Time-Reversal Invariance Violation in Nuclei

Vladimir Gudkov
University of South Carolina

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Neutron EDM

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

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

$\cancel{P}$: $\quad \vec{s} \to +\vec{s}; \quad \vec{r} \to -\vec{r};$

$\cancel{T}$: $\quad \vec{s} \to -\vec{s}; \quad \vec{r} \to +\vec{r};$

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

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

A formal approach

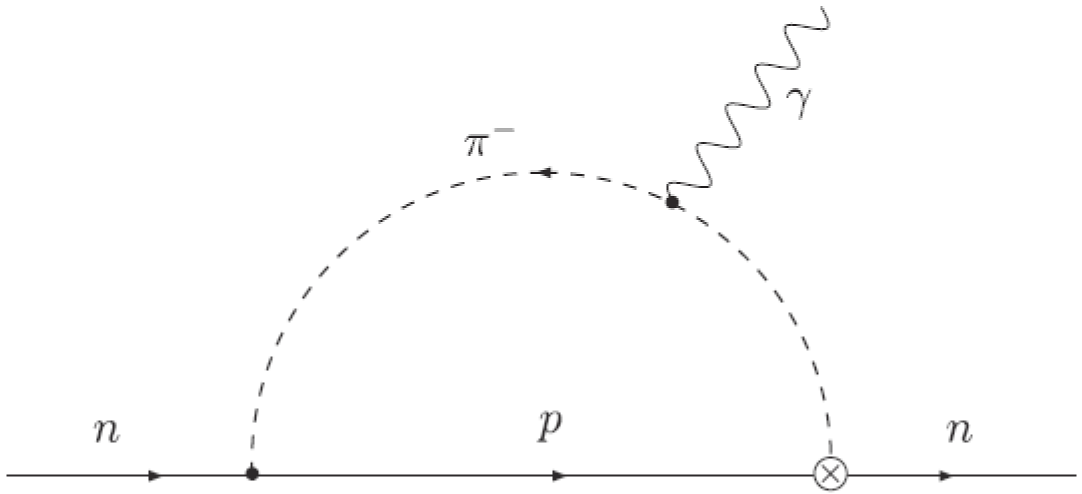
$$< p' \mid J_\mu^{em} \mid p >= e\bar{u}(p')\left\{\gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M}F_2(q^2) - G(q^2)\sigma_{\mu\nu}\gamma_5 q^\nu + \ldots\right\}u(p)$$

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

$$G(0) = d$$

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

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)

