Evaluating $V_{ud}$ from neutron beta decays

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Why evaluate $V_{ud}$ from neutron beta decay . . .

. . . when $V_{ud}$ is so exceptionally well determined in superallowed $0^+ \rightarrow 0^+$ Fermi nuclear beta decays?
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Because measurements of neutron beta decay:

1. are free of nuclear structure and nuclear isospin corrections present in SAF nuclear beta decays, and
2. are part of a larger program of searches for evidence of physics beyond the standard model ("broad band" of new physics, including tensor interactions, MSSM and RH SM extensions),
3. provide information of interest to astrophysics.
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3. provide information of interest to astrophysics.

Items 2 and 3 will not be discussed in this presentation.
Outline

Neutron decays as a probe of CKM unitarity

- basics of neutron beta decay
- measurements of the neutron lifetime
- measurements of the relevant correlation parameters in neutron decay
- outlook

Remarks on an alternative

- pion beta decay

(prompted by Augusto Ceccucci in his talk on Monday)
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Available neutron beta decay channels/final states

**Continuum-state $\beta^-$ decay**

\[ n \rightarrow p + e + \bar{\nu}_e \]

**Bound-state $\beta^-$ decay**

\[ n \rightarrow H + \bar{\nu}_e \]

**Radiative $\beta^-$ decay**

\[ n \rightarrow p + e + \bar{\nu}_e + \gamma, \]
\[ n \rightarrow H + \bar{\nu}_e + \gamma \]
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Focus of this presentation (almost exclusively)

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D. Počanić (UVa)
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Dynamics and observables

Basic beta decay Lagrangian for a baryon

\[ \mathcal{L}_W(x) = -\frac{G_F}{\sqrt{2}} V_{ud} \left[ \bar{\psi}_p(x) \gamma_\mu (1 + \lambda \gamma^5) \psi_n(x) \right] \left[ \bar{\psi}_e(x) \gamma_\mu (1 + \gamma^5) \psi_\nu(x) \right] \]

\[ = -\frac{1}{\sqrt{2}} \left[ \bar{\psi}_p(x) \gamma_\mu (g_V + g_A \gamma^5) \psi_n(x) \right] \left[ \bar{\psi}_e(x) \gamma_\mu (1 + \gamma^5) \psi_\nu(x) \right] \]

where \( g_V = G_F V_{ud} = G_F G_V \) and \( g_A = G_F V_{ud} \lambda = G_F G_A \).

\[ \text{Rate of neutron decay/lifetime is given by:} \quad \Gamma = \frac{1}{\tau_n} = (1 + 3 \lambda^2) G_F^2 V_{ud}^2 \pi \frac{1}{3} f \frac{Z}{F} = \text{Fermi}(E_{\text{max}}) \]
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where \( g_v = G_F V_{ud} = G_F G_V \) and \( g_A = G_F V_{ud} \lambda = G_F G_A \).

\[ G_F \approx 1.1664 \times 10^{-11} \text{ MeV}^{-2} \] (for our purposes, infinitely well determined in \( \mu \) decay)

\[ \lambda \approx -1.272 \] (from correlations in \( n \) decay)
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Rate of neutron decay/lifetime is given by:

$$\Gamma = \frac{1}{\tau_n} = (1 + 3\lambda^2) \frac{G_F^2 V_{ud}^2}{2\pi^3} f_{\text{Fermi}}(E_{\text{max}})$$
Extracting $V_{ud}$ from $n$ decay

Evaluating the preceding relation we get:

$$|V_{ud}|^2 = \frac{4908.7(1.9) \text{sec}}{\tau_n (1 + 3\lambda^2)}, \text{ or}$$

$$\tau_n^{-1} = \text{const.} (G_V^2 + 3G_A^2)$$
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We therefore need to measure:

- neutron lifetime $\tau_n$ (counting neutrons)
- ratio $\lambda = G_A/G_V$ (decay correlations)
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Key questions:

- How thick (uncertain) are the $\tau_n$ ellipse and the $\lambda$ line?
- How reliable and consistent are the results from different methods of $\tau_n$ and $\lambda$ evaluation?
Tools at our disposal:

Cold neutrons

- Wavelength (Å)
  - $10^{-4}$
  - $10^{-3}$
  - $10^{-2}$
  - $10^{-1}$
  - $10^{0}$
  - $10^{1}$
  - $10^{2}$
  - $10^{3}$

- Velocity (m/s)
  - $10^{4}$
  - $10^{5}$
  - $10^{6}$
  - $10^{7}$

- Kinetic energy (eV)
  - $10^{-9}$
  - $10^{-8}$
  - $10^{-7}$
  - $10^{-6}$
  - $10^{-5}$
  - $10^{-4}$
  - $10^{-3}$
  - $10^{-2}$
  - $10^{-1}$
  - $10^{0}$
  - $10^{1}$
  - $10^{2}$
  - $10^{3}$
  - $10^{4}$
  - $10^{5}$
  - $10^{6}$
  - $10^{7}$

- Neutron categories:
  - Ultra Cold
  - Very Cold
  - Cold
  - Thermal
  - Epithermal
  - Fast
Neutron lifetime
Neutron lifetime measurement methods:

Cold neutron decay in flight (beam method):

Ultracold neutron (UCN) decay in a material bottle:

UCN decay in a magneto-gravitational trap:
Beam method: example NIST BL experiment

- Number of trap electrodes can be varied, and the fiducial volume shifted. $N_p$ is fitted against the number of trap electrodes to reduce effects of finite fiducial volume; also fitted against backscatter fraction.

- Neutron beam normalization presents a key systematics challenge; recent breakthrough in calibration [Yue et al., PRL 111 (2013) 222501].

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Vud from neutron decay

Neutron lifetime

30 Nov '16
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Neutron lifetime: material bottle method

Example: ILL – PNPI UCN bottle experiment

[Serebrov et al., PR C 78 (2008) 035505]

- cryogenic perfluoropolyether (fluoropolymer) oil wall coating to minimize wall losses
- rotate bottle to allow high energy UCNs to escape, to vary neutron velocity spectrum
- two storage bottles: one large spherical, second one smaller and cylindrical, to very surface/volume ratio.
\( \tau_n \) magnetic bottle method: example UCN\( \tau \) exp./LANSCE

- magnetic storage to reduce corrections due to losses;
- improved systematics;
- must ensure that UCN energy distribution is truly stochastic;
- still no picnic!
History of neutron lifetime results

![Graph showing the history of neutron lifetime results. The x-axis represents the year, and the y-axis represents the neutron lifetime in seconds. The graph includes data from different methods: beam method, UCN bottle, and magnetic trap. The data points are marked with error bars and color-coded to distinguish between the methods. The graph is courtesy of Fred Wietfeldt.](image-url)
Current status of the neutron lifetime

![Graph showing current status of neutron lifetime with specific data points and markers for different experimental conditions.](image)
Neutron lifetime: PDG view

Citation: C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016)

WEIGHTED AVERAGE
880.2±1.0 (Error scaled by 1.9)

χ²  
18.2
(Confidence Level = 0.0027)

875 880 885 890 895 900
neutron mean life (s)
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PDG mean $\tau_n$ essentially dominated by bottle results!

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PDG mean $\tau_n$ essentially dominated by bottle results!

Are beam method measurements irrelevant?

| Author            | Year | CNTR | $\chi^2$ |
|-------------------|------|------|----------|
| ARZUMANOV         | 15   | CNTR | 0.0      |
| YUE               | 13   | CNTR | 11.2     |
| STEYERL           | 12   | CNTR | 1.3      |
| PICHLMAYER        | 10   | CNTR | 0.1      |
| SEREBROV          | 05   | CNTR | 4.9      |
| BYRNE             | 96   | CNTR |          |
| MAMPE             | 93   | CNTR | 0.8      |

$\chi^2 = 18.2$

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Neutron decay correlations
Neutron beta decay correlation observables (SM)

\[
\frac{d^5 \Gamma}{dE_e d^2 \Omega_e d^2 \Omega_\nu} = \xi(E_e) \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} \right) + \ldots \right]
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where

\[
\xi(E_e) = \frac{G_F^2 V_{ud}^2}{32\pi^5} p_e E_e (E_0 - E_e)(1 + 3\lambda^2) f_{\text{Fermi}}^{Z=1}(E_e)
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In SM:

