Fierz interference term in neutron decay

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Correlation coefficients

Decay rate for polarized neutrons, integrated over electron spin only:

\[
\frac{d^3\Gamma}{dE_e d\Omega_{\nu} d\Omega_e} = \frac{G_F^2 |V_{ud}|^2}{2(2\pi)^5} p_e E_e (E_0 - E_e)^2 (1 + 3|\lambda|^2) \cdot \left( 1 + a \frac{P_e P_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \langle \sigma_n \rangle \left( A \frac{P_e}{E_e} + B \frac{P_\nu}{E_\nu} + D \frac{P_e \times P_\nu}{E_e E_\nu} \right) \right)
\]

- Unitary neutron spin
- Electron asymmetry
- Neutrino asymmetry
- Proton asymmetry
- Triple correlation
- Fierz interference term
- 0 in SM

Neutrino asymmetry
Proton asymmetry
Triple correlation
Fierz interference term

\[f(\lambda)\]

- Wave functions
- Parity-violating constants (Wilson coefficients)
- Scalar, vector, tensor, axialvector and pseudoscalar couplings


Hamitonian

General, Lorentz-invariant description for semileptonic charged current:

\[
H_W = \left( \bar{\psi}_p \psi_n \right) \left( C_S \bar{\psi}_e \psi_\nu + C'_S \bar{\psi}_e \gamma_5 \psi_\nu \right) + \left( \bar{\psi}_p \gamma_\mu \psi_n \right) \left( C_V \bar{\psi}_e \gamma_\mu \psi_\nu + C'_V \bar{\psi}_e \gamma_5 \gamma_\mu \psi_\nu \right) - \frac{1}{2} \left( \bar{\psi}_p \sigma_{\lambda \mu} \psi_n \right) \left( C_T \bar{\psi}_e \sigma_{\lambda \mu} \psi_\nu + C'_T \bar{\psi}_e \sigma_{\lambda \mu} \gamma_5 \psi_\nu \right) - \left( \bar{\psi}_p \gamma_5 \psi_n \right) \left( C_A \bar{\psi}_e \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma_5 \psi_\nu \right) + \left( \bar{\psi}_p \gamma_5 \psi_n \right) \left( C_P \bar{\psi}_e \gamma_5 \psi_\nu + C'_P \bar{\psi}_e \psi_\nu \right)
\]
Fierz interference term

Sensitive to scalar and tensor interaction

\[ b = 2 \frac{C_S + 3\lambda C_T}{1 + C_S^2 + 3\lambda^2 + 3C_T^2} \approx 2 \frac{C_S + 3\lambda C_T}{1 + 3\lambda^2} + O(C_S^2/T) \]

Limit on scalar from super allowed nuclear decays

- Scalar coupling limit from 0+→0+ (global fit to Ft)
- Limit on tensor coupling driven by neutron decay!

Modifies decay rate:

\[ d^3\Gamma \propto \left(1 + b \frac{p}{E_n}\right) \]

PERKEO concept

Analogy to Wu-Experiment from 1956 [1957]

neutron beam experiment:

→ detect charged decay products of neutrons

Decay in magnetic field

- (charged) decay products gyrate to detectors
- full angular coverage

\[ A = A_{\text{theo}} = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \]
\[ \Omega(E_n, \theta) = 1 + \beta(E_n) A_{\text{theo}} \cos \theta \]
\[ A_{\exp} = \frac{N_e^- - N_e^+}{N_e^- + N_e^+} = \beta(E_n) P_n \frac{A_{\text{theo}}}{2} \]

Recent review:
PERKEO III

Central solenoid and two detector vessels
- essential for back scattered electrons
- max. magnetic field in center → magnetic mirror effect

Beam preparation
- Special beam stop
- Collimation with LiF apertures
- Optional polarizer and spin flipper
- Pulsed beam: n velocity selector (5Å)
- Chopper (83Hz)
PERKEO III – Beam time 19/20

From July 19 – Feb 20

Constant personnel
4-5 people
Up to (during core set-up)
12 people
Remote calibration
New Robot for moving 5 radioactive sources

