Transverse Electron Polarization in the Neutron Decay

Direct Search for Scalar and Tensor Couplings in Weak Interaction

Kazimierz Bodek for nTRV Collaboration

Institute of Physics, Jagiellonian University, Cracow, Poland
Electron polarization in $\beta$-decay

$\omega(\langle J_n \rangle \sigma | E_e \Omega_e) \cdot dE_e d\Omega_e$

$\propto \left\{ 1 + \ldots + \left[ R \frac{p_e \times \sigma}{E_e} + N \frac{\sigma}{J_n} + G \frac{p_e \cdot \sigma}{E_e} + \ldots \right] \right\} dE_e d\Omega_e$


- $G$-coefficient can be deduced from the longitudinal electron polarization component.
- $N$-coefficient can be deduced from the transverse electron polarization component contained in the plane parallel to the parent polarization.
- $R$-coefficient can be obtained from the transverse electron polarization component perpendicular to the plane spanned by the neutron polarization and electron momentum.
Electron polarization in $\beta$-decay

Assuming maximal parity violation $C_V = C'_V = \text{Re } C_V = 1$, $C'_A = C_A = \text{Re } C_A = \lambda$ and neglecting terms quadratic in $C_S$ and $C_T$:

$$G = -1 + \frac{\alpha m}{p_e} \cdot \frac{1}{1 + 3\lambda^2} \cdot \text{Im} \left( \frac{C_S + C'_S}{C_V} \right) + \frac{\alpha m}{p_e} \cdot \frac{\lambda^2}{1 + 3\lambda^2} \cdot \text{Im} \left( \frac{C_T + C'_T}{C_A} \right)$$

$$N = \frac{m}{E_e} \cdot \frac{2\lambda(\lambda + 1)}{1 + 3\lambda^2} + \frac{\lambda}{1 + 3\lambda^2} \cdot \text{Re} \left( \frac{C_S + C'_S}{C_V} \right) + \frac{\lambda(2\lambda + 1)}{1 + 3\lambda^2} \cdot \text{Re} \left( \frac{C_T + C'_T}{C_A} \right)$$

$$R = \frac{\alpha m}{p_e} \cdot \frac{2\lambda(\lambda + 1)}{1 + 3\lambda^2} + \frac{\lambda}{1 + 3\lambda^2} \cdot \text{Im} \left( \frac{C_S + C'_S}{C_V} \right) + \frac{\lambda(2\lambda + 1)}{1 + 3\lambda^2} \cdot \text{Im} \left( \frac{C_T + C'_T}{C_A} \right)$$

EM contributions are driven by $C_V$ and $C_A$ couplings and scale with the decay asymmetry parameter $A$:

$$N = -\frac{m}{E_e} \cdot A_{SM} - 0.2175 \cdot \text{Re} \left( \frac{C_S + C'_S}{C_V} \right) + 0.3350 \cdot \text{Re} \left( \frac{C_T + C'_T}{C_A} \right) \approx 0.05$$

$$R = -\frac{\alpha m}{p_e} \cdot A_{SM} - 0.2175 \cdot \text{Im} \left( \frac{C_S + C'_S}{C_V} \right) + 0.3350 \cdot \text{Im} \left( \frac{C_T + C'_T}{C_A} \right) \approx 0.001$$
Scalar and tensor couplings

- **SM contributions:**
  - Mixing phase $\delta_{\text{CKM}}$ gives contribution which is $2^{\text{nd}}$-order in weak interaction: $< 10^{-10}$
  - $\theta$-term contributes through induced NN PVTV interactions: $< 10^{-9}$

- **Candidate models for scalar couplings (at tree-level):**
  - Charged Higgs exchange
  - Slepton exchange (R-parity violating super symmetric models)
  - Vector and scalar leptoquark exchange

- **The only candidate model for tree-level tensor contribution (in renormalizable gauge theories) is:**
  - Scalar leptoquark exchange
Mott scattering

