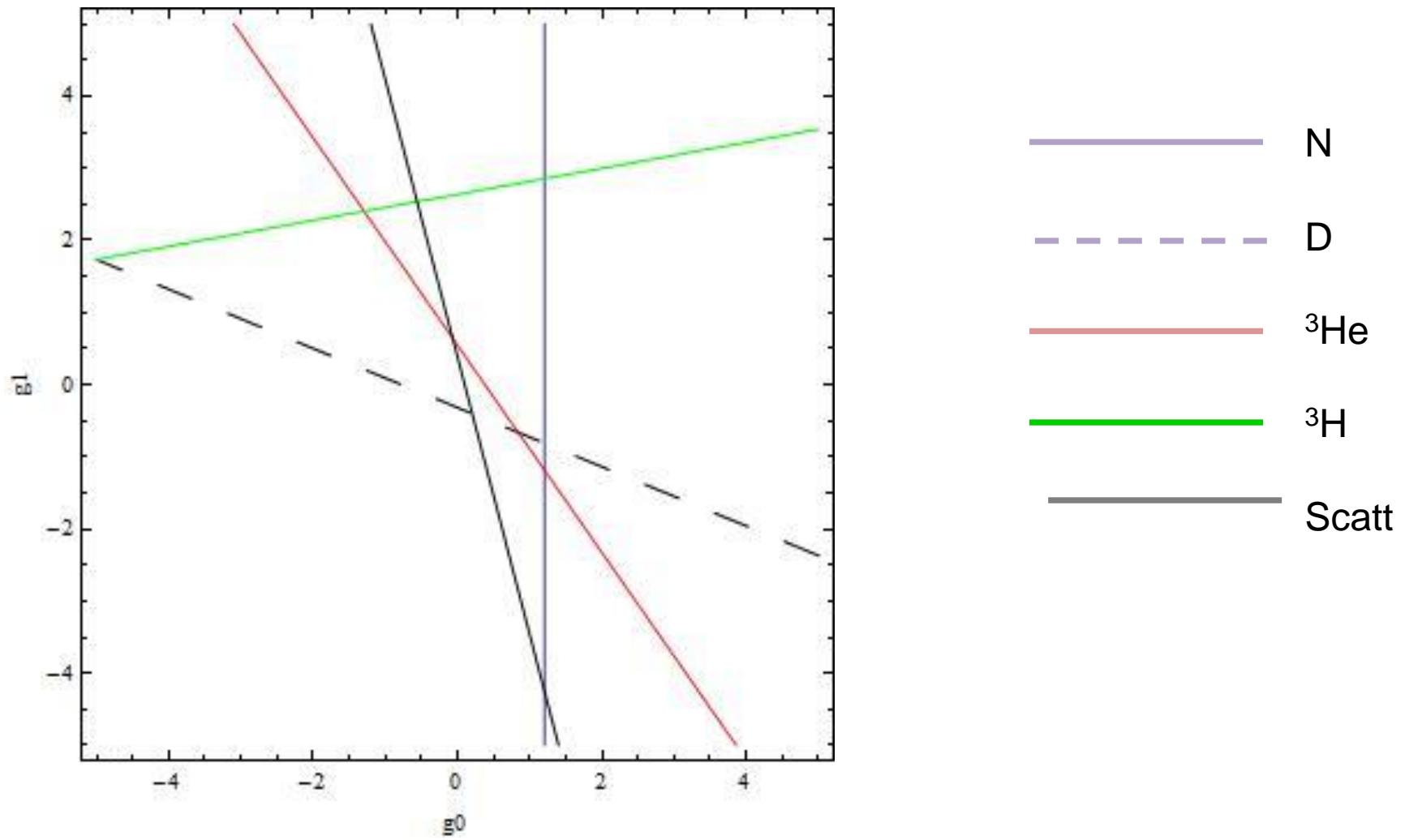
	n	p	d	${}^3\text{He}$	${}^3\text{H}$	Scatt
n	1.	-0.86	0.27	0.7	-0.56	0.66
p	-0.86	1.	0.08	-0.33	0.7	-0.25
d	0.27	0.08	1.	0.81	-0.37	0.6
${}^3\text{He}$	0.706	-0.33	0.81	1.	-0.35	0.91
${}^3\text{H}$	-0.56	0.7	-0.37	-0.35	1.	-0.035
Scatt	0.66	-0.25	0.6	0.91	-0.035	1.

