Evaluating V_{ud} from neutron beta decays

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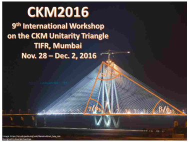
University of Virginia

30 November 2016



9th Int'l. workshop on CKM matrix unitarity
Tata Institute for Fundamental Research
Mumbai, India
28 Nov. – 2 Dec. 2016

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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),
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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

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Remarks on an alternative

- pion beta decay
  (prompted by Augusto Ceccucci in his talk on Monday)

Available neutron beta decay channels/final states

Continuum-state β^- decay

$$n \to p + e + \bar{\nu}_e$$

Bound-state β^- decay

$$n \to \mathrm{H} + \bar{\nu}_e$$

Radiative β^- decay

$$n \to p + e + \bar{\nu}_e + \gamma,$$

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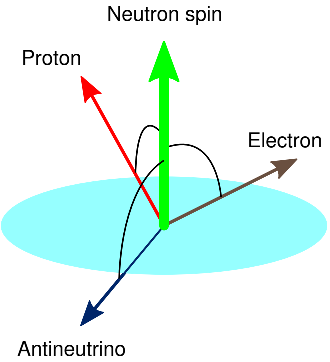


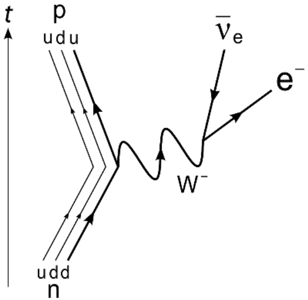
Dynamics and observables

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 $\boxed{g_v = G_F V_{ud} = G_F G_V}$ and $\boxed{g_A = G_F V_{ud}\lambda = G_F G_A}$.



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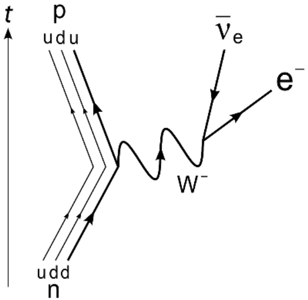

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$\lambda \simeq -1.272$ (from correlations in n decay)

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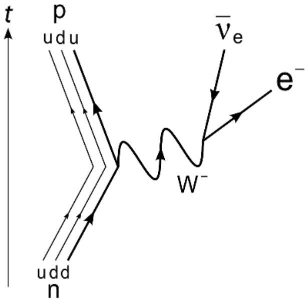

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Rate of neutron decay/lifetime is given by:

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

Extracting V_{ud} from n decay

Evaluating the preceding relation we get:

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

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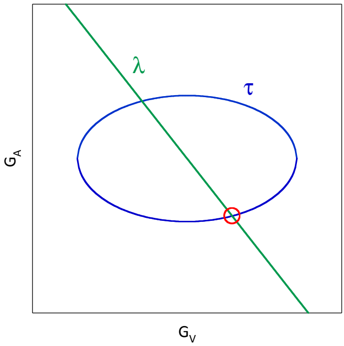

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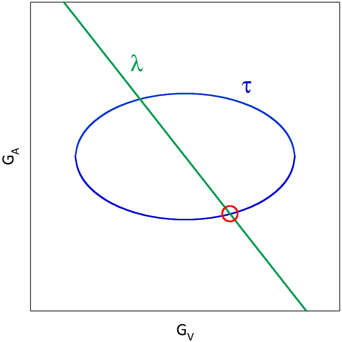

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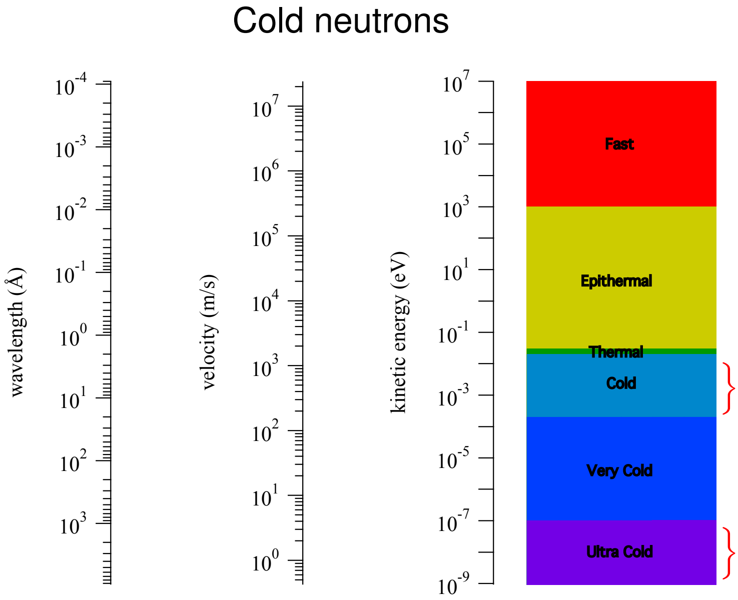
Key questions:

- How thick (uncertain) are the τ_n ellipse and the λ line?
- How reliable and consistent are the results from different methods of τ_n and λ evaluation?

