Time-Reversal Invariance Violation in Nuclei

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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:

$$(n_B - n_{\bar{B}})/n_\gamma \simeq 6\times10^{-10}$$

(WMAP+COBE,2003)

SM prediction:

$$(n_B - n_{\bar{B}})/n_\gamma \sim 6\times10^{-18}$$

Neutron EDM

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

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

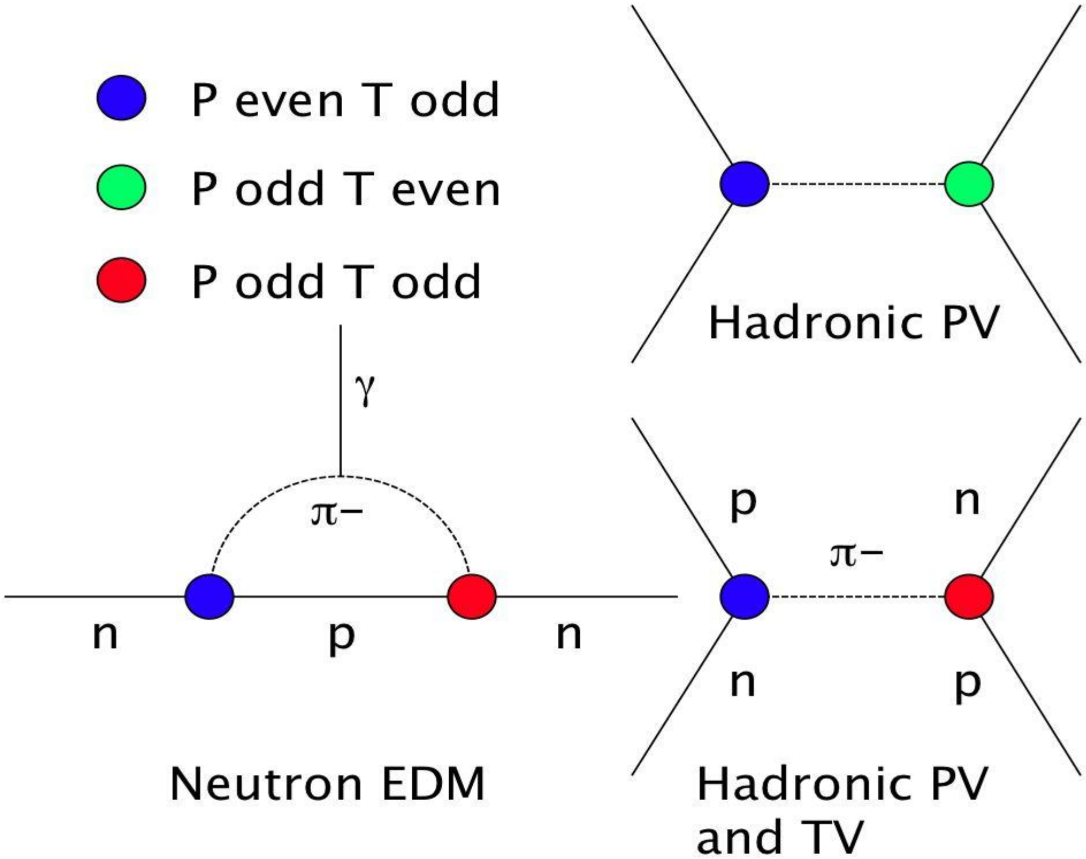
$\not{P}$: $\vec{s} \to +\vec{s};$ $\vec{r} \to -\vec{r};$

