Neutron Beta Decay Correlations: Part 1: ...within the Standard Model

Thanks for contributions from:
Part 1: Contributions to the Standard Model

1. Beta Decay: The study of Parity Violation
2. Measurement of the Beta Asymmetry
3. Measurement of the Neutrino Electron Correlation

Part 2: Searches for physics beyond the Standard Model
(First) discovery of Parity Violation (1928)

R.T. Cox et al., PNAS 14, 544 (1928):

Assumption: Scattering probability depends on spin orientation (that was known for X rays). This is correct, but the reason (Spin-Orbit Interaction) was not discovered yet. Aim: Prove that an electron is a vector particle. Result: Asymmetry of count rate for 90 deg / 270 deg found, was not deemed to be important. Later experiments continued with electrons from a hot filament.
Finally: Parity Violation found by Wu et al, 1956

Now: Construction of Parity-Violating Hamiltonian, which couples leptons and hadrons

$$H_{\text{weak,elementary}} = \frac{G_F}{\sqrt{2}} \langle u | \gamma_\mu \gamma_5 | d \rangle \langle d | \gamma_\mu \gamma_5 | u \rangle + \text{h.c.}$$

Properties: Helicity of fermions is $-v/c$, of antifermions is $v/c$

Complication: Nucleons aren’t elementary particles:

$$H_{\text{weak}} = \frac{G_F V_{ud}}{\sqrt{2}} \langle p | 1 \cdot \gamma_\mu - \lambda \gamma_\mu \gamma_5 | n \rangle \langle e^- | \gamma_\mu - \gamma_\mu \gamma_5 | v_e \rangle + \text{h.c.}$$

Coupling constants are unknown.

Fermi-Transitions: $g_V = G_F \cdot V_{ud}$

Gamow-Teller-Transitions: $g_A = G_F \cdot V_{ud} \cdot \lambda$
Observables in Neutron Beta Decay

Fermi’s golden rule:

\[
\text{Decay probability } w_{i\rightarrow f} = \frac{2\pi}{\hbar} \left| \langle f | H_{\text{weak}} | i \rangle \right|^2 \rho
\]

\[
\frac{d\omega}{dE_e} = \frac{2\pi}{\hbar} G_F^2 V_{ud}^2 \left(1 + 3 |\lambda|^2\right) \rho(E_e)
\]

Neutron lifetime

\[
\tau_n^{-1} = \frac{2\pi}{\hbar} G_F^2 V_{ud}^2 \left(1 + 3 |\lambda|^2\right) \int \rho(E_e)
\]
Observables in Neutron Beta Decay

Jackson et al., PR 106, 517 (1957):

Observables in Neutron beta decay, as a function of generally possible coupling constants (assuming only Lorentz-Invariance)

\[ d\omega \propto \rho(E_e) \cdot \left(1 + 3|\lambda|^2\right) \cdot \left\{1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right\} \]

\[ + \tilde{\sigma}_n \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \]

Beta-Asymmetry \( A = -2 \frac{|\lambda|^2 + \text{Re} \lambda}{1 + 3|\lambda|^2} \)

Neutrino-Electron-Correlation \( a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \)

Neutron lifetime \( \tau_n^{-1} = \frac{2\pi}{\hbar} G_F^2 V_{ud}^2 \left(1 + 3|\lambda|^2\right) \int \rho(E_e) \)
Two unknown parameters, $g_A$ and $g_V$, need to be determined in 2 experiments

1. Neutron-Lifetime: \[ \tau_n^{-1} \propto \left( g_V^2 + 3 g_A^2 \right) \quad \tau_n \approx 885 \text{ s} \]
The Standard Model Parameters $V_{ud}$ and $\lambda$

Two unknown parameters, $g_A$ and $g_V$, need to be determined in 2 experiments

1. Neutron-Lifetime: $\tau_n^{-1} \propto (g_V^2 + 3g_A^2) \quad \tau_n \approx 885 \text{ s}$

2. Beta-Asymmetry: $A = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \approx -0.1 \quad \lambda = \frac{g_A}{g_V}$
Decrease of Neutron Counts $N$ with storage time $t$: $N(t) = N(0)\exp\{-t/\tau_{\text{eff}}\}$

