Time-Reversal Invariance Violation in nuclear reactions with neutrons

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

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

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

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

Observed:

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

(WMAP+COBE,2003)

SM prediction:

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

EDMs Advantage (neutron EDM)

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

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

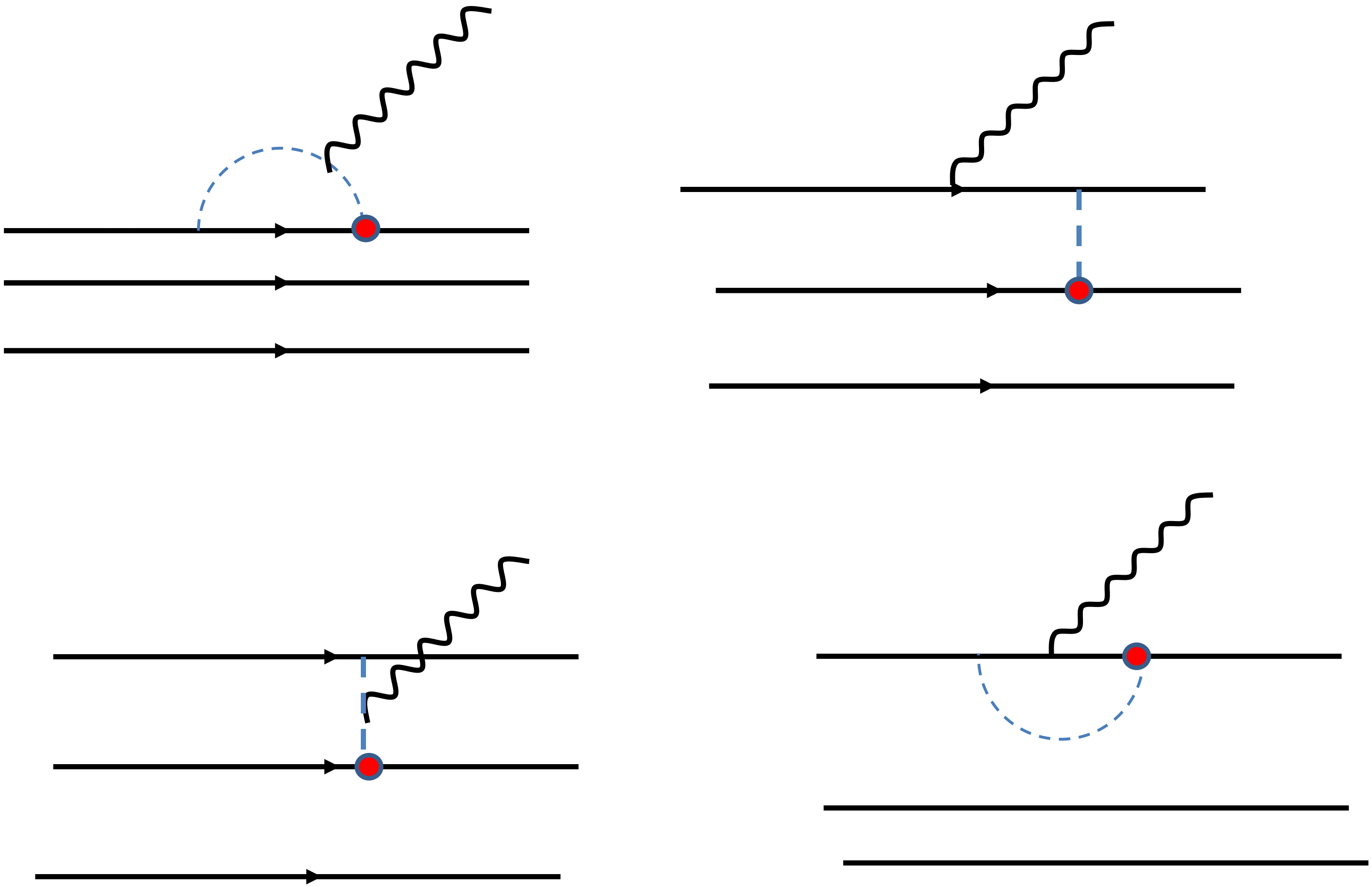
$$\not{P}: \qquad \vec{s} \to +\vec{s}; \qquad \vec{r} \to -\vec{r};$$

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

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

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

EDM's weak points: Complexity due to strong interactions



Transmission of polarized low energy neutrons through polarized nuclear target

"Transmission" = "zero angle elastic scattering"