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

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

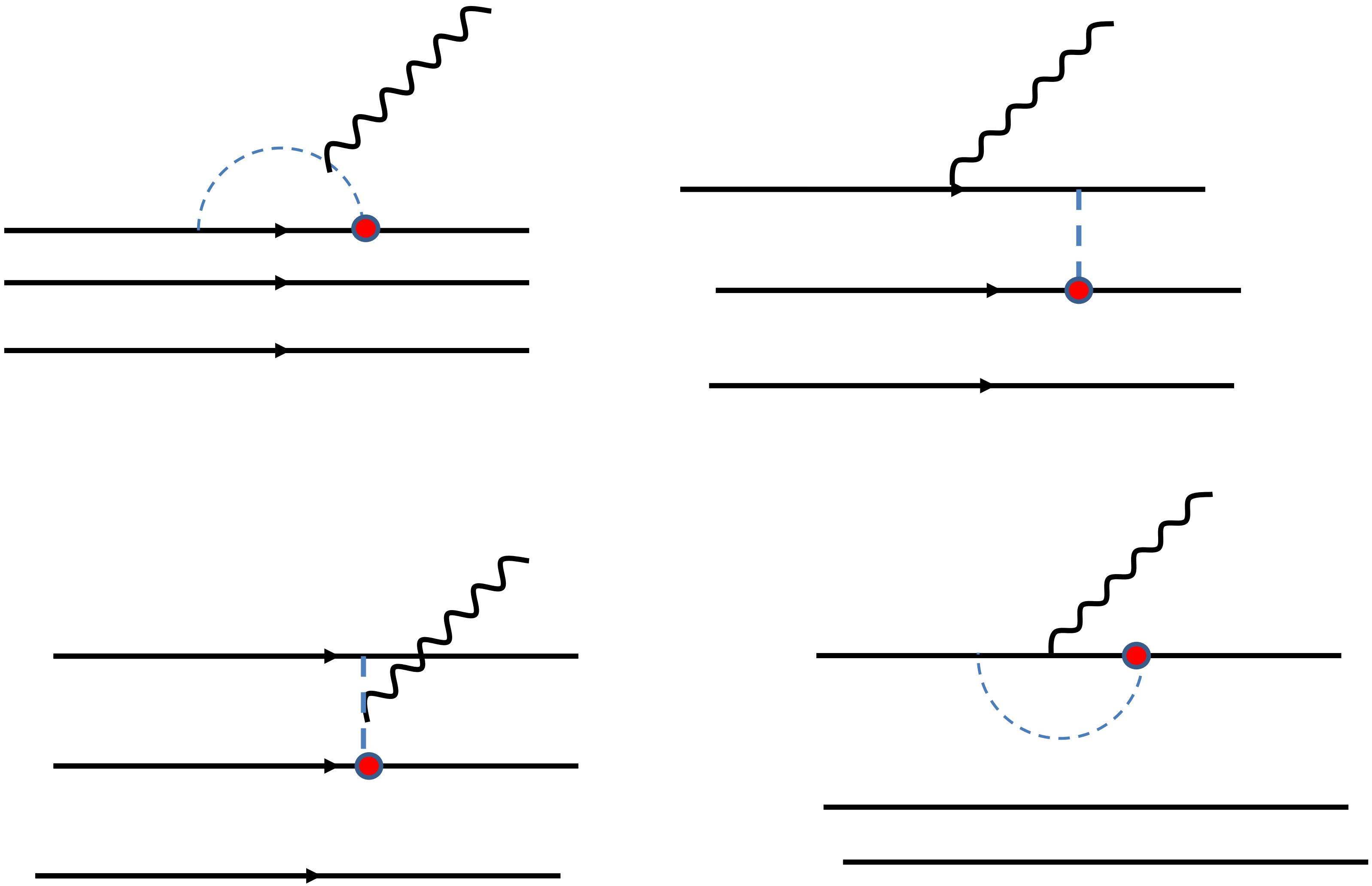
L. Landau, Nucl.Phys. **3**, 127 (1957).