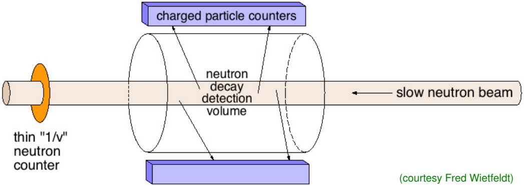
Tools at our disposal:



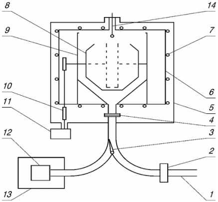
Neutron lifetime

Neutron lifetime measurement methods:

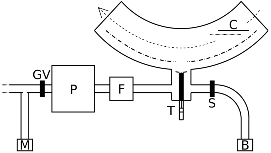
Cold neutron decay in flight (beam method):



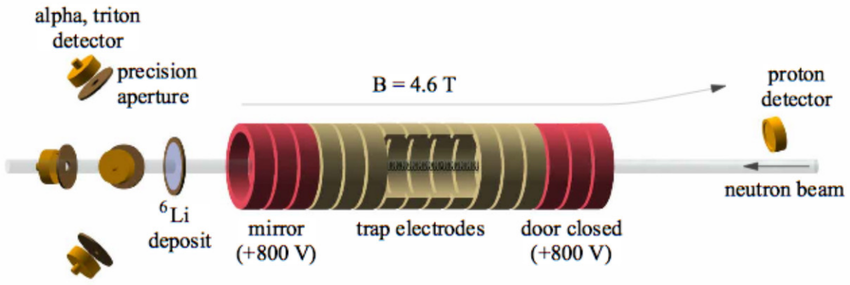
Ultracold neutron (UCN) decay in a material bottle:



UCN decay in a magneto-gravitational trap:



Beam method: example NIST BL experiment



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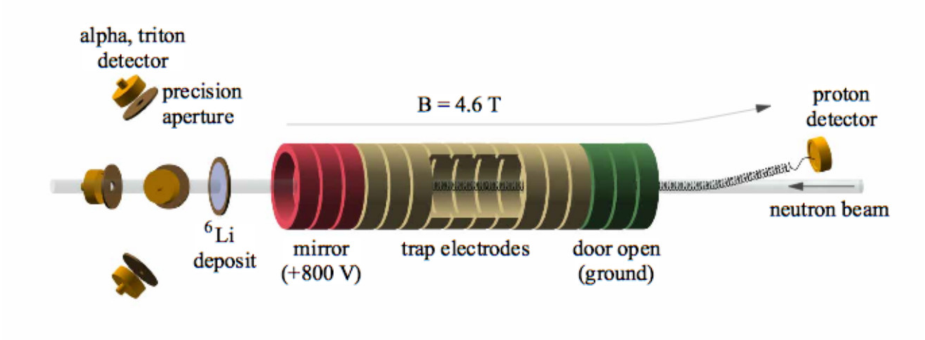

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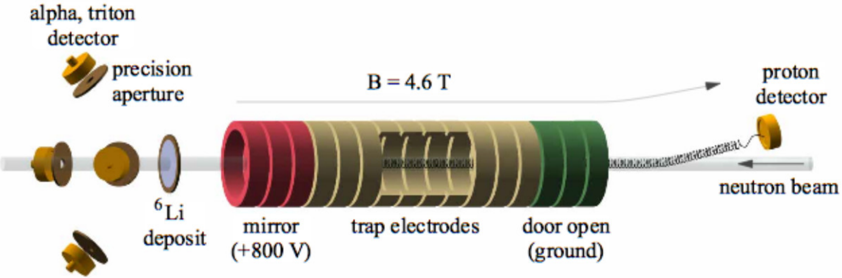
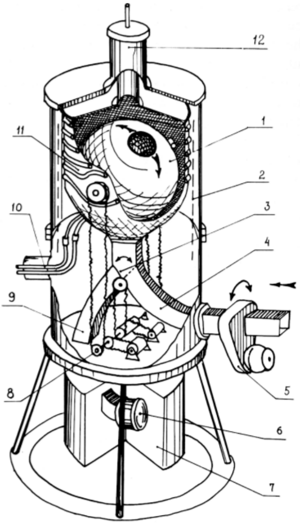


- Number of trap electrodes can be varied, and the fiducial volume shifted. N_p is fitted against the number of trap electrodes to reduce effects of finite fiducial volume; also fitted against backscatter fraction.
- Neutron beam normalization presents a key systematics challenge; recent breakthrough in calibration [Yue et al., PRL **111** (2013) 222501].

