Search for time-reversal symmetry breaking in neutron beta decay

emiT Collaboration

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CP and T violation are sensitive probes to search for new physics

Can there be additional CP violation to be discovered in beta decay?

Explaining the observed baryon asymmetry of the Universe requires CP violation larger than what is provided by the phase in the CKM matrix. One possibility is that this extra source of CP violation should be observable in nuclear beta decay.
Standard Model Weak Interaction at low energies:

\[ H = \bar{\Psi}_f \gamma^\mu \Psi_i \quad C_V \bar{e} \gamma_\mu \nu_e + \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_i \quad C_A \bar{e} \gamma_\mu \gamma_5 \nu_e \]

Resulting decay rate:

\[ dw = dw_0 \left[ 1 + a \frac{p_e}{E_e} \cdot \frac{p_v}{E_v} + b \frac{\Gamma m_e}{E_e} + \right. \]

\[ \frac{\langle \vec{J} \rangle}{J} \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_v}{E_v} + D \frac{\vec{p}_e \times \vec{p}_v}{E_e E_v} \right) \]

\[ D \approx 2 \frac{|\lambda| \sin \varphi}{3|\lambda|^2 + 1} \]

Sensitive to a phase between the axial and vector (or T and S) currents
Cheaper than searches at Belle (¥¥¥) or Babar ($$$),

emiT is a `null experiment’.

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<td>$&lt;$present limit ~$10^{-3}$</td>
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Although we look for a T-odd/P-even signal, people have made connections to EDMs (T-odd/P-odd):
Kurylov, McLaughlin, Ramsey-Musolf PRL 63, 076007 (2001)
Haxton, Horing, Musolf, PRD 50, 3422 (1994)
Khriplovich, Pis’ma Zh. Eksp.Teor. Fiz. 52, 1065 (1990)

These limits are more stringent than the present work, but model dependent.
New results from D0 show unexpected CP-violation in $B^0_s B^0_s$.

A new source of $CP$ violation?

Evidence for an Anomalous Like-Sign Dimuon Charge Asymmetry
V. M. Abazov et al. (D0 Collaboration)
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Evidence for an anomalous like-sign dimuon charge asymmetry
V. M. Abazov et al. (D0 Collaboration)
emiT’s basic sketch:
polarized neutrons;
detect protons and electrons.

Some challenges:
1) Polarize/flip neutrons;
2) Detect <1 keV protons;
3) Detect electrons down to 90 keV with minimal backscatter;

Solutions:
1) Supermirrors (polarize n’s by magnetic component in scattering); flipper=current sheet.
2) Accelerate protons to Si detectors (28 kV);
3) Scintillators with low threshold and position resolution (achieved via timing).
emiT Detector: basic concept and design criteria

- Statistical precision requires highest possible coincidence rate
- High continuous neutron flux ($1.7 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ at “C2” collimator)
- Symmetrical, segmented detector to minimize or cancel instrumental asymmetries that could yield false coincidences
- Detector geometry to maximize sensitivity to $D\sigma_n \cdot (p_e \times p_p)$ (minimize sensitivity to other terms in decay distribution)

emiT gained a factor of three increase in “effective” beam flux over previous “right angle” geometry beam experiments
• 0.1 ns timing resolution  (Pulse arrival time may be used to determine position)
• Thresholds (35-50 keV)  (Software cut on geometric mean)
• Resolution ~18% at 1 MeV
• Cosmic ray muons deposit ~ 1.42 MeV  (well separated)
• Overall rate 300 s⁻¹ per paddle (Signal to accidental ~ 1 to 1)
emiT Detector: Proton Paddle Assembly

Focusing efficiency reaches 90% (Voltage Dependent)
Required detector area reduced by ~ 80%

Surface barrier detectors
- 20 µg Au (less energy loss)
- 300 mm² active area
- 300 µm depletion depth
- Room temperature leakage current ~ µA
Developed a (duo-plasmatron) proton source to test detector.

Detector showed good performance and good signal above noise.