Meson exchange potentials for PV and TVPV interactions



Slide courtesy of D. Bowman

Many Body system EDMs



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'

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 and Forward scattering

$$T^+ - T = iTT^+$$

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)

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*: $<1.2\cdot10^{-3}$, *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

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

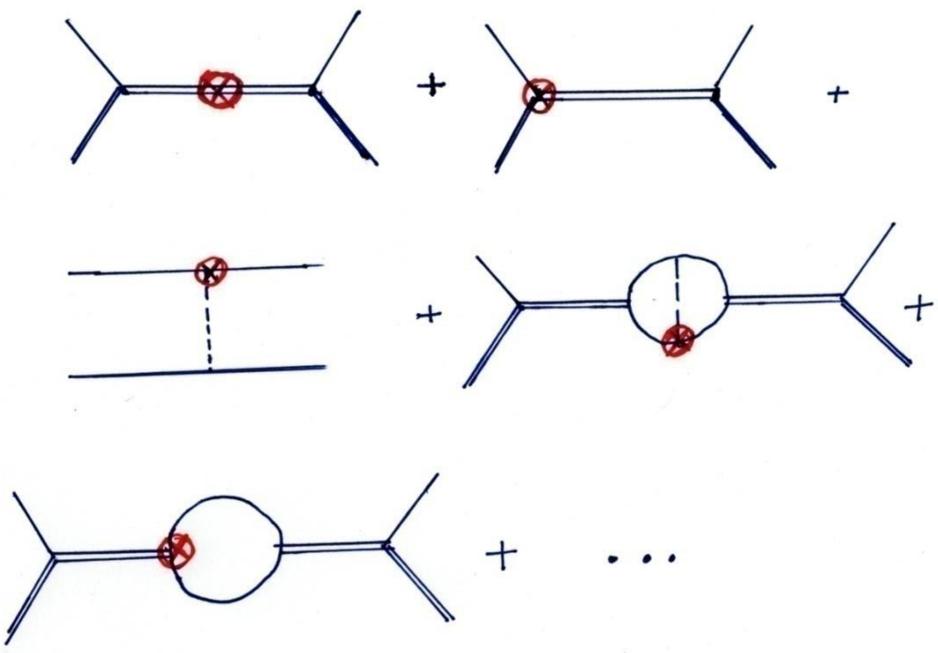
Then the second term in Ψ: $\chi^{+}_m(E)S_m\frac{e^{i\delta}}{E-E_k+i\Gamma_k/2}$