Neutron lifetime: material bottle method

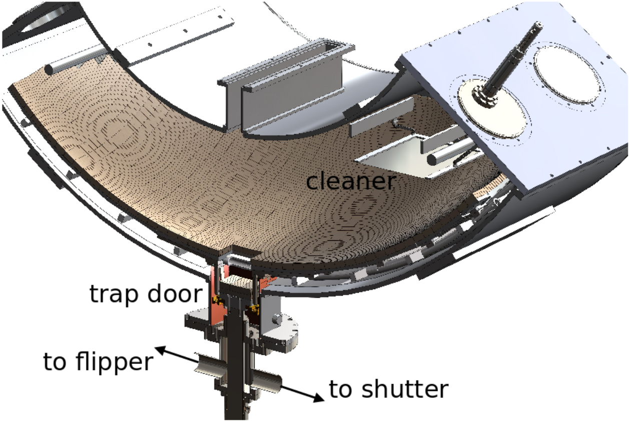


Example: ILL – PNPI UCN bottle experiment

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

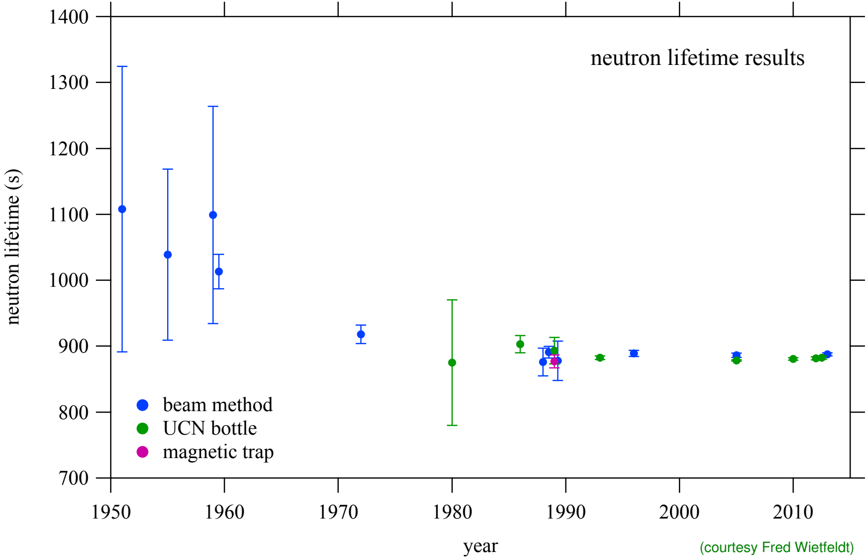
- cryogenic perfluoropolyether (fluoropolymer) oil wall coating to minimize wall losses
- rotate bottle to allow high energy UCNs to escape, to vary neutron velocity spectrum
- two storage bottles: one large spherical, second one smaller and cylindrical, to very surface/volume ratio.

τ_n magnetic bottle method: example UCNτ exp./LANSCE



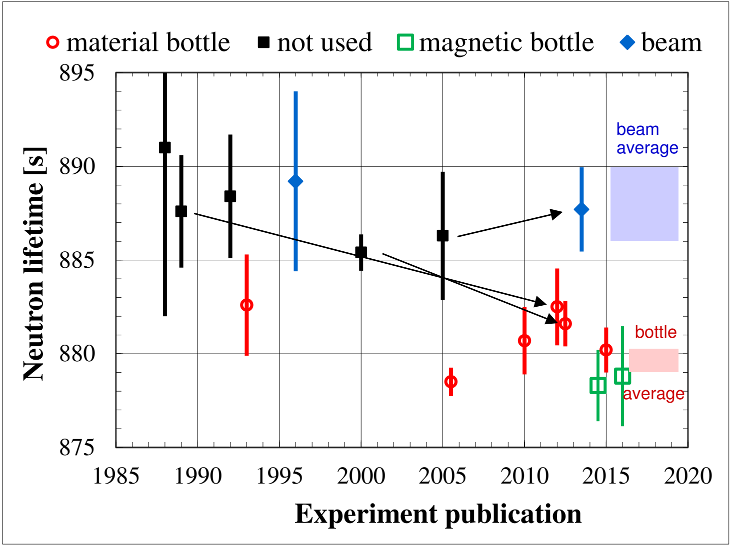
- magnetic storage to reduce corrections due to losses;
- improved systematics;
- must ensure that UCN energy distribution is truly stochastic;
- still no picnic!