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a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \quad A = -2 \frac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2}
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B = 2 \frac{|\lambda|^2 - Re(\lambda)}{1 + 3|\lambda|^2} \quad \lambda = \frac{G_A}{G_V} (\text{with } \tau_n \Rightarrow \text{CKM } V_{ud})
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also proton asymmetry: \( C = \kappa (A + B) \) where \( \kappa \simeq 0.275 \).
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\( \Rightarrow \) **SM overconstrains** \( a, A, B \) observables in n \( \beta \) decay!

Fierz interf. term \( b \) brings add’l. sensitivity to non-SM processes!
In unpolarized neutron decay:

- electron–neutrino correlation

In polarized neutron decay:

- beta (electron) asymmetry
- (anti)neutrino asymmetry
- proton asymmetry

Parameters $a$, $A$, $B$ are all independent functions of $\lambda = \frac{G_A}{G_V}$.

$C$ is a superposition of $A$ and $B$.

Note: If $n$, $p$ were not hadrons (e.g., if they were leptons), we’d have $G_V = 1$ and $G_A = -1$; the deviations reflect the hadronic nature of the nucleons.
Neutron decay correlation parameters visualized

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In polarized neutron decay:

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- \( B \) ... (anti)neutrino asymmetry
- \( C \) ... proton asymmetry

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Sensitivity to $\lambda$

The current world averages are approximately:

\[ a = -0.103(4) \quad A = -0.118(1) \quad B \simeq 0.981(3) \]
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Recall that without hadronic properties we would have:

$$a \equiv A \equiv 0 \quad B \equiv 1.$$
Sensitivity to $\lambda$

The current world averages are approximately:

$$a = -0.103 (4) \quad A = -0.118 (1) \quad B \approx 0.981 (3)$$

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Sensitivity to $\lambda = G + A/G_V$:

$$\frac{da}{d\lambda} \approx -0.30 \quad \frac{dA}{d\lambda} \approx -0.37 \quad \frac{dB}{d\lambda} \approx -0.076$$
Sensitivity to $\lambda$

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In fact, majority of information on $\lambda$ comes from $A$, the beta asymmetry.

The recent decade has witnessed a strong push on measurements of $a$. 
On the measurements of $A$ (the two most recently published results)

**PERKEO II (2013)** $\frac{d\lambda}{\lambda} = 0.11\%$

**UCNA (2013)** $\frac{d\lambda}{\lambda} = 0.24\%$

### Cold Neutron Beam (at ILL)

- Decay rate: $\sim 375 \text{ s}^{-1}$
- Polarization: 99.7(1)
- (Crossed SM polarizer, AFP flipper, 3He analyzer)
- Background Corr: 0.09(9)\%
- Scattering Corr.: 0.08(8)\%
- Mirror Effect: 0.6(2)\%
- $A\beta = -0.11972(63,-55)$

### Ultracold Neutrons (at LANL)

- Decay rate: $\sim 30 - 60 \text{ s}^{-1}$
- Polarization: 99.33(56)
- (Magnetic retarding pot. Polarizer/analyzer, AFP flipper)
- Background Corr: 0.01(2)
- Scattering Corr.: 0.15(43)
- Energy Recon: 0.00(31)
- $A\beta = -0.11954(55)_{\text{stat}}(98)_{\text{sys}}$
Example of a measurement: aCORN at NIST

actual design:

- uses a portion of the full $p$-$e$ phase space (only the region with $|\cos \theta_{e\nu}| \simeq 1$; see Nab slides),
- demanding systematics,
- being moved to new NG-C beamline.
Future of a measurement: Nab at SNS

NB: For a given $E_e$, $\cos \theta_{ev}$ is a function of $p_p^2$ only.
Future of a measurement: Nab at SNS

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Slope $\propto a$

Numerous consistency checks are built-in!
Nab principles of measurement

- Collect and detect both electrons and protons from neutron beta decay.
- Measure $E_e$ and $\text{TOF}_p$ and reconstruct decay kinematics.
- Segmented Si det’s:

Mounting at SNS in 2017
Summary of $\lambda = G_A/G_V$ values

PERKEO II (2013)
UCNA (2013)
UCNA (2010)
Average: $-1.2724(21)$
PERKEO II (2002)
Mostovoi (2001)
Yerosolimskii (1997)
PERKEO I (1986)
Stratowa (1978)

$\Delta \lambda/\lambda = 0.03\%$ (Nab goal)

PDG value slightly different;

Confidence Level $= 2 \times 10^{-4}$
Combining the $\tau_n$ and $\lambda$ values

Recall the combined plot:

It’s time to zoom in on the red circle.

$\Rightarrow$ Need OOM improvement in $\lambda$, and $\tau_n$ inconsistencies to be resolved.
Combining the $\tau_n$ and $\lambda$ values

⇒ Need OOM improvement in $\lambda$, and $\tau_n$ inconsistencies to be resolved.

D. Počanić (UVa)
# Ongoing and planned neutron $\beta$ decay measurements

| experiment  | obs. | uncert. | technique                  | facility/group       |
|-------------|------|---------|----------------------------|----------------------|
| BL2         | $\tau$ | 1 s     | cold $n$ beam              | NIST                 |
| BL3         | $\tau$ | $< 0.3$ s | cold $n$ beam              | NIST                 |
| JPARC       | $\tau$ | $< 0.3$ s | cold $n$ beam              | J-PARC               |
| Gravitrap   | $\tau$ | 0.2 s   | UCN/material bottle        | ILL and PNPI         |
| Ježov       | $\tau$ | 0.3 s   | UCN/magnetic bottle        | ILL                  |
| HOPE        | $\tau$ | 0.5 s   | UCN/magnetic bottle        | ILL (supertherm. src.)|
| PENELLOPE   | $\tau$ | 0.1 s   | UCN/magnetic bottle        | TU Munich            |
| Mainz       | $\tau$ | 0.2 s   | UCN/magnetic bottle        | Mainz TRIGA source   |
| UCN$\tau$   | $\tau$ | $\ll 1$ s | UCN/magnetic bottle        | LANSCE UCN source    |
| UCNA        | $A$   | 0.2%     | UCN                        | LANSCE UCN source    |
| PERKEO III  | $A$   | 0.19%    | cold $n$ beam              | ILL and MLZ (Munich) |
| PERC        | $A$   | 0.05%    | cold $n$ beam              | Munich               |
| aCORN       | $a$   | $\sim 1$% | cold $n$ beam              | NIST                 |
| aSPECT      | $a$   | $\sim 1$% | cold $n$ beam              | ILL/Mainz            |
| Nab         | $a$   | 0.1%     | cold $n$ beam              | SNS                  |
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| PENELLOPE   | $\tau$ | 0.1 s   | UCN/magnetic bottle | TU Munich        |
| Mainz       | $\tau$ | 0.2 s   | UCN/magnetic bottle | Mainz TRIGA source |
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**A flurry of activity: stay tuned!**
Pion beta decay

\[ \pi^+ \rightarrow \pi^0 e^+ \nu_e \]
Pion beta: $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ ($\pi_{e3}$) decay rate in the SM

A pure $0^- \rightarrow 0^-$ vector decay (like SAF nuclear decays), but without nuclear-theoretical uncertainties.

$$\Gamma = \Gamma_0(1 + \delta_\pi) = \frac{G_F^2 |V_{ud}|^2 \Delta^5}{30\pi^3} f(\epsilon, \Delta) \left(1 - \frac{\Delta}{2m_+}\right)^3 \left(1 + \delta_\pi\right),$$

where

$$\Delta = m_+ - m_0 = 4.5936(5) \, \text{MeV}, \quad \epsilon = \left(\frac{m_e}{\Delta}\right)^2 \simeq \frac{1}{81} \quad \text{and}$$

$$f(\epsilon, \Delta) = \sqrt{1-\epsilon} \left(1 - \frac{9}{2}\epsilon - 4\epsilon^2\right) + \frac{\epsilon^2}{4} \ln \left(\frac{1 - \sqrt{1-\epsilon}}{\sqrt{\epsilon}}\right) - \frac{3}{7} \frac{\Delta^2}{(m_+ + m_0)^2} \simeq 0.941$$

and $\delta_\pi \simeq 0.035$ is the sum of radiative/loop corrections with $< 0.02\%$ uncertainty.
Pion beta: \( \pi^+ \rightarrow \pi^0 e^+ \nu_e \ (\pi_{e3}) \) decay rate in the SM