$1/\tau_{\text{eff}} = 1/\tau_{\beta} + 1/\tau_{\text{wall losses}}$

Neutron Lifetime Measurements

Many new attempts underway, mostly with magnetic bottles:
Under (at least) construction: Ezhov et al. (ILL, PNPI Gratchina), Bowman et al. (LANL), Paul et al. (TUM, PSI)
Outline

Part 1: Contributions to the Standard Model
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3. Measurement of the Neutrino Electron Correlation

Part 2: Searches for physics beyond the Standard Model
...
Electron Detector (Plastic Scintillator)

The Beta Asymmetry: PERKEO II

$$dw \propto \left(1 + A \frac{\nu}{c} \cos(p_e, \sigma_n)\right)$$

Experimental Reality:

- Flip neutron spin, don’t compare detectors!
- Two detectors still needed to suppress electron backscattering.

$$\frac{N_{up} - N_{down}}{N_{up} + N_{down}} = A \frac{\nu}{c} \left< \cos(p_e, \sigma_n) \right> Pf$$
On the motivation to achieve high polarization

Easiest type of polarization analysis: (just spin flip ratio):

Spin flip ratio: \[ R = \frac{N_{\text{up}}}{N_{\text{down}}} = \frac{1 + P_1 P_2}{1 - P_1 P_2 + P_1 P_2 f} \approx \left[ \frac{1}{2} (1 - P_1) + \frac{1}{2} (1 - P_2) + (1 - f) \right]^{-1} \]

Result: The spin flip ratio sets a lower limit on the efficiency of devices, even if one couldn’t tell individual numbers for \( P_1, P_2, \) or \( f. \) If this lower limit is close to 100\%, the precision of any scheme used to determine the efficiencies individually doesn’t have to be high. Most experimental errors (Background, Depolarization) cause the true polarization to be even higher than the lower limit given by the spin flip ratio.

Note: Modification of spin flip ratio if analyzer is He-cell (opposite polarization)

Problems of polarization measurement: Inhomogeneities of polarization and spin flip efficiency

Supermirror: … with position, angle, wavelength

He-3: … with wavelength, time
Beam polarization with crossed supermirrors

Supermirror polarizer

\[ \lambda, \theta \]

\[ \oplus \vec{B} \]

Angular dependence

Independent devices

The crossed geometry

\[ \phi_x \]

\[ \phi_y \]

\[ P_{12} = \frac{P_1 + P_2}{1 + P_1 P_2} \]

\[ \approx 1 - \frac{1}{2} (1 - P_1)(1 - P_2) \]

M. Kreuz et al., NIM A 547, 583 (2005)
1. Beam polarization: Crossed supermirrors  
   Kreuz et al., NIM A 547, 583 (2005)

2. Spin flip through adiabatic fast passage

3. Polarization analysis behind experiment with 2nd spin flipper and black He-3 analyzer

Result:  
   M. Schumann et al., PRL 99, 191803 (2007)
   • Spin flip efficiency $f = 100.0(1)\%$
   • Beam polarization $P = 99.7(1)\%$
   • No position dependence of $f$ or $P$
   • No time dependence of $f$ or $P$
PERKEO II: Results

Calibration: Conversion electron sources

\[ \frac{N_{\text{up}}}{N_{\text{up}} + N_{\text{down}}} = \frac{< \cos(p, \sigma_n)> Pf}{1 - < \cos(p, \sigma_n)> Pf} \]
### Uncertainty Budget PERKEO II, last run

<table>
<thead>
<tr>
<th>Error Analysis</th>
<th>Correction</th>
<th>Uncertainty PERKEO II</th>
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<tbody>
<tr>
<td>Statistical uncertainty</td>
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<tr>
<td>Background</td>
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<td>Neutron beam polarization</td>
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<td>Spin flip efficiency</td>
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<td>Detector response</td>
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<td>0.18%</td>
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H. Abele, 2009, preliminary

<table>
<thead>
<tr>
<th>Beam time</th>
<th>Result</th>
<th>Publication</th>
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<tbody>
<tr>
<td>2004</td>
<td>$A = -0.1198(5)$</td>
<td>(preliminary) $\rightarrow \lambda = -1.2762(13)$</td>
</tr>
</tbody>
</table>
Coupling Constants of the Weak Interaction

Coupling Constants in Neutron Decay

\[ n = (udd) \]
\[ p = (udu) \]
\[ n \rightarrow p + e^- + \bar{\nu}_e \]

