Precision measurements of neutron beta decay II – Correlations –

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Experimentalist’s approach on neutron decay

• **What can we measure?** \( n \rightarrow p + e + \bar{\nu}_e \)
  - Neutron: spin direction \( \sigma_n \)
  - Proton: momentum \( p_p \)
  - Electron: momentum \( p_e \), spin direction \( \sigma_e \)
  - Neutrino: momentum \( p_\nu = -p_p + p_e \)

• **Possible correlations (this lecture):**
  - 6 twofold: \( \sigma_n \sigma_e \), \( \sigma_n p_e \), \( \sigma_n p_\nu \), \( p_e p_\nu \), ...
  - 4 threefold: \( \sigma_n (\sigma_e \times p_e) \), ...
  - 5 fourfold: \( (\sigma_e p_e) (p_e p_\nu) \), ...
  - 1 fivefold: \( (\sigma_e p_e) \sigma_n (p_e \times p_\nu) \)
  + Deformation of electron spectrum (Fierz term)

• **Further observables:**
  - Lifetime (lecture I)
  - Rare decay modes: \( n \rightarrow H + \bar{\nu}_e \) (branching ratio, H atomic states)
  \( n \rightarrow p + e + \bar{\nu}_e + \gamma \) (branching ratio, even more correlations)
Content

- Principles & Concepts & Tools & Examples
  - PERKEO \( n \): The quest for accuracy

- Status and outlook
The neutron alphabet

- \( \sigma_n, p_e, p_\nu \): Oriented neutrons, momenta of electron and neutrino
  \[
  dW(\langle \sigma_n \rangle | E_e, \Omega_e, \Omega_\nu) \propto G_E(E_e) \cdot \\
  \left\{ 1 + a \frac{p_e p_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \sigma_n \rangle}{\sigma_n} \left( A \frac{p_e}{E_e} + B \frac{p_\nu}{E_\nu} + D \frac{p_e \times p_\nu}{E_e E_\nu} \right) \right\}
  \]

- \( \sigma_e, p_e, p_\nu \): Spin and momentum of electron, momentum of neutrino
  \[
  dW(\langle \sigma_e \rangle | E_e, \Omega_e, \Omega_\nu) \propto G_E(E_e) \cdot \\
  \left\{ 1 + a \frac{p_e p_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \sigma_e \rangle}{\sigma_e} \left( G \frac{p_e}{E_e} + H \frac{p_\nu}{E_\nu} + K \frac{p_e}{E_e} + L \frac{p_e}{E_e} + m_e \frac{p_e p_\nu}{E_e E_\nu} + M \frac{p_e \times p_\nu}{E_e E_\nu} \right) \right\}
  \]

- \( \sigma_n, \sigma_e, p_e \): Oriented neutrons, momentum and spin of electron
  \[
  dW(\langle \sigma_n \rangle, \langle \sigma_e \rangle | E_e, \Omega_e) \propto G_E(E_e) \cdot \\
  \left\{ 1 + b \frac{m_e}{E_e} + \frac{\langle \sigma_n \rangle}{\sigma_n} A \frac{p_e}{E_e} + \frac{\langle \sigma_e \rangle}{\sigma_e} \left( G \frac{p_e}{E_e} + H \frac{p_\nu}{E_\nu} + K \frac{p_e}{E_e} + L \frac{p_e}{E_e} + m_e \frac{p_e}{E_e} + N \frac{\langle \sigma_n \rangle p_e}{E_n} + Q \frac{p_e}{E_e} + R \frac{\langle \sigma_n \rangle \times p_e}{\sigma_n E_e} \right) \right\}
  \]

- \( \sigma_n, \sigma_e, p_e, p_\nu \): Oriented neutrons, spin and momentum of electron, momentum of and neutrino
  \[
  dW(\langle \sigma_n \rangle, \langle \sigma_e \rangle | E_e, \Omega_e, \Omega_\nu) \propto G_E(E_e) \cdot \\
  \left\{ 1 + \text{All terms from above} + \frac{\langle \sigma_n \rangle}{\sigma_n} \left( S \frac{\langle \sigma_e \rangle p_e p_\nu}{E_e E_\nu} + T \frac{p_\nu \langle \sigma_e \rangle p_e}{E_\nu \sigma_e E_e} + U \frac{p_e \langle \sigma_e \rangle p_\nu}{E_e \sigma_e E_\nu} + V \frac{\langle \sigma_e \rangle \times p_\nu}{E_\nu \sigma_e E_\nu} + W \frac{\langle \sigma_e \rangle p_e}{E_e \sigma_e (E_e + m_e)} + p_e \times p_\nu \right) \right\}
  \]


Challenges in $n \rightarrow pev$, $m_n - m_p - m_e = 782$ keV

**Proton energy** $E_p < 751$ eV
- Sensitive to small electric fields
  - Control space charges
  - Control work functions of surfaces
  - Control field leakages
- Acceleration needed prior to detection
- Optimized detectors
  - Low noise, low thresholds, tiny dead layers
  - Specific technologies

**Electron energy** $E_e < 782$ keV
- Range of background from ($n, \gamma$), beta decays
  - Shielding
  - Magnetic fields for Signal/Background
  - Coincidences ($\Delta E-E$ detectors, proton)
- Exposed to backscattering by detector and scattering by windows/materials
  - Backscatter-suppression or detection
  - Proper design of spectrometer

