SEARCH FOR TRIV IN THE INTERACTION OF POLARIZED NEUTRONS WITH POLARIZED TARGETS

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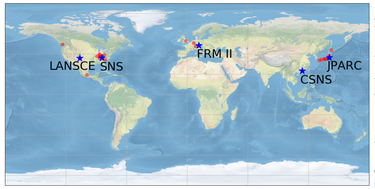
for the NOPTREX collaboration



A multi-national, multi-neutron source collaboration

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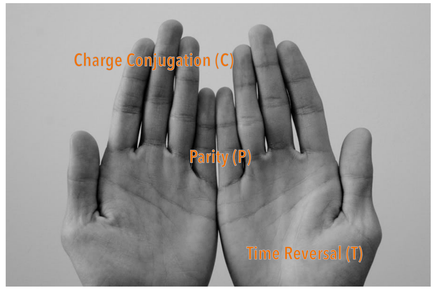
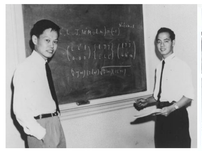
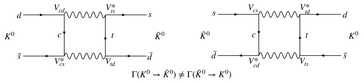
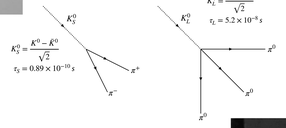
Symmetries in Nature





P violation in the weak interaction





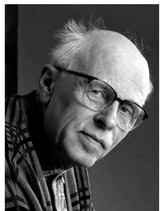
CP violation kaons, B mesons, D mesons

CP Violation

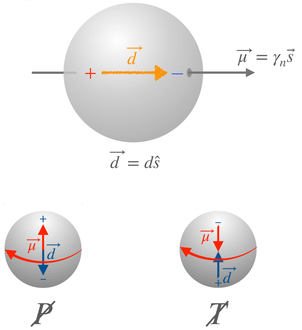
- CP violation equivalent to TRIV (CPT Theorem)
- Phenomenological tool to distinguish matter from antimatter
- One of the ingredients to explain baryon asymmetry
- Strong CP problem
- CP in the Standard Model is too small
- New physics

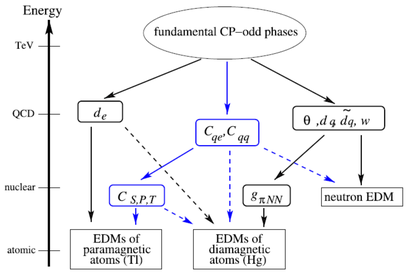
Sakharov conditions for baryogenesis

- *Baryon number violation*
- *C and CP violation*
- *Departure from thermal equilibrium*



Electric Dipole Moments of Particles and Atomic Systems





Pospelov & Ritz, Ann. Phys. 318 (2005) 119

Neutron Optics and Forward Scattering Amplitude

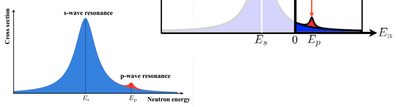
For low energy neutrons ($kR \ll 1$), neutron-nuclei interaction is given by

$$V_F = \frac{2\pi\hbar^2}{m_n} N f$$

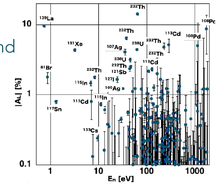
The elastic scattering amplitude at zero angle is

$$f = \underbrace{a_0}_{\text{indep. de espín}} + \underbrace{b_0(\vec{s}_n \cdot \vec{I})}_{\mathcal{P}\,\&\,\mathcal{T}\text{ cons.}} + \underbrace{c_0(\vec{s}_n \cdot \vec{k}_n)}_{\mathcal{P}\,\&\,\mathcal{T}\text{ cons.}} + \underbrace{d_0[\vec{s}_n \cdot (\vec{k}_n \times \vec{I})]}_{\mathcal{P}\,\&\,\mathcal{T}}$$

$$P \sim \frac{W_{sp}}{E_s - E_p}\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}}$$



PV in n - compound nucleus systems



G.E. Mitchell et al. Phys. Rep. 354, 157 (2001)

$$W_{\mathcal{P}} = \frac{Gg}{2\sqrt{2}m}\{(\sigma p), \rho\} \qquad W_{\mathcal{PT}} = \frac{G\eta}{2\sqrt{2}m}(\sigma\nabla)\rho$$

$$\Delta\sigma_{\mathcal{P}} \propto \langle\psi_p|W_{\mathcal{P}}|\psi_s\rangle \qquad \Delta\sigma_{\mathcal{PT}} \propto \langle\psi_p|W_{\mathcal{PT}}|\psi_s\rangle$$

Fadeev and Flambaum, Phys. Rev. C 100 (2019) 015504.

same enhancement is to expect to occur for possible TRIV interactions, no FSI

Theoretical Relations

$$\frac{\Delta\sigma_{\mathcal{PT}}}{\Delta\sigma_{\mathcal{P}}} = \kappa(J)\frac{\langle\psi_p|W_{\mathcal{PT}}|\psi_s\rangle}{\langle\psi_p|W_{\mathcal{P}}|\psi_s\rangle} = \kappa(J)\frac{w}{v}$$

w/v gets determined, and theoretically (Fadeev & Flambaum) it can be related to:

- the contact nuclear interaction ($g_{n,p}$ and $\eta_{n,p}$),
- the meson exchange weak NN coupling constants ($h^{\Delta I}_{\pi,\omega,\rho}$),
- the QCD θ-term,
- the quark chromo-electric dipole moments ($\tilde{d}_u$ and $\tilde{d}_d$),
- axion interaction constants ($g^s g^p$)

$$\frac{w}{v} = \frac{K_{\mathcal{PT}}\sqrt{g_n^2 + 0.76 g_p^2}}{K_{\mathcal{P}}\sqrt{\eta_n^2 + 0.76\eta_p^2}}$$

Fadeev and Flambaum, Phys. Rev. C 100 (2019) 015504.

$$g_n = 2\times 105 W_\rho\left[-118\frac{W_\pi}{W_\rho}f_\pi - 18.9h_\rho^0 + 8.5h_\rho^1 - 1.3h_\rho^2 - 12.8\left(h_\omega^0 + h_\omega^1\right)\right]$$

$$\frac{w}{v} = 5.7\times 10^4|\theta| \qquad |\theta| < 10^{-10}, \quad \frac{w}{v} < 10^{-5}$$

$$\frac{w}{v} = \left|6.5\times 10^{20}\left(4(\tilde{d}_u - \tilde{d}_d) - 0.16(\tilde{d}_u + \tilde{d}_d)\right)\right| /cm$$

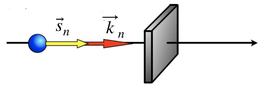
$$|\tilde{d}_u - \tilde{d}_d| < 6\times 10^{-27}\,cm, \quad \left|\frac{1}{2}\tilde{d}_u + \tilde{d}_d\right| < 3\times 10^{-26}\,cm$$

$$\frac{w}{v} \sim |1\times 10^6 g^s g^p|$$

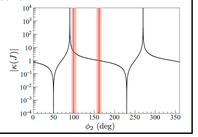
$$d_p = \frac{g^s g^p e}{8\pi^2 m_p}, \; |d_p| < 2\times 10^{-25} e\,cm, \; |g^s g^p| < 10^{-9}, \; \frac{w}{v} < 10^{-3}$$

Experimental Observables

$\Delta\sigma_{\mathcal{P}}$ from PV experiments



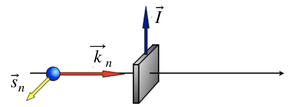
$\kappa(J)$ from angular correlations in neutron radiative capture



Okudaira et al., Phys. Rev. C 97 (2018) 034622.

$\Delta\sigma_{\mathcal{PT}}$ from TRIV experiments?

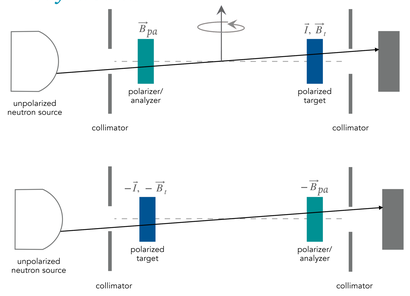
$$f = a_0 + b_0(\vec{s}_n \cdot \vec{I}) + c_0(\vec{s}_n \cdot \vec{k}_n) + d_0[\vec{s}_n \cdot (\vec{k}_n \times \vec{I})]$$



In principle, precise control of relevant vectors is required beyond what is currently possible

However…

A way around



Bowman & Gudkov, Phys. Rev. C 90 (2014) 065503, Kabir, Phys. Rev. D 37 (1988) 1856.

Bowman & Gudkov reanalyzed a possible experiment that was first proposed by Kabir

Considering

$$H = \frac{2\pi\hbar^2}{m_n}Nf - \frac{\mu}{2}(\vec{\sigma}\cdot\vec{B}), \text{ and}$$

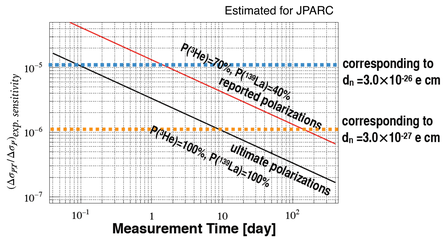
$$f = a_0 + b_0(\vec{s}_n \cdot \vec{I}) + c_0(\vec{s}_n \cdot \vec{k}_n) + d_0[\vec{s}_n \cdot (\vec{k}_n \times \vec{I})]$$

arrived to the TRIV theorem:

If d_0=0 and the apparatus is rotated, with $\vec{B}$ and $\vec{I}$ being reversed, then the transmission of neutrons in both states are equal

Any deviation from the equality of the forward and reversed transmission is a clear manifestation of TRIV interactions

Experimental Sensitivity



- At a MW class spallation source, $(\Delta\sigma_{\mathcal{PT}}/\Delta\sigma_{\mathcal{P}})$ can be determined with uncertainty between 10^{-5} to 10^{-6} in reasonable time
- $\frac{\Delta\sigma_{\mathcal{PT}}}{\Delta\sigma_{\mathcal{P}}} = \kappa(J)\frac{w}{v}$
- From theoretical analysis, $w/v = 5.7\times 10^4|\theta|$ and with $|\theta| < 10^{-10}$, $w/v < 10^{-5}$

New physics discovery potential

Complementarity of TRIV Searches

- EDMs are ground state properties, while highly excited states in heavy nuclei are involved in neutron optics TRIV effects, which offer a quantitatively different environment with different sensitivity to the many possible sources of CP violation.
- Any single type of TRIV search cannot be equally sensitive to all possible CP violation mechanisms, so it is essential to pursue any experiments in different systems which can be realized with sufficient sensitivity.

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