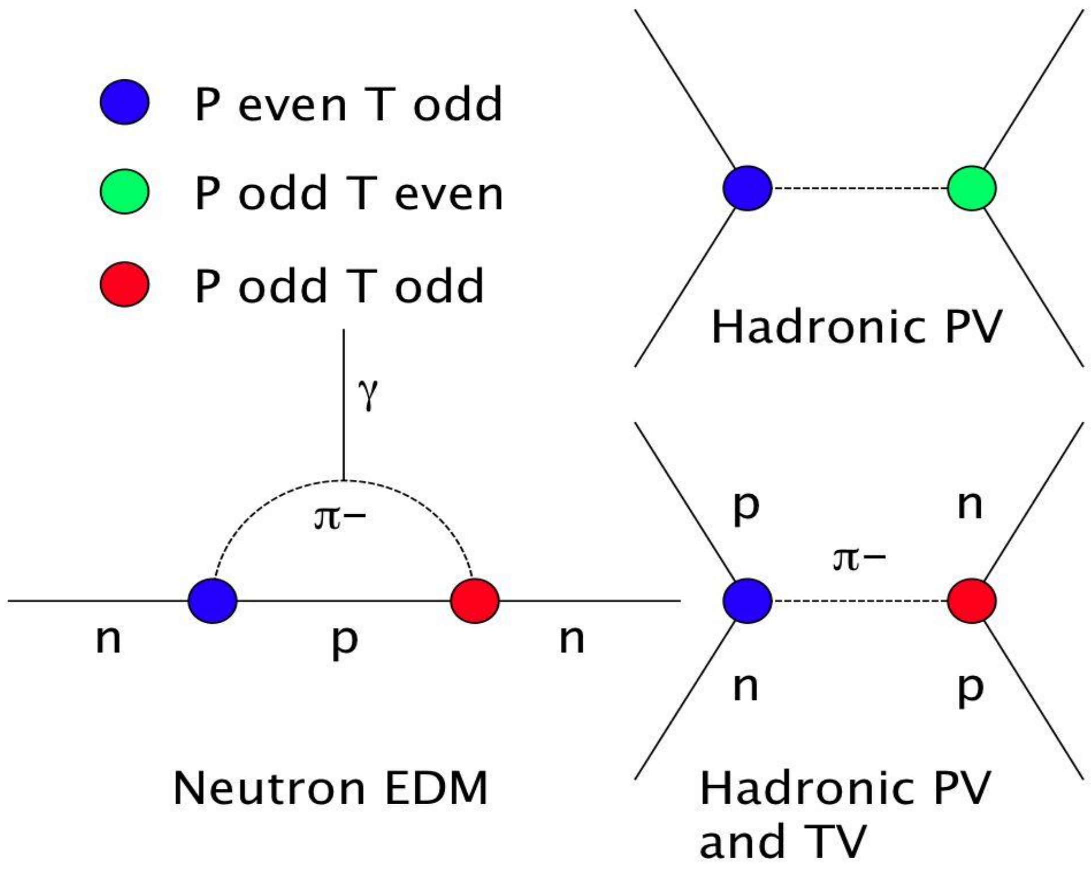
With more details…

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

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

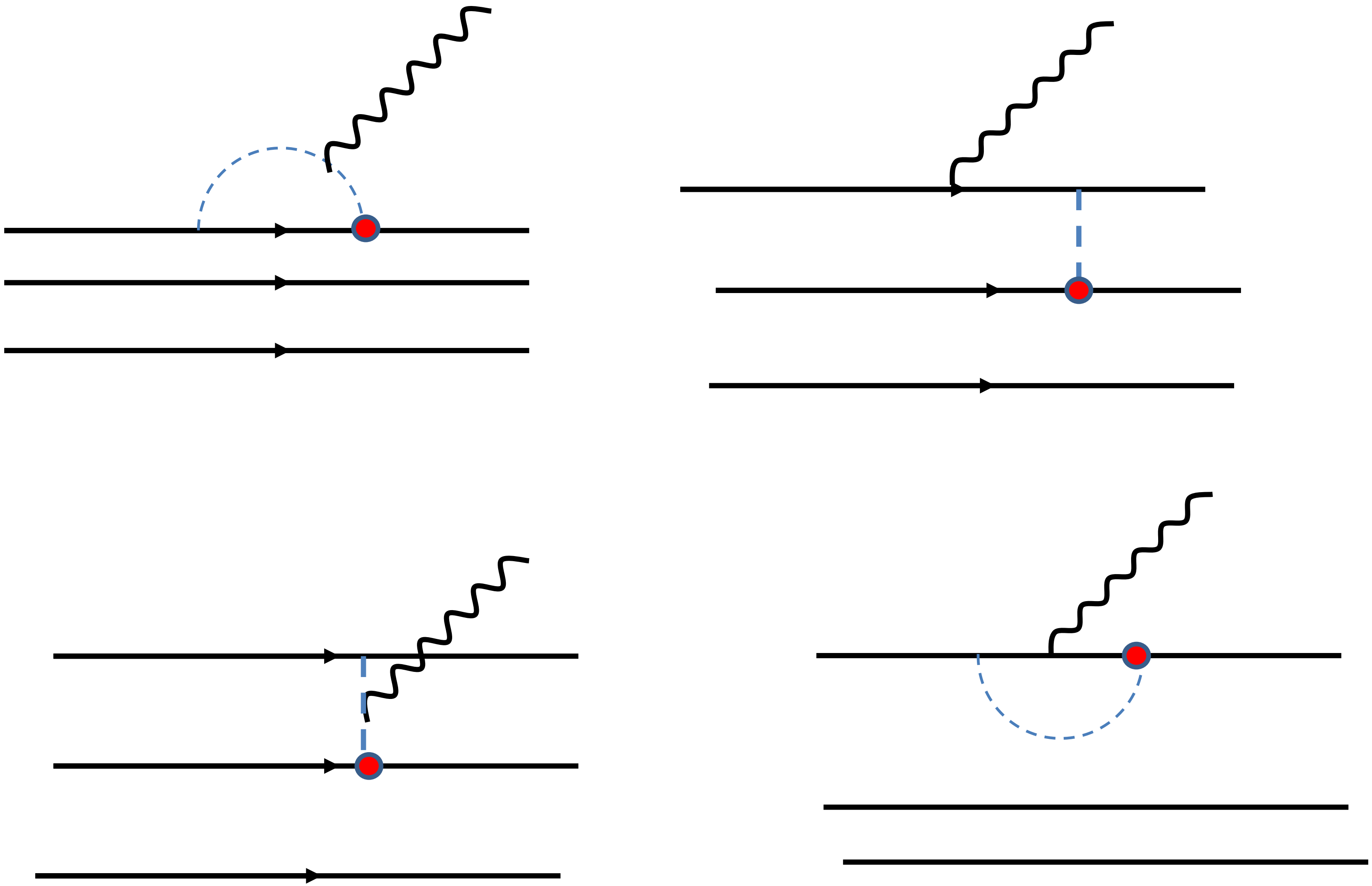
C.-P. Liu and R. G. E. Timmermans, Phys. Rev. C **70**, 055501 (2004)

Meson exchange potentials for PV and TVPV interactions



Slide courtesy of D. Bowman

Many Body system EDMs



^{3}He and ^{3}H

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

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

Major Contributions

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

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

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

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

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

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

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

Why neutron-nuclei?

- Search for TRIV & New Physics

  independent test (for the case of suppression/cancelation)