Primordial Nucleosynthesis

\[ n + \nu_e \leftrightarrow p + e^- \]

Start of Big Bang Nucleosynthesis, Primordial \(^4\)He abundance

Solar cycle

\[ p + p \rightarrow ^2H^+ + e^+ + \nu_e \]

Start of Solar Cycle, determines amount of Solar Neutrinos

Neutrino Detection (SNO, CC)

\[ \nu_e + ^2H^+ \rightarrow p + p + e^- \]

Efficiency of Neutrino Detectors
Unitarity: Situation 2004

$$|V_{ud}| = \sqrt{1 - |V_{us}|^2 - |V_{ub}|^2}$$

Neutron Measurements needed:
- Neutron lifetime $\tau_n$
  $$\tau_n^{-1} \propto G_F^2 V_{ud}^2 \left(1 + 3 |\lambda|^2\right) ; \lambda = g_A/g_V$$
- Beta Asymmetry $A(\lambda)$
  $$A = -2 \frac{|\lambda|^2 + \text{Re} \lambda}{1 + 3 |\lambda|^2}$$
- Neutrino-Electron-Correlation $a(\lambda)$
  $$a = \frac{1 - |\lambda|^2}{1 + 3 |\lambda|^2}$$

Fermi-Transition:
$$g_V = G_F \cdot V_{ud}$$
Gamow-Teller-Transition:
$$g_A = G_F \cdot V_{ud} \cdot \lambda$$
Neutron Measurements needed:

- **Neutron lifetime** $\tau_n$
  
  \[ \tau_n^{-1} \propto G_F^2 V_{ud}^2 \left( 1 + 3 |\lambda|^2 \right) \quad ; \lambda = g_A/g_V \]

- **Beta Asymmetry** $A(\lambda)$
  
  \[ A = -\frac{2 |\lambda|^2 + \text{Re}\lambda}{1 + 3 |\lambda|^2} \]

- **Neutrino-Electron-Correlation** $a(\lambda)$
  
  \[ a = \frac{1 - |\lambda|^2}{1 + 3 |\lambda|^2} \]

Neutron lifetime discrepancies have to be sorted out.

To make $A$ not limiting for neutron-based determination of $V_{ud}$: $\Delta A/A < 0.2\%$ needed.

**Unitarity 2008**

\[ |V_{ud}| = \sqrt{1 - |V_{us}|^2 + |V_{ub}|^2} \]
Determination of $\lambda = g_A/g_V$ from $A$

Probability of disagreement between beta asymmetry measurements due to statistical fluctuations:

$$P = 2.7 \times 10^{-5} (4.2 \, \sigma)$$

Maybe in PDG2010: “The most recent results from PERKEO II are so far from other results that it makes no sense to include them in the average. It is up to workers in this field to resolve this issue??? (THIS IS NOT A SERIOUS PROPOSAL!)"
Corrections in Beta asymmetry measurements

- Uncorrected Result
- Published Result

Electron Asymmetry A

PERKEO

Yerozolimskii

Liaud

PERKEO II

Year of Measurement
New attempts: UCNA (ultracold neutrons)

Test run: $A_0 = -0.1138(46)(21)$  
Pattie et al., PRL 102, 012301 (2009)

A. Young (NCSU), A. Saunders (LANL), et al.
Next generation: PERKEO III

B. Maerkisch, D. Dubbers (Heidelberg), H. Abele (Vienna), T. Soldner (ILL) et al.

detector (plastic scintillator)
detector (plastic scintillator)

Decay volume, 150 mT

Cold neutron beam

velocity selector

chopper

beam dump

Counts [A.U.]

Data from 24 calendar hours, Background subtracted

Energy calibration, cuts, detector response to be revised

Energy [keV]

Counts [A.U.]