→ No FSI = like "EDM"

"Polarized neutrons and nuclear" →

Sensitivity to both TRIV and PV

Relative values → cancelations of "unknowns"

"Low energy neutrons" →

Huge (10^6) enhancement

Reasonably simple theoretical description

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)

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

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

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

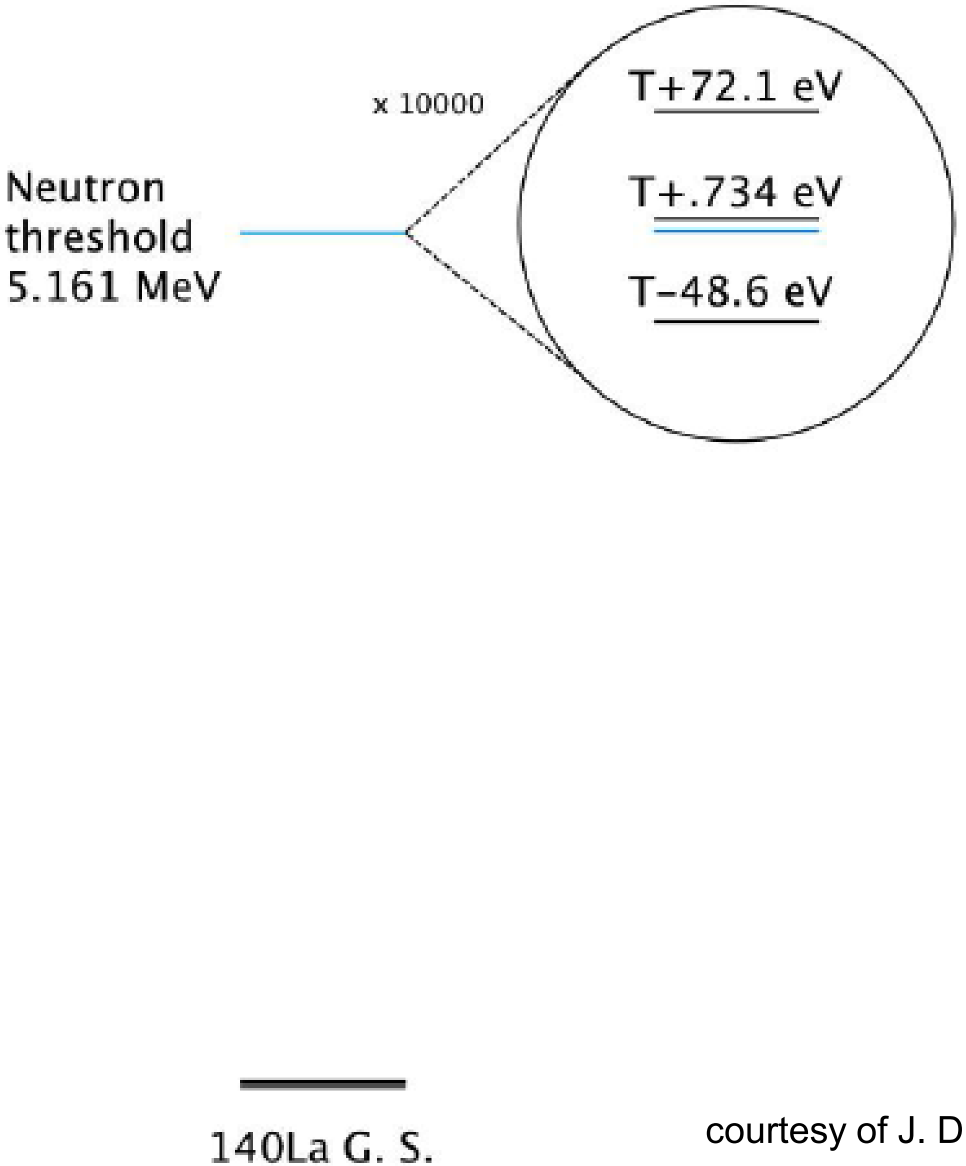
$$a^{\pm}_{k(i,f)}(E) = \frac{\exp(\pm i\delta_{i,f})}{\sqrt{2\pi}}\frac{(\Gamma^{i,f}_k)^{1/2}}{E-E_k \pm i\Gamma_k/2}$$

