# Test of time reversal invariance and low energy nuclear reactions

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*June 28, 2007*

# Motivation

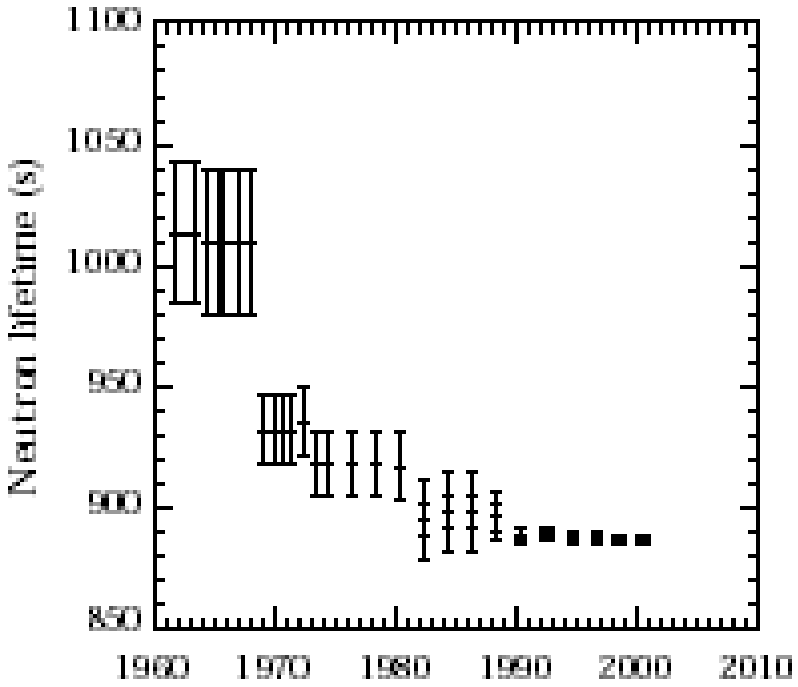
- CPT → CP ~ T

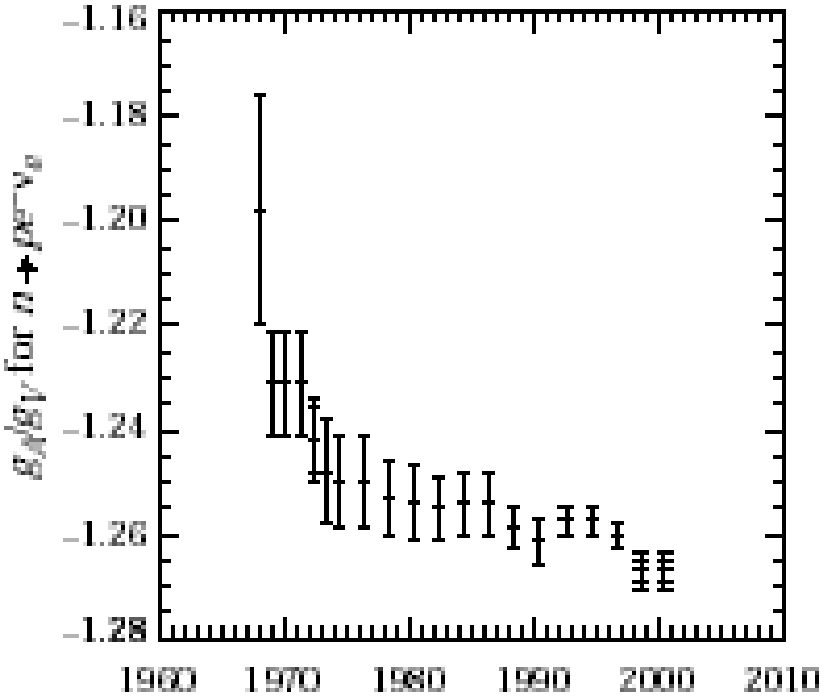
  independent test (for the case of suppression/cancelation)

- CPT-violation:

  T and CP are “independent”

  problems with the standard field theory → even less trusted relations between different processes


Neutron lifetime (s)
1100
1050
1000
950
900
850
1960
1970
1980
1990
2000
2010


$g_A/g_V$ for $n \to pe^-\nu_e$
−1.16
−1.18
−1.20
−1.22
−1.24
−1.26
−1.28
1960
1970
1980
1990
2000
2010