- High Intensity Neutron Facilities

  SNS in Oak Ridge, JSNS at J-PARC

- Nuclear Enhancement

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

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

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

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

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

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

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

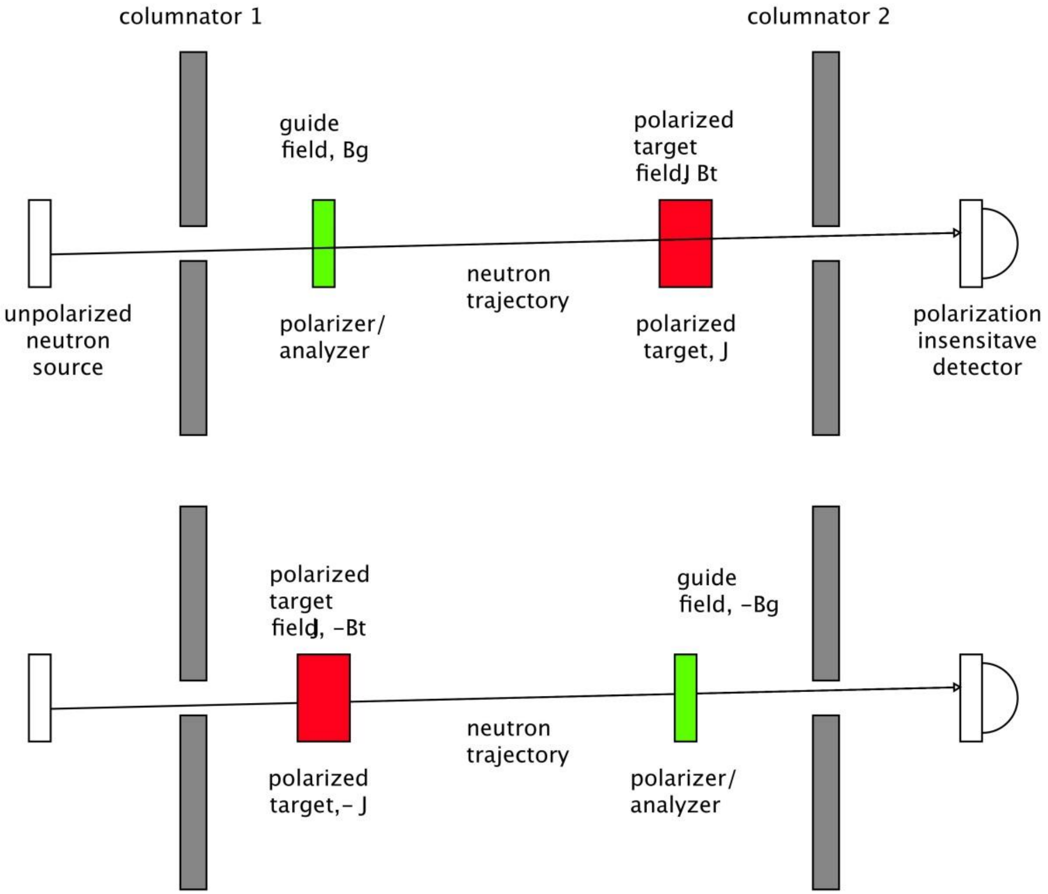
then the probability is even function of time.

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

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

(R. M. Ryndin)

No Systematic



courtesy of J. D. Bowman

TRIV Transmission Theorem

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

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

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

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

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

Neutron transmission

(= "EDM quality")

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P.K. Kabir, PR D25, (1982) 2013

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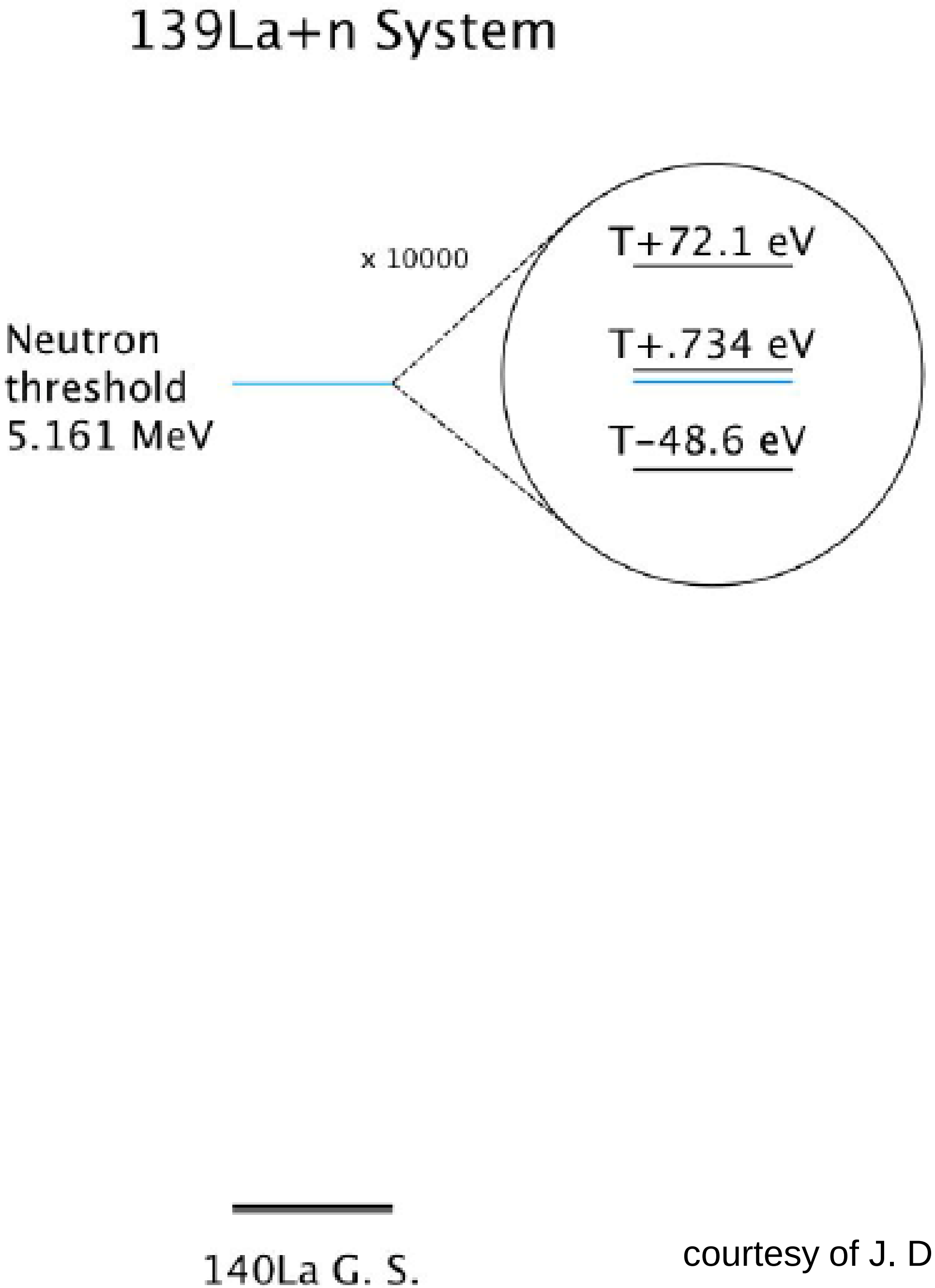
O. P. Sushkov and V. V. Flambaum, JETP Pisma 32 (1980) 377