History of neutron lifetime results



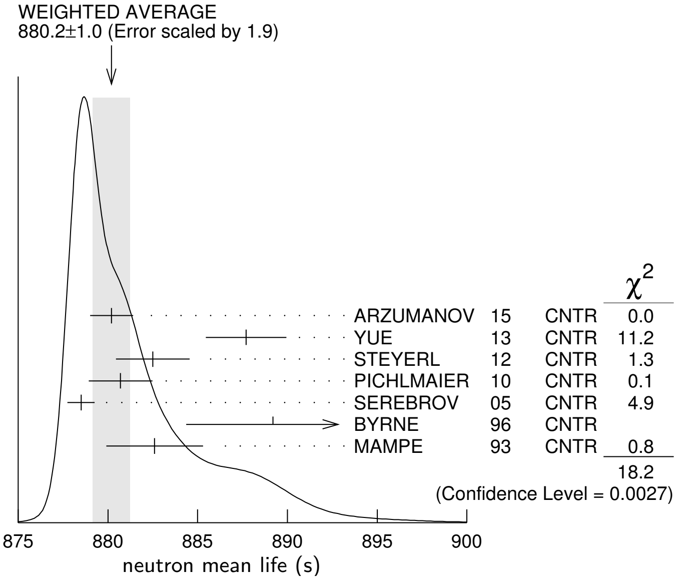
(courtesy Fred Wietfeldt)

Current status of the neutron lifetime



Neutron lifetime: PDG view

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



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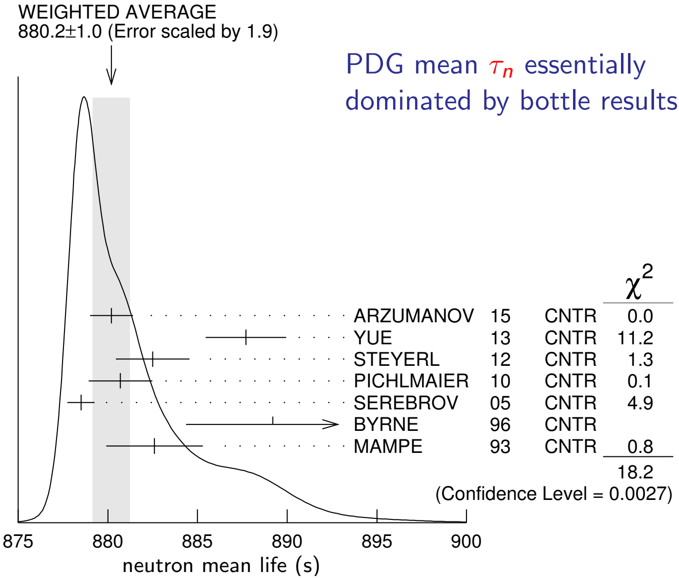

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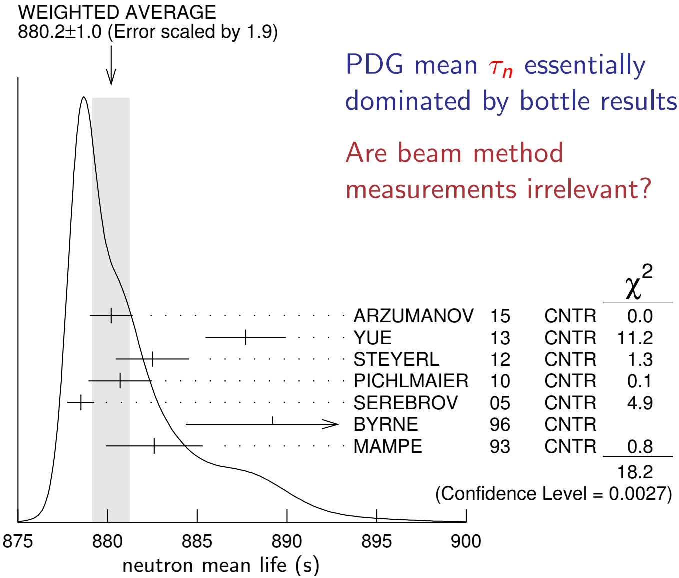

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Are beam method measurements irrelevant?