# T-Reversal Invariance

$$a + A \rightarrow b + B$$

$$\vec{k}_{i,f} \rightarrow -\vec{k}_{f,i} \quad \text{and} \quad \vec{s} \rightarrow -\vec{s}$$

$$< \vec{k}_f, m_b, m_B | \hat{T} | \vec{k}_i, m_a, m_A >= (-1)^{\sum_i s_i - m_i} < -\vec{k}_i, -m_a, -m_A | \hat{T} | -\vec{k}_f, -m_b, -m_B >$$

Detailed Balance Principle (DBP):

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

# DBP test:

- $^{24}Mg + \alpha \leftrightarrow {}^{27}Al + p$

(with the intermediate compound nuclear state $^{28}Si$ excited up to $E^*$~19$MeV$)

$|F| < 2 \cdot 10^{-3}$ ( *E. Burke*, 1983)

- $^{24}Mg + d \leftrightarrow {}^{25}Mg + p$

$|F| < 2 \cdot 10^{-3}$ ( *D. Bodansky,*, 1968)

# Ericson fluctuations

$$|F| \sim \frac{|S_{asym}|}{|S_{sym}|}$$

$$S_{asym} \sim \sum_{c} \left\{ \gamma' \frac{1}{\Delta_c} \gamma + \gamma \frac{1}{\Delta_c} \gamma' + \gamma' \frac{1}{\Delta_{c'}} w \frac{1}{\Delta_c} \gamma \right\}$$

# Asymmetry Theorem:

$$\vec{A}_a = \frac{3s_b}{s_b + 1}\vec{P}_b$$

Proton-proton scattering (*E*=198.5*MeV*)

|F| < 2.6 ·10$^{-3}$ ( *C. A. Davic*, 1986)

## Correlations in *γ-decay transitions:*

$(\vec{J}[\vec{k}\times\vec{\varepsilon}])(\vec{J}\vec{k})(\vec{J}\vec{\varepsilon})$ $E_\gamma$=122*KeV* for $^{57}$*Fe* (*F. Boehm*, 1979)

$$\sin\eta = (3.1 \pm 6.9)\cdot 10^{-4}$$

Mössbauer's thransitions (V. G. Tsinoev, 1982)

$$\sin\eta = (-3.3 \pm 6.6)\cdot 10^{-4}$$

# Statistical properties of compound nuclei

- T-invariant → *Gauss Orthogonal Ensemble* of random matrices → Wigner linear repulsion:

$$p(\varepsilon) \sim \varepsilon$$

- Violation of T-invariance → *Unitary Ensemble* of random matrices :

$$p(\varepsilon) \sim \varepsilon^2$$

$$E_{\pm} = \frac{1}{2}\left(H_{11} + H_{22}\right) \pm \frac{1}{2}\sqrt{\left(H_{11} - H_{22}\right)^2 + 4H_{12}^2 + H_T^2}$$

$1.7 \cdot 10^3$ levels results in $<10^{-3}$

# T-odd correlations in β-decay

Neutron:

$D$ = (-1.1 +/- 1.7) $10^{-3}$ (*R. I. Steinberg*, 1974)

$D$ = (2.2 +/- 3.0) $10^{-3}$ (*B. G. Erozolimsky*, 1978)

$D$ = (-0.6 +/- 1.2(stat) +/- 0.5(syst)) $10^{-3}$ (*The emiT Collab.*, 2000)

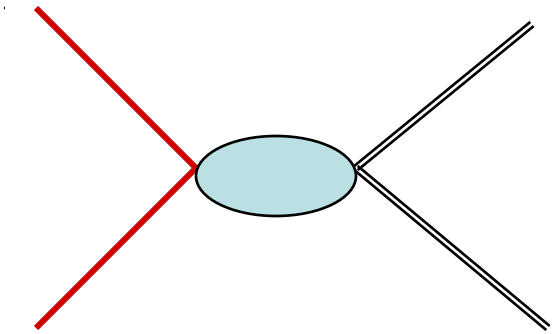
$D$ = (-2.8 +/- 6.4(stat) +/- 3.0(syst)) $10^{-4}$ (*T. Soldner*, 2004)

$^{19}$Ne :

$D$=(0.4 +/- 0.8) $10^{-3}$ (*A. L. Hallin*, 1984)

