Search for Time Reversal Violating Effects in the Neutron Decay

A Measurement of the Transverse Polarization of Electrons from the Decay of Polarized Neutrons

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Angular distribution contains in the lowest order 4 T–odd observables:

\[ \omega(\langle J_n \rangle | E_e \Omega_v \Omega_e) \cdot dE_e d\Omega_e d\Omega_v \propto \left[ 1 + \ldots + D \frac{(p_e \times p_v) \cdot \langle J_n \rangle}{E_e E_v} + \ldots \right] \cdot dE_e d\Omega_e d\Omega_v \]

\[ \omega(\langle J_n \rangle \sigma | E_e \Omega_e) \cdot dE_e d\Omega_e \propto \left[ 1 + \ldots + R \frac{(p_e \times \sigma) \cdot \langle J_n \rangle}{E_e} + \ldots \right] \cdot dE_e d\Omega_e \]

\[ \omega(\sigma | E_e \Omega_v \Omega_e) \cdot dE_e d\Omega_e d\Omega_v \propto \left[ 1 + \ldots + L \frac{\sigma \cdot (p_e \times p_v)}{E_e E_v} + \ldots \right] \cdot dE_e d\Omega_e d\Omega_v \]

\[ \omega(\langle J_n \rangle \sigma | E_v \Omega_v) \cdot dE_v d\Omega_v \propto \left[ 1 + \ldots + V \frac{(p_v \times \sigma) \cdot \langle J_n \rangle}{E_v} + \ldots \right] \cdot dE_v d\Omega_v \]

\[ D, L : \text{T–odd, P–even} \quad R, V : \text{T–odd, P–odd} \]

\textit{T–invariance holds} \implies D, R, V, L = 0!
T–odd correlations in $\beta$–decay

- $D$ and $R$ are sensitive to distinct aspects of T–violation:

$$D \cdot \xi = M_F M_{GT} \frac{I}{I+1} 2 \text{Im} \left( C_S C_T^* - C_V C_A + C'_S C'_T^* - C'_V C'_A \right) + D_{FSI}$$

$$R \cdot \xi = \left| M_{GT} \right|^2 \frac{1}{I+1} 2 \text{Im} \left( C_T C_A^* + C'_T C'_A \right) + R_{FSI}$$

$$\xi = \left| M_F \right|^2 \left( \left| C_S \right|^2 + \left| C_V \right|^2 + \left| C'_S \right|^2 + \left| C'_V \right|^2 \right) + \left| M_{GT} \right|^2 \left( \left| C_T \right|^2 + \left| C_A \right|^2 + \left| C'_T \right|^2 + \left| C'_A \right|^2 \right)$$

- $D$ is primarily sensitive to the relative phase between $V$ and $A$ couplings
- $R$ is sensitive to the linear combination of imaginary parts of scalar and tensor couplings
T-violation in $\beta$-decay

- T-violation in $\beta$-decay may arise from:
  - semileptonic interaction ($d \rightarrow u e^{-}\nu_{e}$)
  - nonleptonic interactions

- SM-contributions for $D$- and $R$-correlations:
  - Mixing phase $\delta_{CKM}$ gives contribution which is 2nd order in weak interactions:
    \[ < 10^{-10} \]
  - $\theta$-term contributes through induced NN PVTV interactions:
    \[ < 10^{-9} \]

- Candidate models for scalar contributions (at tree-level) are:
  - Charged Higgs exchange
  - Slepton exchange (R-parity violating super symmetric models)
  - Leptoquark exchange

- The only candidate model for tree-level tensor contribution is:
  - Spin-zero leptoquark exchange.
Measurements of triple correlations in $\beta$-decay provide direct, i.e., first-order access to the $T$-violating part of the weak interaction coupling constants.
The $R$–correlation in neutron decay

- Transverse electron polarization component contained in the plane perpendicular to the parent polarization.
- Not measured for the decay of free neutron yet!
- Using the formula of D.J. Jackson et al., Phys. Rev. 106, 517 (1957)

$$ R = \frac{\text{Im} \left[ \left( C_V^* + 2C_A^* \right) \left( C_T + C_T' \right) + C_A^* \left( C_S + C_S' \right) \right]}{|C_V|^2 + 3|C_A|^2} $$

and defining:

$$ S = \text{Im} \left( \frac{C_S + C_S'}{C_A} \right); \quad T = \text{Im} \left( \frac{C_T + C_T'}{C_A} \right) $$

- One obtains finally:

$$ R = 0.28 \cdot S + 0.33 \cdot T $$
Anticipated accuracy of the present experiment: $\Delta R$ (neutron) $\approx 5 \times 10^{-3}$

Figure 1: Results from the experiments testing time reversal symmetry in the scalar and tensor weak interaction. The bands indicate $\pm 1\sigma$ limits. Constraints from the study of the $R$-correlation in the free neutron decay with an accuracy of $\pm 0.005$ are attached. This prediction is arbitrarily fixed at $S, T = 0$. 

