Time Reversal Invariance Violation Theory Nuclear Reactions

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Theoretical issues and experimental opportunities in searches for time reversal invariance violation using neutrons

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UNIVERSITY OF SOUTH CAROLINA

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Outline

- (a) theory of TRI violation in nuclear reactions
- (b) status as a null test of TRI violation
- (c) relation of TRIV NN potentials and PV potentials
- (d) relations to EDM constraints

DBP test:

- $^{24}Mg + \alpha \leftrightarrow {}^{27}Al + p$

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

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

- $^{24}Mg + d \leftrightarrow {}^{25}Mg + p$

$|F| < 2 \cdot 10^{-3}$ (*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=198.5MeV)

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

Correlations in *γ-decay transitions:*

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

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

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

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

Statistical properties of compound nuclei

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

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

- Violation of T-invariance → *Unitary Ensemble* of random matrices :

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

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

$1.7 \cdot 10^3$ levels results in $<10^{-3}$

Why neutron-nuclei?

- No FSI ("EDM quality")
- Nuclear Enhancement
- High Intensity Neutron Facilities

  SNS in Oak Ridge, JSNS at J-PARC
- Search for TRIV & New Physics

  independent test (for the case of suppression/cancelation)

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'

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

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

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

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

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

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

“b”-estimates

$$\Psi^{\pm}_{i,f} = \sum_k a^{\pm}_{k(i,f)}(E)\phi_k + \sum_m \int b^{\pm}_{m(i,f)}(E,E')\chi^{\pm}_m(E')dE'$$

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

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

Factorization in "b": $\chi^{+}_{E} \approx \sqrt{\frac{\Gamma_0}{2\pi}}\frac{e^{i\delta}}{E-E_0+i\Gamma_0/2}u(r)$

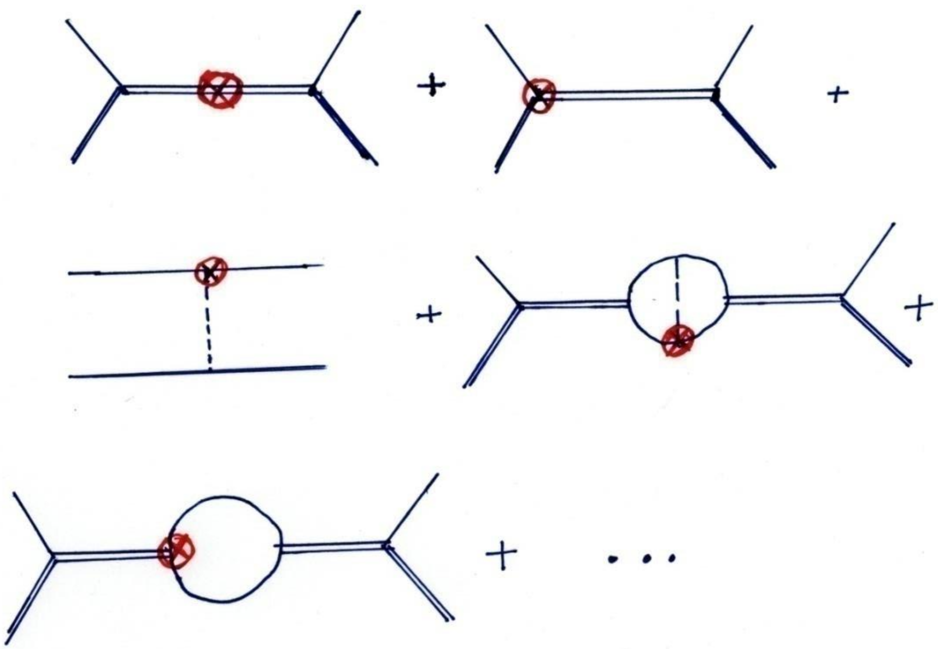
Then the second term in Ψ: $\chi^{+}_m(E)S_m\frac{e^{i\delta}}{E-E_k+i\Gamma_k/2}$