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

139La+n System

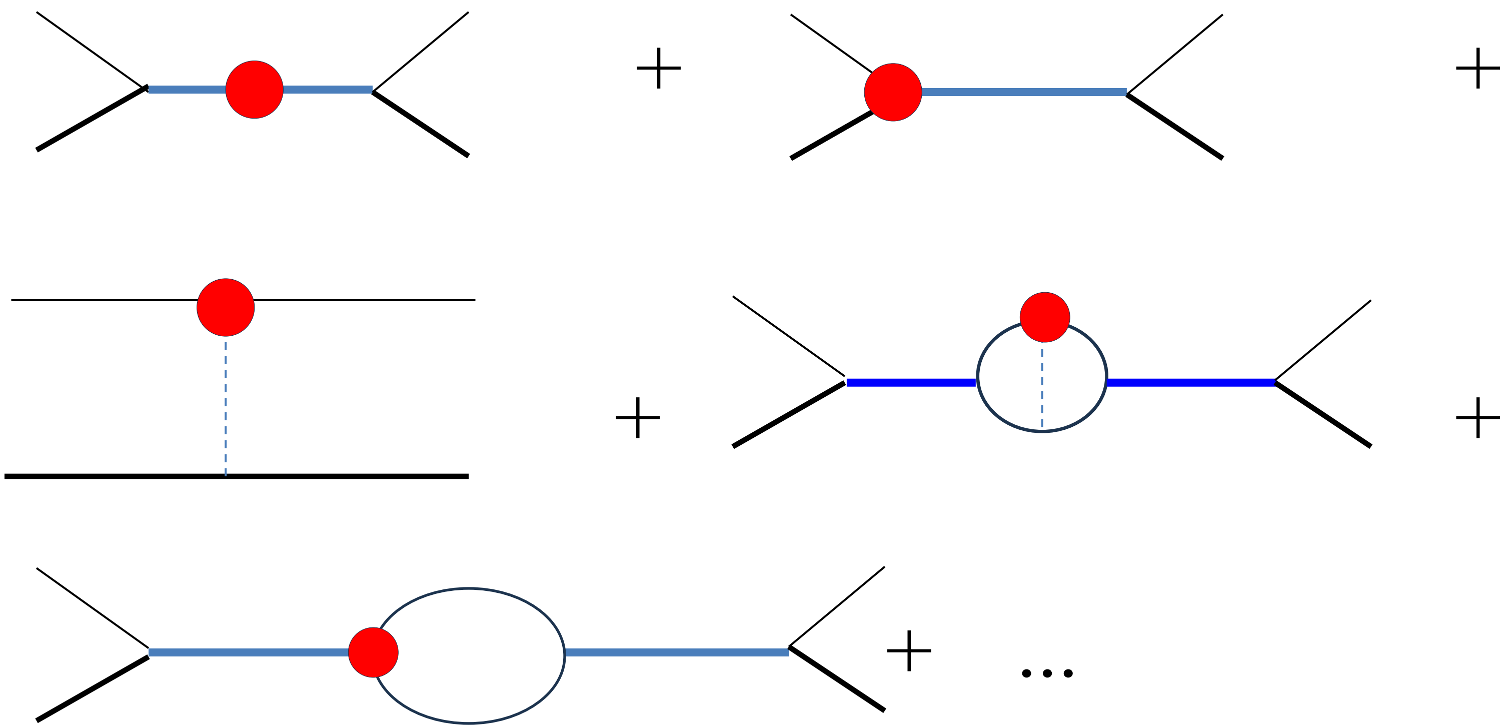


Compound-Nuclear States in ^{139}La+n system

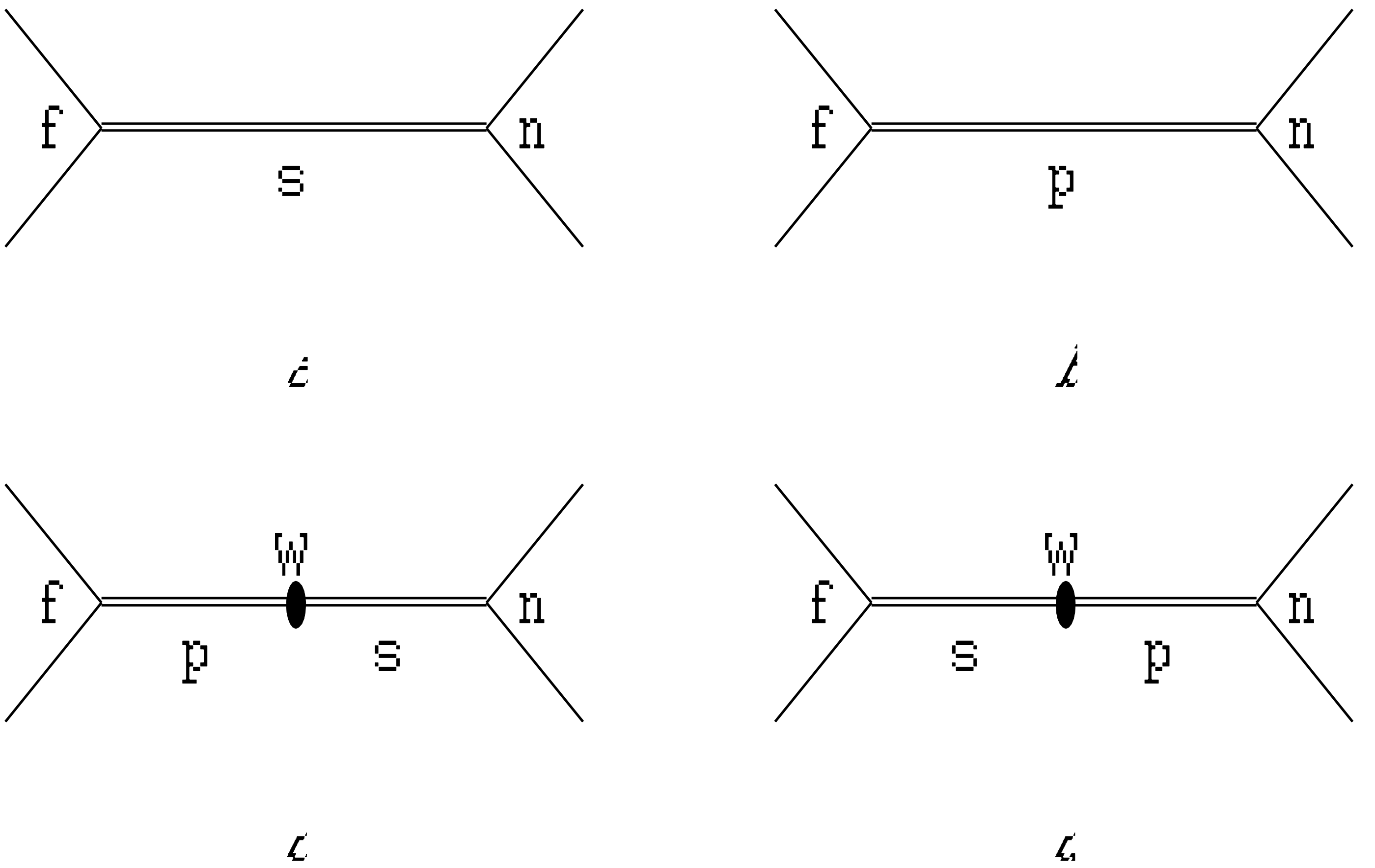
courtesy of J. D. Bowman

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

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