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

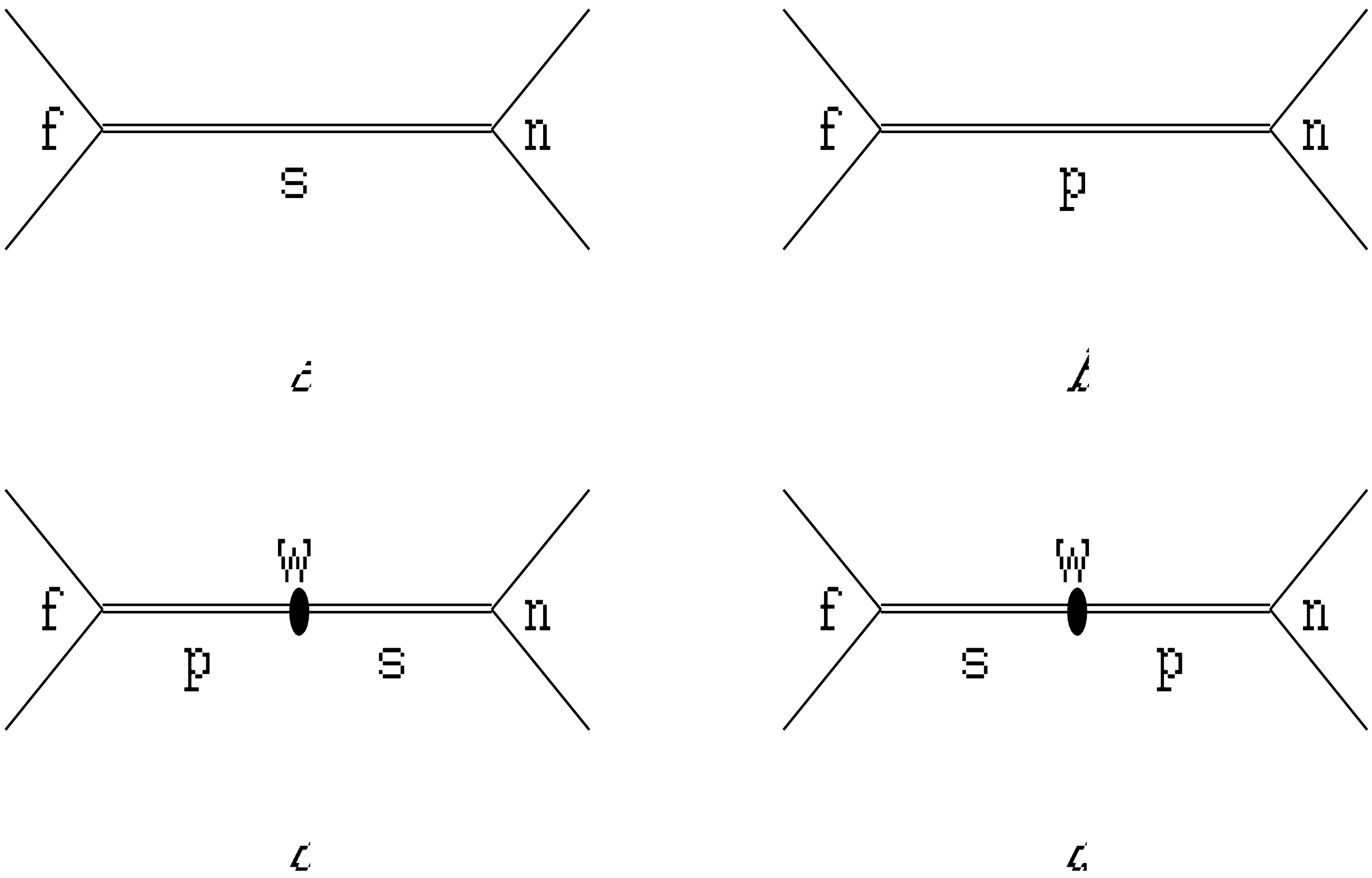
$$\Gamma / D << 1 \quad \Rightarrow$$

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

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



Compound Resonance mechanism is Dominant



General Expressions

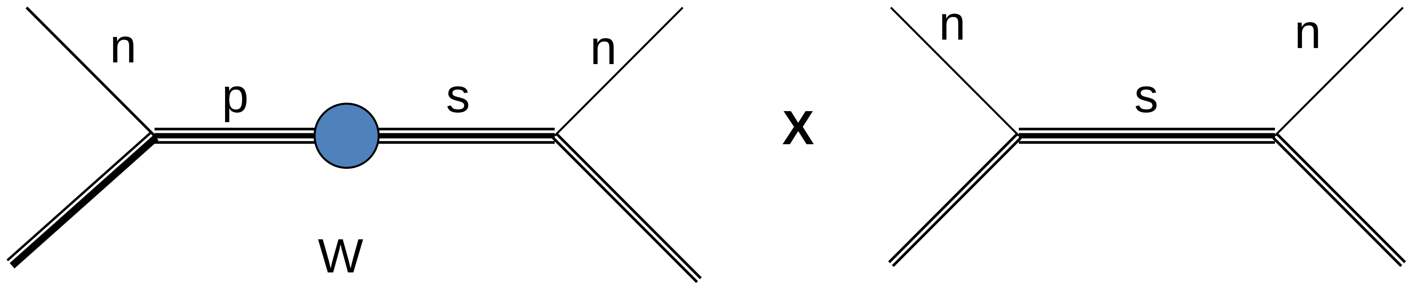
$$\Delta f_{TP} = m\frac{\sqrt{3}I}{8\pi k\sqrt{2I+1}}\left(\frac{\left\langle (I-1/2),0\,|\,R^{I-1/2}\,|\,(I+1/2),1\right\rangle - \left\langle (I+1/2),1\,|\,R^{I-1/2}\,|\,(I-1/2),0\right\rangle}{\sqrt{I+1}}\right.$$