Spectroscopicfactor: $S_m = \Gamma^m/\Gamma^m_0 \sim 10^{-6}$

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

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

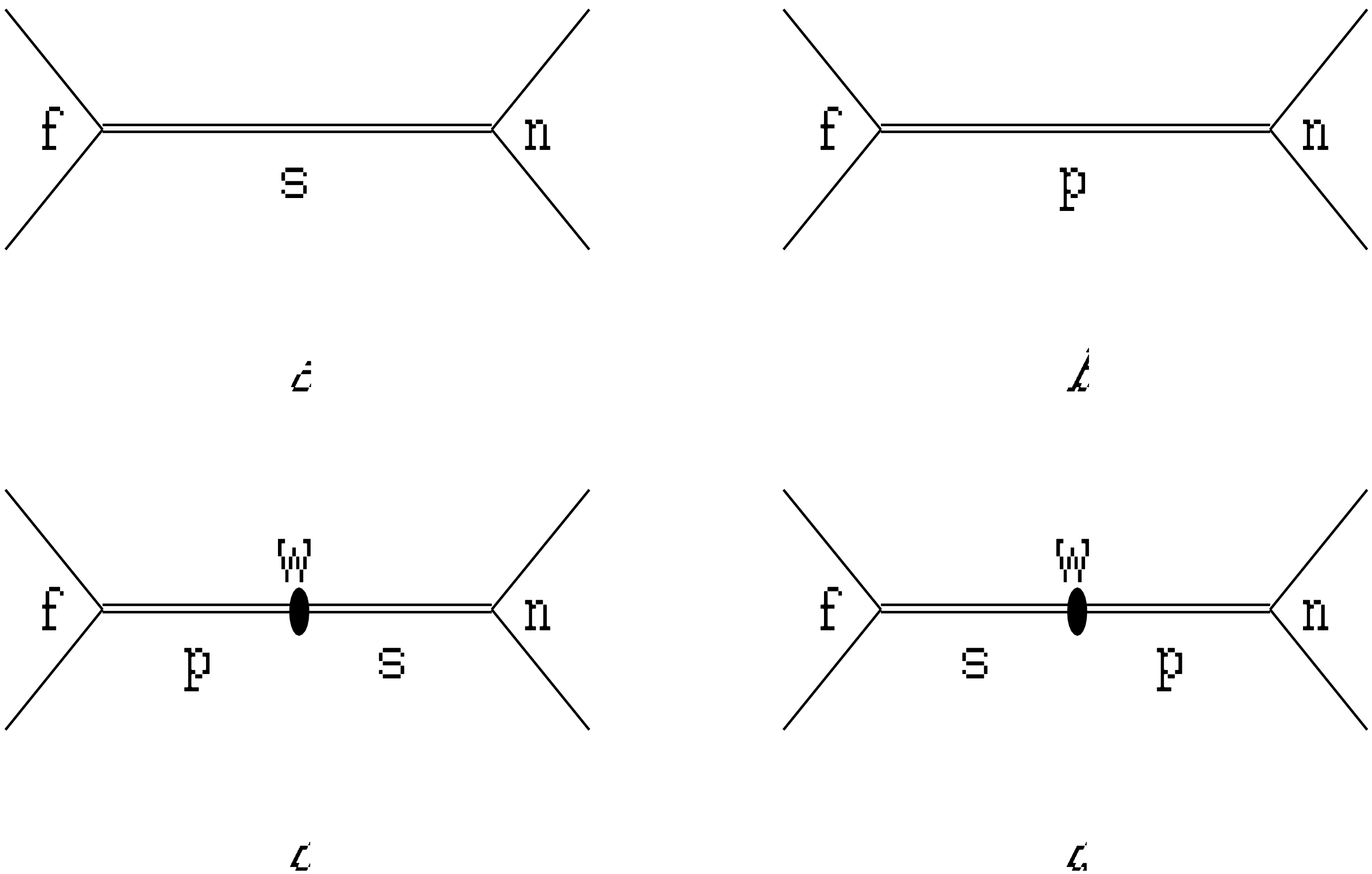
$$+ e^{i(\delta_s^i + \delta_p^f)} < \chi^{+}_{p,f} \,|W|\, \chi_{s,i} > + \ldots$$



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

$$a^{+}_{s,i} a^{+}_{p,f} < \phi_p | W | \phi_s > \sim a^{+}_{s,i} e^{i\delta_p^f} < \chi^{+}_{p,f} | W | \phi_s > \text{ for } | E_p - E_s | > 1keV$$

$$a^{+}_{s,i} a^{+}_{p,f} < \phi_p | W | \phi_s > \sim e^{i(\delta_s^i + \delta_p^f)} < \chi^{+}_{p,f} | W | \chi_{s,i} > \text{ for } D > 0.1MeV$$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General Expressions

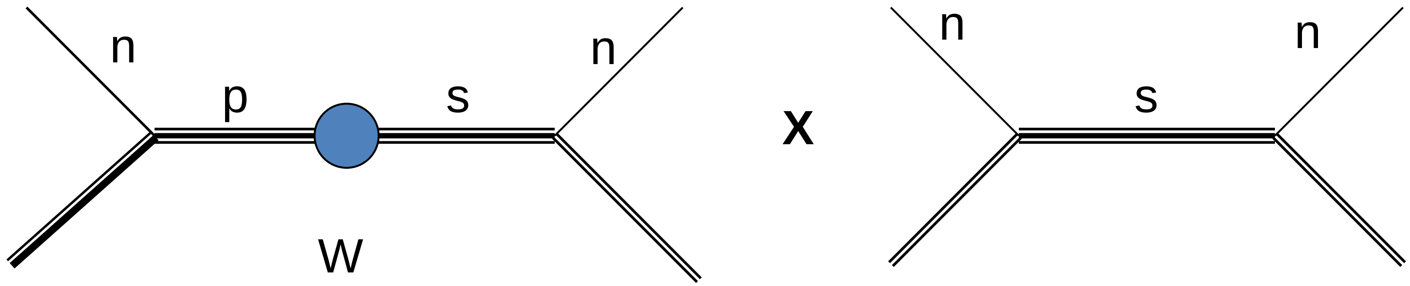
$$\Delta f_{TP} = m \frac{\sqrt{3}I}{8\pi k\sqrt{2I+1}} \left(\frac{\langle (I-1/2),0 \,|\, R^{I-1/2} \,|\, (I+1/2),1 \rangle - \langle (I+1/2),1 \,|\, R^{I-1/2} \,|\, (I-1/2),0 \rangle}{\sqrt{I+1}} \right.$$

$$\left. + \frac{\langle (I+1/2),0 \,|\, R^{I+1/2} \,|\, (I-1/2),1 \rangle - \langle (I-1/2),1 \,|\, R^{I+1/2} \,|\, (I+1/2),0 \rangle}{\sqrt{I}} \right)$$