Compound Resonance mechanism is Dominant



TRIV and PV effects

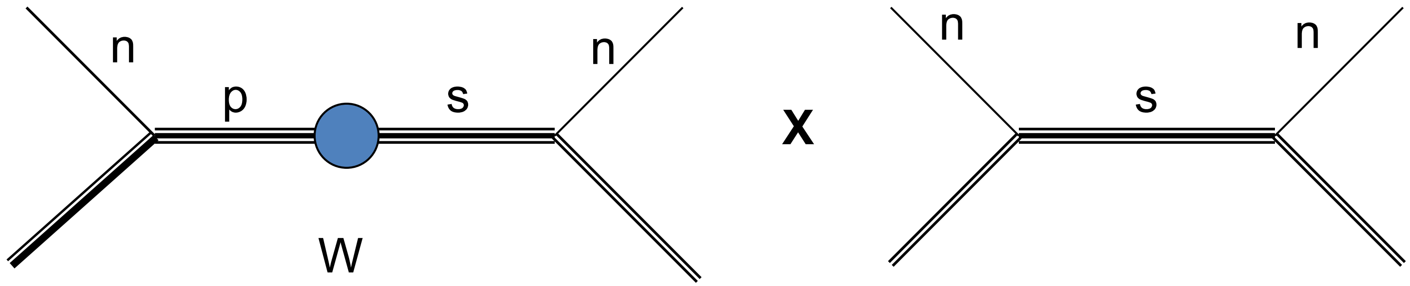
$$\left\langle S' s \,|\, R^J \,|\, S\, p \right\rangle = \frac{\sqrt{\Gamma_s^{\mathrm{n}}(S')}(-iv+w)\sqrt{\Gamma_p^{\mathrm{n}}(S)}}{(E-E_s+i\Gamma_s/2)(E-E_p+i\Gamma_p/2)} e^{i(\delta_s(S')+\delta_p(S))}$$