Neutron decay correlations

Neutron beta decay correlation observables (SM)

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

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:

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad A = -2\frac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2}$$

$$B = 2\frac{|\lambda|^2 - Re(\lambda)}{1 + 3|\lambda|^2} \qquad \lambda = \frac{G_A}{G_V} \text{ (with } \tau_n \Rightarrow \text{CKM } V_{ud}\text{)}$$

also proton asymmetry: $C = \kappa(A + B)$ where $\kappa \simeq 0.275$.

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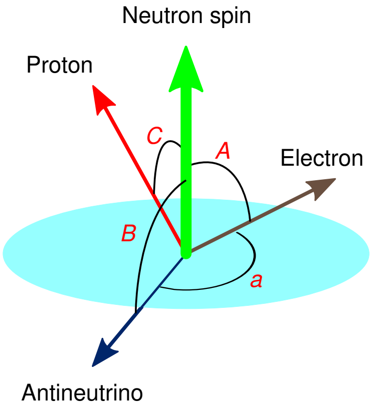
$\Rightarrow$ SM **overconstrains** a, A, B observables in n β decay!
Fierz interf. term b brings add'l. sensitivity to non-SM processes!

Neutron decay correlation parameters visualized



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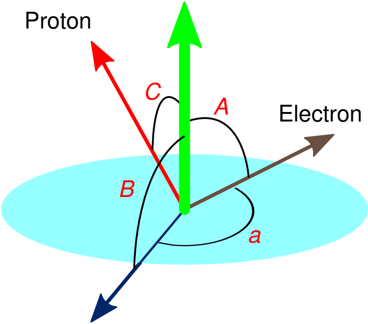

In unpolarized neutron decay:

a ...electron–neutrino correlation

In polarized neutron decay:

A ...beta (electron) asymmetry

B ...(anti)neutrino asymmetry

C ...proton asymmetry

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

[C is a superposition of A and B].

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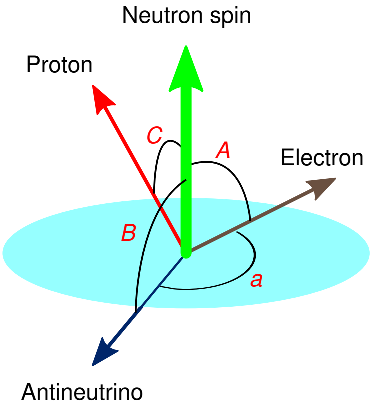

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Note: If n, p were not hadrons (e.g., if they were leptons), we'd have $G_V = 1$ and $G_A = -1$; the deviations reflect the hadronic nature of the nucleons.

Sensitivity to λ

The current world averages are approximately:

$$a = -0.103\,(4) \qquad A = -0.118\,(1) \qquad B \simeq 0.981\,(3)$$

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$$\frac{\mathrm{d}a}{\mathrm{d}\lambda} \simeq -0.30 \qquad \frac{\mathrm{d}A}{\mathrm{d}\lambda} \simeq -0.37 \qquad \frac{\mathrm{d}B}{\mathrm{d}\lambda} \simeq -0.076$$

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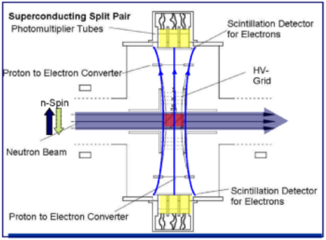
In fact, majority of information on λ comes from A, the beta asymmetry.

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) $d\lambda/\lambda$ =0.11%

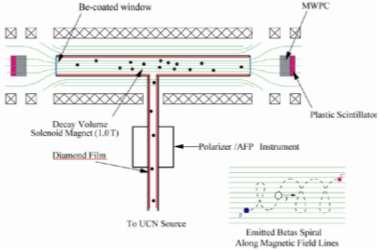


Cold Neutron Beam (at ILL)

Decay rate: ~ 375 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)%

$A\beta$ = -.11972(+63,-55)

UCNA (2013) $d\lambda/\lambda$ =0.24%

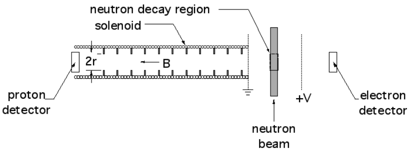


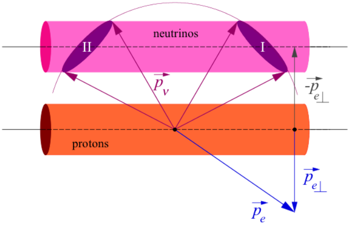
Ulracold Neutrons (at LANL)