$$\langle S^{'} s \,|\, R^{J} \,|\, S\ p \rangle = \frac{\sqrt{\Gamma_s^{\mathrm{n}}(S^{'})}(-iv + w)\sqrt{\Gamma_p^{\mathrm{n}}(S)}}{(E - E_s + i\Gamma_s/2)(E - E_p + i\Gamma_p/2)} e^{i(\delta_s(S^{'}) + \delta_p(S))}$$

$$\int \varphi_s W \varphi_p d\tau = -v - iw$$

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

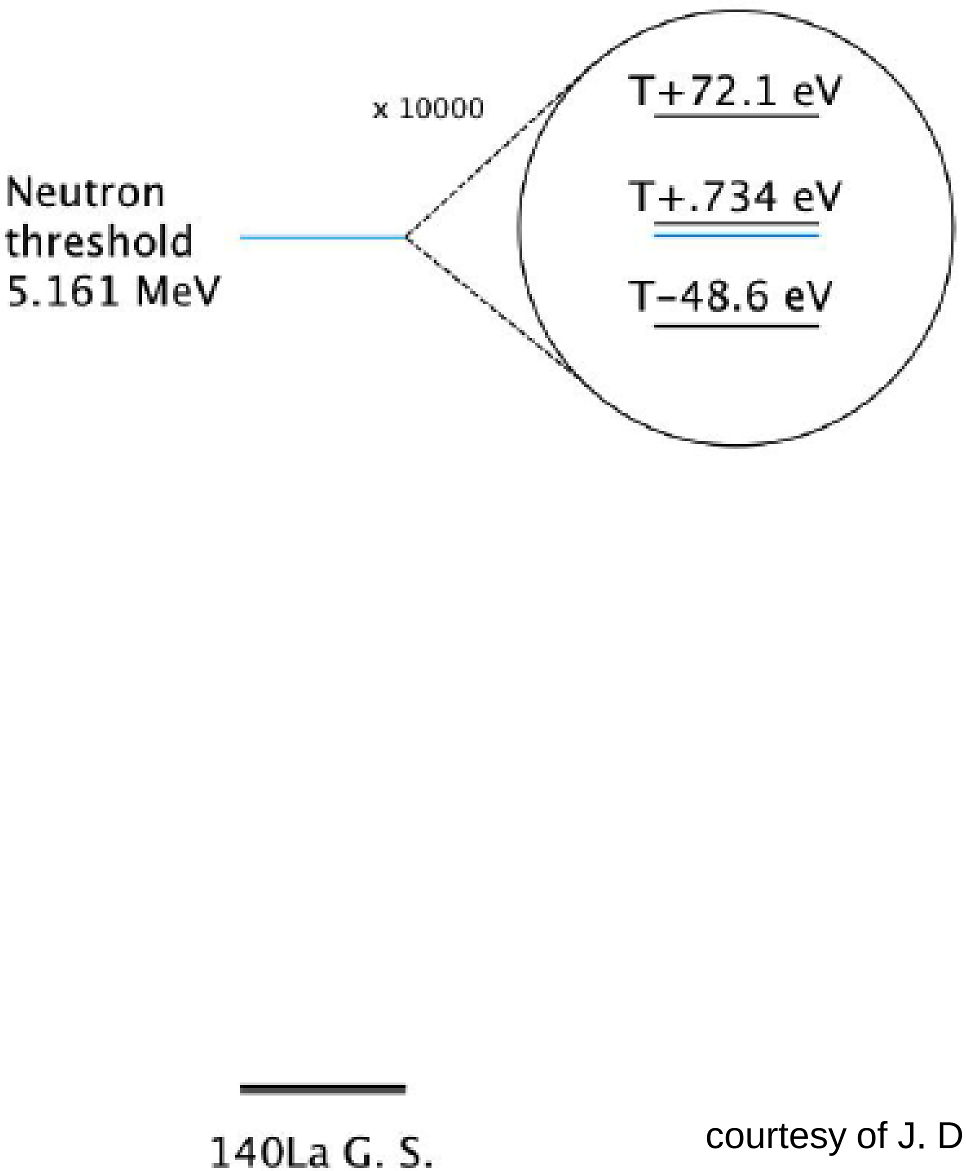


$$\Delta\sigma_T \sim \vec{\sigma}_n \cdot [\vec{k} \times \vec{I}\,] \sim \frac{W\sqrt{\Gamma_s^n \Gamma_p^n (s)}}{(E - E_s + i\Gamma_s/2)(E - E_p + i\Gamma_p/2)} [(E - E_s)\Gamma_p + (E - E_p)\Gamma_s]$$

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

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

139La+n System



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

courtesy of J. D. Bowman

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

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

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

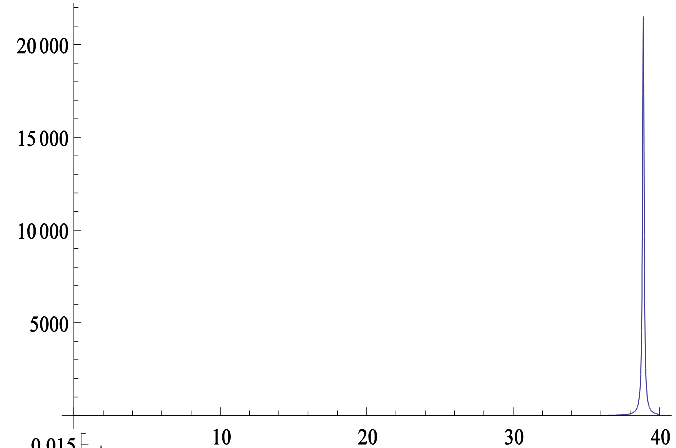
$$P = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+}$$