Energy [keV]
New observable: Weak magnetism

Hadronic current at $q \neq 0$:

$$H_{\text{weak}} = G_F V_{ud} \langle p | 1 \cdot \gamma^\mu - \lambda \gamma^\mu \gamma^5 + i \frac{\mu_p - \mu_n}{2m_p} \sigma^{\mu\nu} q_\nu + ... | n \rangle$$

\[ \cdot \left\langle e^- | \gamma_\mu - \gamma_\mu \gamma_5 | \nu_e \right\rangle \]

weak magnetism

1. First determination in mirror nuclei: Slightly different decay rates due to weak magnetism
2. Determination in hyperons: Not always according to Standard Model
3. New: Determination from beta asymmetry spectrum

$$A(E) = A_0 \left[ 1 + c + a_{\text{WM}} \left( \lambda, \frac{\mu_p - \mu_n}{2} \right) \right]$$

\[ \approx 2\% \]
New attempts at SNS: abBA / Nab / PANDA

Proton Beam 60 Hz

LH₂

Mercury Spallation Target

Biological Shield

Neutron Guide

Shutter

Choppers

Flux Monitor

Adiabatic Spin Flipper

³He Polarizer

Collimator

Spectrometer

Fast, segmented silicon detector:

\[
\begin{align*}
\frac{1}{\Gamma} &= 0.27 \text{ MeV} \\
J^p &= 0^+ \\
\frac{1}{\Gamma} &= 0.27 \text{ MeV} \\
J^p &= 0^+ \\
\frac{1}{\Gamma} &= 21.2 \text{ MeV} \\
J^p &= 1^+ \\
\frac{1}{\Gamma} &= 20.1 \text{ MeV} \\
J^p &= 0^+ \\
\frac{1}{\Gamma} &= 19.8 \text{ MeV} \\
J^p &= 0^+ \\
\end{align*}
\]

³He+n

⁴He

S. Wilburn (LANL),
D. Bowman (ORNL),
S.B. et al.
Part 1: Contributions to the Standard Model
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Part 2: Searches for physics beyond the Standard Model
Determination of the Coupling Constants

Fermi-Decay:
\[ g_V = G_F V_{ud} \]

Gamow-Teller-Decay:
\[ g_A = G_F V_{ud} \lambda \]

Two unknown parameters, \( g_A \) and \( g_V \), need to be determined in 2 experiments

1. Neutron-Lifetime:
\[ \tau_n^{-1} \propto \left( g_V^2 + 3 g_A^2 \right) \]
\[ \tau_n \approx 885 \text{ s} \]

2b. Neutrino-Electron-Correlation \( a \):
\[ a = \frac{1 - \lambda^2}{1 + 3 \lambda^2} \approx -0.1 \]
\[ \lambda = \frac{g_A}{g_V} \]
A measurement of $a$ is independent of possible unknown errors in $A$, systematics are entirely different.

Present experiments have $\Delta a/a \sim 5\%$, an order of magnitude improvement is desirable.
aSPECT (Mainz, Munich, ILL, Virginia)

\[ dw \propto \left( 1 + a \frac{\nu}{c} \cos(p_e, p_{\bar{\nu}_e}) \right) \]

**Sensitivity of the Proton Spectrum to \( a \):**

![Graph showing the decay rate \( w(E) \) vs. Proton kinetic energy \( E \) in eV. The graph compares the proton spectrum for \( a = +0.3 \) and \( a = -0.103 \) (PDG 2006).]
Transmission function $T_U(E)$ in the adiabatic limit:

$$T_U(E) = \begin{cases} 
0 & ; & E < eU \\
1 - \sqrt{1 - \frac{B_0}{B_A} \left(1 - \frac{eU}{E}\right)} & ; & \text{otherwise} \\
1 & ; & E > \frac{eU}{1 - \frac{B_A}{B_0}} 
\end{cases}$$
First results of 2008 beamtime @ ILL

Silicon drift detector, at -15kV

Pulse height spectrum:

- 470 counts per second at $U_A = 50$ V (one detector pad)
- Statistical sensitivity on $a$ about 2% per 24 hours measurement time
- Background stable

Integrated Proton Spectrum:

Simulation for $a = +0.3$

and for $a = -0.103(4)$ (PDG 2008)

Experimental data (offset subtracted)

$N(U) \propto \int T_U(E)w(E)\,dE$
Trapping problems solved

- Neutron Beam
- g30 kV
- Proton Detector
- Decay Volume
- Analyzing Plane
- ExB
- ExB
- Trapped e⁻

- new detector -HV electrode, SDD detector
- new ExB electrode
- Internal getter pumps

Measurements without neutron beam

- Beam time at FRM-II, Munich (2006)
- Beam time at ILL, Grenoble (2008)