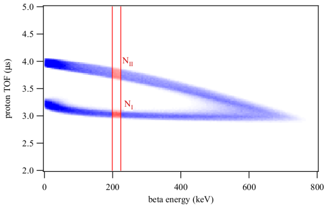
Decay rate: ~ 30 - 60 s^{-1}
Polarization: 99.33(56)
(Magnetic retardiing pot. Polarizer/analyzer, AFP flipper)
Background Corr: 0.01(2)
Scattering Corr.: 0.15(43)
Energy Recon: 0.00(31)

$A\beta$ = -.11954$(55)_{stat}(98)_{sys}$

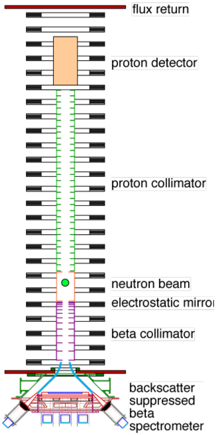
Example of *a* measurement: aCORN at NIST





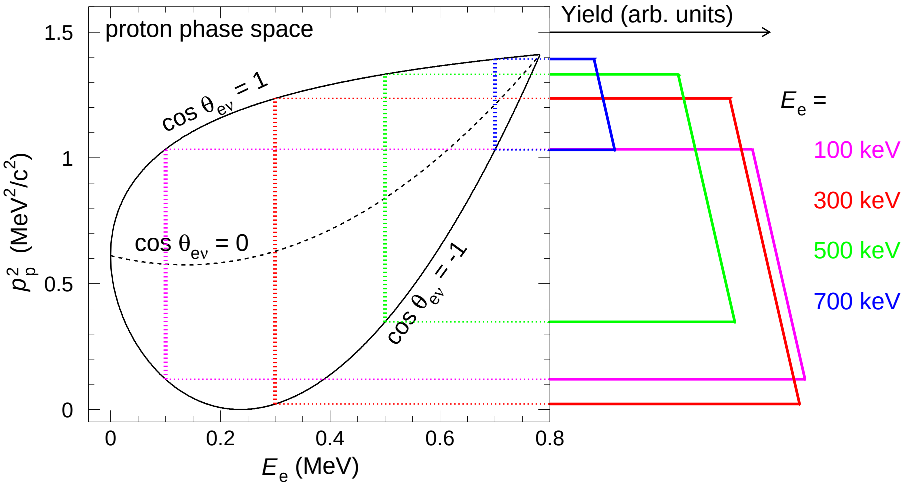


actual design:



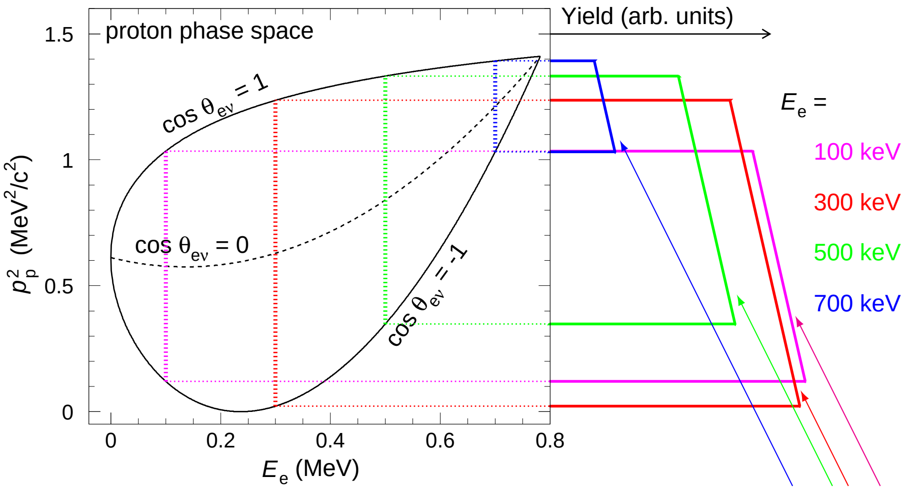
- uses a portion of the full *p*-*e* phase space (only the region with $|\cos\theta_{e\nu}| \simeq 1$; see Nab slides),
- demanding systematics,
- being moved to new NG-C beamline.