**Long lifetime** $\tau_n \approx 880$ s
- Low decay rate, low statistics
- Low relative decay rate for cold neutrons
  - $\sim 1000$ m/s: $\sim 10^{-7}$/m
- All other neutrons can create background
  - Captures ($n, \gamma$), ...
  - Scattering from apertures $\sim 10^{-3}$
Detector geometry – principles

\[
dW (\langle \sigma_n \rangle | E_e, \Omega_e, \Omega_v) \propto G_E(E_e) \cdot \left\{ 1 + a \frac{p_e p_v}{E_e E_v} + b \frac{m_e}{E_e} + P \left( A \frac{p_e}{E_e} + B \frac{p_v}{E_v} + D \frac{p_e \times p_v}{E_e E_v} \right) \right\}
\]

\[
K_a = \int_{e\text{Det},p\text{Det}} G_E(E_e) \frac{p_e p_v}{E_e E_v} dE_e d\Omega_e d\Omega_v
\]

\[
K_b = \int_{e\text{Det},p\text{Det}} G_E(E_e) \frac{m_e}{E_e} dE_e d\Omega_e d\Omega_v
\]

Often analysis in function of \( E_e \) (i.e. \( K_i = K_i(E_e) \), no integration over \( E_e \))

\[
N_{e,p} \propto 1 + aK_a + bK_b + P(AK_A + BK_B + DK_D)
\]

Asymmetries with neutron spin:

\[
\alpha = \frac{N_{e,p}(P) - N_{e,p}(-P)}{N_{e,p}(P) + N_{e,p}(-P)} \cdot \frac{P(AK_A + BK_B + DK_D)}{1 + aK_a + bK_b}
\]

Goals of detector design:

- Maximize sensitivity to wanted coefficient \( i \)
  - Maximize \( K_i \)
  - Maximize statistics

- Suppress other coefficients
  - Suppress by symmetry or minimize \( K_{j \neq i} \)
Example $D$: Discrete symmetries and detector design

\[ dW \propto 1 + D \frac{\langle \sigma_n \rangle p_e \times p_v}{\sigma_n E_e E_v} \]
Example $D$: Discrete symmetries and detector design

\[ dW \propto 1 + D \left( \frac{\langle \sigma_n \rangle p_e \times p_v}{\sigma_n} \right) \frac{E_e E_v}{E_e E_v} \]

Principle Set-Up

\[ \kappa_\xi = \frac{K_\xi}{1 + aK_a + bK_b} \]

\[ \alpha = \frac{n_{ep} \circ - n_{ep} \otimes}{n_{ep} \circ + n_{ep} \otimes} = DP \kappa_D \]
Example D: Discrete symmetries and detector design

\[
dW(\langle \sigma_n \rangle | E_e, \Omega_e, \Omega_v) \propto G_E(E_e) \cdot \left\{ 1 + a \frac{p_e p_v}{E_e E_v} + b \frac{m_e}{E_e} + \frac{\langle \sigma_n \rangle}{\sigma_n} \left( A \frac{p_e}{E_e} + B \frac{p_v}{E_v} \right) + D \frac{\langle \sigma_n \rangle p_e \times p_v}{\sigma_n E_e E_v} \right\}
\]

P violating, asymmetry with spin flip

**Principal Set-Up**

[Diagram showing particle directions and rotations]

\[
\alpha = \frac{n_{ep} \bigcirc - n_{ep} \bigotimes}{n_{ep} \bigcirc + n_{ep} \bigotimes} = D \kappa_D + A \kappa_A + B \kappa_B
\]

\[
\kappa_\xi = \frac{K_\xi}{1 + aK_a + bK_b}
\]
Example D: Discrete symmetries and detector design

\[
\begin{align*}
    dW(\langle \sigma_n \rangle | E_e, \Omega_e, \Omega_\nu) & \propto G_E(E_e) \cdot \left\{ 1 + a \frac{p_e p_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \sigma_n \rangle}{\sigma_n} \left( A \frac{p_e}{E_e} + B \frac{p_\nu}{E_\nu} \right) + D \frac{\langle \sigma_n \rangle p_e \times p_\nu}{\sigma_n E_e E_\nu} \right\}
\end{align*}
\]

P violating, asymmetry with spin flip

Principle Set-Up

Suppression of parity-violating correlations if detector setup and neutron volume share two orthogonal mirror planes

Breaking of symmetry \(\rightarrow\) Systematic effects

\[
\kappa_\xi = \frac{K_\xi}{1 + aK_a + bK_b}
\]

\[
D = \frac{\alpha^{00} - \alpha^{01} - \alpha^{10} + \alpha^{11}}{4P_\kappa^{00}}
\]
$D$: Detector design – Minimizing and maximizing

$\leftarrow$ Minimize $\kappa_{A,B}/\kappa_D$

$\downarrow$ Maximize Figure of merit $w(P\kappa_D)^2$
$D: \text{ Status}$

**Trine**

- Electron tracking

![Diagram of MWPC and detector setup]