$s = \text{Im} \left[ \frac{(C_S + C'_S)}{C_A} \right]$, 

$t = \text{Im} \left[ \frac{(C_T + C'_T)}{C_A} \right]
Transverse electron polarization

- $R$ coefficient can be obtained from the transverse electron polarization

$$\omega(\langle J_n \rangle \sigma | E_e \Omega_e) \cdot dE_e d\Omega_e \propto \left[ 1 + \ldots + R \frac{p_e \times \sigma \cdot \langle J_n \rangle}{E_e} + N \sigma \cdot \langle J_n \rangle + \ldots \right] \cdot dE_e d\Omega_e$$
The $N$–correlation

- Can be determined from the transverse electron polarization component contained in the plane of lepton momentum and parent polarization:

$$N = \langle \tilde{\sigma}_{T1} \rangle / \sin \theta_e,$$

- Conserves $T$ and $P$, not measured for $\beta$–decay yet

$$N \cdot \xi = 2 \cdot |M_G|^2 \frac{1}{I + 1} \cdot \text{Re}\left[\frac{m}{2E}(|C_T|^2 + |C_A|^2 + |C'_T|^2ight]$$

$$+ |C'_A|^2) + (C_T C_A^* + C'_T C_A^{**})]$$

$$+ 2 \cdot M_F M_G \sqrt{\frac{I}{I + 1}} \cdot \text{Re}\left[(C_S C_A^* + C_V C_T^* + C'_S C_A^{**}ight]$$

$$+ C'_V C_T^{**})] + \frac{m}{E}(C_S C_T^* + C_V C_A^* + C'_S C_T^{**} + C'_V C_A^{**})]$$
The $N$–correlation in neutron decay

- Can be deduced from the transverse electron polarization component contained in the plane parallel to the parent polarization.
- Scales with the decay asymmetry $A (\lambda \equiv C_A / C_V)$:

$$N_{SM}^n = -\frac{m}{E} A_{SM} = \frac{m}{E} \frac{2(\lambda^2 + \lambda)}{1 + 3\lambda^2} \approx +0.1173 \frac{m}{E}$$

- Self calibration tool for $R$–correlation measurement.
- Excellent cross check for systematic effects in $R$–correlation.
Conclusion:

Simultaneously measure both components of the transverse polarization of electrons emitted in neutron decay.
FUNSPIN – Polarized Cold Neutron Facility at PSI

Figure 4: Layout of the Polarized Cold Neutron Facility at PSI.

$I_n \geq 10^{10} \text{s}^{-1}$

$P_n \geq 90\%$
Mott scattering

- Mott scattering:
  - Analyzing power caused by spin–orbit force
  - Parity and time reversal conserving (electromagnetic process)
  - Sensitive exclusively to the transversal polarization
Mott polarimeter

- **Challenges:**
  - Weak and diffuse decay source
  - Electron depolarization in multiple Coulomb scattering
  - Low energy electrons (<783 keV)
  - High background (n-capture)

- **Solutions:**
  - Tracking of electrons in low-mass, low-Z MWPCs
  - Identification of Mott-scattering vertex
  - Frequent neutron spin flipping
  - "foil-in" and "foil-out" measurements
Experimental setup

Analyzing power $\langle S_{\text{Mott}} \rangle \approx 0.2$
MWPCs, scintillators and electronics
“Single-track events”
Energy calibration

- Conversion electrons from $^{207}$Bi

- Hodoscope 1

  - $\sigma_1 = 29.39$ keV
  - $\sigma_2 = 45.12$ keV
$\beta$–energy distribution – background subtraction

Absorption threshold

Electronic threshold
Decay asymmetry

\[ A(\gamma) \equiv \frac{\omega(\gamma, +P_n) - \omega(\gamma, -P_n)}{\omega(\gamma, +P_n) - \omega(\gamma, -P_n)} = P_n A_n \cdot \beta \cos \gamma \]

\[ \langle P_n \rangle = 0.89 \pm 0.08 \]
\[ \langle P_n \rangle = 0.87 \pm 0.01 \text{ (super-mirror polarimeter)} \]
“V–tracks”: Mott scattering events
"V-track" events - on-line display
Projection of vertices onto XY-plane
Projection of vertices onto Pb–foil planes
Mott scattering vertex distribution