Future of a measurement: Nab at SNS



NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

Future of *a* measurement: Nab at SNS



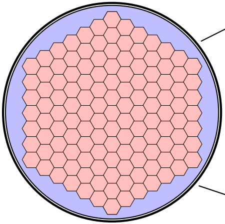
NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

Slope ∝ **a**

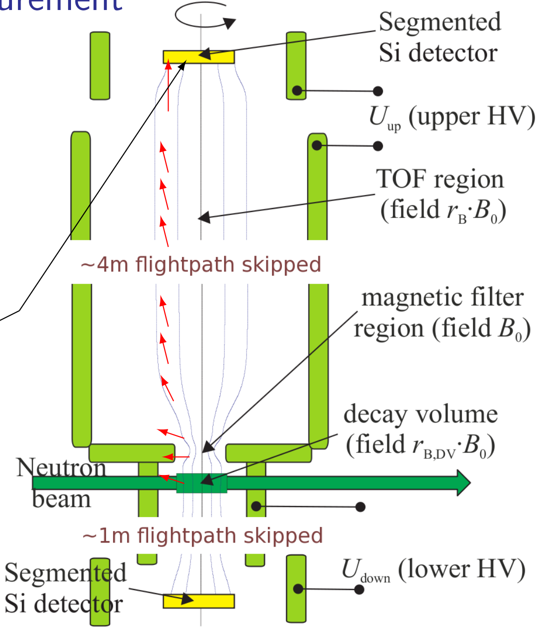
Numerous consistency checks are built-in!

Nab principles of measurement

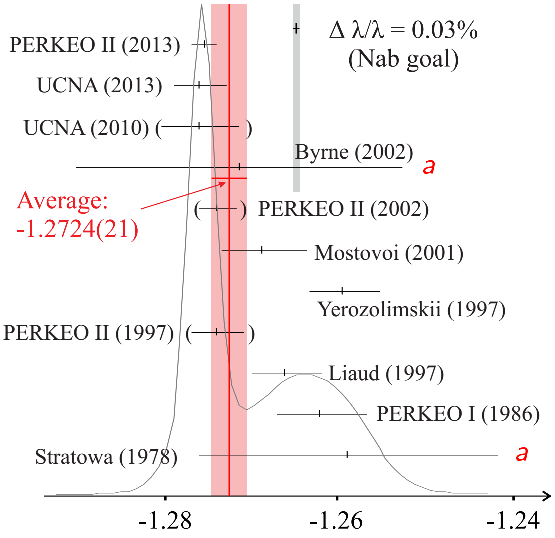
- Collect and detect both electrons and protons from neutron beta decay.
- Measure E_e and TOF_p and reconstruct decay kinematics
- Segmented Si det's:



Mounting at SNS in 2017



Summary of $\lambda = G_A/G_V$ values



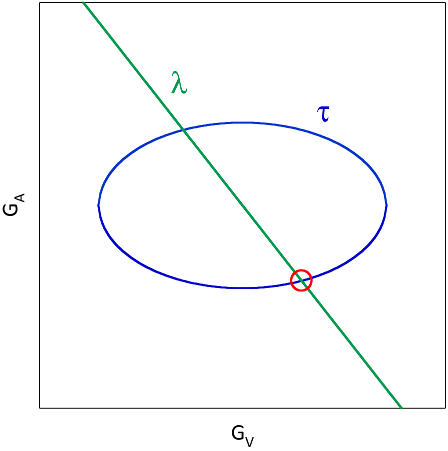
PDG value slightly different;

Confidence Level $= 2 \times 10^{-4}$

Combining the τ_n and λ values

Recall the combined plot:

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



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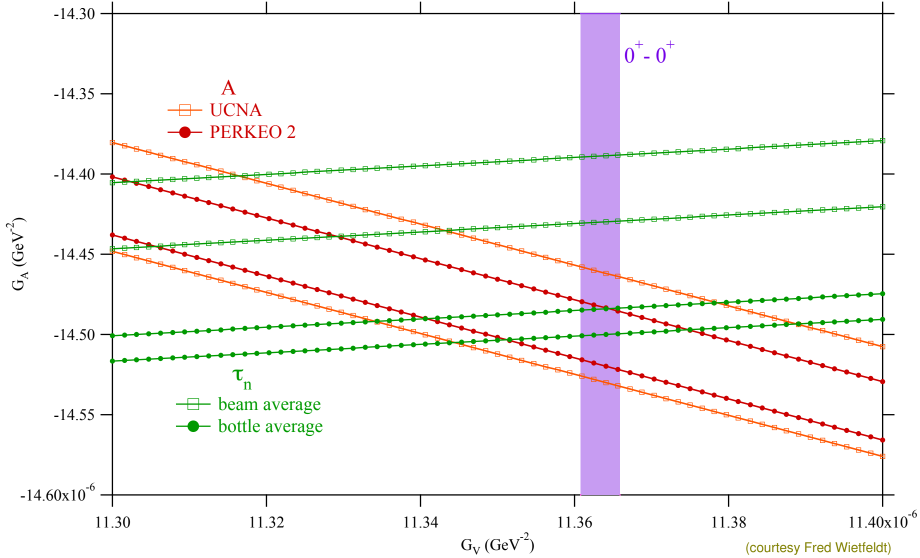

(courtesy Fred Wietfeldt)

⇒ Need OOM improvement in λ, and τ_n inconsistencies to be resolved.