Enables regular measurements
→ Drift, full calibration and 2D scan

Sources on ultra-thin carbon foils
→ Thickness of 4-12 µg/cm²

Sources used:
$^{109}$Cd, $^{139}$Ce, $^{207}$Bi, $^{113}$Sn, $^{137}$Cs
**PERKEO III – Beam time 19/20**

New detectors
- BC440 plastic scintillator (240 x 240 mm)
- 2 x 8 Mesh Photomultipliers (PMTs)

Shorter, thicker light guides and thicker scintillators → increased homogeneity

Larger cooling reservoir for added drift stability
Signal reconstruction

Developed new analysis framework **panter**: Perkeo ANalysis Tool for Evaluation and Reduction (Python)

Detector amplitude from raw data of **one event**

\[ A_{total} = \sum_{i=1}^{2} c_{i,Drift} \sum_{j=1}^{8} c_{ij,Scan2D} \cdot f_{Rate}(A_{ij} - P_{ij}) \]

**Systematics & Corrections**

- Pedestal (electronics self-signal)
- Electronics induced rate dependency
- Dead time correction
- Trigger response
- Calibration source position error
- **Spatial response**
  - Light yield non-linearity (geometric energy dependence)
  - **Drift** (temperature induced gain fluctuations)
- Background (time variation, chopper)
- Calibration
- Missing backscatter energy
- Undetected back scattering
- Trapped electrons
- Edge effect (probability of electron to miss detector)
- (Hidden) polarization
- Scintillator non-linearity
- Radiative corrections

Max Lamparth | Origins RU-A Day | 07.10.21
2D response correction

2D scan with mono energetic beta source
→ create map of peak positions

Causes:
→ Geometric (light distribution)
→ PMT gain tuning
→ Source mispositioning

Uniformity measure:
Mean squared error (MSE) from initial center peak
→ Symmetric response desirable

\[ A_{\text{total}} = \sum_{i=1}^{2} c_{i,\text{Drift}} \sum_{j=1}^{8} c_{i,j,\text{Scan2D}} \int \text{Rate}(A_{ij} - P_{ij}) \]

→ Optimize 2D response with individual PMT gain factor
2D response correction

Optimization
→ non-convex problem
→ highly correlated
→ MCMC and TPE fail (with reasonable trials)
→ Need sample-efficient method

Bayesian optimization
Gaussian processes for posterior distribution
Mixture EI and LCB for acquisition function

Loss/Objective value
\[
\mathcal{L} = \frac{1}{n_{\text{files}}} \sum_{\text{files}} (\mu_{\text{center}} - \mu_i)^2 + \frac{\alpha}{n_{\text{outer}}} \sum_{\text{outer}} (\mu_{\text{left},i} - \mu_{\text{right},i})^2 + \frac{\alpha}{n_{\text{outer}} - 1} \sum_{\text{outer} - 1} (\mu_{\text{top},i} - \mu_{\text{bot},i})^2
\]

Unoptimized:
Symmetry loss 9250

Optimized:
Symmetry loss 670
-93%!
Signal reconstruction

Detector amplitude from raw data of one event

\[ A_{total} = \sum_{i=1}^{2} c_{i,Drift} \sum_{j=1}^{8} c_{ij,Scan2D} \cdot f_{Rate}(A_{ij} - P_{ij}) \]

- due to small temperature changes
- exponential effect on signal

Correct sum over one detector (instead of single PMT)
→ Proven robust

Gaussian process regression to get underlying signal

Drift correction

Gain fluctuations

- due to small temperature changes
- exponential effect on signal

Correct sum over one detector (instead of single PMT)
→ Proven robust

Gaussian process regression to get underlying signal

Drift correction upstream detector
Summary

PerC - next Gen!

Delivered last month!

Promising data
→ Collected 5e8 neutron events
→ good SN, drift control and light yield

Blinded analysis in progress
→ 5e-3 limit in Fierz term seems reachable

Latest results for Fierz interference term
from beta spectrum

\[ b_{UCNA} = 0.067 \pm 0.005_{\text{stat}}^{+0.090}_{-0.061}_{\text{syst}} \]


H. Saul et al., arXiv:1911.01766

from combined A-b

\[ -0.012 < b_{UCNA} < 0.114 \]

\[ 0.035 < b_{PERKEO} < 0.068 \]

@90% CL