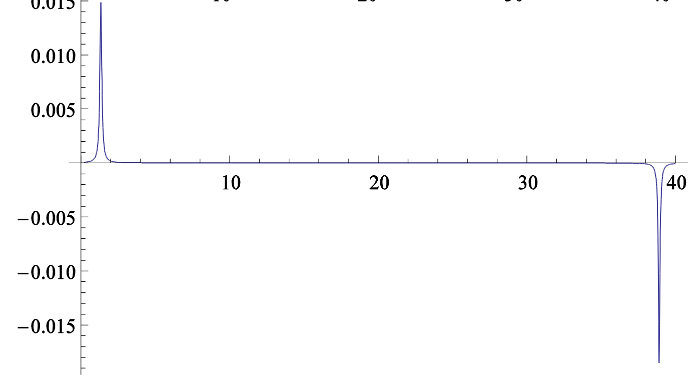
$$P(E_p) \sim 8\frac{w}{D}\sqrt{\frac{\Gamma_p^n}{\Gamma_s^n}}\left(\frac{D^2}{\Gamma_s \Gamma_p}\right)\left[1+\frac{\sigma_p(E_p)+\sigma_{pot}(E_p)}{\sigma_s(E_p)}\right]^{-1} \sim$$

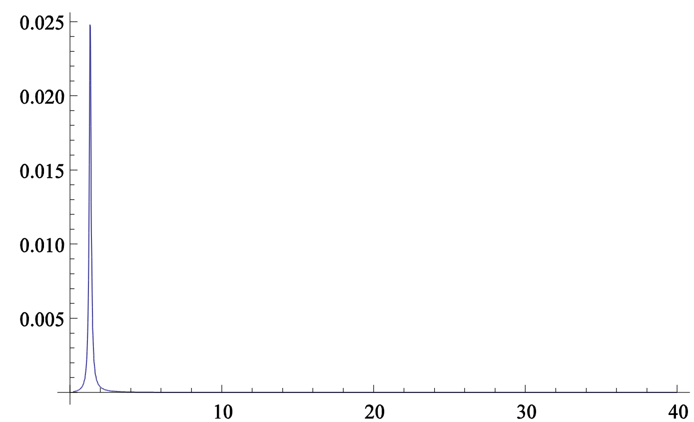
$$\sim \frac{w}{E_+ - E_-}(kR)\left(\frac{D}{\Gamma}\right)^2 \qquad (\tau \sim 1/D \;\; \& \;\; \tau_R \sim 1/\Gamma)$$