**Leading systematics:**
- Inhomogeneity of MWPC
- Asymmetry of beam profile
- Asymmetry of scintillator

$$D = (-2.8^{+6.4}_{-3.0}\text{stat}^{+3.0}_{-2.8}\text{syst}) \cdot 10^{-4}$$

**emiT**

- Fully exploits geometrical optimization

![Diagram of emiT detector layout]

**Measurements of “0” systematically easier than absolute measurements:**
- One “just” needs a symmetric detector
- Most systematic effects scale with the measured asymmetry

**Theory says:** EDMs are more sensitive than TRI searches in $n$ decay ... 😞
How to measure spin asymmetries

\[ dW(P_n|E_e, \Omega_e) \propto G_E(E_e) \cdot \left(1 + A \frac{P_n p_e}{E_e}\right) \]

(observe only electron \(\rightarrow\) \(\Omega_v\) integrated out. \(\frac{\langle \sigma_n \rangle}{\sigma_n} \equiv P_n\))

\[ N_{\uparrow\downarrow}(E_e) = \text{const} \cdot G_E(E_e) \cdot \int_{\text{Det}} \left\{1 \pm A P_n \beta(E_e) \cos(\mathcal{A}(P_n, p_e))\right\} d\Omega_e \]

\[ \frac{N_{\uparrow\uparrow} - N_{\downarrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow}}(E_e) = A \beta(E_e) k P_n \]

**We need:**

- Polarization \(P_n\)
- Identical polarization (and amount of neutrons) in both states
- Precise detector solid angle with respect to polarized neutrons \(k\)
- Electron energy \(\beta = \beta(E_e)\)

If flipping efficiency (probability that a spin gets flipped) \(f < 1\):

- Polarization after flipper: \(P_\parallel = -(2f - 1)P_\uparrow\)
- Resulting asymmetry:

\[ \frac{N_{\uparrow\uparrow} - N_{\downarrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow}} = A \beta k P_n f \cdot \left[1 - A \beta k P_n (1 - f) + \mathcal{O}(A \beta k P_n (1 - f)^2)\right] \]

Sensitive to neutron flux variations in first order!
How to measure spin asymmetries

\[ dW(P_n|E_e, \Omega_e) \propto G_E(E_e) \cdot \left(1 + A \frac{P_n p_e}{E_e}\right) \]

(observe only electron \( \rightarrow \Omega_v \) integrated out. \( \frac{\langle \sigma_n \rangle}{\sigma_n} \equiv P_n \))

\[ N_{\uparrow1}(E_e) = \text{const} \cdot G_E(E_e) \cdot \int \{1 + AP_n\beta(E_e)\cos(4(P_n, p_e))\} d\Omega_e \]

\[ k_i = k(\text{Det } i, \text{Beam}) = \int_{\text{Det } i} \cos(4(P_n, p_e)) d\Omega_e \]

We need:

- Polarization \( P_n \)
- 2 identical detectors (same efficiency, same response)
- Precise detector solid angle with respect to polarized neutrons \( k \)
- Electron energy \( \beta = \beta(E_e) \)

With different detectors \( k_i \):

\[ \bar{k} \equiv \frac{k_1 + k_2}{2}, \Delta_{k,rel} \equiv \frac{k_1 - k_2}{k_1 + k_2} \]

- Resulting asymmetry:

\[ \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} = A\beta P_n \cdot \left[1 - A\beta \bar{k}P_n \Delta_{k,rel} + \mathcal{O}((A\beta \bar{k}P_n \Delta_{k,rel})^2)\right] \]

Insensitive to neutron flux variations!

But to Det1≠Det2
How to measure spin asymmetries

Two detectors + neutron spin flipping

**Det1**

\[
A_{exp,1} \equiv \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = A\beta k_1 P_n f
\]

**Det2**

\[
A_{exp,2} \equiv \frac{N_{\downarrow\downarrow} - N_{\downarrow\uparrow}}{N_{\downarrow\downarrow} + N_{\downarrow\uparrow}} = -A\beta k_2 P_n f
\]

Note: for D this applies, too:

→ Measures both signs of the asymmetry at the same time

• **Analysis by detector, arithmetic average of both results** \( A = \frac{A_1 + A_2}{2} \) or joint fit

→ Suppresses neutron flux fluctuations in first order

→ Compensates some systematics (e.g. shift of beam towards one detector), depending on experiment

• **Super-ratio of detector rates**:

\[
A_{SR} = \frac{1 - R}{1 + R} = A\beta k P_n, \quad R = \frac{N_{\uparrow\uparrow} N_{\downarrow\uparrow}}{N_{\uparrow\downarrow} N_{\downarrow\uparrow}}
\]

→ Neutron flux fluctuations fully cancel

• Both have similar sensitivity to \( \Delta_k \) and to \( f < 1 \)
Cold neutron polarization in a nutshell

Magnetic mirrors and supermirrors

\[
U = U_{\text{opt}} \mp \mu_n B \\
O(10^{-7}\text{eV}) \quad O(10^{-7}\text{eV}) \quad 10^{-7}\text{eV}
\]

- No passage without reflection
- Typical performance: \(P_{\text{Beam}} \approx 98\%\)