Det 0

Foil-IN

Foil-OUT

Det 1

Subtracted

Int. from -250 to -200: 2042736

sig/backgr: 11.03(0.3%)

Subtracted

Int. from 200 to 250: 21724

sig/backgr: 12.32(0.3%)
“Short-arm” asymmetry

- “Short-arm” of a V-track must reveal UP–DOWN asymmetry ($\beta$–decay)

\[ -0.6 \leq \cos \gamma \leq -0.2 \]
\[ -0.2 \leq \cos \gamma \leq 0.2 \]
\[ +0.2 \leq \cos \gamma \leq +0.6 \]
Influence of magnetic field on V–tracks

- Bending of electron tracks in the magnetic field of about 0.5 mT can be traced back in the matching of track segments.
Projection of V-track events onto $\alpha$
Electron transverse polarization

- Mott scattering asymmetry:
  - Efficiency and acceptance are complicated and unknown functions but they do not change with neutron spin flip

\[
\bar{\chi}(\alpha) = \frac{\bar{\omega}(P,\alpha) - \bar{\omega}(-P,\alpha)}{\bar{\omega}(P,\alpha) + \bar{\omega}(-P,\alpha)}
\]

\[
= AP\bar{\beta}\bar{F}(\alpha) + P\bar{\beta}\bar{S}(\alpha)\left[ N'\bar{G}(\alpha) + R\bar{H}(\alpha) \right]
\]

\[
N' \equiv N / \beta
\]

\[
\bar{F}(\alpha) = \langle \hat{J} \cdot \hat{p}_e \rangle, \quad \bar{G}(\alpha) = \langle \hat{n} \cdot \hat{J} \rangle, \quad \bar{H}(\alpha) = \langle \hat{n} \cdot (\hat{J} \times \hat{p}_e) \rangle
\]

- Average values of the geometry factors \( \bar{F}(\alpha), \bar{G}(\alpha), \bar{H}(\alpha), \bar{\beta}(\alpha) \) are calculated event-by-event from reconstructed momenta and are known to a high precision

- Asymmetry parameter \( A \) is taken from another, high precision, dedicated experiment
Geometrical factors

![Graphs showing various geometrical factors as functions of \( \alpha \) (rad)].
Electron transverse polarization

PRELIMINARY

$N_{SM} = 0.066$
$R_{SM} = 0.0$

$N = 0.059 \pm 0.015$
$R = 0.026 \pm 0.024$
Electron transverse polarization

- Super–ratio:
  - Makes use of geometrical symmetry of the detecting system
  - Correction due to decay asymmetry suppressed by an order of magnitude (~0.1 → ~0.01)
  - Only $N$ parameter can be extracted

\[ \bar{F}(-\alpha) \overset{=}{} N \cdot \bar{F}(\alpha), \quad \bar{G}(-\alpha) \overset{=}{} \bar{G}(\alpha), \quad \bar{H}(-\alpha) \overset{=}{} \bar{H}(\alpha) \]

\[ \bar{S}(-\alpha) \overset{=}{} \bar{S}(\alpha), \quad \bar{\beta}(-\alpha) \overset{=}{} \bar{\beta}(\alpha) \]

\[ \bar{E}(\alpha) = \frac{\bar{r}(\alpha) - 1}{\bar{r}(\alpha) + 1}, \quad \bar{r}(\alpha) \equiv \sqrt{\frac{\bar{\omega}^+(-\alpha)\bar{\omega}^-(-\alpha)}{\bar{\omega}^+(-\alpha)\bar{\omega}^-(-\alpha)}} \]

\[ \bar{E}(\alpha) \overset{=}{} \frac{N \cdot P \bar{S}(\alpha) \bar{G}(\alpha)}{1 - \frac{1}{2} \left[ PA \bar{\beta}(\alpha) \bar{F}(\alpha) \right]^2} \]
Electron transverse polarization (from “super-ratio”)

P R E L I M I N A R Y

\[ N_{\text{SM}} = 0.066 \]
Limits on $S$ and $T$ coupling constants
Conclusions

- Collected data are sufficient for $\Delta R = 0.010 \div 0.015$
- Assessment of systematic effects – in progress
- Total experimental uncertainty is dominated by statistics
- Final data taking scheduled for 2007 (4 months)
- The anticipated accuracy $\Delta R = 0.005$ should be reached (if nothing unexpected happens!)
What next?
2nd-generation experiment

- Feasible sensitivity: $\Delta R = 5 \times 10^{-4}$
- Needed $10^8$ reconstructed V-track events

**General features of the experimental setup:**

- Axial polarimeter geometry
  - 2.5 m long beam acceptance
- Drift chambers:
  - Hexagonal cell geometry
  - $x$-, $y$-coordinates from drift time
  - $z$-coordinate from charge division
  - Reduced pressure (0.2–0.3 bar) both in the beam line and in the drift chambers (promising tests underway)
- Additional background suppression:
  - Pulsed beam (?)
  - $^3$He spin filter (?)