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

$$PV \sim \frac{\sqrt{\Gamma_s^{\mathrm{n}}(S')}(-iv)\sqrt{\Gamma_p^{\mathrm{n}}(S)}}{(E-E_s+i\Gamma_s/2)(E-E_p+i\Gamma_p/2)} e^{i(\delta_s(S')+\delta_p(S))}$$

$$TRIV \sim \frac{\sqrt{\Gamma_s^{\mathrm{n}}(S')}(w)\sqrt{\Gamma_p^{\mathrm{n}}(S)}}{(E-E_s+i\Gamma_s/2)(E-E_p+i\Gamma_p/2)} e^{i(\delta_s(S')+\delta_p(S))}$$

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



$$\Delta\sigma_T \sim \vec{\sigma}_n \cdot [\vec{k} \times \vec{I}] \sim \frac{w(\Gamma_s^n \Gamma_p^n(s))^{1/2}}{[(E-E_s)^2 + \Gamma_s^2/4][(E-E_p)^2 + \Gamma_p^2/4]}[(E-E_s)\Gamma_p + (E-E_p)\Gamma_s]$$

$$\Delta\sigma_P \sim (\vec{\sigma}_n \cdot \vec{k}) \sim \frac{v(\Gamma_s^n \Gamma_p^n(s))^{1/2}}{[(E-E_s)^2 + \Gamma_s^2/4][(E-E_p)^2 + \Gamma_p^2/4]}[(E-E_s)\Gamma_p + (E-E_p)\Gamma_s]$$

$$\frac{\Delta\sigma_T}{\Delta\sigma_P} = \kappa(J)\frac{w}{v} \sim \lambda = \frac{g_T}{g_P}$$

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

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

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

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

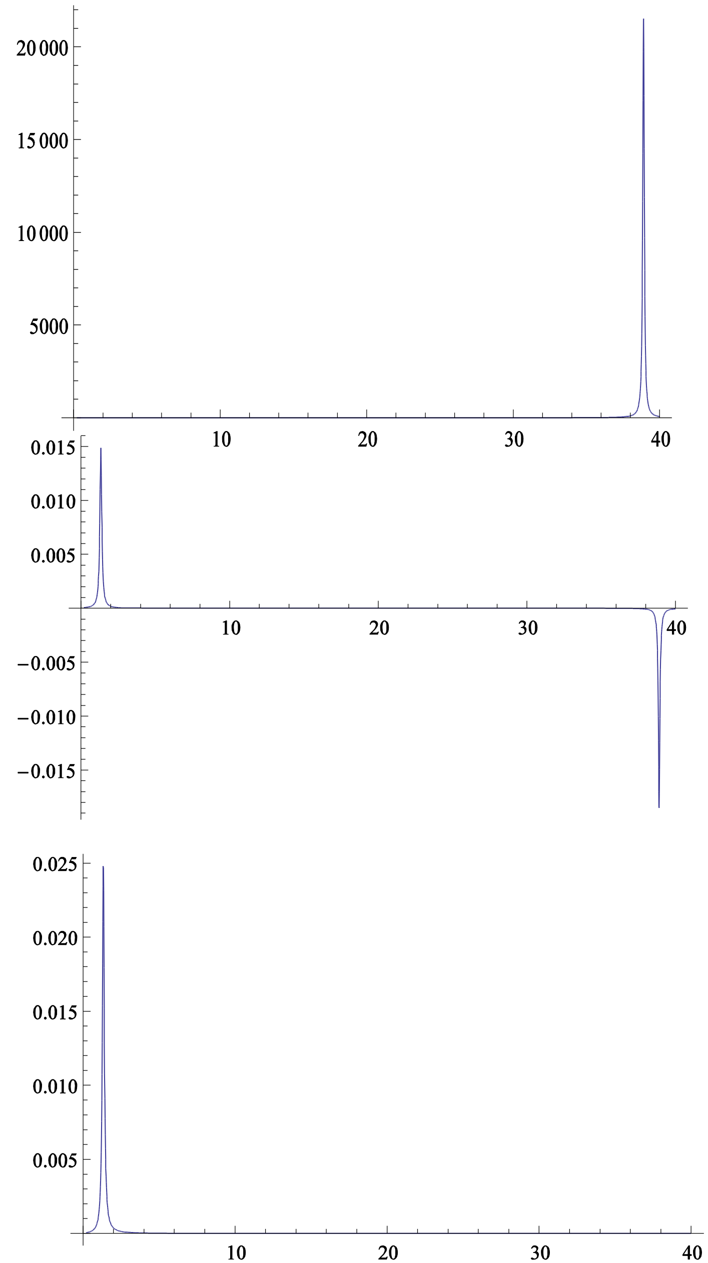
$$P=\frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+}$$