Increase critical angle

Match index of refraction

Polarizing benders

- No passage without reflection
- Typical performance: \(\langle P \rangle \approx 98\%\)

\[
q_0, \Delta q = q_0, \Delta q(\lambda, \theta)
\]

\(P\) wavelength dependent

\(P\) angle dependent

(Average accepted \(\theta\)) \(\lambda\)

(Average accepted \(\lambda\)) \(\theta\)
Neutron polarization and systematics

Beam average may not be relevant!

\[ dW \propto 1 + A \frac{P_n p_e}{E_e} \]

\[ \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \propto A \left( \int_{\text{Det}} P_n p_e d\Omega_e \right) \]

Neutron beams are large, divergent, inhomogeneous

Solutions

1) Detector averages beam (requires mag field)

Detector average of \( P \)

 Beam average of \( P \) \uparrow

 Beam average of \( P \) \uparrow

2) “Perfect” polarization (here: homogeneous)

Detector average of \( P \)

 Beam average of \( P \) \uparrow

 Beam average of \( P \) \uparrow
(Almost) perfect polarization

X-SM geometry

\[ P_X = \frac{P_1 + P_2}{1 + P_1 P_2} \approx 1 - \frac{1}{2} (1 - P)^2 \]

→ Imperfections suppressed quadratically
→ Dependences on \( \lambda, \theta \) strongly reduced

\[ T_{1 \times 2} = T_1 T_2 \]

(Almost) perfect polarization

X-SM geometry

\[ P_x \approx 1 - \frac{1}{2} (1 - P)^2, \quad T_{1\times2} = T_1 T_2 \]

Solid-state polarizer with quartz or sapphire substrate

- Finite minimum angle \( \theta \), thus \( q \)
- \( U_{\text{Substrate}} \geq U_{\text{Fe}} - |\mu_n B| \)
- Strongly reduced \( \lambda, \theta \) dependence
- Compact \( \rightarrow \) high magnetizing field

\[ \langle P \rangle = 99.7\% \]


\[ \langle P \rangle = 99.8\% \]

[Petoukhov et al, Rev. Sci. Instrum. 94 (2023) 023304]
Polarization analysis

$^3$He spin filters $^3$He($n,p$) $^3$H: $\sigma_{\uparrow\downarrow} \gg \sigma_{\uparrow\uparrow}$

- $\sigma_{c,0} = 5333(7)$ barn, $\sigma_{\uparrow\downarrow}/\sigma_{c,0} = 1.010(32)$

\[ T_{\uparrow\uparrow} = \frac{1}{2} \exp(-[\text{He}]\sigma_c(\lambda)(1 \mp P_{\text{He}})) \]

- For unpolarized beam: $O(\lambda) = \frac{0.0733 \ p \ \lambda}{\text{bar cm } \AA}$
  \[ P_n(\lambda) = \tanh(O(\lambda)P_{\text{He}}) \]
  \[ T_n(\lambda) = \exp(-O(\lambda)) \cosh(-O(\lambda)P_{\text{He}}) \]

- Relaxation of hyperpolarized $^3$He polarization:
  \[ P_{\text{He}}(t) = P_{\text{He}}(t) \exp\left(-\frac{t}{t_0}\right) \]

- In-situ flipping of $^3$He spin $\rightarrow$ separation of neutron spin flip efficiency and polarization:
  \[ PA = \frac{n_{\uparrow\uparrow} - n_{\uparrow\downarrow}}{n_{\uparrow\uparrow} + n_{\uparrow\downarrow}}, \quad 2f - 1 = \frac{n_{\uparrow\uparrow} - 2n_{\uparrow\downarrow} + n_{\uparrow\uparrow}}{n_{\uparrow\uparrow} - n_{\uparrow\downarrow}} \]

Performance

- $\sim$Angle-independent

\[ P_n \xrightarrow{O \rightarrow \infty} 1. \quad P_n > 99.99\% \text{ demonstrated:} \]

- Typical numbers: $P_{\text{He}}(0) > 75\%, \ t_0 > 400 \text{ h}$, $P_{\text{He}}$ loss per in-situ $^3$He spin flip: $\lesssim 10^{-5}$

C. Klauser, PhD thesis (2013)

\[ l = 14 \text{ cm} \]
\[ P_{\text{He}} = 1.69 \text{ bar} \]
\[ \chi^2 / \text{ndf} = 18.16 / 23 \]
\[ \text{Prob} = 0.749 \]
\[ P_{\text{He}} = 0.7096 \pm 0.0048 \]
\[ \text{Depol} = 2.335e-05 \pm 7.816e-06 \]
Precise detector solid angle?