**Overall gain factor in the rate of reconstructed V-track events:** 20 – 30 (as compared to the present setup)
2nd-generation experiment

Drift chamber (He+…, 0.2-0.3 bar)

Pb-foil

scintillator

He, 0.2-0.3 bar

CN beam
Questions

- Final State Interaction ?
- Direct vs. indirect constrains ?
- Sensitivity to particular models ?
1\textsuperscript{st} order FSI contribution

\[
R_{\text{FSI}} \cdot \xi = 2 \cdot \frac{\alpha Z m}{p} \cdot [ |M_{GT}|^2 \frac{1}{I + 1} \cdot \text{Re}(C_T C'_T^* - C_A C''_A) \\
+ M_F M_{GT} \sqrt{\frac{I}{I + 1}} \cdot \text{Re}(C_S C'_T^* + C'_S C_T^* - C_V C''_A - C'_V C_A) ]
\]

- In the SM:

\[
C_V = C'_V = \text{Re}C_V = 1, \quad C_A = C'_A = \text{Re}C_A = -1.26, \\
|C_S|, |C'_S|, |C_T|, |C''_T| = 0:
\]

\[
R_{\text{FSI,SM}} = \frac{\alpha Z m}{p} \cdot A_{\text{SM}}.
\]

For neutron decay, \( A = -0.1173(13) \)

\[
R_{\text{SM}}^n \approx 0.001
\]
Theoretical uncertainty of $R_{FSI}$

- Jackson’s formula [Nucl. Phys. 4 (1957) 206]:
  - “Allowed approximation”
  - Electron wave function for point like Coulomb potential
  - $\Rightarrow$ Theoretical uncertainty: $\Delta R_{FSI}/R_{FSI} \approx 10\%$
  - $\Rightarrow \Delta R_{FSI}^{\text{neutron}} \approx 10^{-4}$

- Vogel & Werner [NP 404 (1983) 345] corrected for:
  - $2^{\text{nd}}$-forbidden term
  - Higher terms in the lepton function expansion
  - Radiative effects
  - Finite nuclear size
  - Electron screening effect
  - $\Rightarrow$ Theoretical uncertainty: $\Delta R_{FSI}/R_{FSI} \approx 1\%$
  - $\Rightarrow \Delta R_{FSI}^{\text{neutron}} \approx 10^{-5}$
Specific case for neutron decay:

- Corrections for proton charge distribution are small (small energy release); can be calculated (A. Czarnecki) with improved proton charge radius (from muonic hydrogen Lamb shift – PSI project)
- No uncertainty due to atomic screening

Expected theoretical uncertainty: $\Delta R_{\text{FSI}}/R_{\text{FSI}} \approx 0.5 \%$

$\Rightarrow \Delta R_{\text{FSI}(\text{neutron})} \approx 5 \times 10^{-6}$

"Discovery potential" or "exclusion power" (4 standard deviations) of the $R$-parameter in the free neutron decay with present FSI theory is: $R_n \approx 2 \times 10^{-5}$

$$\text{Im}(C_S + C'_S) + 1.2 \times \text{Im}(C_T + C'_T) \approx 10^{-4}$$
Indirect bounds for $\text{Im}(C_{S,T} + C'_{S,T})$

  - Indirect, stringent bounds on T–odd, P–even interactions are obtained from atomic EDM searches:

$$\text{Im}(C_{S,T} + C'_{S,T}) \leq 10^{-4}$$

- Linear combination of $\text{Im}(C_S + C'_S)$ and $\text{Im}(C_T + C'_T)$:
  - Different than in the $R$–correlation
  - Weaker bounds on $\text{Im}(C_S + C'_S)$ than on $\text{Im}(C_T + C'_T)$
  - Model uncertainty may be large

Should the indirect limits from atomic EDMs be viewed as *complementary* rather than *competitive* to the direct ones from $R$–correlation?
Sensitivity to particular models

Contrary to $D$–coefficient, $R$–coefficient lacks of a particular model scenario where it could outperform other methods

Is the above statement true?

Suggestions from theory are welcomed!
Backup slides
Mott polarimeter

Analyzing power

$\langle S_{\text{Mott}} \rangle \approx 0.2$