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

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





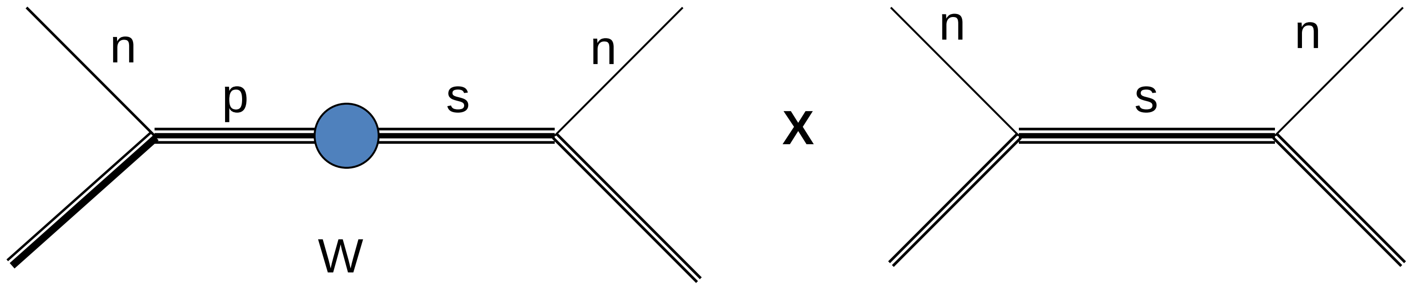


Dynamical Enhancement

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

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

P- and T-violation in Neutron transmission



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

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

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

One-particle potential

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

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

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

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

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

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

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

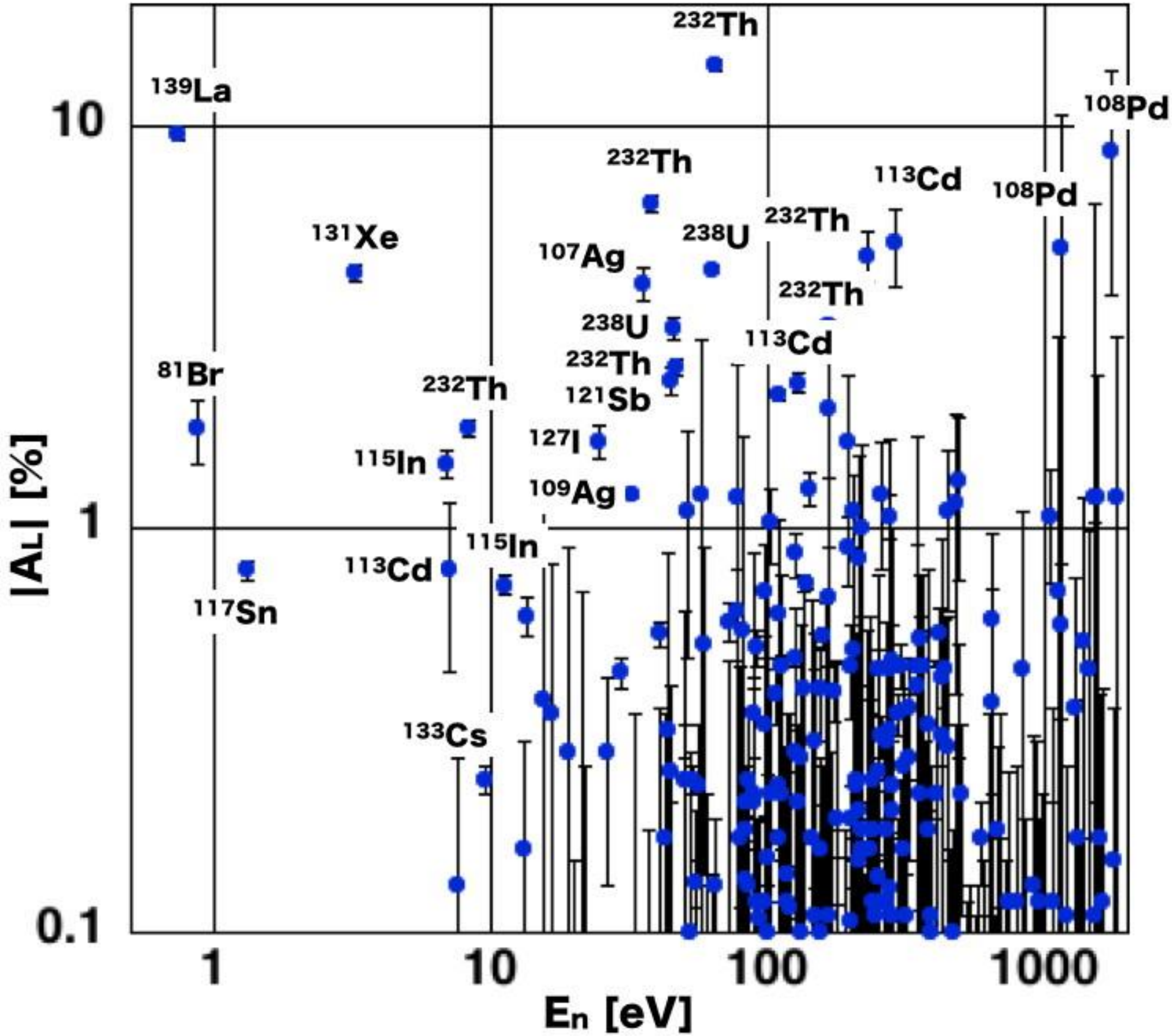
$$-i\frac{\langle a'|V^{P,T}|a\rangle}{\langle a'|V^{P}|a\rangle} = \kappa^{(1)}\frac{\overline{g}^{(1)\prime}_{\pi NN}}{g^{(0)\prime}_{\rho NN}}$$

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))



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

Slide courtesy of H. Shimizu

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

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

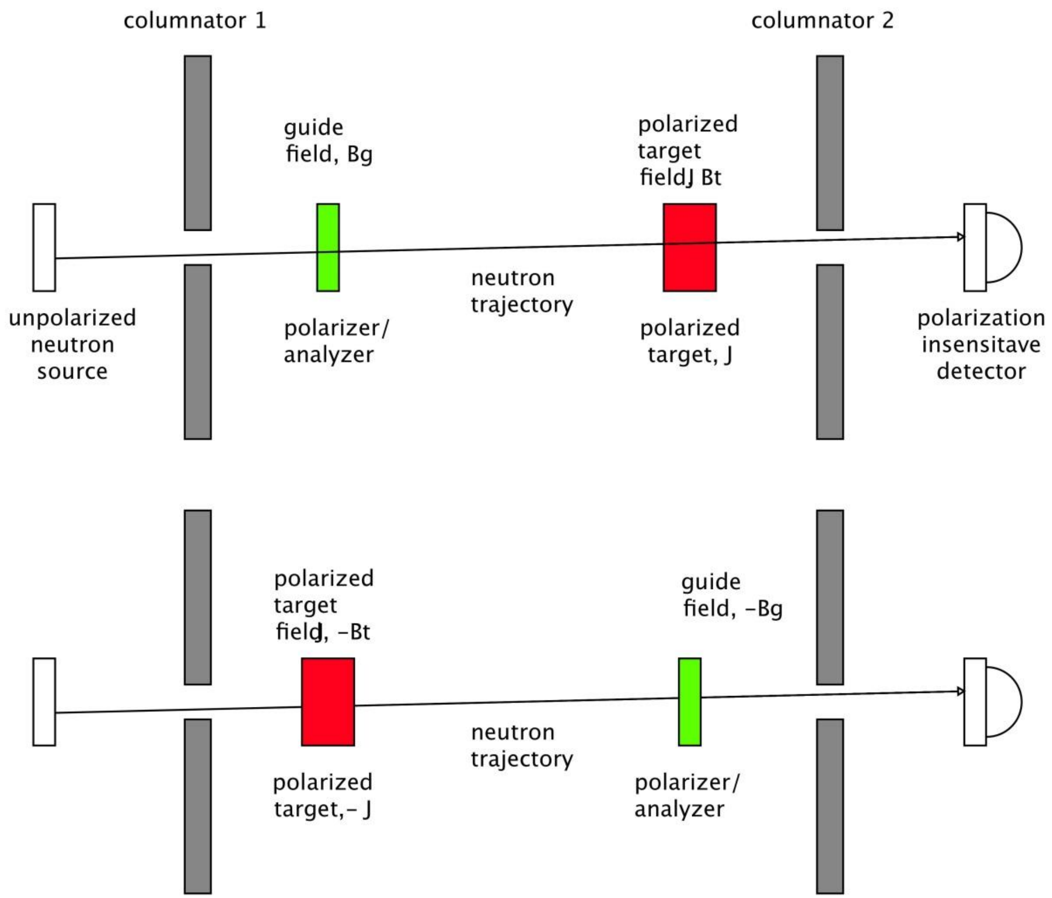
then the probability is even function of time.