Infinitely small and far away

- No integration needed:
  \[ \cos(\angle(P_n, p_e)) = 1 \text{ (if aligned)} \]
- No statistics
- **Approximation:** tracking detector →
  \[ \cos(\angle(P_n, p_e)) \text{ known for each track} \]

Infinitely large

- Integration = mean over hemisphere:
  \[ \langle \cos(\angle(P_n, p_e)) \rangle_{2\pi} = \frac{1}{2} \]
- Full statistics (but dilution factor 1/2)
- **Realization:** Strong magnetic field

In between → Monte Carlo

Requires accurate knowledge of neutron distribution and detector response in space

Neutron beams are large, divergent, inhomogeneous
The beauty of (strong) magnetic fields

- Defined solid-angle integration
- Full beam averaging (if large detector)
- Collection of full statistics
- Transport to detectors far away from beam
- Confinement of backscattered particles, too
- Momentum manipulation by magnetic mirror effect

\[ \sin \vartheta \sin \vartheta_0 = B/B_0 \]

- Magnetic focusing and selection:
  \[ \sin \vartheta_C = \sqrt{B_0/B_1} \]
- Magnetic alignment/collimation
  \( \rightarrow \) Reduced backscattering probability
  \( \rightarrow \) Improved resolution of electrostatic filters
- Magnetic mirror \( \rightarrow \) part of backscattered particles reflected
Parameters of the SM, Sensitivities to $\lambda = g_A / g_V$

\[ a = \frac{1 - \lambda^2}{1 + 3\lambda^2} \]

\[ A = -2 \frac{\lambda(1 + \lambda)}{1 + 3\lambda^2} \]

\[ B = 2 \frac{\lambda(\lambda - 1)}{1 + 3\lambda^2} \]

\[ C = x_C (A + B) \]

\[ \tau = \frac{4908.6(1.9) \text{ s}}{|V_{ud}|^2(1 + 3\lambda^2)} \]

(Lecture I)

$\tau$ and $\lambda$ necessary to determine SM parameter $V_{ud}$

- $a$, $A$ most sensitive for determination of $\lambda$
- $B$, $C$ most suitable to search for new physics

(assuming similar experimental accuracy)
\[ \mathcal{A} : \quad \text{d}W \propto 1 + a \frac{p_e p_\nu}{E_e E_\nu} \]

**e–ν asymmetry and proton spectrum**

- Correlation as spatial asymmetry:
  \[ a \propto \frac{n_{\uparrow \uparrow} - n_{\uparrow \downarrow}}{n_{\uparrow \uparrow} + n_{\uparrow \downarrow}} \]

\[ a > 0 \quad \text{Proton spectrum shifted to higher energy} \]
\[ a < 0 \quad \text{Proton spectrum shifted to lower energy} \]

---

**Two principles of measurement**

- Proton spectrum (Example aSPECT)

\[ a = +0.3 \]
\[ a = -0.103(4) \quad \text{PDG 2008} \]

- **e–p Asymmetry** (example aCORN)

\[ \nu \]

\[ |p_\nu| = \frac{Q - E_e^{\text{rel}}}{c} \]

→ Asymmetry I versus II from \( p \)-TOF

\[ p_{\nu, \perp} \]

\[ p_{\nu} \]

\[ p_e \]

\[ p_{e, \perp} \]
\( a : \text{aSPECT} \)

**Integral proton spectrum from MAC-E filter**

- Magnetic Adiabatic Collimation \( 2.2 \, \text{T} \rightarrow 0.44 \, \text{T} \) sharpens transmission function of electrostatic filter

\[
\begin{align*}
a & = -0.10402(82) \quad (b = 0) \\
\text{and correlated } (a, b) \text{ analysis}
\end{align*}
\]


Beck et al., arXiv:2308.16170

- Stringent requirements on magnetic field, electrodes work functions, detector energy dependence, vacuum, high-voltage stability
\( \langle a \rangle = -0.10859 (125^{\text{stat}})(133^{\text{sys}}) \)

Wietfeldt et al, arXiv:2306.15042
Beta asymmetry $A$

**Early experiments**

- Coincidence of electron and proton (needed close to reactor) to reduce background
  - Proton detection by electron multiplication
  - Electron detection by scintillator

→ Small decay volume, low rate
→ Not compatible with 2 symmetric detectors
→ One needs to collect all protons in order to integrate out neutrino:

$$
\frac{dW}{dE} \propto (\sigma_n | E_e, \Omega_e, \Omega_\nu) \\
\propto \left\{ 1 + a \frac{p_e p_\nu}{E_e E_\nu} + \frac{\sigma_n}{\sigma_e} \left(A \frac{p_e}{E_e} + B \frac{p_\nu}{E_\nu}\right) \right\}
$$

Incomplete collection → systematics from $B$ and $a$

---

Example: First measurement of $A$ ($\& B, D$)

$A = -0.114(19), \frac{\Delta A}{A} = 17%$

[Burgy et al, Phys. Rev. 120 (1960) 1829]
New possibilities and new concept

- Cold neutron guide of 120 m length
- Supermirror polarizer

**PERKEO spectrometer:**

- Longitudinal magnetic field (1.5 T, 1.7 m)
  - Strongly enhanced counting rate
  - Strongly improved signal/background
  - Accurate knowledge of solid angle
  - Reconstruction of electron backscatter events after transport to other detector

- Downstream detector difficult to shield
- Field maximum in center, decreases to both sides to avoid traps
  - Magnetic mirror effect: 10% correction on asymmetry
  - (Inverse) magnetic mirror effect reduces backscattering
- Background subtraction with shutter after pol
  - Downstream beam-related BG not included

\[ A = -0.1146(19), \frac{\Delta A}{A} = 1.7\% \]
Improvements to PERKEO

- Magnetic field perpendicular to neutron beam (1.1 T, Ø of coils 1 m)
  - Detectors at larger distance to beam → Signal/Background in ROI 20:1
  - Decays only close to maximum → Reduced magn. mirror effect

