$V_{ud}$ from Neutron Decay

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PERKEO III

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Two Experimental Inputs

$V_{ud}$ from neutron decay requires only very few inputs:

\[ V_{ud} = \left( \frac{5099.34 s}{\tau_n (1 + 3\lambda^2)(1 + \Delta_R)} \right)^{1/2} \]

Updated „master formula“ with radiative corrections $\Delta_R$

\[ \Delta_R V_{ud} = 5099.34 \text{s} \]

Neutron lifetime $\tau$

Material storage of UCN,
Magnetical storage of UCN,
In-beam (cold neutrons)

Ratio of axial-vector and vector-couplings $\lambda = g_A/g_V$

Beta-Asymmetry $A$
Electron-Neutrino-Correlation $\alpha$
Others

Many new results!

C.-Y. Seng, M. Gorchtein, M.J. Ramsey-Musolf
Phys. Rev. Lett. 121, 241804 (2018) and

See talk by Mikhail Gorchtein

F. M. Gonzalez et al.,

See talk by Chen-Yu Liu


This talk

Also: percent level LQCD results on $g_A$, many theory articles: Czarnecki et al., Hayen et al., Ivanov et al., Falkowski et al.
Status of Neutron Lifetime

Most precise experimental results using material traps or magnetic traps consistent.

Grey data are not included in world-average. Some re-analyzed, updated, or retracted older measurements.

Magnetic and material bottle measurements in agreement with SM prediction based on nuclear $F_t$ values and $\lambda$: mostly excludes exotic new decay channels.


PDG avg. currently does not consider beam.

Neutron Lifetime: Material Storage; Bottle Method

Measure lifetime by relative comparison of number of stored neutrons $N$ after different storage times $t$

$$\frac{1}{\tau_m} = \frac{1}{t_2 - t_1} \cdot \ln \frac{N(t_1)}{N(t_2)}$$

**Measured** storage time is (potentially) modified by systematic effects: wall-losses, UCN-leaks, rest gas interaction, …

$$\frac{1}{\tau_m} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\text{wall}}} + \frac{1}{\tau_{\text{leak}}} + \frac{1}{\tau_{\text{vacuum}}} + \ldots$$

Minimize wall losses by choice of material and/or low temperature (since $E_{UCN} \ll k_B T$). Variation of trap size and neutron spectrum.

$\tau = (878.5 \pm 0.8) \text{ s}$
Neutron Lifetime: *Magnetic Storage*

**UCN\(\tau\) at LANL, USA**

Measurement of the neutron lifetime using a magneto-gravitational trap. This avoids material interaction and associated losses.

\[877.75 \pm 0.33\, \text{s}\]

Largest correction to raw result smaller than uncertainty. Most precise result.


See talk by Chen-Yu Liu
Neutron Lifetime: *Beam Method*

![Image of neutron beam experiment](image)

Improved Determination of the Neutron Lifetime

\[ \tau = (877.7 \pm 2.2) \text{ s} \]

BL-2: improved detector, electrostatic trap, electronics, statistics; measurement recommences with availability of neutrons at NIST. Successor BL-3 funded.

Measure lifetime by **absolute** determination of neutron flux and neutron decay rate: slope!

\[ n_\beta = \frac{dN}{dt} = -\frac{N_0}{\tau_n} e^{-\frac{t}{\tau_n}} \]

Lifetime Projects

**PENeLOPE, TUM**
- superconducting multipole magnet, in-situ decay detection

**tauSPECT, Mainz**
- permanent magnet multipole, superconducting magnet, horizontal
- Kahlenberg 10.25358/openscience-5455

**Gravitrap-2, ILL**
- material, giant size
- first result: $\tau_n = 880.7(7)_{\text{stat}}(6)_{\text{sys}}$

**LiNA, J-PARC**
- cold, pulsed beam; TPC with $^4\text{He}$ and He admixture in magnetic field
- Predecessor: Hirota *et al.*, Prog. Theor. Exp. Phys. 12, 123C02 (2020)

**HOPE, ILL**
- permanent magnets, vertical in-situ decay detection

**Successors to UCNtau (Tau2), Ezhov bottle, BL3, …**
Status of $\lambda = g_A/g_V$ from Decay Correlations

All 4 results by PERKEO II, 4 results by UCNA, and the PERKEO III result are consistent - since 1997! (Not pre-2002…)

But disagree with older measurements of beta asymmetry $A$ and new aSpect electron-neutrino correlation $a$ result.