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

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

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

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



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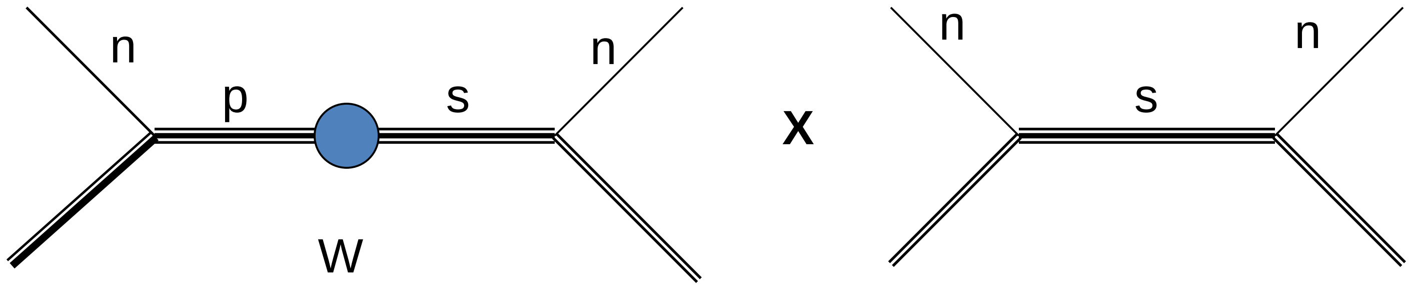
P- and T-violation in Neutron transmission



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

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

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

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 $^{(2)}$

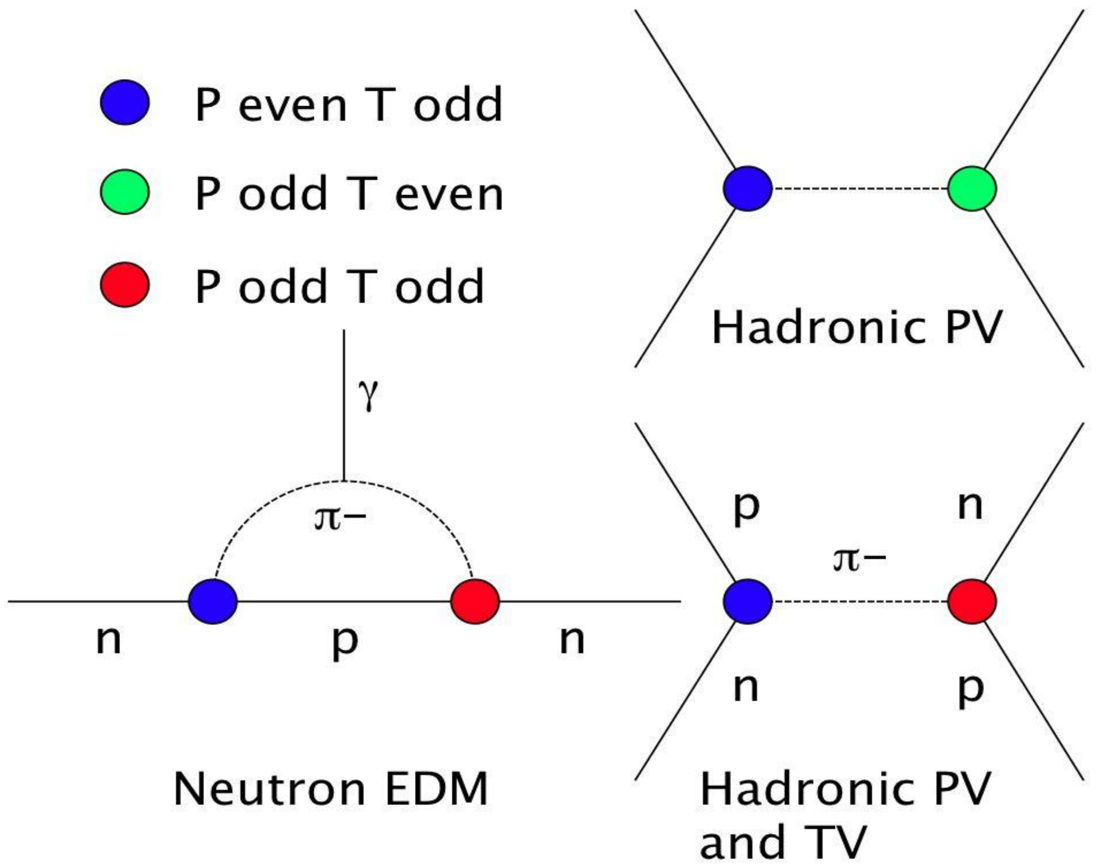
$$\bar{g}_{\pi}^{(1)} < 0.5 \cdot 10^{-10}$$

$$\Rightarrow \quad \frac{\cancel{T}\cancel{P}}{\cancel{P}} \sim 10^{-3} \quad \text{from the current EDMs}$$