<table>
<thead>
<tr>
<th>Background count rate [s⁻¹]</th>
<th>Analyzing Plane Voltage $U_A$ [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>800</td>
</tr>
<tr>
<td>4</td>
<td>600</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

preliminary
Aim: $\Delta a/a \sim 2\%$, maybe 0.5% after NIST upgrade

Tulane (F. Wietfeldt), Indiana, NIST, et al.
The $\cos \theta_{ev}$ spectrometer Nab @ SNS

Kinematics:
- Energy Conservation
  \[ E_\nu = E_{e,\text{max}} - E_e \]
- Momentum Conservation
  \[ p_p^2 = p_e^2 + p_\nu^2 + 2p_e p_\nu \cos \theta_{ev} \]

![Graph showing $p_p^2$ vs. $E_e$ with phase space and $\cos \theta_{ev}$ values]

$\nu_e$ 

electron and proton phase space

$\theta_{ev}$

$\nu_e$

$E_e$ (MeV)

$0.0\,\,\,0.1\,\,\,0.2\,\,\,0.3\,\,\,0.4\,\,\,0.5\,\,\,0.6\,\,\,0.7\,\,\,0.8$

$p_p^2$ (MeV^2/c^2)

$0\,\,\,0.2\,\,\,0.4\,\,\,0.6\,\,\,0.8\,\,\,1.0\,\,\,1.2\,\,\,1.4$

$\cos \theta_{ev} = 1$

$\cos \theta_{ev} = 0$

$\cos \theta_{ev} = -1$
The $\cos \theta_{ev}$ spectrometer Nab @ SNS

- Spectrometer and detector shared with abBA
- Background suppression through coincidences
- Aim: $a \sim 0.1\%$

D. Pocanic, S.B. (Virginia), D. Bowman (ORNL), et al.
Advantages of asymmetric configuration:

• Reduced sensitivity to electrostatic potential inhomogeneities
• Statistical: Bigger decay volume vs. Angular acceptance
• Detection function: Improved flight path length
• Avoidance of deep Penning trap
• Polarized experiment (abBA, PANDA) still possible
Future in Europe (@ILL or FRM-2): PERC

PERC example: \( B_0 = 2 \text{ T}, B_1 = 8 \text{ T}, B_2 = 0.5 \text{ T} \):

- count rates:
  - 70000 s\(^{-1}\), continuous unpolarized n-beam
  - 14000 s\(^{-1}\), continuous beam polarized to 98%
  - 6000 s\(^{-1}\), pulsed unpolarized beam
  - 370 s\(^{-1}\), pulsed beam polarized to 99.7%

- beam time:
  - ½ h
  - 2 h
  - 10 h
  - 4 d

for \( \sim 10^{-4} \) statistical error

Dubbers et al., NIM A 596, 238 (2008)
Neutron Beta Decay Correlations: Part 2: …beyond the Standard Model

Stefan Baeßler

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Part 2: Searches for physics beyond the Standard Model
1. Fierz interference and S,T currents
2. Asymmetries involving protons and right-handed currents
3. Search for Time Reversal Violation
4. Radiative Beta Decay
5. Bound Beta Decay
General Beta Decay Hamiltonian

\[
H_{\text{if}} = \frac{2G_F V_{ud}}{\sqrt{2}} \sum_{j \in \{V,A,S,T\}} L_j \langle p | \Gamma_j | n \rangle \langle e^- | \frac{1-\gamma_5}{2} | \nu_e \rangle + R_j \langle p | \Gamma_j | n \rangle \langle e^- | \frac{1+\gamma_5}{2} | \nu_e \rangle
\]

Left-handed neutrino \hspace{1cm} Right-handed neutrino

with operators: \( \Gamma_V = \gamma_\mu \); \( \Gamma_A = i\gamma_\mu\gamma_5 \); \( \Gamma_S = 1 \); \( \Gamma_T = \frac{i[\gamma_\mu, \gamma_\nu]}{2\sqrt{2}} \)

Standard Model: \( L_V = 1 \); \( L_A = \lambda \); \( L_S = L_T = R_V = R_A = R_S = R_T = 0 \)

Neutron lifetime: \( \tau_n \propto \left( \left| L_V \right|^2 + 3 \left| L_A \right|^2 + \left| L_S \right|^2 + 3 \left| L_T \right|^2 + \left| R_V \right|^2 + 3 \left| R_A \right|^2 + \left| R_S \right|^2 + 3 \left| R_T \right|^2 \right) \)