F. Naab et al.
NIM 197, 278 (2002)
• 3 Hz singles per proton Surface Barrier det
• 0.55 Average coincidence rate per pair
• 25 Hz average coincidence rate

• Essentially no high voltage noise (Modified focusing assembly)
• Signal to noise better than 100/1
• Clear separation of cosmic Landau peak
Proton threshold effect

$W_{inv} \sim 0.01$

Largely Cancels in $\nu$ - correction: $(-0.29 \pm 0.41) \times 10^{-4}$ (MC and fits to spectra) threshold variations, etc.
Expect number of coincidences between a proton and beta detector:

\[ N_{J,R} = N \varepsilon_R \varepsilon_p \left( K_1^R + aK_a^R \right) \left\{ 1 + J \left( A K_A^R + B K_B^R + D K_D^R \right) \right\} \]

To extract signal

\[ \nu_a = R - 1 = \frac{N_{1,a}^{\uparrow} N_{2,a}^{\downarrow}}{N_{1,a}^{\downarrow} N_{2,a}^{\uparrow}} - 1 \]
Spin transport

- High neutron flux (1.7 x 10^8 cm^{-2} s^{-1} at “C2”)
- 560 μT guide field, monitored during run
- Beam profile at 3 positions via Dysprosium foil activation
- Polarization measured with supermirror analyzer flipping ratio measurement
Intentional field rotation (Maximal polarization misalignment)

\[ \phi = (-89.9 \pm 0.2)^\circ \]
\[ \bar{v} = (0.8 \pm 1.5) \times 10^{-3} \]

\[ \phi = (0.1 \pm 0.2)^\circ \]
\[ \bar{v} = (3.2 \pm 1.4) \times 10^{-3} \]
Comparison between data and expectations looks good

V factors

- Paddle A: off's: 5.62±1.25, c2/df = 22.2/15
- Paddle B: off's: -31.28±1.22, c2/df = 42.6/15
- Paddle C: off's: -18.48±1.26, c2/df = 32.5/15
- Paddle D: off's: 4.86±1.23, c2/df = 40.0/15

Monte Carlo (90 keV thin foil)
- data odd
- even
Another subtle issue: beta and proton backscattering

Data at 45 degrees
Results versus time (run number)
The experiment was stable.

Results versus axial coordinate
The average of all these results is our final value.
Corrections ($10^{-4}$)
All studies completed while data were still “blind”

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<tr>
<th>Source</th>
<th>Correction</th>
<th>Uncertainty</th>
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<tr>
<td>BR asymmetry</td>
<td>upper limit</td>
<td>0.30</td>
</tr>
<tr>
<td>BR subtraction</td>
<td>0.03</td>
<td>0.00</td>
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<tr>
<td>Electron Backscattering</td>
<td>0.11</td>
<td>0.03</td>
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<tr>
<td>Proton Backscattering</td>
<td>upper limit</td>
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<tr>
<td>Beta threshold uniformity</td>
<td>0.04</td>
<td>0.10</td>
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<tr>
<td>Proton threshold effect</td>
<td>-0.29</td>
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<tr>
<td>Beam Expansion/B-field</td>
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<tr>
<td>Pol uniformity</td>
<td>upper limit</td>
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<tr>
<td>Asymmetric-beam/Trans. Pol (ATP)</td>
<td>-0.07</td>
<td>0.72</td>
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<tr>
<td>ATP twist</td>
<td>upper limit</td>
<td>0.24</td>
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<tr>
<td>Spin correlated flux</td>
<td>&lt;1e-6</td>
<td>0.00</td>
</tr>
<tr>
<td>Spin correlated polarization(^a)</td>
<td>&lt;1e-6</td>
<td>0.00</td>
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<tr>
<td>Polarization (95±5%)</td>
<td>Included in $\tilde{D}$</td>
<td>0.04</td>
</tr>
<tr>
<td>$K_D$ (0.378±0.019)</td>
<td>Included in $\tilde{D}$</td>
<td>0.05</td>
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<tr>
<td>Total</td>
<td>-1.68</td>
<td>1.01</td>
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\(^a\) Includes spin-flip time, cycle asymmetry, and flux variation.
Previous results:

\[ D^{(19 \text{ Ne})} = (4 \pm 8) \times 10^{-4} \]

Hallin et al.,

\[ D(n) = (-0.6 \pm 1.2_{\text{syst}} \pm 0.5_{\text{stat}}) \times 10^{-3} \]

Lising et al.,

\[ D(n) = (-2.8 \pm 7.1) \times 10^{-4} \]

Soldner et al.,

\[ D(n) = (-0.96 \pm 1.01_{\text{syst}} \pm 1.89_{\text{stat}}) \times 10^{-4} \]

Mumm et al.,

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