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

![Graphs showing Mott scattering data.]
FUNSPIN – Polarized Cold Neutron Facility at PSI

\[ I_n \approx 10^{10} \text{s}^{-1} \quad P_n \approx 80\% \]
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 (“V-track”)
- Frequent neutron spin flipping
- “foil-in” and “foil-out” measurements
Neutron polarization from decay asymmetry

\[ E(\gamma) \equiv \frac{N(\gamma,+P_n) - N(\gamma,-P_n)}{N(\gamma,+P_n) - N(\gamma,-P_n)} = \langle P_n \rangle A_n \langle \beta \rangle \cos \gamma \]

\[ A_n = -0.1173 \]

- Average neutron polarization from decay rate asymmetry ("single-track" events)
- Averaging super-mirror polarimeter data:
  \[ \langle P_n \rangle = 0.87 \pm 0.01 \]
- Offset in data well understood and corrected for (spin flipper related deadtime)

\[ \chi^2/\text{dof} = 1.15 \]

\[ \langle P_n \rangle = 0.776 \pm 0.003 \]
Two-parameter fit

\[ A(\alpha) = \frac{n(+P, \alpha) - n(-P, \alpha)}{n(+P, \alpha) + n(-P, \alpha)} \]

\[ = A P \beta(\alpha) F(\alpha) + P S(\alpha) \left[ N G(\alpha) + R \beta(\alpha) H(\alpha) \right] \]

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

\[ \hat{n} \text{ – normal to Mott scattering plane} \]

\[ N = 0.062 \pm 0.012 \quad R = 0.004 \pm 0.012 \]
Single parameter fit

\[ S(|\alpha|) = \frac{\sqrt{n(\alpha, +\alpha)n(-\alpha, -\alpha)} - \sqrt{n(\alpha, -\alpha)n(-\alpha, +\alpha)}}{\sqrt{n(\alpha, +\alpha)n(-\alpha, -\alpha)} + \sqrt{n(\alpha, -\alpha)n(-\alpha, +\alpha)}} \]

\[ = N \frac{PSG(|\alpha|)}{\beta(|\alpha|) (1 - A^2P^2 \beta^2(|\alpha|)F^2(|\alpha|))} \] (3)

\[ U(|\alpha|) = \frac{\sqrt{n(\alpha, +\alpha)n(\alpha, -\alpha)} - \sqrt{n(-\alpha, +\alpha)n(-\alpha, -\alpha)}}{\sqrt{n(\alpha, +\alpha)n(\alpha, -\alpha)} + \sqrt{n(-\alpha, +\alpha)n(-\alpha, -\alpha)}} \]

\[ = AP\beta(|\alpha|)F(|\alpha|) + RPS(|\alpha|)H(|\alpha|) \] (4)
Final results

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<th>$P \times 10^2$</th>
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<td>19000</td>
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<th>$N \times 10^3$ (Eq. 3)</th>
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<td>67±11±4</td>
<td>4±12±5</td>
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</table>

$N_{SM} = (68 ±1)\times 10^3$

$R_{SM} = 0.5\times 10^3$
Limits on $S$ and $T$ contributions

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$R$-parity violating super-symmetric contributions to the neutron beta decay


\[ R = (-1)^{2j+3B+L}. \]

$\ell = \begin{cases} 100 \text{ GeV} \\
M_n - M_p \\
m_d - m_u \\
m_{\bar{e}_L} = 100 \text{ GeV}
\end{cases}$
What next?
Transverse electron polarization

\[ \omega(E_e, \Omega_e, \Omega_{\bar{\nu}}) \propto \]

\[ 1 + a \frac{p_e \cdot p_{\bar{\nu}}}{E_e E_{\bar{\nu}}} + b \frac{m_e}{E_e} + \frac{\langle J \rangle}{J} \cdot \left[ A \frac{p_e}{E_e} + B \frac{p_{\bar{\nu}}}{E_{\bar{\nu}}} + D \frac{p_e \times p_{\bar{\nu}}}{E_e E_{\bar{\nu}}} \right] \]