- Two shutters for background estimation
  - Upstream shutter → only environmental background
  - Downstream shutter → (enhanced) beam related background
  - Strong n and γ sources along beam line → same shape as from downstr. shutter (multiple scattering to reach detectors)

→ Extrapolation of background spectrum above beta endpoint into fit region

$A = -0.1189(12), \frac{\Delta A}{A} = 1.0\%$

[A: PERKEO II [1997]

A: PERKEO II [1997 → 2002 → 2013]

Improvements [1997] → [2002]

- Cutter for long wavelengths (>13Å)
  - Suppression of lowly polarized neutrons
- “Horse” for polarization measurement, non-depolarizing chopper
  - Separately benchmarked against $^3$He spin filter and polarized proton spin filter
- Improved beam line and shielding
  - Beam stop further away
  - Removal of scattered neutrons
  → Sg/beam-related Bg improved by factor 3

Improvements [2002] → [2013]

- X-SM polarizer, $^3$He spin filters
  - Strongly reduced spatial and $\lambda_n$ dependence, correction and error
- New beam line PF1B, 4 × higher flux
  - Part traded for systematics (X-SM)
- Further improved beam line and shielding
  → Sg/beam-related Bg improved by factor 8

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<tr>
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<th>[1997]</th>
<th>[2002]</th>
<th>[2013]</th>
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<tbody>
<tr>
<td>Cor [%]</td>
<td>+2.34</td>
<td>+1.4</td>
<td>+0.30</td>
</tr>
<tr>
<td>Err [%]</td>
<td>0.75</td>
<td>0.31</td>
<td>0.14</td>
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<tr>
<td>Polarization</td>
<td></td>
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<tr>
<td>Background</td>
<td>+1.55</td>
<td>+0.5</td>
<td>+0.10</td>
</tr>
<tr>
<td>Detcor [%]</td>
<td>0.45</td>
<td>0.25</td>
<td>0.10</td>
</tr>
<tr>
<td>Detector response</td>
<td>−0.20</td>
<td>−0.24</td>
<td>−0.13</td>
</tr>
<tr>
<td>Detcor [%]</td>
<td>0.25</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>Other systematics</td>
<td>+0.10</td>
<td>0.17</td>
<td>−0.06</td>
</tr>
<tr>
<td>Detcor [%]</td>
<td>0.10</td>
<td>0.17</td>
<td>0.02</td>
</tr>
<tr>
<td>Total systematics</td>
<td>0.91</td>
<td>0.51</td>
<td>0.31</td>
</tr>
<tr>
<td>Detcor [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiative cor.</td>
<td>+0.09</td>
<td>0.05</td>
<td>−0.11</td>
</tr>
<tr>
<td>Statcor [%]</td>
<td>0.42</td>
<td>0.45</td>
<td>0.38</td>
</tr>
<tr>
<td>Total error</td>
<td>1.0</td>
<td>0.68</td>
<td>0.49</td>
</tr>
<tr>
<td>$A$</td>
<td>−0.1189(12)</td>
<td>−0.1189(7)</td>
<td>−0.11972(±53)</td>
</tr>
</tbody>
</table>

A: PERKEO III

• PERKEO II finally limited by statistics. Strong cut in beam divergence to minimize background

• PERKEO III: Accept full beam divergence, long decay volume → Factor 100 in event rate

• Large beam → can accept large gyration radii, lower magnetic field (160 mT), normal conducting

• Detectors can be placed far from beam compared to PERKEO I. However, larger area detectors, downstream detector difficult to shield
A: PERKEO III

• PERKEO II finally limited by statistics. Strong cut in beam divergence to minimize background

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• Detectors can be placed far from beam compared to PERKEO I. However, larger area detectors, downstream detector difficult to shield

A: PERKEO III

2 m
A: PERKEO III

- **Almost monochromatic beam → X-SM polarizer not needed, only single bender**
  - Polarization analysis with opaque $^3$He spin filters, exact mapping of full beam
- **Pulsed beam suppresses beam-related background**
- **Improved detector homogeneity**
- **Blind analysis:** Polarization, Asymmetry and Mirror effect analyzed by independent people, combined only at the end

![Diagram of PERKEO III setup]

- **Longitudinal field → increased magnetic mirror effect and uncertainty ($0.45 \cdot 10^{-3}$)**

<table>
<thead>
<tr>
<th></th>
<th>[2013] Cor [10^{-3}]</th>
<th>Err [10^{-3}]</th>
<th>[2019] Cor [10^{-3}]</th>
<th>Err [10^{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td>+3.0</td>
<td>1.4</td>
<td>+9.07</td>
<td>0.64</td>
</tr>
<tr>
<td>Background</td>
<td>+1.0</td>
<td>1.0</td>
<td>-0.27</td>
<td>0.11</td>
</tr>
<tr>
<td>Detector response</td>
<td>-1.3</td>
<td>2.6</td>
<td>-1.32</td>
<td>0.63</td>
</tr>
<tr>
<td>Other systematics</td>
<td>-0.6</td>
<td>0.2</td>
<td>+4.61</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Total systematics</strong></td>
<td><strong>3.1</strong></td>
<td><strong>1.03</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiative cor.</td>
<td>-1.1</td>
<td>0.5</td>
<td>-1.0</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Statistics</strong></td>
<td><strong>3.8</strong></td>
<td><strong>1.40</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total error</td>
<td>4.9</td>
<td>1.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>$-0.11972^{+53}_{-65}$</td>
<td>$-0.11985(21)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A: Status