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

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

Meson exchange potentials for PV and TVPV interactions



Slide courtesy of D. Bowman

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

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

PV nucleon Potential

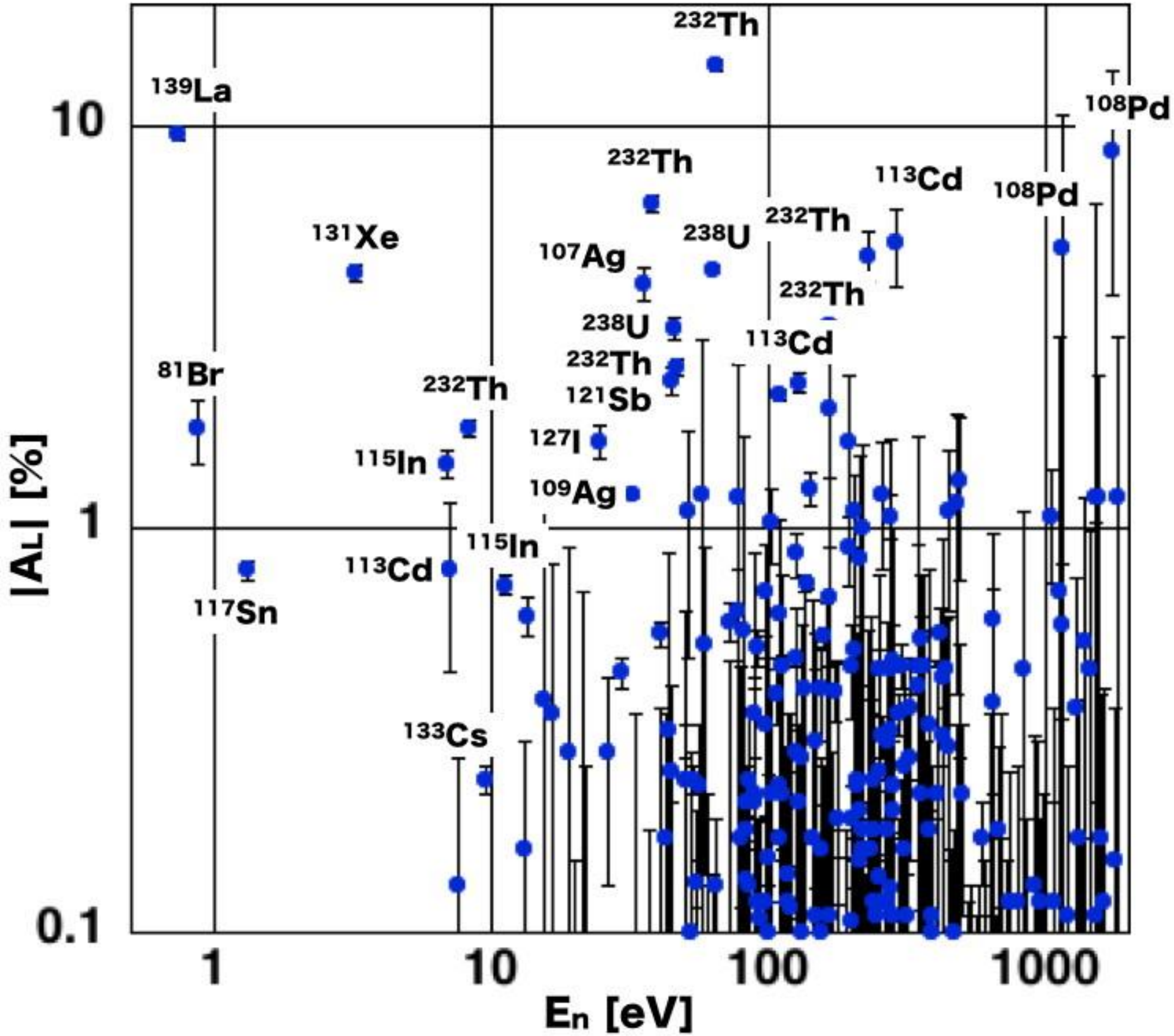
n	c_n^{DDH}	$f_n^{\mathrm{DDH}}(r)$	$c_n^{\not\pi}$	$f_n^{\not\pi}(r)$	c_n^{π}	$f_n^{\pi}(r)$	$O_{ij}^{(n)}$
1	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}C_6^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$(\tau_i \times \tau_j)^z(\boldsymbol{\sigma}_i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

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

- 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



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

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PHYSICAL REVIEW C, VOLUME 62, 054607

Statistical theory of parity nonconservation in compound nuclei

S. Tomsovic
Department of Physics, Washington State University, Pullman, Washington 99164

Mikkel B. Johnson, A. C. Hayes, and J. D. Bowman
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

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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	$1.6^{+2.0}_{-0.7}$

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 $10^2 – 10^4$

at SNS ORNL and JSNS J-PARC

T violation in Neutron Optics: TREX

- T – odd term in FORWARD scattering amplitude (a null test, like EDMs) with polarized n beam and polarized nuclear target
- P-odd/T-odd (most interesting) $\vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$
- Amplified on select P-wave epithermal neutron resonances by ~5-6 orders of magnitude
- Estimates of stat sensitivity at SNS/JSNS look very interesting:

Existing technology/sources->$\Delta\sigma_{PT}/\Delta\sigma_{P}$~1E-5. sensitivity can be ~x100 present n EDM limit

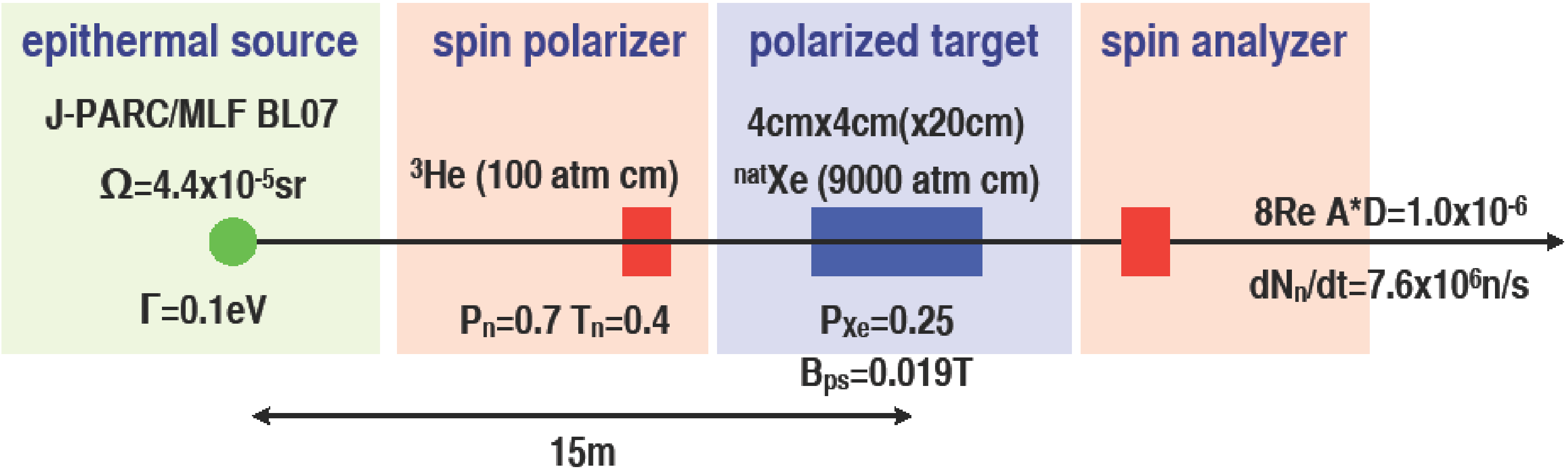
- The nuclei of interest, resonance energies, and P-odd asymmetry amplifications are measured. ^{139}La can be polarized using DNP ($LaAlO_3$). ^{3}He with SEOP can be used as a polarizer for eV neutrons

Nucleus	Resonance Energy	PV asymmetry
^{131}Xe	3.2 eV	0.043
^{139}La	0.748 eV	0.096
^{81}Br	0.88 eV	0.02

Slide courtesy of W. M. Snow

NOP-T (Neutron Optics for T-violation)

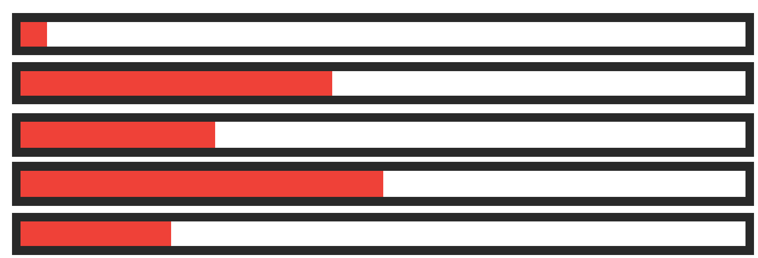
assembling promising technologies



discovery potential → $T \simeq 4 \times 10^5$ [s] $= 4.5$ [days]

beyond

- transport optics
- spin polarizer/analyzer (P^2T)
- target polarization
- target quantity
- abundance



search for more appropriate target nuclei

Slide courtesy of H. Shimizu

Time Reversal Experiment "TREX"
Neutron Optics for T Violation "NOP-T"
Proto-collaborations

M. Snow	Indiana U
S. Penttila	ORNL
D. Bowman	ORNL
T. Tong	ORNL
V. Gudkov	U South Carolina
C. Gould	North Carolina State U
C. Crawford	U Kentucky
B. Plaster	U Kentucky
N. Fomin	U Tennessee
Z. Tang	LANL
B. Goodson	SIU

H Shimizu	Nagoya U
M. Kitaguchi	Nagoya U
K. Hirota	Nagoya U
G. Ichikawa	Nagoya U
T. Ino	KEK
T. Shima	Osaka
T. Iwata	Yamakata U
T. Yoshioka	Kyushu U
Y. Yamagata	RIKEN

M. Hino	Kyoto
T. Momose	UBC
K. Asahi	Tokyo I. Tech.
K. Sakai	JAEA
H. Harada	JAEA
A, Kimura	JAEA

Merge the acronyms:

NOPTREX

Slide courtesy of W. M. Snow

Thank you!

