A New Limit on Time-Reversal-Invariance Violation in Beta Decay: Results of the emiT-II Experiment

T.E. Chupp, K.P. Coulter & R.L. Cooper  
University of Michigan

S.J. Freedman & B.K. Fujikawa  
University of California - Berkeley/  
Lawrence Berkeley National Laboratory

G.L. Jones  
Hamilton College

A. Garcia  
University of Washington

National Institute of Standards and Technology

C. Trull & F.E. Wietfeldt  
Tulane University

J.F. Wilkerson  
University of North Carolina

NEW RESULT: $D=[-0.96\pm 1.89(\text{STAT})\pm 1.01(\text{SYS})] \times 10^{-4}$

$\varphi_{AV} = 180.013 \pm 0.028$  
$\frac{g_A}{g_V} = |\lambda| e^{i\varphi_{AV}}$

Work supported in part by NIST and grants from the DOE and NSF
Polarized neutron decay

1957: In the wake of the Parity Revolution (Le, Yang, Ambler, Wu)
Jackson, Treiman, Wyld:

\[ H_{\text{int}} = \sum_{i=V,A,S,P,T}(\bar{\psi}_p O_i \psi_n)(C_i \bar{\psi}_e O_i \psi_v + C'_i \bar{\psi}_e \gamma_5 O_i \psi_v) \]

**SM:** \( C'_V = C_V \) and \( C'_A = C_A \)

\( C_i \) real if \( T \)-symmetry

\[
\frac{dw}{dE_e d\Omega_e d\Omega_v} = G(E_e) \left( 1 + a \frac{p_e \cdot p_v}{E_e E_v} + b \frac{m_e}{E_e} + P \cdot \left( A \frac{p_e}{E_e} + B \frac{p_v}{E_v} + D \frac{p_e \times p_v}{E_e E_v} \right) \right)
\]

-0.103(4)  
-0.1187(8)  
0.9807(30)

*Fierz interference (S, T) unmeasured for neutron*
Time (motion) Reversal

Motion reversal, initial and final states not exchanged but phase shifts lead to final state interactions: \( |D_{f.s.}| \sim 2 \times 10^{-5} \)

Note \( R \) coefficient - \( \sigma_n \cdot (\sigma_e x p_e) \) (T-odd, P-odd):

\( R_{8\text{Li}} = [0.9 \pm 2.2] \times 10^{-3} \) (Sromicki et al. Phys Rev. Lett. 82 57: 1999)

\( R_n = [8\pm15\text{(stat)}\pm5\text{(sys)}] \times 10^{-3} \) (Kozela et al. Phys. Rev. Lett. 102 17230: 2009)
Beyond SM Physics

\[
D_r \approx \frac{1}{1 + 3|\lambda|^2} \left\{ -2 \frac{\text{Im}(C_v C_A^*)}{|C_v|^2} + \frac{\text{Im}(C_s C_T^* + C'_s C_T^*)}{|C_v|^2} + \frac{\alpha m}{p_e} \left( \lambda^* \frac{\text{Re}(C_T + C'_T)}{C_A^*} + \lambda^* \frac{\text{Re}(C_s + C'_S)}{C_V^*} \right) \right\}
\]

\[
2 \frac{\text{Im}(\lambda)}{1 + 3|\lambda|^2}
\]

\[
\frac{C_A}{C_V} = |\lambda| e^{i\varphi_{AV}}
\]

|CS/CV| < 0.067 and |CT/CA| < 0.081 (95% c.l.)

N. Severijns et al. RMP, 78 p991 (2006)
## Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Contribution to D</th>
<th>Constrained by</th>
</tr>
</thead>
<tbody>
<tr>
<td>CKM Phase</td>
<td>$10^{-12}$</td>
<td>K-meson/b-meson</td>
</tr>
<tr>
<td>$\theta_{QCD}$</td>
<td>$2 \times 10^{-15}$</td>
<td>EDMs ($n,^{199}\text{Hg}$)</td>
</tr>
<tr>
<td>Left-right symmetry</td>
<td>$10^{-7}$-$10^{-5}$</td>
<td>$W_L$ limits (B)+EDMs</td>
</tr>
<tr>
<td>Non-SM Fermions</td>
<td>$10^{-7}$-$10^{-5}$</td>
<td>Direct production+EDMs</td>
</tr>
<tr>
<td>Charged Higgs SUSY</td>
<td>$10^{-7}$-$10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Leptoquark</td>
<td>$4.5 \times 10^{-4}$</td>
<td>This experiment</td>
</tr>
</tbody>
</table>

Our limit: $|D_T| < 4.5 \times 10^{-4}$ (95% c.l.)