$A_{avg} = -0.11958(21), \quad S = 1.2$

Newer measurements of $A$ have order of magnitude smaller corrections.

UCNA, PERKEO III, aCorn, aSpect: blinded analysis.

(Newer results of UCNA & PERKEO II include older results)

UCNA: A. Saunders, CKM2018
Correlations in Neutron Decay

Determination of $\lambda = g_A/g_V$ from neutron decay via angular correlations; (typically) beta asymmetry $A$, or electron-neutrino correlation $a$:

$$A = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \quad a = \frac{1 - \lambda^2}{1 + 3\lambda^2}$$

Typically, specialised instruments / setups required for different observables.

More on neutron beta decay:
Current Neutron Decay Correlation Experiments

- PERKEO III
  - A, B, C, b
  - ILL

- aCORN
  - a
  - NIST

- UCNA / UCNB
  - A, B, b
  - LANL

- aSpect
  - a
  - ILL

- aSpect
  - NIST

- PERC
  - A, B, C, b
  - MLZ / FRM II

- Nab
  - a, b
  - SNS
PERKEO: Measuring Beta Asymmetry – **Symmetric Layout**

\[
W(\mathcal{G}, E) = 1 + \frac{V}{c} A \cos \mathcal{G}
\]

within Standard Model:

\[
A = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \quad \lambda = \frac{g_A}{g_V}
\]

magnetic field for spin alignment

integration over hemispheres:

\[2 \times 2 \pi \text{ detection}\]

experimental asymmetry, polarisation \(P\)

\[
A_{\exp} = \frac{N|^\uparrow - N|^\downarrow}{N|^\uparrow + N|^\downarrow} = \frac{1}{2} \frac{V}{c} PA
\]

**symmetric layout enables detection of backscattered electrons**
Spectrometer PERKEO III

- ~50,000 decays/s in polarised continuous beam; time avg. ~200 s⁻¹ in polarised pulsed mode,
- ~800 s⁻¹ in unpolarised pulsed mode
Background Subtraction with Pulsed Neutron Beam

Free neutron pulse does not interact with matter during measurement.

Same background condition in *signal* and *background time window*.

**Related Uncertainties:**
- Time dependence
  \[ \Delta A/A = 0.8 \times 10^{-4} \]
- Chopper disc uniformity
  \[ \Delta A/A = 0.7 \times 10^{-4} \]
Summary of Corrections and Result

**Corrections** to the „raw“ fit result on the $10^{-3} – 10^{-4}$ level only.

**Analysis blinded** to remove potential bias.
Separate analyses by independent teams:
- electron and background measurements,
- neutron polarisation: opaque $^3$He spin filters,
- magnetic mirror effect.

\[
\lambda = -1.27641(45)_{\text{stat}}(33)_{\text{sys}} \\
= -1.27641(56) \\
A = -0.11985(17)_{\text{stat}}(12)_{\text{sys}} \\
= -0.11985(21). \\
\]

\[\frac{\Delta \lambda}{\lambda} = 4.4 \times 10^{-4}\]


**BSM analysis including scalar & tensor couplings (Fierz term):**

\[A_{\exp}(E_e) = \frac{N^\downarrow(E_e) - N^\uparrow(E_e)}{N^\downarrow(E_e) + N^\uparrow(E_e)} = \frac{1}{2} P_n \gamma A_c\]

6×10^8 events, 
\[(\Delta A/A)_{\text{stat}} = 14 \times 10^{-4}\]
**aSPECT at ILL**