Standard Model: \( 1+3\lambda^2 \) \hspace{1cm} Standard Model: \( 0 \)

Beta Asymmetry: \( A = \frac{2 \text{Re} \left( -\left| L_A \right|^2 - L_V L_A^* + L_T^2 + L_S L_T^* + \left| R_A \right|^2 + R_V R_A^* - R_T^2 - R_S R_T^* \right)}{\left| L_V \right|^2 + 3 \left| L_A \right|^2 + \left| L_S \right|^2 + 3 \left| L_T \right|^2 + \left| R_V \right|^2 + 3 \left| R_A \right|^2 + \left| R_S \right|^2 + 3 \left| R_T \right|^2} \)

Neutrino Electron Correlation: \( a = \frac{\left| L_V \right|^2 - \left| L_A \right|^2 - \left| L_S \right|^2 + \left| L_T \right|^2 + \left| R_V \right|^2 - \left| R_A \right|^2 - \left| R_S \right|^2 + \left| R_T \right|^2}{\left| L_V \right|^2 + 3 \left| L_A \right|^2 + \left| L_S \right|^2 + 3 \left| L_T \right|^2 + \left| R_V \right|^2 + 3 \left| R_A \right|^2 + \left| R_S \right|^2 + 3 \left| R_T \right|^2} \)

Glück et al., NPA 593, 125 (1995), Jackson, PR 106, 517 (1957)
More observables: Fierz Interference Term

Jackson et al., PR 106, 517 (1957):

\[ dW \propto \rho(E_e) \cdot \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right. \\
\left. + \vec{\sigma}_n \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + N \vec{\sigma}_e + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} + \ldots + R \frac{\vec{p}_e \times \vec{\sigma}_e}{E_e} \right) \right\} \]

Fierz-Interference Term: \[ b = \frac{2 \text{Re} \left( L_S L_\nu^* + 3 L_A L_T^* + R_S R_\nu^* + 3 R_A R_T^* \right)}{\left| L_\nu \right|^2 + 3 \left| L_A \right|^2 + \left| L_S \right|^2 + 3 \left| L_T \right|^2 + \left| R_\nu \right|^2 + 3 \left| R_A \right|^2 + \left| R_S \right|^2 + 3 \left| R_T \right|^2} \]

- Signal expected for left-handed scalar and tensor interaction (neutrino is left-handed, electron is right-handed). Could be caused by leptoquarks or charged Higgs bosons.
- Signal expected for MSSM: \( b \sim 10^{-3} \) (Ramsey-Musolf, 2007)
- Not measured (directly) in neutron beta decay (detector, background), Nab might be able to.
- Tight bound for scalar part from superallowed decays
Search for left-handed scalar and tensor currents

Based on P.A. Vetter et al., PRC 77, 035502 (2008)

(Time reversal invariance assumed)

• Most stringent limit comes from superallowed nuclear decays (missing energy dependence of partial lifetime due to Fierz Term):

\[ dW \propto \rho(E_c) \cdot \left(1 + b \frac{m_e}{E_c}\right) \]

• Approximation: Extracted correlation coefficients \((a, A, \ldots)\), where the analysis assumes \(b = 0\), are in general

\[
\frac{a}{1 + b \left(\frac{m_e}{E_c}\right)} , \frac{A}{1 + b \left(\frac{m_e}{E_c}\right)} \ldots
\]

• Better if experimentalists would discuss the non-V-A case (correct electron energy dependence, possible influence of \(b\) on systematics).
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The neutrino asymmetry $B$

Fermi-Decay:

$g_V = G_F V_{ud}$

Gamow-Teller-Decay:

$g_A = G_F V_{ud} \lambda$

$g_A$ and $g_V$ can be determined with $B$ and $\tau_n$ (as before) but one is not very sensitive

Neutrino Asymmetry:

$$B = 2 \frac{\lambda^2 - \lambda}{1 + 3\lambda^2} \approx 0.98$$

$$\lambda = \frac{g_A}{g_V}$$

This can be turned around to look for deviations from the Standard Model (e.g., right-handed W bosons)
More observables: Neutrino Asymmetry

\[ dW \propto \rho(E_e) \cdot \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_{\nu}} + b \frac{m_e}{E_e} \right\} \]

\[ + \vec{\sigma}_n \cdot \left\{ A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_{\nu}} + N \vec{\sigma}_e + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_{\nu}} + ... + R \frac{\vec{p}_e \times \vec{\sigma}_e}{E_e} \right\} \]