$$\vec{O}_i = \sum_{i=1}^{10} O_i^k \vec{g}_k$$

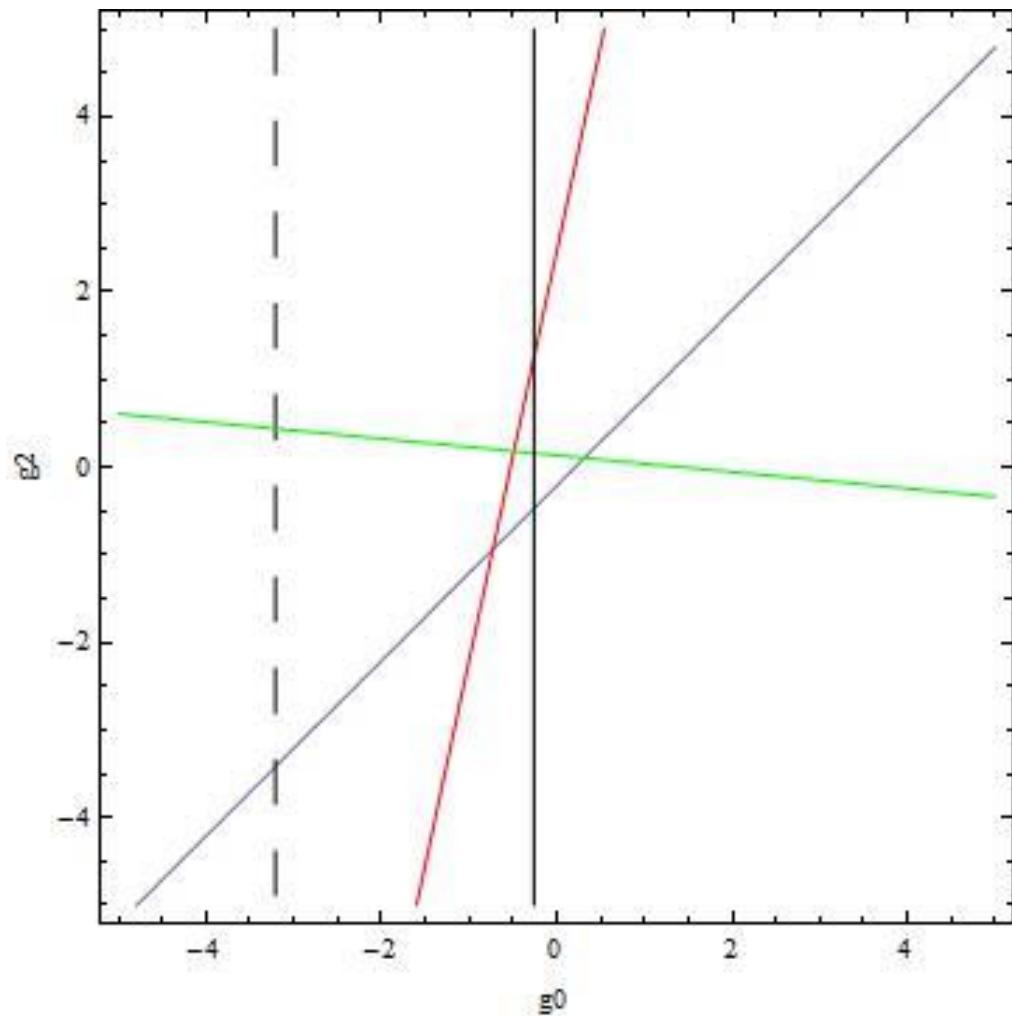
Orthonormal representations

$$M = \|(\vec{O}_i \vec{O}_j)\|$$

Sensitivities (0-1)