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

$$\left\langle S^{'}s\,|\,R^{J}\,|\,S\;p\right\rangle = \frac{\sqrt{\Gamma_{s}^{\mathrm{n}}(S^{'})}(-iv+w)\sqrt{\Gamma_{p}^{\mathrm{n}}(S)}}{(E-E_{s}+i\Gamma_{s}/2)(E-E_{p}+i\Gamma_{p}/2)}e^{i(\delta_{s}(S^{'})+\delta_{p}(S))}$$

$$\int \varphi_{s} W \varphi_{p}\, d\tau = -v - iw$$

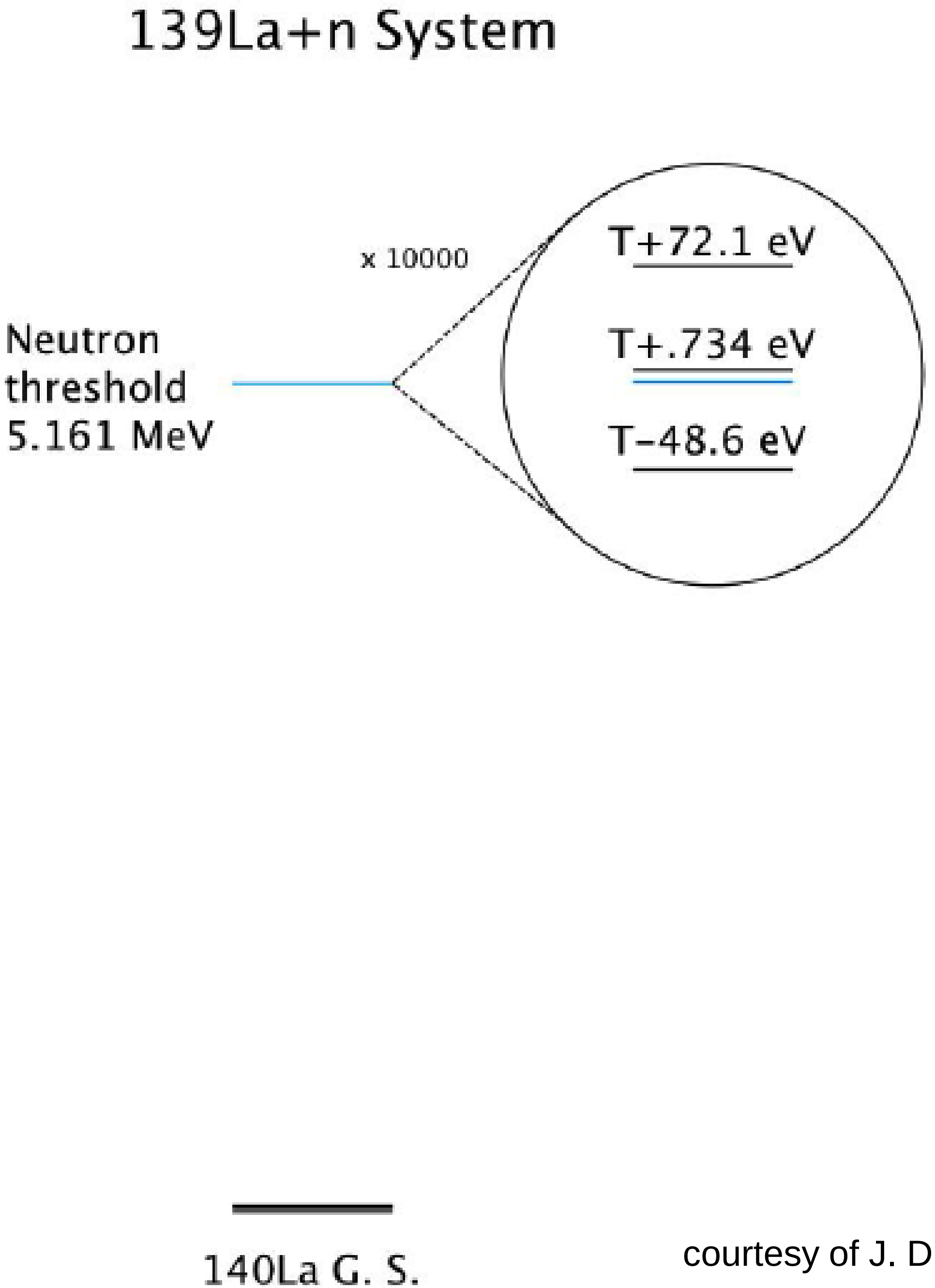
P- and T-violation in a Relative measurement!!! & Enhancements