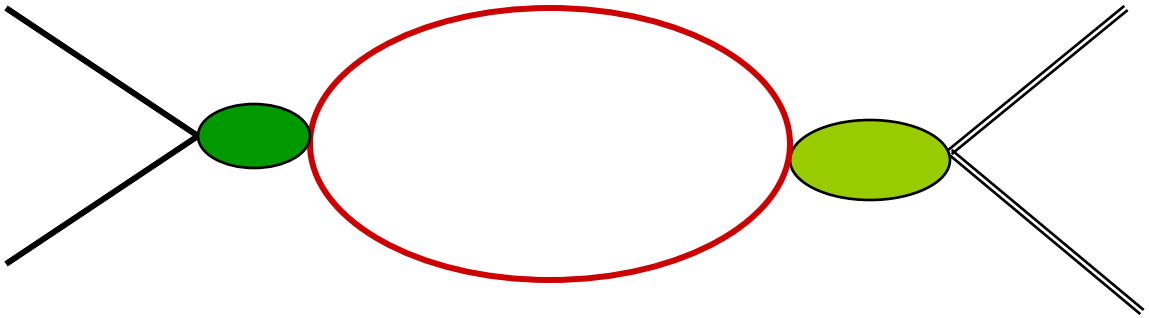
# High Energy Physics with Low Energy Neutrons

***HEP:***



$E \rightarrow \infty$

***FNP:***



$\Delta E/E \rightarrow 0$

# High Energy Physics with Low Energy Neutrons

***Neutron Reactions***

- *Neutron Energy 0.01 – 100 eV*
- *Nuclear Excitation Energy 6 – 7 MeV ⇒ Energy resolution $10^{-9}$*
- 
- 

- *Flux ⇒ precision*
- *Polarization*
- *Low Energy enhancement*
  *Complex nuclear system by $10^{6}$*
- *RELATIVE Measurements & MANY Targets*
- *The possibility to eliminate Theoretical uncertainties*

⇒ ***Symmetry Tests & Fundamental Constants***

# Neutron transmission

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

Enhanced of about $10^6$

- 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)

"phase-shift"

($<10^{-2}$, *E. D. Davis*, 2005)

# Important features:

- Large enhancement factor (~$10^6$)
- No FSI
- Reasonably simple theoretical descriptions (*relative effects*)
- New facilities with large fluxes will be available soon

# FSI

$$T^{+} - T = iTT^{+}$$

in the first Born approximation $T$-is hermitian

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

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

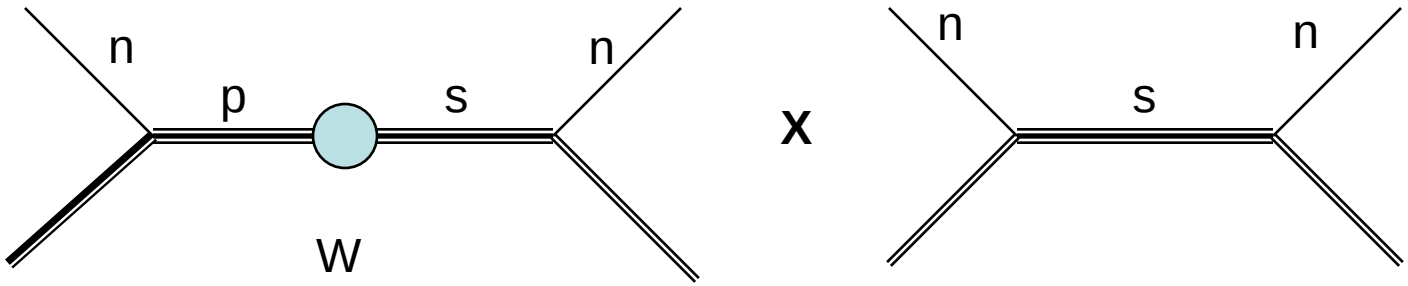
$$\Rightarrow |< f | T | i >|^{2} = |< -f | T | -i >|^{2}$$

then the probability is even function of time.

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

"T-odd correlations" = "T-violation"

# P- and T-violation in Neutron transmission




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

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

# Theoretical predictions

| Model | $\lambda$ |
|---|---|
| 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) | $\leq 2\times10^{-3}$ |

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

# Simple systems: n-d

$$(\vec{\sigma}_n \cdot [\vec{k} \times \vec{I}])(\vec{k} \cdot \vec{I}) \qquad \left\{ {}^3S_1(T=0) \leftrightarrow {}^3D_1(T=0), \quad {}^3P_1(T=1) \leftrightarrow {}^1P_1(T=0) \right\}$$

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

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

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

# Conclusions

- For T-violating P-conserving interactions the current limit could be easily improved by about of 2-3 orders of magnitude
- For T-violating P-violating interactions it may be possible to reach $\lambda \sim 10^{-4} - 10^{-5}$
- New possibilities for search for new physics – why miss the opportunity?