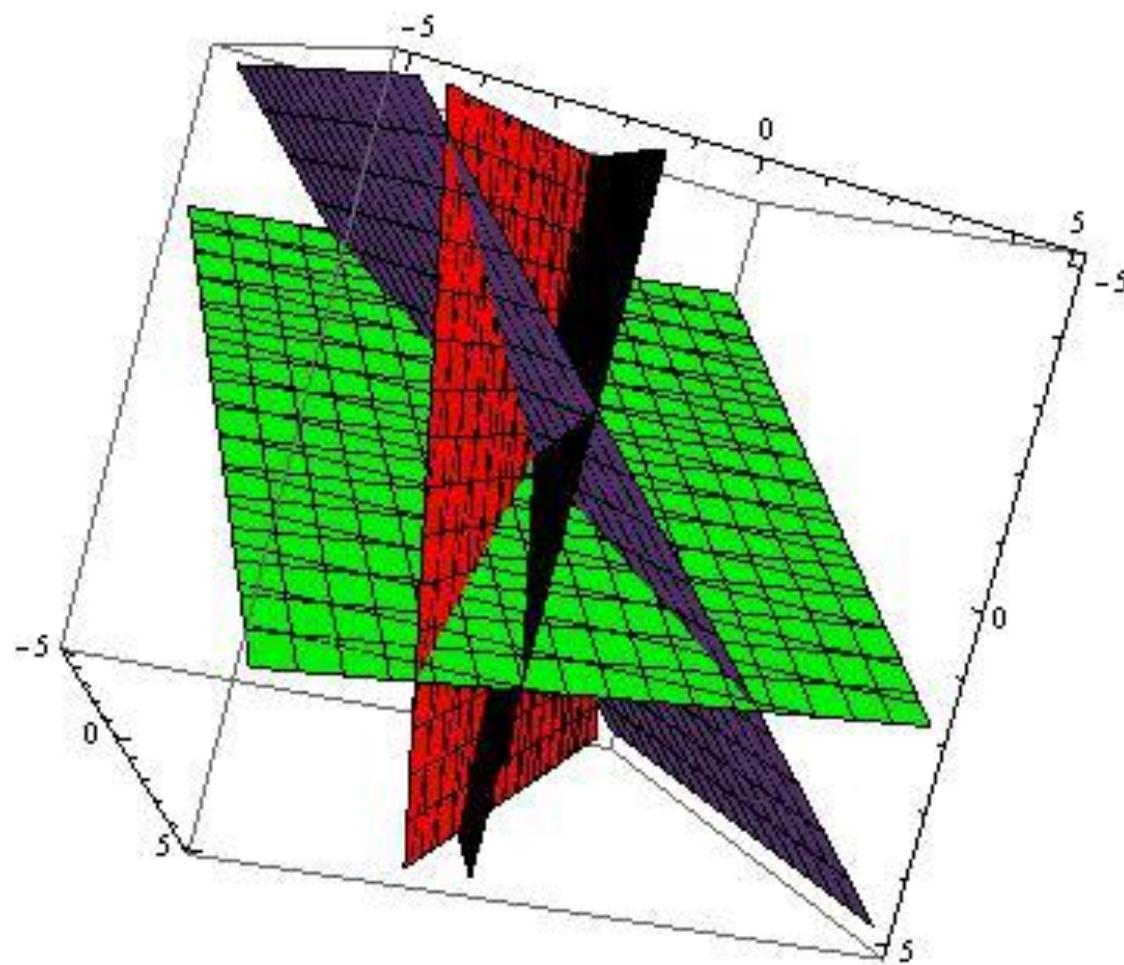


Sensitivities (0-2)



N
D
 ^3He
 ^3H
Scatt

Sensitivities (pion-coupling space)



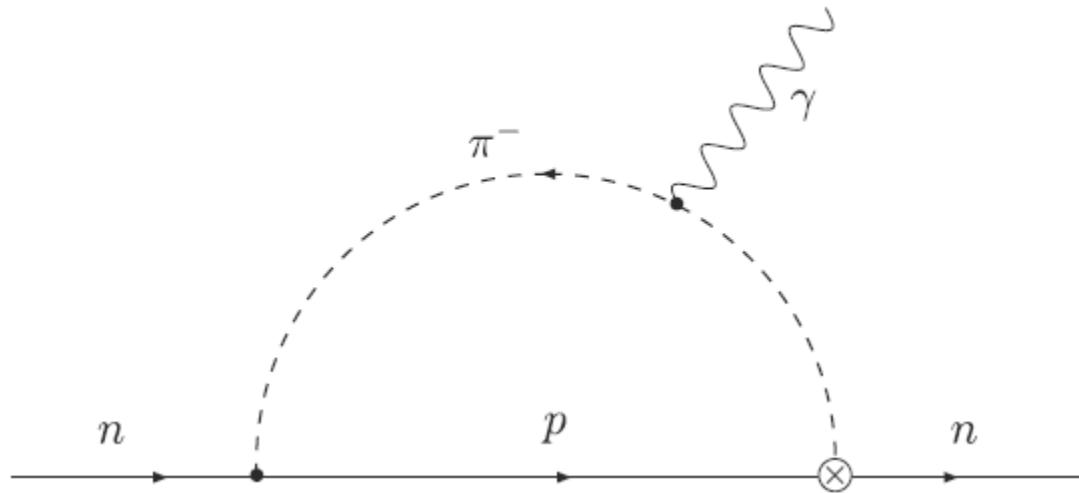
Conclusions

- No FSI = like “EDM”
- 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

Extra Slides:

Chiral Limit



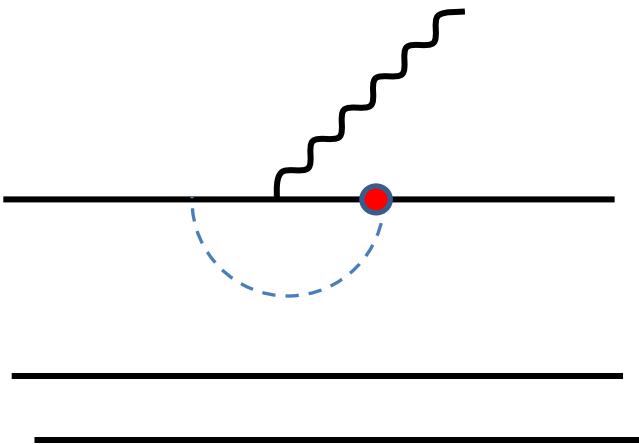
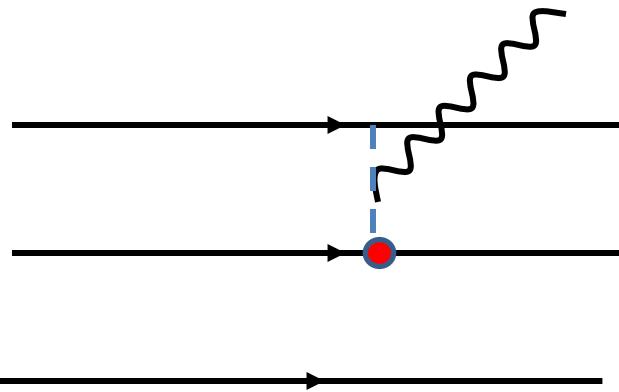
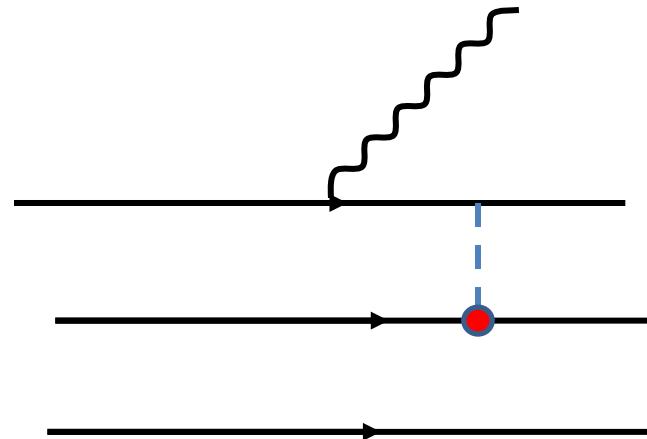
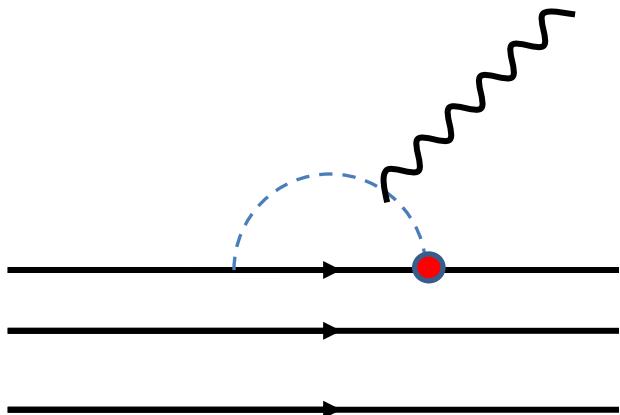
$$d_n = -d_p = \frac{e}{m_N} \frac{g_\pi (\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})}{4\pi^2} \ln \frac{m_N}{m_\pi} \simeq 0.14 (\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})$$

With more details...