Extra Slides:

Structure of observables:

$$\alpha_{fi} = \frac{2\sum_{l'} \Re e\{<l'|T^{J_1}|0><l'+1|T^{J_2}|0>^* - <l'|T^{J_1}|1><l'+1|T^{J_2}|1>^*\}}{\sum_{l'} |<l'|T^J|0>|^2}$$

$$\alpha_{fi}^{LR} = -\frac{2\sum_{l'} \Im m\{<l'|T^{J_1}|0><l'+1|T^{J_2}|1>^* + <l'+1|T^{J_1}|0><l'|T^{J_2}|1>^*\}}{\sum_{l'} |<l'|T^J|0>|^2}$$

$$\Phi = \frac{\Re e\{<1|T^j|0> + <0|T^j|1>\}}{\Im m\{<0|T^j|0> + <1|T^j|1>\}}$$

$$P = \frac{\Im m\{<1|T^j|0> + <0|T^j|1>\}}{\Im m\{<0|T^j|0> + <1|T^j|1>\}}$$

DWBA

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

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

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

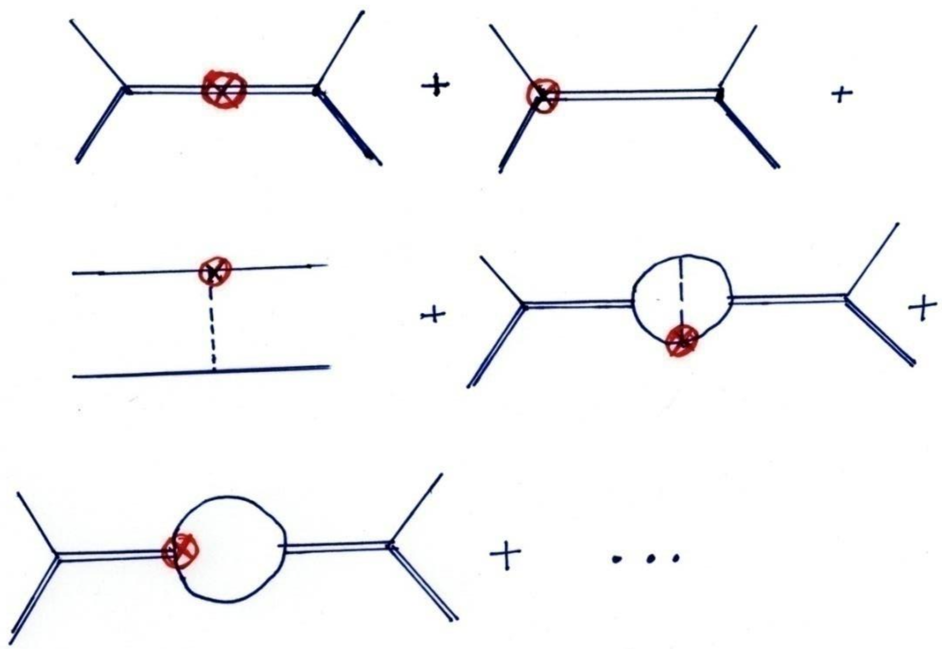
$$(\Gamma_k^i)^{1/2} = \sqrt{2\pi} < \chi_i(E') | V | \phi_k >$$

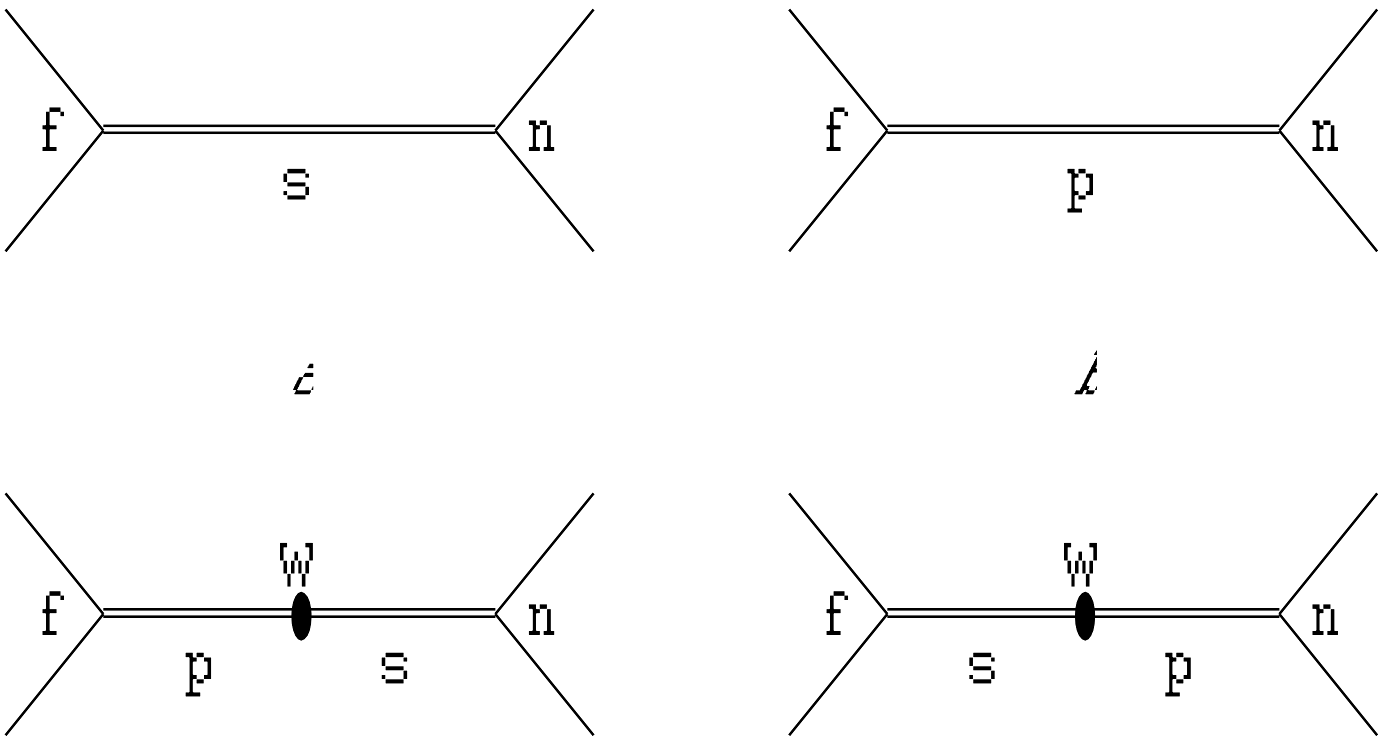
$$b_{m,\alpha}^{\pm}(E,E') = \exp(\pm i\delta_\alpha)\delta(E - E') + a_{k,\alpha}^{\pm} \frac{< \phi_k | V | \chi_m(E') >}{E - E' \pm i\varepsilon}$$