PDG world average of $A$

$A = -0.1135(14)$, $\frac{\Delta A}{A} = 1.2\%$

[Yerozolimsky et al (PNPI): Traditional]

$A = -0.1160(15)$, $\frac{\Delta A}{A} = 1.3\%$


[Brown et al: UCNA $\rightarrow$ next slide]
• First measurements of any angular correlation with UCN

• 1 T solenoidal spectrometer with 3 m long UCN decay volume

• Polarization:
  ➢ passage through 7 T magnet
  ➢ AFP spin flipper with single-pass spin-flip efficiency > 99.9%

• Detectors:
  ➢ MWPC (position reconstruction and backscattering identification)
  ➢ Plastic scintillator (timing and energy reconstruction)
Systematics

**Foil at end of UCN decay trap**
- a\ffect\ backscattering and angular acceptance
- Measurements (and MC) with different foils

**Calibration**
- neutron activated Xe gas with MWPC for homogeneity, conversion electron lines for linearity

**Backscattering classification**
- Energy cut on MWPC to statistically assign Type 2/3 events to the correct side, reduces Monte Carlo corrections for backscattering events

**cos θ correction**
- High energy, low pitch angle events more apt to trigger the detectors and carry higher asymmetry information
- Increase measured asymmetry

\[
A = -0.12054(44)^{\text{stat}}(68)^{\text{syst}}, \quad \frac{\Delta A}{A} = 0.7\%
\]

**Super-ratio method**
- Suppression of spin-dependent trap filling

\[
A_{SR} = \frac{1 - \sqrt{R}}{1 + \sqrt{R}}
\]
\[ B: \quad \text{d}W \propto 1 + B \frac{\langle \sigma_n \rangle p_\nu}{\sigma_n E_\nu} \]

Just the same with \( \nu \) detector...

- Opposite e, p detectors: \( p_\nu \)
  reconstruction very sensitive to \( E_e \)

- Measures combination of \( B, a \) and \( A \)
- \( K_B, K_a, K_A \) to be calculated, \( a \) and \( A \) from other experiments

- Dominating systematics:
  - Polarization
  - \( E_e \) energy resolution

\[ B = 0.9801 \pm 0.0025^{\text{stat}} \pm 0.0038^{\text{sys}} \]

Serebrov et al., JETP 86 (1998) 1074
B: \[ dW \propto 1 + B \frac{\langle \sigma_n \rangle p_0}{\sigma_n E_0} \]

Just the same with \( \nu \) detector...

- Opposite e, p detectors: \( p_0 \) reconstruction very sensitive to \( E_e \)
  - Only used for cross-checks in PERKEO II analysis

- e, p in same detector:
  - \( p_0 \) emitted in opposite direction, reconstruction insensitive to \( E_e \)
  - Result of PERKEO II

PERKEO II B (with X-SM)

- \( A \) and \( a \) enter (here in fit function)
- Very clean systematics in principle
- **But:** Very different statistical weight of the two detectors (because of high voltage instabilities) \( \rightarrow \) inefficient compensation of beam displacement in arithmetic mean

\[ B = 0.9802 \pm 0.0034^{\text{stat}} \pm 0.0036^{\text{sys}} \]

$$B: \quad dW \propto 1 + B \frac{\langle \sigma_n \rangle p_\nu}{\sigma_n E_\nu}$$

Just the same with $\nu$ detector...

- Opposite $e$, $p$ detectors: $p_\nu$
  - reconstruction very sensitive to $E_e$
    - Only used for cross-checks in PERKEO II analysis

- $e$, $p$ in same detector:
  - $p_\nu$ emitted in opposite direction, reconstruction insensitive to $E_e$
    - Result of PERKEO II

PERKEO II B (with X-SM)

- $A$ and $a$ enter (here in fit function)
- Very clean systematics in principle
- But: Very different statistical weight of the two detectors (because of high voltage instabilities) $\rightarrow$ inefficient compensation of beam displacement in arithmetic mean

$$B = 0.9802 \pm 0.0034_{\text{stat}} \pm 0.0036_{\text{sys}}$$

Proton asymmetry parameter $C$

- Not included in alphabet
- Proton detection sufficient, in principle
- Related to $A$ and $B$ by kinematics: $C = x_C (A + B)$, $x_C = 0.27484$
  → Access to $B$ without coincidence measurement

$C: \quad dw \propto 1 + C \frac{\langle \sigma_n \rangle p_p}{\sigma_n p_p}$

So far only: Perkeo II B

- Coincident $e$-$p$ detection:
  - Distinguish $p$ from $e$ by TOF
  - Suppresses background, too
  - $a, A, B$ enter (here in fit function)
- Need to integrate out electron
  