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)

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

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

Enhanced of about 10^6

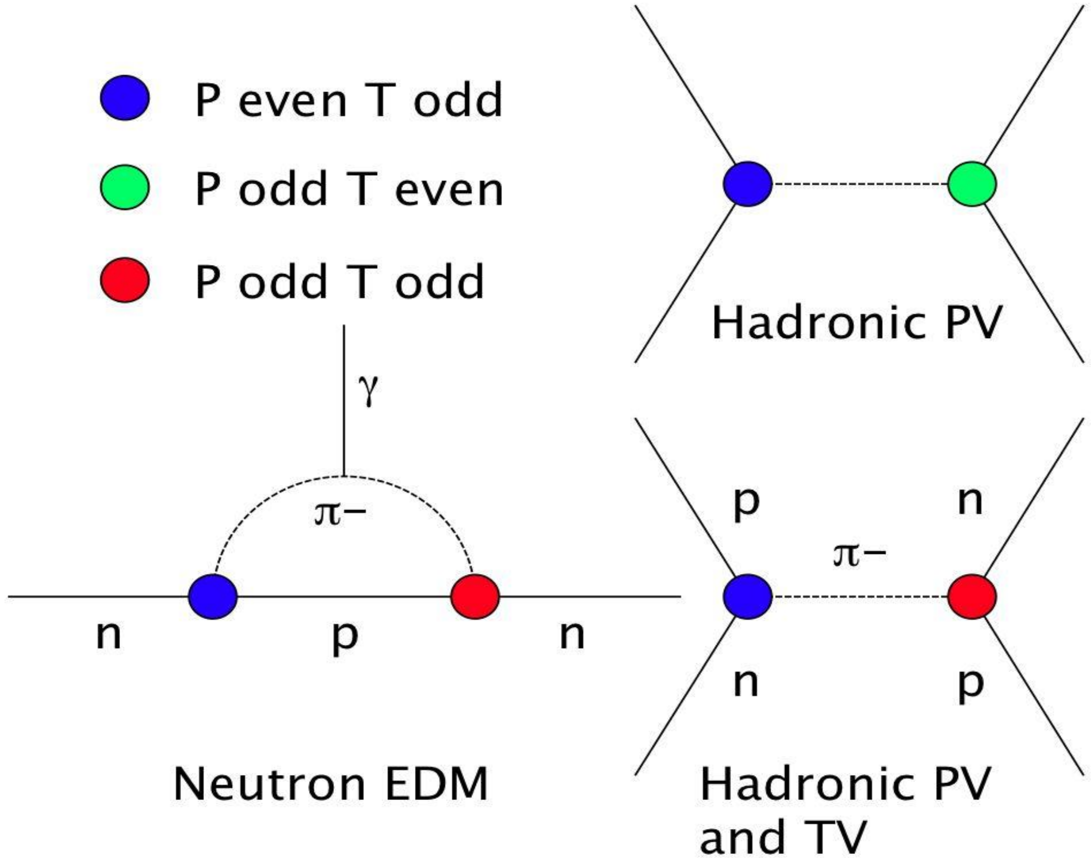
O. P. Sushkov and V. V. Flambaum, JETP Pisma 32 (1980) 377

V. E. Bunakov and V.G., Z. Phys. A303 (1981) 285

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

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

Meson exchange potentials for PV and TVPV interactions



Slide courtesy of D. Bowman

TVPV vs PV

PV

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

TVPV

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

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

$$
\begin{aligned}
V^{\rm PV}_{\rm DDH}(\vec r) = {} & i\frac{h^1_\pi g_A m_N}{\sqrt{2}F_\pi}\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\vec\sigma_1+\vec\sigma_2)\cdot\left[\frac{\vec p_1-\vec p_2}{2m_N}, w_\pi(r)\right] \\
& - g_\rho\left(h^0_\rho\tau_1\cdot\tau_2 + h^1_\rho\left(\frac{\tau_1+\tau_2}{2}\right)_3 + h^2_\rho\frac{(3\tau^3_1\tau^3_2-\tau_1\cdot\tau_2)}{2\sqrt{6}}\right) \\
& \times\left((\vec\sigma_1-\vec\sigma_2)\cdot\left\{\frac{\vec p_1-\vec p_2}{2m_N}, w_\rho(r)\right\}\right. \\
& \left. + i(1+\chi_\rho)\vec\sigma_1\times\vec\sigma_2\cdot\left[\frac{\vec p_1-\vec p_2}{2m_N}, w_\rho(r)\right]\right) \\
& - g_\omega\left(h^0_\omega + h^1_\omega\left(\frac{\tau_1+\tau_2}{2}\right)_3\right) \\
& \times\left((\vec\sigma_1-\vec\sigma_2)\cdot\left\{\frac{\vec p_1-\vec p_2}{2m_N}, w_\omega(r)\right\}\right. \\
& \left. + i(1+\chi_\omega)\vec\sigma_1\times\vec\sigma_2\cdot\left[\frac{\vec p_1-\vec p_2}{2m_N}, w_\omega(r)\right]\right) \\
& -\left(g_\omega h^1_\omega - g_\rho h^1_\rho\right)\left(\frac{\tau_1-\tau_2}{2}\right)_3(\vec\sigma_1+\vec\sigma_2)\cdot\left\{\frac{\vec p_1-\vec p_2}{2m_N}, w_\rho(r)\right\} \\
& - g_\rho h'^1_\rho i\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\vec\sigma_1+\vec\sigma_2)\cdot\left[\frac{\vec p_1-\vec p_2}{2m_N}, w_\rho(r)\right].
\end{aligned}
$$

