Discover Potential in a Search for Time-Reversal Invariance Violation in Nuclei

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Motivation

- CPT $\rightarrow$ CP ~ T

  independent test (for the case of suppression/cancelation)

- CPT-violation:

  T and CP are “independent”

  problems with the standard field theory $\rightarrow$ even less trusted relations between different processes

- High Intensity Neutron Facilities

  SNS in Oak Ridge, JSNS at J-PARC, ESS in Lund

TRIV effects in nuclei

- Is it unambiguous test?
- (no FSI)

- Could they be reliably calculated?
- (calculations of relative values)

- How they are related to “standard” methods?
- (discovery potential)

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).

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):

$$\frac{(2s_a+1)(2s_A+1)}{(2s_b+1)(2s_B+1)} \frac{k_i^2}{k_f^2} \frac{(d\sigma/d\Omega)_{if}}{(d\sigma/d\Omega)_{fi}} = 1$$

PV (First order effects)

$$f = f_{PC} + f_{PV}$$

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

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

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

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)

Neutron transmission
(= "EDM quality")

- P- and T-violation: $\vec{\sigma}_n \cdot [\vec{k} \times \vec{I}\,]$

- T-violation: $(\vec{\sigma}_n \cdot [\vec{k} \times \vec{I}\,])(\vec{k} \cdot \vec{I}\,)$

(for 2 *MeV*, on ^{165}*Ho*: $<5\cdot10^{-3}$, *J. E. Koster*, 1991)

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

Enhanced of about 10^6

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

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

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

TVPV potential

P. Herczeg (1966)

$$V_{\not T \not P} = \left[-\frac{\bar{g}_\eta^{(0)} g_\eta}{2m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) + \frac{\bar{g}_\omega^{(0)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \boldsymbol{\sigma}_- \cdot \hat{r}$$
$$+ \left[-\frac{\bar{g}_\pi^{(0)} g_\pi}{2m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\rho^{(0)} g_\rho}{2m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) \right] \tau_1 \cdot \tau_2 \boldsymbol{\sigma}_- \cdot \hat{r}$$
$$+ \left[-\frac{\bar{g}_\pi^{(2)} g_\pi}{2m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\rho^{(2)} g_\rho}{2m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) \right] T_{12}^z \boldsymbol{\sigma}_- \cdot \hat{r}$$
$$+ \left[-\frac{\bar{g}_\pi^{(1)} g_\pi}{4m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\eta^{(1)} g_\eta}{4m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) + \frac{\bar{g}_\rho^{(1)} g_\rho}{4m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) + \frac{\bar{g}_\omega^{(1)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \tau_+ \boldsymbol{\sigma}_- \cdot \hat{r}$$
$$+ \left[-\frac{\bar{g}_\pi^{(1)} g_\pi}{4m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) - \frac{\bar{g}_\eta^{(1)} g_\eta}{4m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) - \frac{\bar{g}_\rho^{(1)} g_\rho}{4m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) + \frac{\bar{g}_\omega^{(1)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \tau_- \boldsymbol{\sigma}_+ \cdot \hat{r}$$

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

TVPC potential

P. Herczeg (1966)

$$
\begin{aligned}
H^{\not T P} = {} & \left(g_1(r) + g_2(r)\tau_1\cdot\tau_2 + g_3(r)T_{12}^z + g_4(r)\tau_+\right)\hat{r}\cdot\frac{\boldsymbol{p}}{m_N} \\
& + \left(g_5(r) + g_6(r)\tau_1\cdot\tau_2 + g_7(r)T_{12}^z + g_8(r)\tau_+\right)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\hat{r}\cdot\frac{\bar{\boldsymbol{p}}}{m_N} \\
& + \left(g_9(r) + g_{10}(r)\tau_1\cdot\tau_2 + g_{11}(r)T_{12}^z + g_{12}(r)\tau_+\right) \\
& \quad \times\left(\hat{r}\cdot\boldsymbol{\sigma}_1\frac{\bar{\boldsymbol{p}}}{m_N}\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_2\frac{\bar{\boldsymbol{p}}}{m_N}\cdot\boldsymbol{\sigma}_1 - \frac{2}{3}\hat{r}\cdot\frac{\bar{\boldsymbol{p}}}{m_N}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right) \\
& + \left(g_{13}(r) + g_{14}(r)\tau_1\cdot\tau_2 + g_{15}(r)T_{12}^z + g_{16}(r)\tau_+\right) \\
& \quad \times\left(\hat{r}\cdot\boldsymbol{\sigma}_1\hat{r}\cdot\boldsymbol{\sigma}_2\hat{r}\cdot\frac{\bar{\boldsymbol{p}}}{m_N} - \frac{1}{5}(\hat{r}\cdot\frac{\bar{\boldsymbol{p}}}{m_N}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_1\frac{\bar{\boldsymbol{p}}}{m_N}\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_2\frac{\bar{\boldsymbol{p}}}{m_N}\cdot\boldsymbol{\sigma}_1)\right) \\
& + g_{17}(r)\tau_-\hat{r}\cdot(\boldsymbol{\sigma}_\times\times\frac{\bar{\boldsymbol{p}}}{m_N}) + g_{18}(r)\tau_\times^z\hat{r}\cdot(\boldsymbol{\sigma}_-\times\frac{\bar{\boldsymbol{p}}}{m_N}),
\end{aligned}
$$