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

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

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



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

courtesy of J. 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

$\rho(770)\ \ I^G(J^{PC}) = 1^+(1^{--})\ \ \&\ \ h_1(1170)\ \ I^G(J^{PC}) = 0^-(1^{+-})$

PV nucleon Potential

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

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^{DDH}	$f_n^{\text{DDH}}(r)$	$c_n^{\not{\pi}}$	$f_n^{\not{\pi}}(r)$	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	$\frac{\sqrt{2}\pi g_A^3\Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$\tilde{L}_\Lambda(r)$	$(\tau_i \times \tau_j)^z(\sigma_i + \sigma_j)\cdot X_{ij,-}^{(15)}$

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

Some advantages:

- 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
- Many targets → avoiding cancellations (for EDM – only one value)

How it relates to EDM limits

From n EDM [1]

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

From ^{199}Hg EDM [2]

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

$$\Rightarrow \quad \frac{\not{T}\not{P}}{\not{P}} \sim 10^{-3}$$ 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)

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)

Where to search?

- Strong p-wave resonances

- Target spins?

  Low energy neutrons* (s-, p-, d-waves)!!!!

$$I = \tfrac{1}{2} \; - \; \text{only vector polarization}$$

$$I = 1 - \text{vector and tensor rank 2}$$

$$I \geq 3/2 - \text{vector and tensor rank 2 and 3}$$

*V. Gudkov and H. Shimizu, PRC (2020)

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

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

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

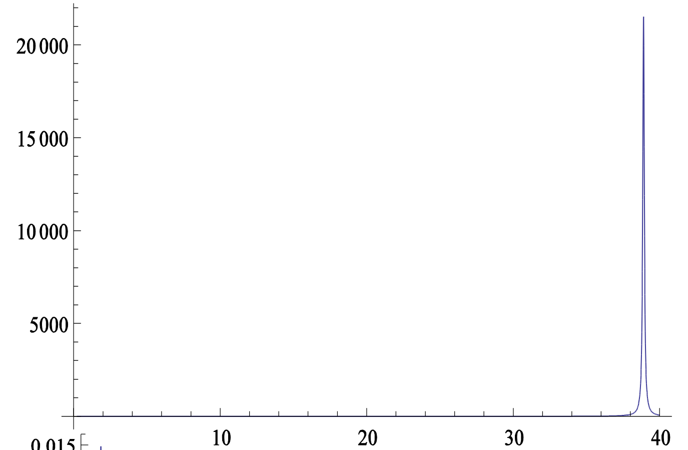
$$P = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+}$$

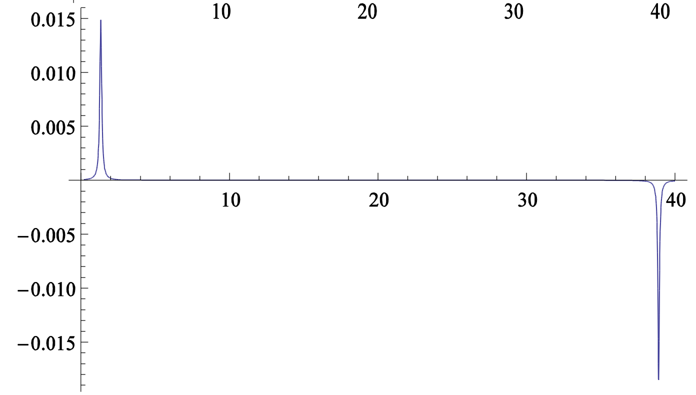
$$P(E_p) \sim 8\frac{w}{D}\sqrt{\frac{\Gamma_p^n}{\Gamma_s^n}}\left(\frac{D^2}{\Gamma_s \Gamma_p}\right)\left[1+\frac{\sigma_p(E_p)+\sigma_{pot}(E_p)}{\sigma_s(E_p)}\right]^{-1} \sim$$