$D_{FSI} \sim 2 \times 10^{-5}$
Emit-I: $D = ( -6 \pm 12 \text{(stat.)} \pm 5 \text{(syst.)}) \times 10^{-4}$ \textit{Phys. Rev. C 62} 055501 (2000)


$^{19}\text{Ne}$: $D = (1 \pm 6) \times 10^{-4}$ F. Calaprice, in Hyperfine Interactions (1985)
emiT: 8-fold symmetry - 64 proton SBDs/4 β scintillators

- Proton-electron momenta anticorrelated
  - Coincidence rate favors 180°
  - $\sin \theta_{ep}$ favors 90°
  - FOM $(1/\sigma^2)$ 9x improved at 135°
- Symmetrical, segmented detector:
  - Minimize sensitivity to $A$ and $B$
  - Investigate nonuniformities
  - Study systematic effects
emiT proton detection

- Focusing
- Cells

Monte Carlo - 28 kV
**Neutron Beam and Spin transport**

- High neutron flux \((1.7 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \text{ at “C2”})\) (fission chamber)
- 560 µT guide field, monitored during run
- Beam profile measured at 3 positions via Dysprosium foil activation
- Polarization measured with supermirror analyzer flipping ratio measurement
Data and cuts

Rates
- 3 Hz singles per proton surface barrier detectors
- 100 Hz singles per beta plastic scintillators
- 25 Hz average total coincidence rate
- BR determined by pre-prompt events: S/B = 30/1

Filtering
- Data collected with acceptable operational parameters (magnetic fields, currents, spin state, ...) : 12% removed
- $\beta$-energy threshold set to 90 keV, to minimize detection efficiency drifts arising from PMT gain drifts : 14% removed
- Require single $\beta$ detector in coincidence with single proton event : 7% removed

Final data set ~ 300 million accepted coincidence events.
Measurement Principle

Spin-flip asymmetry

\[ w^{p_ie_j} = \frac{N_{+}^{p_ie_j} - N_{-}^{p_ie_j}}{N_{+}^{p_ie_j} + N_{-}^{p_ie_j}} \]

For a single proton cell:

\[ w^{p_ie_j} \approx \mathbf{P} \cdot \left( A\tilde{K}_{A}^{p_ie_j} + B\tilde{K}_{B}^{p_ie_j} + D\tilde{K}_{D}^{p_ie_j} \right) \]

Combine \( w \)'s

\[ v^{p_i} = \frac{1}{2} (w^{p_iR} - w^{p_iL}) \]

\[ \propto \int \frac{(\vec{p}_p \times \vec{p}_e)}{E_e E_v} \, dE_e \, d\Omega_e \, d. \]

\[ v^{p_i} = PD \hat{z} \cdot \left( \tilde{K}^{p_i e_R}_D - \tilde{K}^{p_i e_L}_D \right) + A\hat{z} \cdot \frac{\Delta \vec{p}_e}{E_e} \]

Proton Detector

Electron Detector
Transverse Polarization (5 mR guide field misalignment)

\[ \omega^{p_i e_j} \approx \mathbf{P} \cdot \left( A\tilde{K}^{p_i e_j}_A + B\tilde{K}^{p_i e_j}_B + D\tilde{K}^{p_i e_j}_D \right) \]

\[ \nu^{p_i} = \frac{1}{2} (\omega^{p_i R} - \omega^{p_i L}) \]
Transverse polarization, B and beam expansion
emiT II Result

Blind analysis: \( w^{p_i e_j} = \frac{N^{p_i e_j}_+ - N^{p_i e_j}_-}{N^{p_i e_j}_+ + N^{p_i e_j}_-} + B \hat{z} \cdot \tilde{K}^{p_i e_j}_D \)

\[ \nu^{p_i} = \frac{1}{2} (w^{p_i R} - w^{p_i L}) \]

\[ \bar{\nu} \approx \bar{K}_D P \tilde{D} \rightarrow D \quad \text{(with corrections)} \]

\[ \bar{K}_D = 0.378 = \hat{z} \cdot ( \tilde{K}^{p_i e_R}_D - \tilde{K}^{p_i e_L}_D ) \]

Weighted average: \( \tilde{D} = (0.72 \pm 1.89) \times 10^{-4} \)

\[ D = (-0.96 \pm 1.89\text{(stat)} \pm 1.01\text{(sys)}) \times 10^{-4} \]
Cuts suggest proton HV dependence

No correlation (constant D): $\chi^2 = 10.4/12$ df.
Correlation with HV: $\chi^2 = 5.6/11$ df (2.1 sigma)
- Conclude it’s accidental correlation
**Corrections (10^{-4})**

All studies completed while data were still “blind”