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

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

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

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



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

B. Desplanques, J. F. Donoghue, and B. R. Holstein (1980)

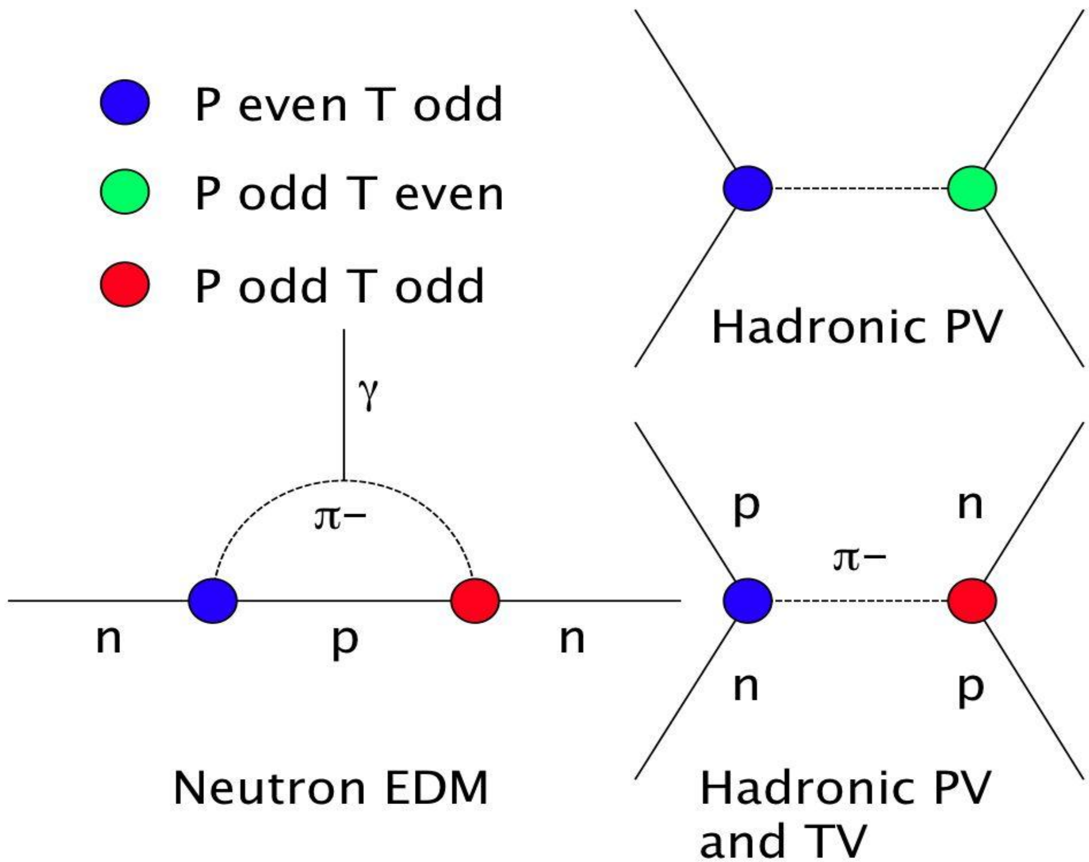
$$
\begin{aligned}
V_{\mathrm{DDH}}^{\mathrm{PV}}(\vec{r}) = {} & i\frac{h_\pi^1 g_A m_N}{\sqrt{2}F_\pi}\left(\frac{\tau_1 \times \tau_2}{2}\right)_3 (\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\left[\frac{\vec{p}_1 - \vec{p}_2}{2m_N}, w_\pi(r)\right] \\
& - g_\rho\left(h_\rho^0 \tau_1\cdot\tau_2 + h_\rho^1\left(\frac{\tau_1+\tau_2}{2}\right)_3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