PV nucleon Potential

n	c_n^{DDH}	$f_n^{\mathrm{DDH}}(r)$	$c_n^{\not\pi}$	$f_n^{\not\pi}(r)$	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	$-\frac{g_\rho}{2m_N}h_\rho^{\prime 1}$	$f_\rho(r)$	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

Neutron EDM

Only $\vec{s}$: $(\vec{s} \sim [\vec{r} \times \vec{p}])$

if $\exists\ \vec{d}_n = e \cdot \vec{r}$

$\not{P}$: $\vec{s} \to +\vec{s};$ $\vec{r} \to -\vec{r};$

$\not{T}$: $\vec{s} \to -\vec{s};$ $\vec{r} \to +\vec{r};$

$\Rightarrow$ $\vec{d}_n = \vec{0}$

L. Landau, Nucl.Phys. **3**, 127 (1957).

A formal approach

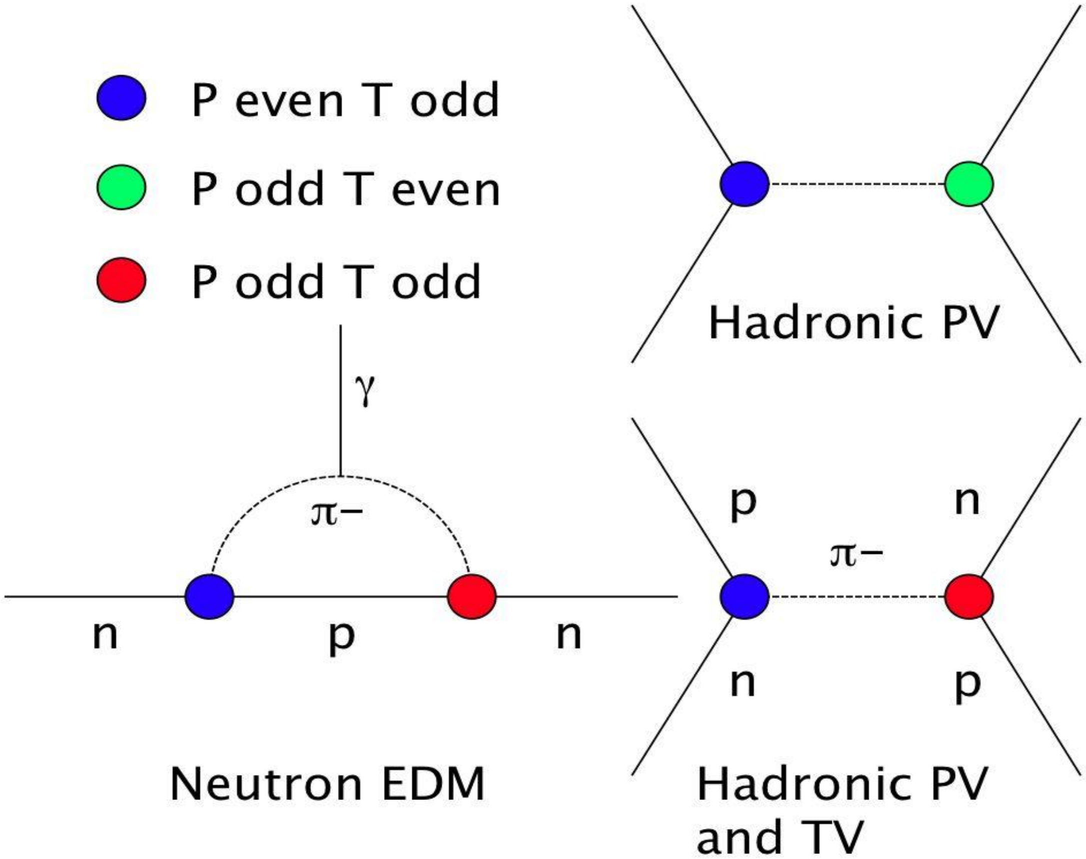
$$< p' | J_\mu^{em} | p >= e\bar{u}(p')\left\{\gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M}F_2(q^2) - G(q^2)\sigma_{\mu\nu}\gamma_5 q^\nu + ...\right\}u(p)$$