Neutrino-Asymmetry \[ B = \frac{2 \text{Re}\left( |L_A|^2 - L_V L_A^* + |L_T|^2 - L_S L_T^* - |R_A|^2 + R_V R_A^* - |R_T|^2 + R_S R_T^* \right)}{|L_V|^2 + 3 |L_A|^2 + |L_S|^2 + 3 |L_T|^2 + |R_V|^2 + 3 |R_A|^2 + |R_S|^2 + 3 |R_T|^2} \]

\[ + \frac{2 \text{Re}\left( -L_S L_A^* - L_V L_T^* + 2 L_A L_T^* + R_S R_A^* + R_V R_T^* - 2 R_A R_T^* \right)}{|L_V|^2 + 3 |L_A|^2 + |L_S|^2 + 3 |L_T|^2 + |R_V|^2 + 3 |R_A|^2 + |R_S|^2 + 3 |R_T|^2} \cdot \frac{m_e}{E_e} \]

Signal expected for MSSM at \[ \Delta B \sim 10^{-3} \] (Ramsey-Musolf, 2007)
The neutrino asymmetry $B$ from PNPI

Result: $B = 0.9821(40)$

A. Serebrov et al., JETP 86, 1074 (1998)
The neutrino asymmetry $B$ from PERKEO II

Combine both $B$ values with $A$ (PERKEO II) and $\tau_n$ (own average):

→ Limit on right-handed $W$ boson: $m(W_R) > 296$ GeV/c$^2$  
  M. Schumann et al., PRL 99, 191803 (2007)

Compare with limits from D0 (assuming left- and right handed coupling constants are equal):

$m(W_R) > 1000$ GeV/c$^2$  
  V.M. Abazov et al., PRL 100, 031804 (2008)
The proton asymmetry $C$ from PERKEO II

- Result: $C = \int C_{\exp} \, dE_e = -0.2377(26)$ M. Schumann et al., PRL 100, 151801 (2008); in SM: $C = -0.27484(A + B)$ (PERKEO-II measurement of $B$ not independent of PERKEO-II measurement of $C$)
The proton asymmetry $C$ from PANDA

A similar measurement is planned with aSPECT

T. Chupp (Michigan), S.B., et al.
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5. Bound Beta Decay
More observables: Triple correlation

Jackson et al., PR 106, 517 (1957):

\[
dW \propto \rho(E_e) \cdot \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \vec{\sigma}_n \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + N \vec{\sigma}_e + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} + \ldots + R \frac{\vec{p}_e \times \vec{\sigma}_e}{E_e} \right) \right\}
\]

Triple correlation \[ D = 2 \frac{\text{Im} \lambda}{1 + 3 |\lambda|^2} \]

• A non-zero \( D \) coefficient violates Time reversal symmetry.
  \( \rightarrow \) complex contribution in Hamiltonian. In SM only in high order
• Final state effects give \( D \sim 10^{-5} \)
• Serves to restrict leptoquark extensions to the Standard Model
Measurement of the $D$ coefficient with TRINE-β

\[ D\tilde{\sigma}_n \frac{\vec{p}_e \times \vec{p}_v}{E_e E_v} = D\tilde{\sigma}_n \frac{\vec{p}_e \times (-\vec{p}_e - \vec{p}_p)}{E_e E_v} = -D\tilde{\sigma}_n \frac{\vec{p}_e \times \vec{p}_p}{E_e E_v} \]

Principle Setup

\[ \alpha^{00} = \frac{N_{e0,p0}^\uparrow - N_{e0,p0}^\downarrow}{N_{e0,p0}^\uparrow + N_{e0,p0}^\downarrow} = DP\kappa_D \]

But: Imperfect alignment gives too high sensitivity to $A$ and $B$.