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	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}C_6^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$(\tau_i \times \tau_j)^z(\sigma_i + \sigma_j)\cdot X_{ij,-}^{(1)}$
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	$\frac{\sqrt{2}\pi g_A^3\Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$\tilde{L}_\Lambda(r)$	$(\tau_i \times \tau_j)^z(\sigma_i + \sigma_j)\cdot X_{ij,-}^{(15)}$

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

Meson exchange potentials for PV and TVPV interactions



Slide courtesy of D. Bowman

TVPV vs PV vs TVPC

PV

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

TVPV

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

TVPC

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

One-particle potential

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

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

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

$$R \sim A^{1/3}$$

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

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

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

F. C. Mitchel, PR 113, 329B (1964); O.P. Sushkov et al.ZhETF 87, 1521 (1984);
V.G., Phys. Lett. B243, 319 (1990); P. Fadeev and V. V. Flambaum, PRC 100, 015504 (2019); V. V. Flambaum and A. J. Mansour, PR C 105, 015501 (2022)

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

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)

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

PHYSICAL REVIEW C, VOLUME 62, 054607

Statistical theory of parity nonconservation in compound nuclei

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(Received 22 November 1999; published 10 October 2000)

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

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

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

Enhancements:

- **"Weak" structure**

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

$h_\pi^1 \sim 2.6 \cdot 10^{-7}$ $\quad np \to d\gamma$ (2018)

or ~ 10 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)

How it relates to EDM limits

From n EDM $^{(1)}$ $(< 1.8 \cdot 10^{-26} e \cdot cm)$

$$\bar{g}_{\pi}^{(0)} < 7.5 \cdot 10^{-11}$$

From ^{199}Hg EDM $^{(2)}$ $(< 7.4 \cdot 10^{-30} e \cdot cm)$

$$\bar{g}_{\pi}^{(1)} < 1 \cdot 10^{-12}$$

$$\Rightarrow \quad \frac{\cancel{T}\cancel{P}}{\cancel{P}} \sim 10^{-3} \text{ - } 10^{-4} \quad \text{from the current EDMs}$$

$$\equiv \text{"discovery potential" } 10^{2} \text{ (nucl) -- } 10^{3} \text{ (nucl \& "weak")}$$

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

TRIV in Nuclei vs EDMs: (why they are complementary)

- If one can calculate PV effects, TVPV can be calculated with even better accuracy
  → benchmark for calculations

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

- Relative measurements → cancellations of many strong interaction contributions (for EDM – absolute value)

Conclusions

- No FSI = like "EDM"
- Very large and experimentally confirmed enhancements
- Reasonably simple theoretical description
- Relative values → cancelations of "unknowns"
- "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 $10^2 - 10^3$

Thank you!