**MAC-E type spectrometer to derive electron-neutrino correlation from proton spectrum**

**Multiple configurations**: runs with changes of measurement configuration from optimum:
Total $10^9$ events in analysis

**Multidimensional fit** to determine instrument parameters:
- 144 data points int. proton spectrum, 192 auxiliary measurements & MC results;
- 68 fit parameters.
- Scale error to account for red. $\chi^2$

$$a = -0.10430(84), \Delta a/a = 0.8\%$$
$$\lambda = -1.2677 \pm 0.0028$$


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Nab at SNS

Running at the Spallation Neutron Source, Oak Ridge, TN

Determine $a$ from slope of cuts through Dalitz plot. Determine electron energy from Si detector, proton energy from time-of-flight.

Goal of current measurement run

\[
(\Delta a/a) = 2 \cdot 10^{-3}
\]

\[
(\Delta \lambda/\lambda) = 5 \cdot 10^{-4}
\]

pNab proposal:

\[
(\Delta A/A)_{\text{stat}} = 8 \cdot 10^{-4}
\]

\[
(\Delta \lambda/\lambda)_{\text{stat}} = 2 \cdot 10^{-4}
\]

Fry et al., EPJ Web Conf. 219, 04002 (2019)
Počanić et al., NIM A 611, 211 (2009)
PERC Facility at MLZ

Innovative concept

- Cold (pulsed) neutron beam (MEPHISTO / hall east)
- Non-depolarising neutron guide as active volume
- Magnetic filter ($B_1 = 3 - 6$T) to enhance systematics
- Source of electrons and protons to user-spectrometers

Goal:

$$\frac{\Delta A}{A} = 5 \cdot 10^{-4}$$

$$\frac{\Delta \lambda}{\lambda} = 1 \cdot 10^{-4}$$

X. Wang, C. Ziener et al. (PERC Collaboration), EPJ Web Conf. 219, 04007 (2019)
PERC Magnet Delivered!

PERC’s main component, a 12m long superconducting magnet system, arrived at FRM II, Garching.
Proposed Cold Beamline for Particle Physics at ESS

Particle Physics Beamline at the European Spallation Source

ESS design goal is same time average neutron flux as ILL. Peak brightness in pulse: $30 \times$ ILL

Using pulsed beam for particle physics already at reactor sources!

Statistics gain factor for a PERC-like system: $x \ 15$ !

ANNI – *A pulsed cold neutron beam facility for particle physics at the ESS*  

General purpose particle physics beam line:

Neutron beta decay, EDM, hadronic weak interaction, Baryon number violation, …

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Neutron and $V_{ud}$ Summary and Outlook

**Breakthrough result in neutron lifetime**

UCN\(\tau\) halves the error on neutron lifetime: \(\tau_n = 877.75(33)\)s  
Bottle measurements (magnetic and material) mostly consistent: \(\tau_n = 878.5(5)\)s, \(S = 1.9\)  
Tension with beam measurement remains: improved BL-2 measurement ongoing

**Ratio of axial-vector and vector coupling**

PERKEO III result improves world-average of beta asymmetry by factor 5,  
\[ A = -0.11958(21), \, S = 1.2 \quad \lambda_A = -1.2757(5) \]  
Tension in particular with aSPECT result on electron-neutrino correlation:  
\[ \lambda_{\text{avg}} = -1.2754(13), \, S = 2.7 \]

**Matrix element $V_{ud}$ from neutrons competitive!**

Beta asymmetry:  
\[ V_{ud} = 0.97408(11)_{RC}(28)_{\tau}(32)_{\lambda} = 0.97408(44) \]  
All data:  
\[ V_{ud} = 0.97427(11)_{RC}(28)_{\tau}(82)_{\lambda} = 0.97427(88) \]  
Nuclear decays  
\[ V_{ud} = 0.97373(31) \quad \text{Hardy & Towner, Phys. Rev. C 102, 045501 (2020)} \]  

Improved experiments running or under construction,