Better use the following combination:

\[ D = \frac{\alpha^{00} - \alpha^{01} - \alpha^{10} + \alpha^{11}}{4P\kappa_D^{00}} \]

Result: $D = (-2.8 \pm 7.1) \times 10^{-4}$

T. Soldner et al., PLB 581, 49 (2004)
Measurement of the $D$ coefficient with EMIT

- Statistically favorable geometry
- Detection of protons with surface barrier detectors at -28 kV (Earlier: PIN diodes), electrons with scintillators
  - First results published $D = (-6 \pm 13) \times 10^{-4}$ (EMIT I)
    - L. Lising et al., PRC 62, 055501 (2000)
- Difficult systematics if beam polarization is not homogeneous
- EMIT-2 is still being analyzed, result for $D$ at several times $10^{-4}$ expected

Extract $D$ from asymmetry with left detector minus right detector to suppress unwanted dependencies on other correlations.
More Pseudo T violation: R/N correlation

Jackson et al., PR 106, 517 (1957):

\[
dW \propto \rho(E_e) \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right. \\
+ \left. \vec{\sigma}_n \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + N \vec{\sigma}_e + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} + \ldots + R \frac{\vec{p}_e \times \vec{\sigma}_e}{E_e} \right) \right\} 
\]

Electron polarization \( N = \sqrt{1 - \left( \frac{\nu}{c} \right)^2} A \)

- Standard-Model: \( N_{\text{SM}} = 0.07; R_{\text{SM}} = 0.0066 \sim 0 \)
- Scalar or Tensor Interactions lead to deviations (Leptoquarks, charged Higgs, Sleptons in SUSY)
- Of special interest: \( R \), as it is Time-Reversal violating, measures imaginary part of coupling constants
The Standard Model Parameters $V_{ud}$ and $\lambda$

Fermi-Decay:

\[ g_V = G_F V_{ud} \]

\[ \frac{1}{\sqrt{2}} \left\{ e^- \bar{v}_e - e^- v_e \right\} \quad N = 0 \]

Gamow-Teller-Decay:

\[ g_A = G_F V_{ud} \lambda \]

\[ \frac{1}{\sqrt{2}} \left\{ e^- \bar{v}_e + e^- v_e \right\} \quad N = 0 \]

\[ \frac{1}{\sqrt{2}} e^- \bar{v}_e \quad N = 1 \]

\[ dw \propto (1 + N \cos(\sigma_e, \sigma_n)) \]
Detection of electron polarization through Mott scattering in Pb foil: The probability of having a V track is electron spin dependent.

Result:

\[ N_{\text{exp}} = 0.056(11)(5) \]
\[ (N_{\text{SM}} = 0.066) \]
\[ R_{\text{exp}} = 0.008(15)(5) \]
\[ (R_{\text{SM(FSI)}} = 0.00066) \]

K. Bodek (Cracow), Villigen, CAEN, Leuven, Kattowice,

R/N correlation and implications on S/T couplings

Grey: Other limits from neutrons and nucleons

N. Severijns et al., RMP 78, 991 (2006)

Based on Bodek et al., Phys. Rev. Lett. 102, 172301 (2009)
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Motivation: Neutron radiative decay
Previously unmeasured process in a fundamental semileptonic decay. Testing QED in a weak process.

Groundwork for other investigations: new correlations, photon polarization, corrections O(0.5%).

RDK I operated at NIST NCNR cold neutron source. Measured e-γ coincidences followed by delayed proton.

Measured branching ratio:

\[ BR_{RDK\, I} = (3.13 \pm 0.34) \times 10^{-3} \]
\[ BR_{QED} = 2.81 \times 10^{-3} \]


Measurement goal of current run: 1%

Collaboration: NIST, Tulane, Maryland, Michigan, Sussex, Arizona State
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Neutron decay into hydrogen

Production rate: $\sim 4\times10^{-6}$, only 10% end up in 2s state (needed for spin state analysis)

$$p(H) = -p(\bar{\nu}_e) \quad H(H) = \frac{\sigma(H) \cdot p(H)}{|\sigma(H)| \cdot |p(H)|} = 0, -H(\bar{\nu}_e)$$

Left-handed anti-neutrino?

Other application: Search for scalar and tensor couplings, which influence occupation numbers of spin states

W. Schott et al., EPJ A 30, 603 (2006)
Summary

• Rich experimental program with the study of neutron decay correlations

• New physics might be found with precision measurements. Maybe soon!

• Main problem: Neutron lifetime disagreement

Thank you for your interest!!