TVPC potential

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

$$\mathcal{L}^{\not{T}P} = -\frac{\bar{g}_\rho}{2m_N}\bar{N}\sigma^{\mu\nu}\epsilon^{3ab}\tau^a \partial_\nu \rho^b_\mu N + i\frac{\bar{g}_h}{2m_N}\bar{N}\sigma^{\mu\nu}\gamma_5 \partial_\nu h_\mu N,$$

$$g_5^{ME}(r) = \left(-\frac{4 g_h \bar{g}_h}{3 m_N}\right)\left(\frac{m_h^2}{4\pi}Y_1(m_h r)\right) = C^{\not{T}P}_{5,h} f^{\not{T}P}_{5,h}(r, \mu = m_h),$$

$$g_9^{ME}(r) = \left(-\frac{2 g_h \bar{g}_h}{m_N}\right)\left(\frac{m_h^2}{4\pi}Y_1(m_h r)\right) = C^{\not{T}P}_{9,h} f^{\not{T}P}_{9,h}(r, \mu = m_h),$$

$$g_{18}^{ME}(r) = \left(\frac{g_\rho \bar{g}_\rho}{2 m_N}\right)\left(\frac{m_\rho^2}{4\pi}Y_1(m_\rho r)\right) = C^{\not{T}P}_{18,\rho} f^{\not{T}P}_{18,\rho}(r, \mu = m_\rho),$$

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

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**

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

$$h_{\pi}^{1} \sim 4.6 \cdot 10^{-7} \qquad \text{"best" DDH}$$

or 10 - 100 Enhancement!!!

- **“Strong” structure**

P-violation:

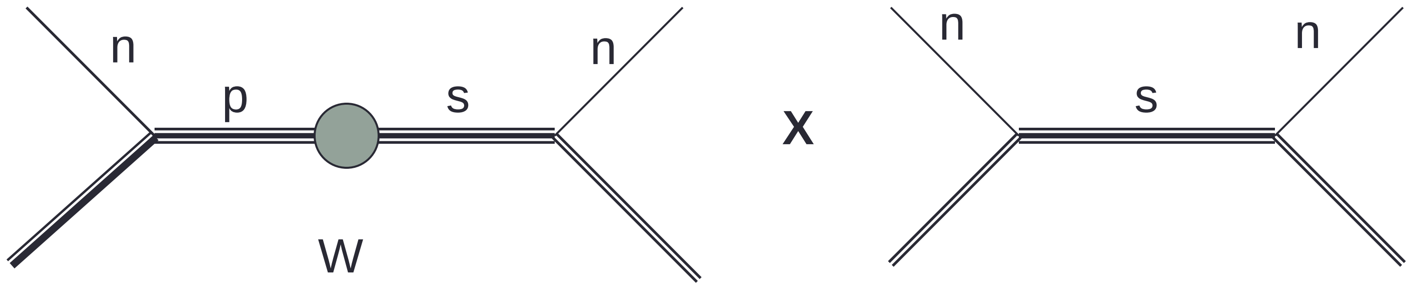
$$(\vec{\sigma}_n \cdot \vec{k}) \sim 10^{-1} (not \;\; 10^{-7})$$

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

P- and T-violation in Neutron transmission



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

$$\Delta\sigma_T / \Delta\sigma_P \sim \lambda = \frac{g_T}{g_P}$$

V. E. Bunakov and V.G., Z. Phys. A308 (1982) 363

V.G., Phys. Lett.B243 (1990) 319

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)	$\leq 2\times10^{-3}$

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

EDM limits

From n EDM [1]

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

$$d_n = \frac{e}{4\pi m_N} \bar{g}_{\pi}^{(0)} g_{\pi} \ln \frac{\Lambda}{m_{\pi}}$$

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)

Simple systems: n-d

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

$$\left\{ {}^3S_1(T=0) \leftrightarrow {}^3D_1(T=0), \quad {}^3P_1(T=1) \leftrightarrow {}^1P_1(T=0) \right\}$$

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

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

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

V.G., Z. Phys. A337 (1990) 247

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)

Conclusions

- No FSI = "EDM"- quality data
- Reasonably simple theoretical description
- A possibility for an additional enhancement
- New facilities with high neutron fluxes

The possibility to improve limits on TRIV

(or to discover new physics) by 10^2 - 10^4