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

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

Many Body system EDMs



How to calculate?

$$d = \langle JJ|\hat{D}|JJ\rangle = \sqrt{\frac{J}{(2J+1)(J+1)}}\langle J||\hat{D}||J\rangle$$

$$\hat{D}_{TP}^{\text{nucleon}} = \sum_i \frac{1}{2} [(d_p + d_n) + (d_p - d_n)\tau_i^z] \sigma_i \quad \hat{D}_{TP}^{\text{pol}} = \sum_i Q_i \mathbf{r}_i$$

$$d = \frac{1}{\sqrt{6}} \left[\langle \Psi || \hat{D}_{TP}^{nucleon} || \Psi \rangle + \langle \Psi_{TP} || \hat{D}_{TP}^{pol} || \Psi \rangle + \langle \Psi || \hat{D}_{TP}^{pol} || \Psi_{TP} \rangle \right]$$

Deuteron EDM

$$\hat{D}_{TP}^{nucleon} \rightarrow (d_p + d_n) \frac{\sigma_{(+)}}{2} + (d_p - d_n) \frac{\tau_{(-)}^z \sigma_{(-)} + \tau_{(+)}^z \sigma_{(+)}}{4}$$

$$d_d^{nucleon} = d_p + d_n$$

$$d_d^{(pol)} = 18.95 \times 10^{-2} \bar{g}_\pi^1 + 3.52 \times 10^{-3} \bar{g}_\eta^1 + 17.13 \times 10^{-4} \bar{g}_\rho^1 - 49.09 \times 10^{-4} \bar{g}_\omega^1$$

3-nucleon system

$$(E - H_0 - V_{ij}) \psi_k = V_{ij}(\psi_i + \psi_j),$$

$$V_{ij} = V_{ij}^{TC} + V_{ij}^{TP}$$

$$\psi_k = \psi_k^+ + \psi_k^-.$$

$$(E - H_0 - V_{ij}^{TC}) \psi_k^+ = V_{ij}^{TC}(\psi_i^+ + \psi_j^+),$$

$$(E - H_0 - V_{ij}^{TC}) \psi_k^- = V_{ij}^{TC}(\psi_i^- + \psi_j^-) + V_{ij}^{TP}(\psi_i^+ + \psi_j^+ + \psi_k^+)$$

^3He and ^3H

$$\begin{aligned} d_{^3\text{He}} = & (-0.0542d_p + 0.868d_n) + 0.072[\bar{g}_\pi^{(0)} + 1.92\bar{g}_\pi^{(1)} \\ & + 1.21\bar{g}_\pi^{(2)} - 0.015\bar{g}_\eta^{(0)} + 0.03\bar{g}_\eta^{(1)} - 0.010\bar{g}_\rho^{(0)} \\ & + 0.015\bar{g}_\rho^{(1)} - 0.012\bar{g}_\rho^{(2)} + 0.021\bar{g}_\omega^{(0)} - 0.06\bar{g}_\omega^{(1)}] \text{efm} \end{aligned}$$

$$\begin{aligned} d_{^3\text{H}} = & (0.868d_p - 0.0552d_n) - 0.072[\bar{g}_\pi^{(0)} - 1.97\bar{g}_\pi^{(1)} \\ & + 1.26\bar{g}_\pi^{(2)} - 0.015\bar{g}_\eta^{(0)} - 0.030\bar{g}_\eta^{(1)} \\ & - 0.010\bar{g}_\rho^{(0)} - 0.015\bar{g}_\rho^{(1)} - 0.012\bar{g}_\rho^{(2)} \\ & + 0.022\bar{g}_\omega^{(0)} + 0.061\bar{g}_\omega^{(1)}] \text{efm}. \end{aligned}$$

TRIV:

$$\frac{1}{N} \frac{d\phi^{T\Phi}}{dz} = (-65 \text{ rad} \cdot \text{ fm}^2) [\bar{g}_\pi^{(0)} + 0.12\bar{g}_\pi^{(1)} + 0.0072\bar{g}_\eta^{(0)} + 0.0042\bar{g}_\eta^{(1)} \\ - 0.0084\bar{g}_\rho^{(0)} + 0.0044\bar{g}_\rho^{(1)} - 0.0099\bar{g}_\omega^{(0)} + 0.00064\bar{g}_\omega^{(1)}]$$

$$P^{T\Phi} = \frac{\Delta\sigma^{T\Phi}}{2\sigma_{tot}} = \frac{(-0.185 \text{ b})}{2\sigma_{tot}} [\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)} - 0.0012\bar{g}_\eta^{(0)} + 0.0034\bar{g}_\eta^{(1)} \\ - 0.0071\bar{g}_\rho^{(0)} + 0.0035\bar{g}_\rho^{(1)} + 0.0019\bar{g}_\omega^{(0)} - 0.00063\bar{g}_\omega^{(1)}].$$

DBP test:



(with the intermediate compound nuclear state ^{28}Si excited up to $E^* \sim 19 MeV$)

$$|F| < 2 \cdot 10^{-3} \quad (E. Burke, 1983)$$



$$|F| < 2 \cdot 10^{-3} \quad (D. Bodansky, 1968)$$

Ericson fluctuations

$$| F | \sim \frac{| S_{asym} |}{| S_{sym} |}$$

$$S_{asym} \sim \sum_c \left\{ \gamma' \frac{1}{\Delta_c} \gamma + \gamma \frac{1}{\Delta_c} \gamma' + \gamma' \frac{1}{\Delta_{c'}} w \frac{1}{\Delta_c} \gamma \right\}$$

Asymmetry Theorem:

$$\vec{A}_a = \frac{3s_b}{s_b + 1} \vec{P}_b$$

Proton-proton scattering ($E=198.5\text{MeV}$)

$$|F| < 2.6 \cdot 10^{-3} \quad (\text{C. A. Davic, 1986})$$

Correlations in γ -decay transitions:

$$(\vec{J}[\vec{k} \times \vec{\varepsilon}]) (\vec{J}\vec{k}) (\vec{J}\vec{\varepsilon}) \quad E_\gamma = 122\text{KeV for } {}^{57}\text{Fe} \quad (\text{F. Boehm, 1979})$$

$$\sin \eta = (3.1 \pm 6.9) \cdot 10^{-4}$$

Mössbauer's transitions (V. G. Tsinoev, 1982)

$$\sin \eta = (-3.3 \pm 6.6) \cdot 10^{-4}$$

Statistical properties of compound nuclei

- T-invariant \rightarrow *Gauss Orthogonal Ensemble* of random matrices \rightarrow Wigner linear repulsion:

$$p(\varepsilon) \sim \varepsilon$$

- Violation of T-invariance \rightarrow *Unitary Ensemble* of random matrices :

$$p(\varepsilon) \sim \varepsilon^2$$

$$E_{\pm} = \frac{1}{2}(H_{11} + H_{22}) \pm \frac{1}{2}\sqrt{(H_{11} - H_{22})^2 + 4H_{12}^2 + \textcolor{red}{H_T}^2}$$

1.7·10³ levels results in <10⁻³

T-odd correlations in β -decay

Neutron:

$$D = (-1.1 \pm 1.7) 10^{-3} \quad (\text{R. I. Steinberg, 1974})$$

$$D = (2.2 \pm 3.0) 10^{-3} \quad (\text{B. G. Erozolimsky, 1978})$$

$$D = (-0.6 \pm 1.2(\text{stat}) \pm 0.5(\text{syst})) 10^{-3} \quad (\text{The emiT Collab., 2000})$$

$$D = (-2.8 \pm 6.4(\text{stat}) \pm 3.0(\text{syst})) 10^{-4} \quad (\text{T. Soldner, 2004})$$

$$D = (-0.96 \pm 1.89(\text{stat}) \pm 1.01(\text{syst})) 10^{-4} \quad (\text{H. P. Mumm, 2011})$$

$$D = (-0.94 \pm 1.89(\text{stat}) \pm 0.97(\text{syst})) 10^{-4} \quad (\text{T. E. Chupp, 2012})$$

^{19}Ne :