\[ + \hat{\sigma} \perp \cdot \left[ H \frac{p_{\bar{\nu}}}{E_{\bar{\nu}}} + L \frac{p_e \times p_{\bar{\nu}}}{E_e E_{\bar{\nu}}} + N \frac{\langle J \rangle}{J} + R \frac{\langle J \rangle \times p_e}{J E_e} \right. \]

\[ \left. + S \frac{\langle J \rangle}{J} \frac{p_e \cdot p_{\bar{\nu}}}{E_e E_{\bar{\nu}}} + U \frac{\langle J \rangle \cdot p_e}{J E_e E_{\bar{\nu}}} + V \frac{p_{\bar{\nu}} \times \langle J \rangle}{J E_{\bar{\nu}}} \right] \]

\[ X = X_{\text{SM}} + X_{\text{FSI}} + c_{\text{Re}S} \mathcal{R}(S) + c_{\text{Re}T} \mathcal{R}(T) + c_{\text{Im}S} \mathcal{I}(S) + c_{\text{Im}T} \mathcal{I}(T) \]
## Sensitivity factors for scalar and tensor couplings

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<tr>
<th></th>
<th>SM ($\lambda$)</th>
<th>FSI ($\lambda$)@</th>
<th>Re$S$</th>
<th>Re$T$</th>
<th>Im$S$</th>
<th>Im$T$</th>
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<td>$-0.104793$</td>
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<td>$0.171405^\dagger$</td>
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<td>$b$</td>
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<td>$A$</td>
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<td>$B$</td>
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<td>$U$</td>
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<td>$V$</td>
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<td>$0$</td>
<td>$0$</td>
<td>$-0.217582$</td>
<td>$+0.217582$</td>
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</tbody>
</table>

* Kinematical factor averaged over $E_k = (200,783)$ keV

$^\dagger$ $(|C_s|^2+|C'_s|^2)/2$ instead of Re$S$ and $(|C_T|^2+|C'_T|^2)/2$ instead of Re$T$, respectively

@ 1st order, static field, point charge, no recoil
Impact of $H, L, N, R, S, U, V$ measurement with anticipated accuracy of $5 \times 10^{-4}$

- Constraints on real scalar contributions dominated by:
  - Super-allowed $0^+ \rightarrow 0^+$
  - Correlations in mirror transitions

- $n$-decay correlations could join the game!
2\textsuperscript{nd}-generation experiment with CN beam

- General features of the experimental setup:
  - Axial polarimeter geometry (instead of planar)
    - 2.5 m long beam acceptance
  - Multi Wire Drift Chambers (instead of MWPC):
    - Hexagonal cell geometry
    - $x$-$y$-coordinates from drift time ($\Delta x = \Delta y = 0.5$ mm)
    - $z$-coordinate from charge division ($\Delta z = 1.0$ mm)
    - Reduced pressure (0.2-0.3 bar) \textbf{WORKS!}
  - Additional background suppression and higher polarization:
    - 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)

- Expected sensitivity for all coefficients: $5 \times 10^{-4}$
2nd-generation experiment with CN beam

Pb-foil

scintillator

He, 0.2–0.3 bar

MWDC
(He+isobutane, 0.2–0.3 bar)

CN beam
With detection of electrons and recoil protons...

Grounded vacuum window: 6 µm Mylar, reinforced with Kevlar fibers

Longitudinal neutron polarization, Axial guiding field $B = 0.1\div0.5$ mT

Mott scattering foil

Plastic scintillator

MWPC, 1 layer

Grounded grid

$p-e$ conversion foil

LiF (20nm) + Al (10nm) + 6F6F(100nm), -25 kV


MWDC, hexagonal, 5 layers
Electron-proton kinematics

\[ \theta_{e-p} \]

\[ p_e \]

\[ p_p \]

\[ p_v \]

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Electron-proton kinematics

- Measured electron energy, reconstructed proton flight path and measured proton time-of-flight must match!
- Constraints from 3-body kinematics will considerably reduce coincidence time
- With $10^5$ decays per second: single rate (per wire) $< 1$ kHz
**SCINTILLATOR (TRIGGER)**