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

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

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





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Nuclear dependent factor

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

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

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

$$\gamma = \left[\Gamma_p^n(I+1/2)/\Gamma_p^n(I-1/2)\right]^{1/2}$$

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

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 $\overline{g}^{(1)\prime}_{\pi NN}=1.0\times10^{-11}$ and $g^{(0)\prime}_{\rho NN}=-11.4\times10^{-7}$. 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)

Theoretical predictions

Model	λ
Kobayashi – Maskawa	$\leq 10^{-10}$
Right – Left	$\leq 4\times10^{-3}$
Horizontal Symmetry	$\leq 10^{-5}$
Weinberg (charged Higgs bosons)	$\leq 2\times10^{-6}$
Weinberg (neutral Higgs bosons)	$\leq 3\times10^{-4}$
θ-term in QCD Lagrangian	$\leq 5\times10^{-5}$
Neutron EDM (one π-loop mechanism)	$\leq 4\times10^{-3}$
Atomic EDM (^{199}Hg)	$\leq 2\times10^{-3}$

$$\lambda = \frac{g_{CP}}{g_P} \qquad g_P = ??? \qquad \Rightarrow \qquad \text{n+p} \to d + \gamma$$

Statistical Approach (1)

- Matrix elements are elements of random statistical distribution

- PV observables are related to an averaged square of the matrix element

$$M^2 = \frac{1}{N_s N_p} \sum_{i,k} \left| \left\langle \Psi_{s_i} \,|\, O \,|\, \Psi_{p_k} \right\rangle \right|^2$$

- Then, we need only “strong” wave functions, since

$$\sum_{i,k} \left| \left\langle \Psi_{s_i} \,|\, O \,|\, \Psi_{p_k} \right\rangle \right|^2 = \sum_{i,k} \left\langle \Psi_{s_i} \,|\, O \,|\, \Psi_{p_k} \right\rangle \left\langle \Psi_{p_k} \,|\, O \,|\, \Psi_{s_i} \right\rangle$$

$$= \sum_{i} \left\langle \Psi_{s_i} \,|\, OO \,|\, \Psi_{s_i} \right\rangle$$

Statistical Approach (2)

- A description of large-scale behavior that leads to the strength function of weak interaction with spreading width:

$$\Gamma_w = 2\pi \left| M_J \right|^2 / D_J$$

- The shape of the spreading width of PV matrix elements for a short-range residual interactions is Gaussian, and the width is independent of the shell-model state. (S. Tomsovic)

Strength Function intro (B&M)

$$H = H_0 + V; \qquad H_0 \,|\, a >= E_a \,|\, a >; \qquad H_0 \,|\, \alpha >= E_\alpha \,|\, \alpha >$$

$$\langle a \,|\, V \,|\, \alpha \rangle = v; \qquad \langle a \,|\, V \,|\, a \rangle = \langle \alpha \,|\, V \,|\, \alpha \rangle = 0$$

After diagonalization:

$$E_a - E_i = \sum_\alpha \frac{v^2}{E_\alpha - E_i}$$

$$|\, i >= c_a(i) \,|\, a > + \sum_\alpha c_\alpha(i) \,|\, \alpha >$$

$$c_\alpha(i) = -\frac{v}{E_\alpha - E_i} c_a(i)$$

$$c_a(i) = \left(1 + \sum_\alpha \frac{v^2}{(E_\alpha - E_i)^2} \right)^{-1/2}$$

Strength Function intro (B&M) -2

- The for $E_\alpha = \alpha D \qquad \alpha = 0, \pm 1, \pm 2, \ldots$

the probability of the state *a* per unit energy interval of the spectrum is

$$S_a(E) = \frac{1}{D} c_a^2 (E_i \approx E) = \frac{1}{2\pi} \frac{\Gamma}{\left(E_a - E\right)^2 + (\Gamma/2)^2}$$

$$\Gamma = 2\pi \frac{v^2}{D}$$

s-wave Strength Function (B&M)

$$\langle \sigma \rangle = \sum_{I_r = I_0 \pm \frac{1}{2}} \frac{2I_r + 1}{2(2I_0 + 1)} \frac{\pi \lambda\!\!\!^{-2}}{D} \int \frac{\Gamma_n \Gamma}{(E - E_r)^2 + (\Gamma/2)^2} \, dE$$

$$= \pi \lambda\!\!\!^{-2} \left(2\pi \frac{\Gamma_n}{D} \right)$$

Ranking

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

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

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

Dominant

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

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

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

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

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

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

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

Sub-Dominant

Sensitivities (0-1)