$$D = (0.4 \pm 0.8) 10^{-3} \quad (\text{A. L. Hallin, 1984})$$

TVPC potential

P. Herczeg (1966)

$$\begin{aligned} H^{TP} = & (g_1(r) + g_2(r)\tau_1 \cdot \tau_2 + g_3(r)T_{12}^z + g_4(r)\tau_+) \hat{r} \cdot \frac{\mathbf{p}}{m_N} \\ & + (g_5(r) + g_6(r)\tau_1 \cdot \tau_2 + g_7(r)T_{12}^z + g_8(r)\tau_+) \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \hat{r} \cdot \frac{\bar{\mathbf{p}}}{m_N} \\ & + (g_9(r) + g_{10}(r)\tau_1 \cdot \tau_2 + g_{11}(r)T_{12}^z + g_{12}(r)\tau_+) \\ & \quad \times \left(\hat{r} \cdot \boldsymbol{\sigma}_1 \frac{\bar{\mathbf{p}}}{m_N} \cdot \boldsymbol{\sigma}_2 + \hat{r} \cdot \boldsymbol{\sigma}_2 \frac{\bar{\mathbf{p}}}{m_N} \cdot \boldsymbol{\sigma}_1 - \frac{2}{3} \hat{r} \cdot \frac{\bar{\mathbf{p}}}{m_N} \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \right) \\ & + (g_{13}(r) + g_{14}(r)\tau_1 \cdot \tau_2 + g_{15}(r)T_{12}^z + g_{16}(r)\tau_+) \\ & \quad \times \left(\hat{r} \cdot \boldsymbol{\sigma}_1 \hat{r} \cdot \boldsymbol{\sigma}_2 \hat{r} \cdot \frac{\bar{\mathbf{p}}}{m_N} - \frac{1}{5} (\hat{r} \cdot \frac{\bar{\mathbf{p}}}{m_N} \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + \hat{r} \cdot \boldsymbol{\sigma}_1 \frac{\bar{\mathbf{p}}}{m_N} \cdot \boldsymbol{\sigma}_2 + \hat{r} \cdot \boldsymbol{\sigma}_2 \frac{\bar{\mathbf{p}}}{m_N} \cdot \boldsymbol{\sigma}_1) \right) \\ & + g_{17}(r)\tau_- \hat{r} \cdot (\boldsymbol{\sigma}_\times \times \frac{\bar{\mathbf{p}}}{m_N}) + g_{18}(r)\tau_\times^z \hat{r} \cdot (\boldsymbol{\sigma}_- \times \frac{\bar{\mathbf{p}}}{m_N}), \end{aligned}$$

TVPC potential

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

$$\mathcal{L}^{TP} = -\frac{\bar{g}_\rho}{2m_N} \bar{N} \sigma^{\mu\nu} \epsilon^{3ab} \tau^a \partial_\nu \rho_\mu^b N + i \frac{\bar{g}_h}{2m_N} \bar{N} \sigma^{\mu\nu} \gamma_5 \partial_\nu h_\mu N,$$

$$g_5^{ME}(r) = \left(-\frac{4g_h \bar{g}_h}{3m_N} \right) \left(\frac{m_h^2}{4\pi} Y_1(m_h r) \right) = C_{5,h}^{TP} f_{5,h}^{TP}(r, \mu = m_h),$$

$$g_9^{ME}(r) = \left(-\frac{2g_h \bar{g}_h}{m_N} \right) \left(\frac{m_h^2}{4\pi} Y_1(m_h r) \right) = C_{9,h}^{TP} f_{9,h}^{TP}(r, \mu = m_h),$$

$$g_{18}^{ME}(r) = \left(\frac{g_\rho \bar{g}_\rho}{2m_N} \right) \left(\frac{m_\rho^2}{4\pi} Y_1(m_\rho r) \right) = C_{18,\rho}^{TP} f_{18,\rho}^{TP}(r, \mu = m_\rho),$$

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

Simple systems: n-d

$$(\vec{\sigma}_n \cdot [\vec{k} \times \vec{I}]) (\vec{k} \cdot \vec{I}) \quad \left\{ {}^3S_1(T=0) \leftrightarrow {}^3D_1(T=0), \quad {}^3P_1(T=1) \leftrightarrow {}^1P_1(T=0) \right\}$$

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

$$\Delta\sigma_T = -\frac{40\pi}{3} g_A \textcolor{red}{g_T} \frac{(\alpha_s + \alpha_t) \alpha_t k^2}{(\alpha_t^2 + k^2)^2 (\alpha_s^2 + k^2)} \sim -3.5 \times 10^{-4} \textcolor{red}{g_T} E_{eV} (\textit{barn})$$

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

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)

(a) The possible reason for the existing discrepancy in PV nuclear data analysis using the DDH approach

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

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

(a) The possible reason for the existing discrepancy in PV nuclear data analysis using the DDH approach (2)

$$\frac{1}{N} \frac{d\phi^P}{dz} = (59 \text{ rad} \cdot \text{fm}^2) [h_\pi^1 + h_\rho^0(0.10) + h_\omega^0(0.14) + h_\rho^1(-0.042) + h_\omega^1(-0.12) + h_\rho'^1(0.014)] \quad P^P = \frac{\Delta\sigma^P}{2\sigma_{tot}} = \frac{(0.140 \text{ b})}{2\sigma_{tot}} [h_\pi^1 + h_\rho^0(0.021) + h_\omega^0(0.022) + h_\rho^1(0.002) + h_\omega^1(-0.044) + h_\rho'^1(-0.012)]$$

$$a_n = 0.42h_\pi^1 - 0.17h_\rho^0 + 0.085h_\rho^1 + 0.008h_\rho^2 - 0.238h_\omega^0 + 0.086h_\omega^1 - 0.010h_\rho'^1 = 4.11 \times 10^{-7}$$