- $E_e$

**MWDC**

- $dt_1$
- $dt_2$
- $dt_3$
- $dt_4$
- $dt_5$

**MWPC**

- Time-of-Flight

<table>
<thead>
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<th>Quantity</th>
<th>Exp. Information</th>
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<tr>
<td>Electron momentum</td>
<td>Scintillation light &amp; electron track*</td>
</tr>
<tr>
<td>Proton momentum</td>
<td>Time-of-flight &amp; hit position</td>
</tr>
</tbody>
</table>

* Electron track reconstructed with drift times ($x$, $y$) and charge division ($z$)
Conclusions

- **Within 3 months long data taking:**
  - $3 \times 10^8$ Mott scattered electrons ($N, R$)
  - $10^8$ protons in coincidence with Mott scattered electrons ($H, L, S, U, V$)
  - $10^{12}$ single electrons ($A$)
  - $3 \times 10^{11}$ e-p coincidences ($a, B, D$)

- **Advantages:**
  - Complete set of competitive constrains for scalar and tensor contributions from neutron decay alone
  - In further perspective, $a, b, A, B, D$ correlations with different systematic effects
  - Systematic study of FSI effects in neutron decay

- **Theory challenges:**
  - Deeper analysis of electron spin related correlation coefficients (e.g. LRSM)

- **Experimental challenges:**
  - Intensive, parallel and highly polarized CN beam (with well known phase space)
  - $p$-e conversion foil ($2 \text{ m}^2$ !) [S. Hoedl et al., J. Appl. Phys. 99, 084904 (2006)]
  - Vacuum window ($3 \text{ m}^2$ !)
  - Low pressure MWDC

- **Possible locations:**
  - NIST, ILL, ...
Backup slides
Measurements of the transverse electron polarization in n-decay provide direct, i.e. first-order access to the exotic scalar and tensor coupling constants.

In order to simultaneously access REAL and IMAGINARY parts of the exotic couplings - measure both components of the transverse polarization of electrons emitted in neutron decay.
Systematic errors (2007)

- Decay origin “from/off beam” (mm):
  - $x_{1\text{max}}$, $y_{1\text{max}}$, $z_{1\text{max}}$
- Electron energy “from/off neutron decay” (keV):
  - $E_{L\text{min}}$, $E_{L\text{max}}$, $E_{H\text{min}}$, $E_{H\text{max}}$
  - $X_{\text{min}}$, $X_{\text{max}}$, $Y_{\text{max}}$, $Z_{\text{max}}$
- Mott vertex position (mm):

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<th>$\delta R \times 10^4$</th>
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<td>17</td>
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<td>$z_{1\text{max}} \in (240,250)$</td>
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<td>9</td>
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<td>$y_{1\text{max}} \in (100,120)$</td>
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<td>$E_{L\text{min}} \in (200,260)$</td>
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<td>$E_{H\text{max}} \in (1400,1900)$</td>
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<td>$X_{\text{min}} \in (190,210)$</td>
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<td>Total</td>
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RPV MSSM contributions to n-decay

R-parity violating super-symmetric contributions to the neutron beta decay

\[ R = (-1)^{2j+3B+L}. \]

\[ M_{\tilde{e}_L} = \sum_{i=2,3} \frac{(\lambda_{1i1} - \lambda_{i11})\lambda'_{i11}}{8m_{\tilde{e}_Li}^2} \bar{u}(1 + \gamma_5) d \cdot \bar{e}(1 - \gamma_5) \nu_e \]

\[ = \sum_{i=2,3} \frac{\lambda_{1i1} \lambda'_{i11}}{4m_{\tilde{e}_Li}^2} \bar{u}(1 + \gamma_5) d \cdot \bar{e}(1 - \gamma_5) \nu_e , \]

\[ M_{\tilde{d}_R} = \sum_{i=1,2,3} \frac{|\lambda'_{11i}|^2}{4m_{\tilde{d}_{Ri}}^2} \bar{\nu}_e(1 - \gamma_5) d \cdot \bar{u}(1 + \gamma_5)e^c \]

\[ = \sum_{i=1,2,3} \frac{|\lambda'_{11i}|^2}{8m_{\tilde{d}_{Ri}}^2} \bar{u}\gamma^\mu(1 - \gamma_5) d \cdot \bar{\nu}_e^c \gamma_\mu(1 + \gamma_5)e^c \]

\[ = \sum_{i=1,2,3} \frac{|\lambda'_{11i}|^2}{8m_{\tilde{d}_{Ri}}^2} \bar{u}\gamma^\mu(1 - \gamma_5) d \cdot \bar{e}_\gamma\mu(1 - \gamma_5)\nu_e . \]
Experimental setup