<table>
<thead>
<tr>
<th>Source</th>
<th>Correction</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<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>
</tr>
<tr>
<td>Electron Backscattering</td>
<td>0.11</td>
<td>0.03</td>
</tr>
<tr>
<td>Proton Backscattering</td>
<td>upper limit</td>
<td>0.03</td>
</tr>
<tr>
<td>Beta threshold uniformity</td>
<td>0.04</td>
<td>0.10</td>
</tr>
<tr>
<td>Proton threshold effect</td>
<td>-0.29</td>
<td>0.41</td>
</tr>
<tr>
<td>Beam Expansion/(\mathbf{B})-field</td>
<td>-1.50</td>
<td>0.40</td>
</tr>
<tr>
<td>Pol uniformity</td>
<td>upper limit</td>
<td>0.10</td>
</tr>
<tr>
<td>Asymmetric-beam/Trans. Pol (ATP)</td>
<td>-0.07</td>
<td>0.72</td>
</tr>
<tr>
<td>ATP twist</td>
<td>upper limit</td>
<td>0.24</td>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>Total</td>
<td>-1.68</td>
<td>1.01</td>
</tr>
</tbody>
</table>

\(^{a}\) Includes spin-flip time, cycle asymmetry, and flux variation.
Improvements

- Major systematics
  - Beam expansion/magnetic field: reduce field
  - ATP error also limited by beam shape
    - AFP spin flipper
    - $^3$He Polarizer
  - Proton threshold requires detector/electronics improvement
- NIST-NGC beam line could provide factor 10 increase in neutron decay rate
Summary: \( D = (-0.96 \pm 1.89 \text{ (stat)} \pm 1.10 \text{(sys)}) \times 10^{-4} \)

\( \phi_{\text{AV}} = 180.013^\circ \pm 0.028^\circ \)

Thank You!
Beam profiles

Upstream

Downstream
P>91% (for $f=1$, $P=A$) (95% c.l.)

$f=95\pm 5\%$ (calculated)
Proton threshold effect

Largely Cancels in $v$ - correction: $(-0.29 \pm 0.41) \times 10^{-4}$ (MC and fits to spectra) threshold variations, etc.
Beam Expansion Effect

Magnetic field changes e-p angular acceptance. Expansion changes average.

\[ A\sigma_n \cdot \frac{p_e}{E_e} \]

Correction from Monte Carlo: \((-1.5 \pm 0.4) \times 10^{-4}\)

uncertain beam shape, etc.
\[ w^{p_{i ej}} \approx \mathbf{P} \cdot \left( A\tilde{K}^{p_{i ej}}_A + B\tilde{K}^{p_{i ej}}_B + D\tilde{K}^{p_{i ej}}_D \right) \]
\[ u^{p_i} = \frac{1}{2} (w^{p_i R} - w^{p_i L}) \]
Asymmetry beam/Transverse Polarization (ATP)

\[ \omega_{pi ej} \approx P \cdot \left( A\tilde{K}_{A}^{pi ej} + B\tilde{K}_{B}^{pi ej} + D\tilde{K}_{D}^{pi ej} \right) \]

\[ \nu_{pi} = \frac{1}{2} \left( \omega_{pi R}^{p} - \omega_{pi L}^{p} \right) \]

ATP correction from calibration runs
ATP correction: \((-0.07 \pm 0.72) \times 10^{-4}\) (\(\theta_p \sim 5\) mrad)
Transverse Polarization

![Graph showing the relationship between paddle angle and voltage](image-url)
\[
\frac{dw}{dE_e d\Omega_e d\Omega_{\nu}} = G(E_e) \left( 1 + a \frac{p_e \cdot p_{\nu}}{E_e E_{\nu}} + b \frac{m_e}{E_e} + P \cdot \left( A \frac{p_e}{E_e} + B \frac{p_{\nu}}{E_{\nu}} + D \frac{p_e \times p_{\nu}}{E_e E_{\nu}} \right) \right)
\]

|     | % error | Ref       | SM (tree level) | $\frac{1}{\alpha} |\partial \alpha/\partial \lambda|$ |
|-----|---------|-----------|-----------------|----------------------|
| $\lambda$ | -1.2694±0.0028 | PDG | 0.2 | 0.3 |
| $a$ | -0.103±0.004 | PDG | 3.9 | 0.7 |
| $A$ | -0.1187 ± 0.0008 | W.A. | 0.7 | 0.7 |
| $B$ | 0.9807 ± 0.0030 | PDG | 0.3 | 0.3 |
| $C$ | -0.2377 ± 0.0036 | PERKEOII-B | 1.1 | 1.1 |
| $D$ | (-0.96±2.14)×10^{-4} | our result | - | - |
| $\phi_{AV}$ | 180.013±0.0028 | our result | - | - |

$k=0.27484$ for $0 \leq E_p \leq 750$ eV

\[
\frac{1}{1 + 3|\lambda|^2} = \tau_n G_F^2 |V_{ud}|^2 \frac{m_e^5}{c^5} (1 + \delta_R)
\]

$C/k=-0.8649±0.0095$  
$A+B=0.8619±0.0031$  
$k(A+B)=0.2369±0.0009$