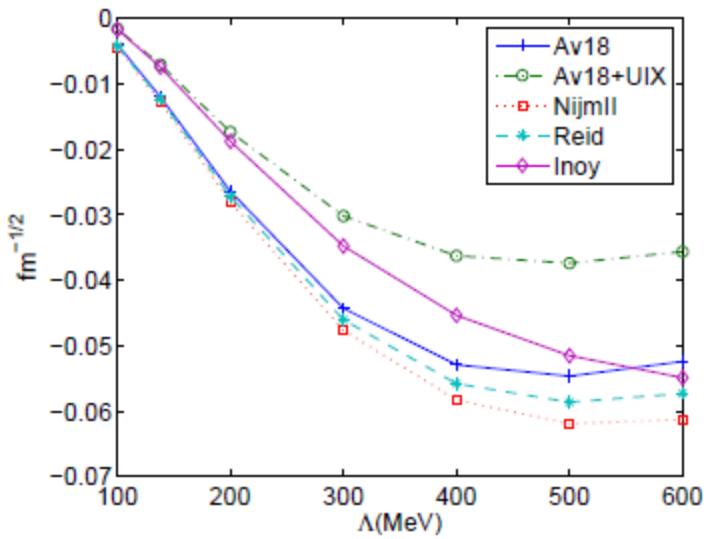
$$P_\gamma = -1.05h_\pi^1 + 0.19h_\rho^0 - 0.096h_\rho^1 - 0.018h_\rho^2 + 0.28h_\omega^0 - 0.046h_\omega^1 + 0.023h_\rho'^1 = -7.31 \times 10^{-7}$$

$$A_d^\gamma = -1.51h_\pi^1 + 0.17h_\rho^0 - 0.083h_\rho^1 - 0.024h_\rho^2 + 0.024h_\omega^0 + 0.013h_\omega^1 + 0.032h_\rho'^1 = -9.05 \times 10^{-7}.$$

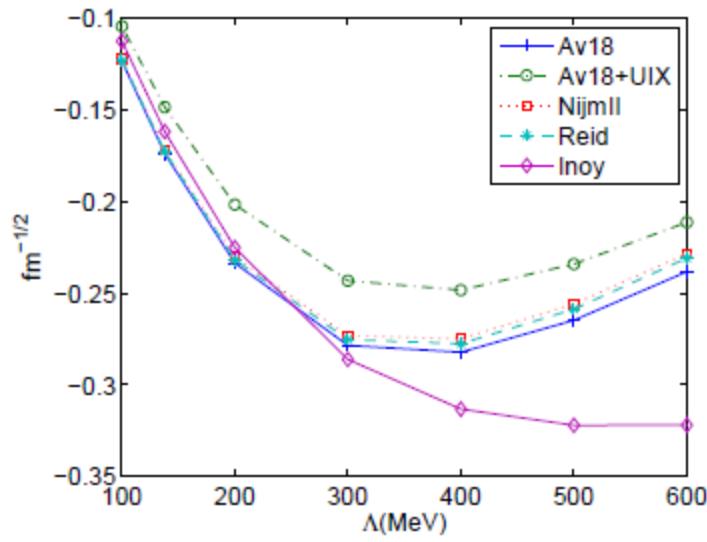
(a) The possible reason for the existing discrepancy in PV nuclear data analysis using the DDH approach (3)

models	DDH-best values			4-parameter fits		
	a_n	P_γ	A_d	a_n	P_γ	A_d
AV18+UIX/DDH-I	3.30	-6.38	-8.23	1.97	-2.16	-1.81
AV18/DDH-II	4.61	-8.30	-10.3	4.60	-5.18	-4.46
AV18+UIX/DDH-II	4.11	-7.30	-9.04	4.14	-4.71	-4.09
Reid/DDH-II	4.74	-8.45	-10.4	4.70	-5.25	-4.46
NijmII/DDH-II	4.71	-8.45	-10.5	4.76	-5.26	-4.41
INOY/DDH-II	9.24	-12.9	-13.8	17.5	-17.9	-13.5

(a) The possible reason for the existing discrepancy in PV nuclear data analysis using the DDH approach (4)



(a) $\mu^2 \tilde{\mathcal{E}}_{\frac{3}{2}(+)}^{}$ for operator 1



(b) $\mu^2 \tilde{\mathcal{E}}_{\frac{3}{2}(+)}^{}$ for operator 9