Magnet coils
Plastic scintillators

Concrete
Lead
Boron

Pb foil
MWPC

$^6$LiF collimator

$^6$LiF beam dump

2m
MWPCs, scintillators and electronics

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“V-track” events – on-line display
Energy resolution

- Conversion electrons from $^{207}\text{Bi}$

![Graph showing energy resolution with two peaks: $\sigma_1 = 29.39$ keV and $\sigma_2 = 45.12$ keV.](image)
Observation:

Spectral distribution of background depends weakly on the electron origin.
Mott scattering vertex distribution

Coinciding vertices in V and H projections

Vertex in V projection only

Vertex in H projection only

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Electron energy distribution

Single-track events (no Mott scattering)

Double V-track events (Mott scattering)
Neutron beam “tomography”

![Graphs showing neutron beam tomography results for different angles S, V-V, V, H. Each graph indicates counts and energy range (E > 850 keV, E < 750 keV).]
Projection of vertices onto XY-plane

Pb-foil

Scint.

MWPC

Pb-foil

Scint.
Projection of vertices onto Pb-foil planes
2nd-generation experiment with CN beam

Statistics

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<td>2. Beam fiducial volume</td>
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</tr>
<tr>
<td>3. Detector acceptance</td>
<td>10</td>
</tr>
<tr>
<td>4. Beam polarization</td>
<td>1.2</td>
</tr>
<tr>
<td>5. Analyzing power</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>780</strong></td>
</tr>
</tbody>
</table>

Systematical uncertainty

<table>
<thead>
<tr>
<th>Item</th>
<th>Reduction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Background subtraction</td>
<td>10</td>
</tr>
<tr>
<td>2. Average neutron polarization</td>
<td>5</td>
</tr>
<tr>
<td>3. Analyzing power</td>
<td>3</td>
</tr>
</tbody>
</table>
Reconstruction of momenta

Actual position of the decay vertex is not known

But:
It **must be located** on the electron trajectory segment coincident with the beam

Neutron decay density distribution in the beam **is known**

Finally:
In extraction of correlation coefficients we sum over momenta – ambiguity in vertex position is not essential

assigned weight is proportional to the decay density
Electron-proton kinematics

[Diagrams showing the relationship between proton and electron kinetic energies and time-of-flight.]
Figure-of-Merit for Mott scattering

Electron energy threshold

Electron kinetic energy (keV)

Polar Mott-scattering angle (deg)
MWDC operation in lowered gas pressure

8 mm

20 mm

Gas mixture

Ambient air

K. Bodek, PANIC11
Current preamplifier (for readout from both wire ends)

\[
z = \frac{q_1 - q_2}{q_1 + q_2} \approx \frac{R_2 - R_1}{R_2 + R_1}
\]

Gas amplification ion cloud
Achieved performance

Gas mixture: He (90%) + isobutane (10%), $P = 300$ mbar
Wire resistance = 3 Ohm; Preamplifier input impedance = 10 Ohm

From drift time

$\sigma < 0.5$ mm

From charge division

$\sigma < 1.5$ mm
\[
m = \frac{(J \times p_e)}{|J \times p_e|}
\]

\[
n = \frac{(p_e \times p_s)}{|p_e \times p_s|}
\]

\[
k = \frac{(m \times n)}{|m \times n|}
\]

\[
k \parallel p_e
\]

\[
\gamma \text{ – decay angle}
\]

\[
\delta \text{ – Mott scattering angle}
\]

\[
\alpha \text{ – event projection angle}
\]