  $p_{\uparrow, \downarrow}^1 = \int_{E_e} \left( Q_{\uparrow, \downarrow}^{p1,e1}(E_e) + Q_{\uparrow, \downarrow}^{p1,e2}(E_e) \right) dE_e$
  
  $\alpha^1 = \frac{p_{\uparrow}^1 - p_{\downarrow}^1}{p_{\uparrow}^1 + p_{\downarrow}^1}$

  - Proton efficiency drops out but electron energy integral in two different detectors
  - Electron threshold + lower cutoff by HV
  - Fit theoretical spectra and extrapolate
  - Dominating systematics: $E_e$ calibration & resolution
  - Only one proton detector used for result

\[ C = -0.2377^{+0.0010}_{-0.0024}\text{stat}^{+0.0024}_{-0.0010}\text{sys} \]

How to go further – PERC

• **PERKEO III**: Accept full beam divergence, long decay volume $\rightarrow$ Factor 100 in event rate

• Yet, beam divergence limits length of decay volume. Large beam, low field $\rightarrow$ Large detectors $\rightarrow$ PERC:

  ![Diagram of PERKEO III and PERC](image)

• **Conserve neutron density** by keeping them in guide. Strong field to collect charged decay products
• **Magnetic filter for improved systematics** – compensates absence of upstream detector
• **Pulsed neutron beam** to avoid regions of ill-defined spectrometer response (not needed for all observables)

---

PERC

- Tunable selector field 3...6 T
- **Secondary spectrometers** optimized for observable
- Observables:
  - Electrons: $A, b$
  - Protons: $a, C$
  - Coincidences: no
- Target sensitivity: $\mathcal{O}(10^{-4})$
  - Individual systematic effects for PERC estimated $< 10^{-4}$
  - Depends on secondary spectrometer
- Installation in progress at FRM-II

Wang et al, EPJ Web of Conferences 219 (2019) 04007
BRAND

Measure all correlations simultaneously

• Only existing project with electron tracking and measurement of transversal electron polarisation

• Access to yet unmeasured correlations

• Independent systematics for measured correlations \((a, b, A, B, D)\)

• Based on measurement of \(N, R\) at PSI

• **Target statistical sensitivity:**
  
  ➢ \(5 \cdot 10^{-4}\) for coefficients involving electron polarisation
  
  ➢ A few times \(10^{-5}\) for \(a, A, B, D\)

• First tests of prototype components at PF1B, R&D ongoing

Reminder from start of lecture:

\[
\frac{dW(\langle \sigma_n \rangle, \langle \sigma_e \rangle | E_e, \Omega_e, \Omega_v)}{E_e E_v} \propto G_E(E_e) \cdot \\
\left\{1 + a \frac{p_e p_v}{E_e E_v} + \ldots\right\}
\]
How to go further – ANNI @ ESS (proposal)

Pulsed beams are good for us!

- **Spatial localization** of neutron pulse
  - Separation of beam-related background
  - Separation of ill-defined spectrometer response

- **Separation by neutron wavelength**
  - Velocity dependence of signal and systematics
  - Time-dependent neutron optics
  - Loss-free monochromatization

- **Time localization** of neutron pulse
  - Improved signal/background
  - Suppression of background and drifts with different time constant than signal

ANNI simulated gain factors (@ 5 MW)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Facility</th>
<th>Gain Event rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPDGamma</td>
<td>FnPB (SNS)</td>
<td>27</td>
</tr>
<tr>
<td>PERC</td>
<td>MEPHISTO (FRM II)</td>
<td>15</td>
</tr>
<tr>
<td>PERKEO III</td>
<td>PF1B (ILL)</td>
<td>17</td>
</tr>
<tr>
<td>aSPECT</td>
<td>PF1B (ILL)</td>
<td>1.3</td>
</tr>
</tbody>
</table>

TS et al., EPJ Web of Conferences 219 (2019) 10003
Abele et al, Physics Reports 1023 (2023) 1–84
Status and outlook

Presently most precise experiment

• $\Delta a/a = 8 \times 10^{-3}$ [aSPECT 2020]
• $\Delta b = 0.02$ [PERKEO III 2020]
• $\Delta A/A = 1.7 \times 10^{-3}$ [PERKEO III 2019]
• $\Delta B/B = 5 \times 10^{-3}$ [Serebrov 98, PERKEO II 2008]
• $\Delta C/C = 1\%$ [PERKEO II 2007]
• $\Delta D = 2 \times 10^{-4}$ [emiT 2012]
• $\Delta R = 0.013$ [Kozela 2012]

Ongoing projects

• Nab @ SNS: $a, b$
  ➢ First data taken
  ➢ Goals: $\Delta a/a \approx 0.1\%$, $\Delta b \approx 0.003$
  ➢ Proposal for pNab

• PERC @ FRM-II: $A, b, a, C$
  ➢ Installation in progress
  ➢ Goals: a few times $10^{-4}$

• BRAND @ ILL / ESS: $a, A, B, D, H, L, N, R, S, U, V$
  ➢ R&D ongoing
  ➢ Goals: $a, A, B, D$ : not limited by stat (few times $10^{-5}$)
    $H, L, \ldots$ (with transversal electron polarization): $5 \times 10^{-4}$