Extra slides

About Physics of the Resonance Enhancement

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

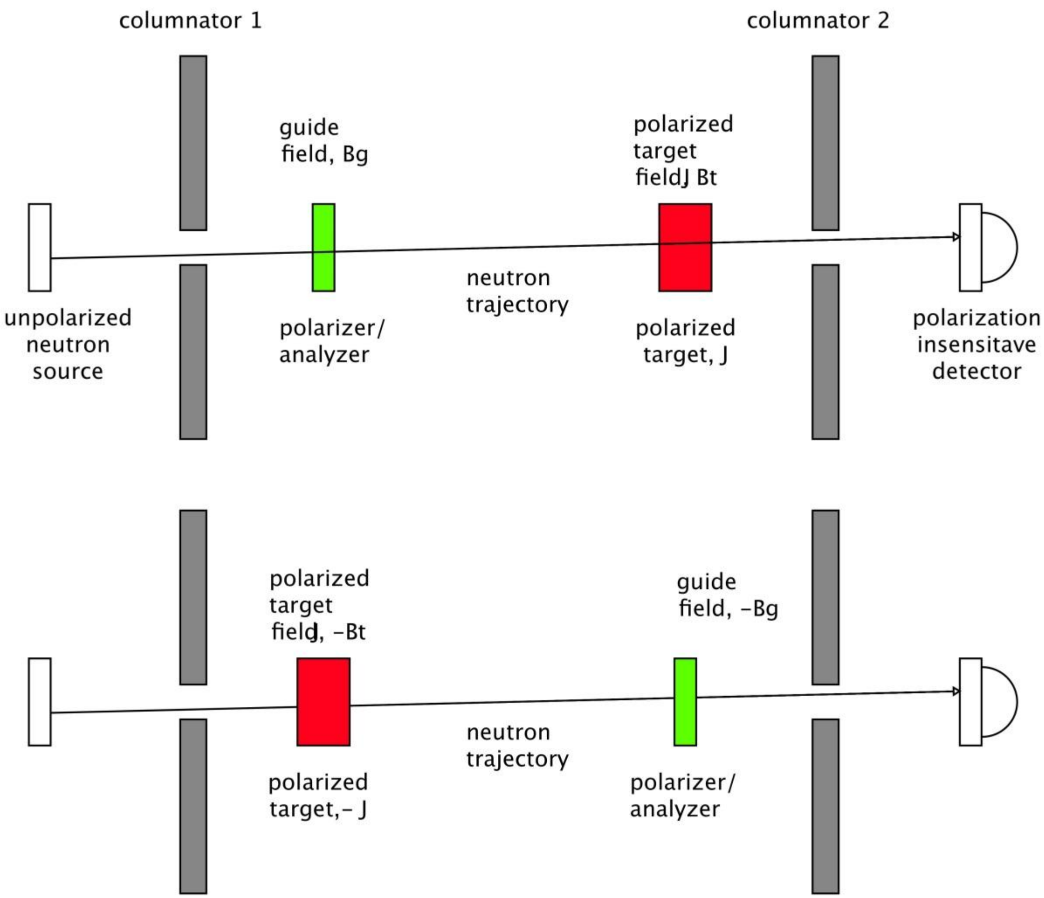
$$P(E_p) \sim 8 \frac{w}{D} \sqrt{\frac{\Gamma_p^n}{\Gamma_s^n}} \left(\frac{D^2}{\Gamma_s \Gamma_p} \right) \left[1 + \frac{\sigma_p(E_p) + \sigma_{pot}(E_p)}{\sigma_s(E_p)} \right]^{-1} \sim$$

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

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

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

No Systematics



courtesy of J. D. Bowman

TRIV Transmission Theorem

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

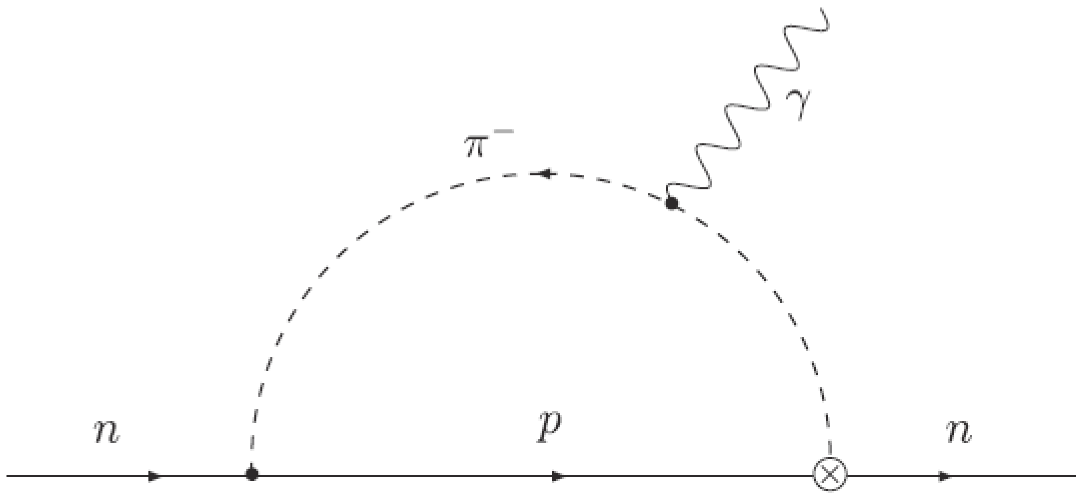
$$U_F = \prod_{j=1}^{m} \exp\left(-i\frac{\Delta t_j}{\hbar} H_j^F\right) = \alpha + (\vec{\beta} \cdot \vec{\sigma})$$

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

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

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

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)

^{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).

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)