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

$$G(0) = d$$

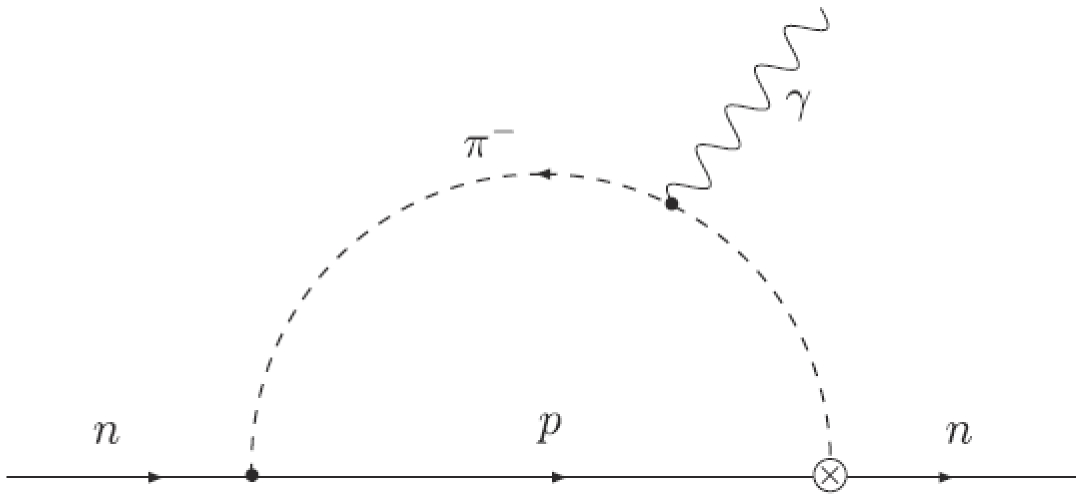
$$H_{EDM} = i\frac{d}{2}\bar{u}\sigma_{\mu\nu}\gamma_5 u F^{\mu\nu} \rightarrow -(\vec{d} \cdot \vec{E})$$

Meson exchange potentials for PV and TVPV interactions



Slide courtesy of D. Bowman

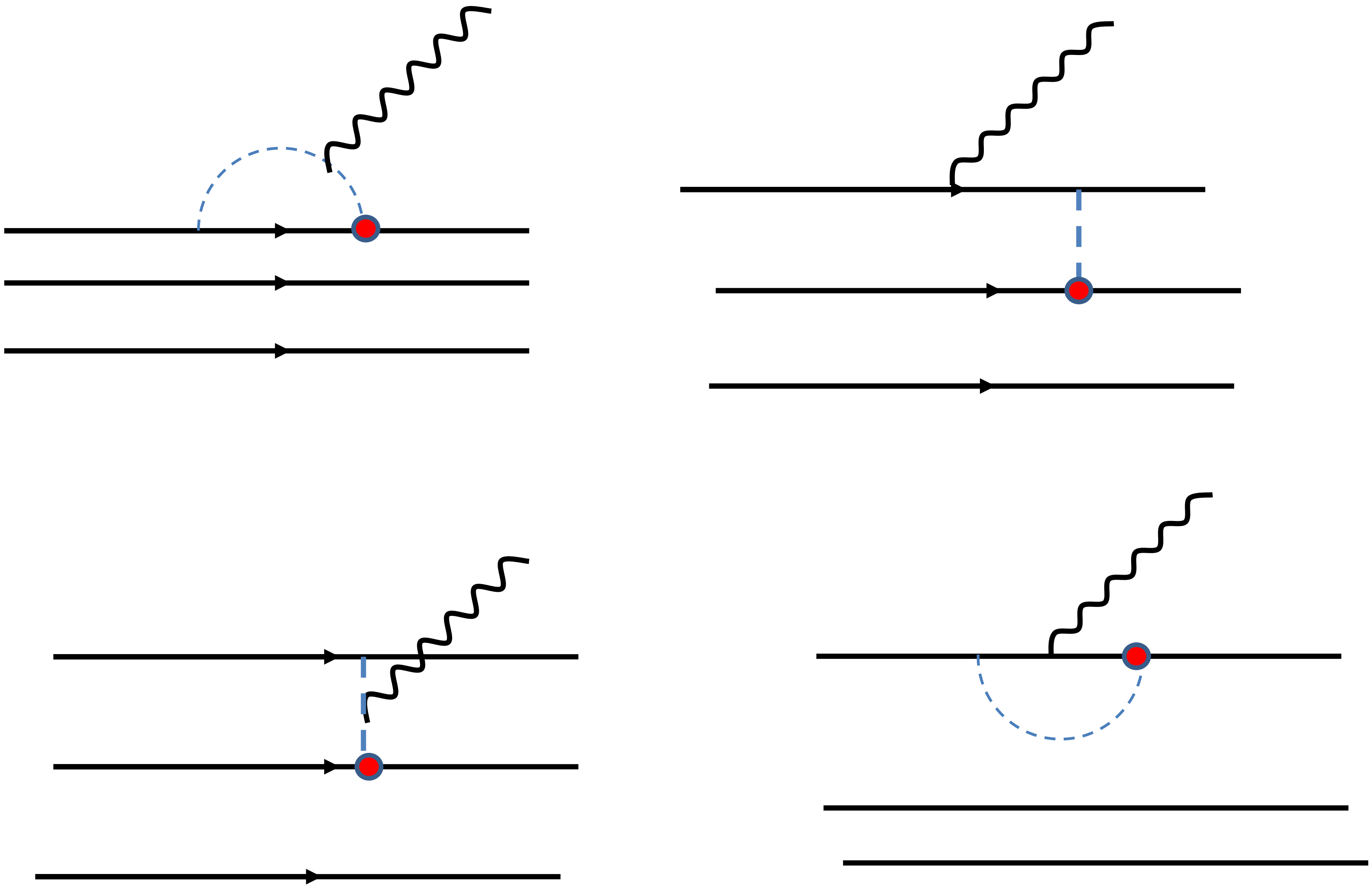
Chiral Limit



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

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

Many Body system EDMs



^{3}He and ^{3}H

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

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

TVPV n-D $\vec{\sigma}_n \cdot [\vec{k} \times \vec{I}]$

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

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

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

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

Enhancements:

- **"Weak" structure**

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

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

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 $10^2 – 10^4$ at SNS ORNL and JSNS J-PARC

Thank you!