A pure \( 0^- \rightarrow 0^- \) vector decay (like SAF nuclear decays), but without nuclear-theoretical uncertainties.

\[
\Gamma = \Gamma_0 (1 + \delta_\pi) = \frac{G_F^2 |V_{ud}|^2 \Delta^5}{30\pi^3} f(\epsilon, \Delta) \left( 1 - \frac{\Delta}{2m_+} \right)^3 (1 + \delta_\pi),
\]

where

\[
\Delta = m_+ - m_0 = 4.5936(5) \text{ MeV}, \quad \epsilon = \left( \frac{m_e}{\Delta} \right)^2 \approx \frac{1}{81} \quad \text{and} \quad f(\epsilon, \Delta) = \sqrt{1 - \epsilon} \left( 1 - \frac{9}{2} \epsilon - 4\epsilon^2 \right) + \frac{\epsilon^2}{4} \ln \left( \frac{1 - \sqrt{1 - \epsilon}}{\sqrt{\epsilon}} \right) - \frac{3}{7} \frac{\Delta^2}{(m_+ + m_0)^2} \approx 0.941
\]

and \( \delta_\pi \approx 0.035 \) is the sum of radiative/loop corrections with \(< 0.02\%\) uncertainty.

Pion beta decay provides the theoretically cleanest access to \( V_{ud} \).

**Huge** fly in the ointment: \( B \sim 10^{-8} \)!
The PIBETA/PEN apparatus

- $\pi E1$ beamline at PSI
- stopped $\pi^+$ beam
- active target counter
- 240-detector, spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms
- stable temp./humidity

Measured $B_{\pi e_3}$ to $\sim 0.5\%$  

[PRl 93 (2004) 181803]
Conclusions and outlook

What would it take to improve the pion $V_{ud}$ significantly?

- A more precise value of $B(\pi^+ \rightarrow e^+ \nu_e)$ — currently under way: PEN and PIENU experiments ($\times 4$−$5$ more precision still needed!).
- $>100$-fold increase in event statistics/rate! Challenging and expensive to achieve; however, substantial additional BSM payoff would result as well!
- Eventually, a more precise value of $\Delta \equiv m_{\pi^+} - m_{\pi^-}$.

⇒ For the time being it makes sense to let the neutron measurements play out before a substantial new effort is initiated on pion beta decay.

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Conclusions and outlook

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Additional slides
aSPECT: a measurement of $a$ at ILL

Use blocking potential to map proton yield as $f(E_p)$:
Nab spectrometer coil design and $\vec{B}$ field profile

\[ \begin{align*}
\text{upper detector} \\
\text{lower detector} \\
\text{NBL} \\
\text{NBU} \\
\text{F} \\
\text{TOF} \quad \text{TOF}' \\
\text{NBU'} \\
\text{NBL'} \\
\text{UDET'} \\
\text{UDET} \\
\text{LDET} \\
\text{LDET'} \\
\text{neutron beam} \\
\end{align*} \]

3.5 m flight path omitted

Magnetic field $B \ [T]$

\[ \begin{align*}
0 & \quad 1 & \quad 2 & \quad 3 & \quad 4 \\
-1 & \quad 0 & \quad 1 & \quad 2 & \quad 3 & \quad 4 & \quad 5 \\
\text{fiducial} \\
\text{volume} \\
\text{lower} \\
\text{detector} \\
\text{upper} \\
\text{detector} \\
\end{align*} \]

\[ \begin{align*}
\text{Magnetic field } B \ [T] \\
0 & \quad 1 & \quad 2 & \quad 3 & \quad 4 \\
\text{fiducial volume} \\
\text{filter} \\
\text{on axis} \\
\text{off axis} \\
\end{align*} \]

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