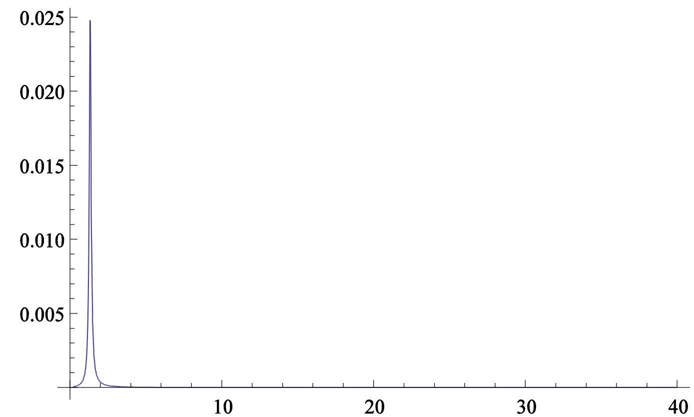
$$\sim \frac{w}{E_+ - E_-}(kR)\left(\frac{D}{\Gamma}\right)^2 \qquad (\tau \sim 1/D \;\;\&\;\; \tau_R \sim 1/\Gamma)$$

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

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







About Physics of the Resonance Enhancement

$$P = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+} \rightarrow ??? \qquad P(E_p) \sim 8 \frac{w}{E_p - E_s} \sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}} \; ???$$

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

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

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

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

Conclusions

- No FSI = like “EDM”
- Relative values → cancelations of “unknowns”
- Reasonably simple theoretical description
- A possibility for an additional enhancements
- “Unlimited”# of targets:
  - Sensitive to a variety of TRIV couplings
  - Avoiding possible cancellations
- 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!

EDM

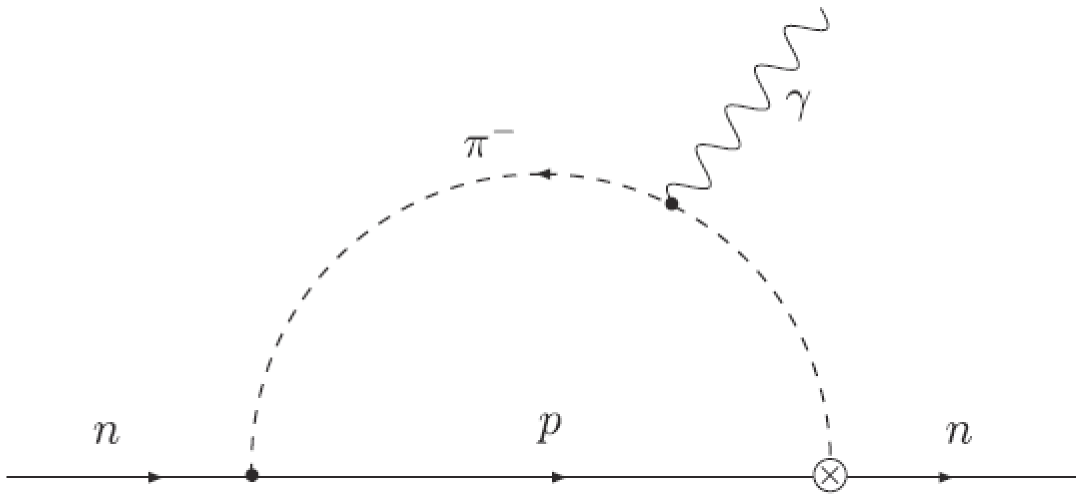
$$< p' \,|\, J_{\mu}^{em} \,|\, p >= e\bar{u}(p')\left\{\gamma_{\mu}F_1(q^2) + \frac{i\sigma_{\mu\nu}q^{\nu}}{2M}F_2(q^2) - G(q^2)\sigma_{\mu\nu}\gamma_5 q^{\nu} + \ldots\right\}u(p)$$

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

$$G(0) = d$$

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

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…

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

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

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

^{3}He and ^{3}H

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

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

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).