Ongoing and planned neutron β decay measurements

experiment	obs.	uncert.	technique	facility/group
BL2	τ	1 s	cold *n* beam	NIST
BL3	τ	< 0.3 s	cold *n* beam	NIST
JPARC τ	τ	< 0.3 s	cold *n* beam	J-PARC
Gravitrap	τ	0.2 s	UCN/material bottle	ILL and PNPI
Ježov	τ	0.3 s	UCN/magnetic bottle	ILL
HOPE	τ	0.5 s	UCN/magnetic bottle	ILL (supertherm. src.)
PENELOPE	τ	0.1 s	UCN/magnetic bottle	TU Munich
Mainz	τ	0.2 s	UCN/magnetic bottle	Mainz TRIGA source
UCNτ	τ	$\ll 1$ 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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A flurry of activity: **stay tuned**!

Pion beta decay

$$\pi^+ \to \pi^0 e^+ \nu_e$$

Pion beta: $\pi^+ \to \pi^0 e^+ \nu_e$ (π_{e3}) decay rate in the SM

A pure $0^- \to 0^-$ 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

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

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

and $\delta_\pi \simeq 0.035$ is the sum of radiative/loop corrections with $< 0.02\%$ uncertainty.

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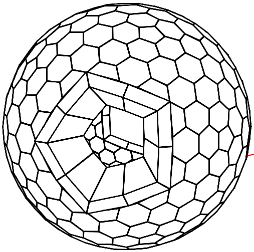
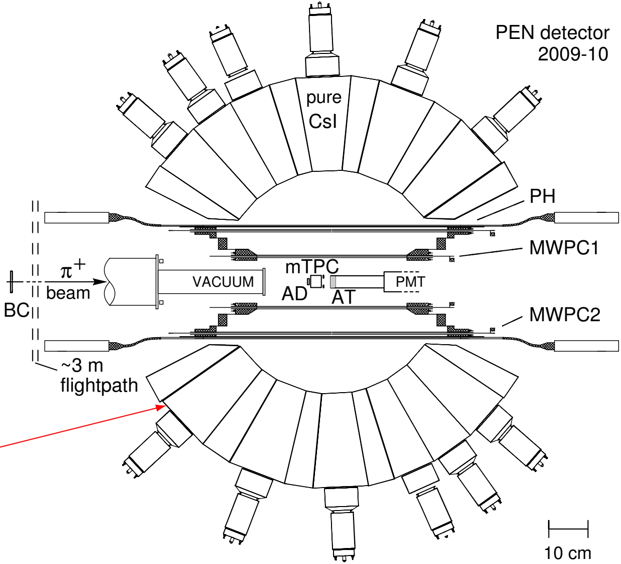
Pion beta decay provides the theoretically cleanest access to V_{ud}.
Huge fly in the ointment: $B \sim 10^{-8}$!

The PIBETA/PEN apparatus

- πE1 beamline at PSI
- stopped π^+ beam
- active target counter
- 240-detector, spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms
- stable temp./humidity





Measured $B_{\pi_{e3}}$ to $\sim$0.5% [PRL **93** (2004) 181803]

Conclusions and outlook

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- A more precise value of $B(\pi^+ \to e^+\nu_e)$ — currently under way: PEN and PIENU experiments (but $\times 4 - 5$ 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 $\Delta \equiv m_{\pi^+} - m_{\pi^-}$.

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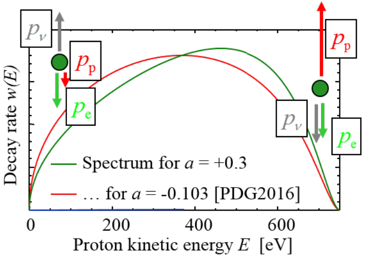
- Eventually, a more precise value of $\Delta \equiv m_{\pi^+} - m_{\pi^-}$.

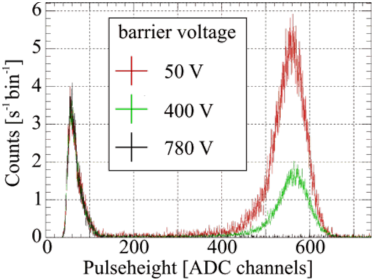
$\Rightarrow$ For the time being it makes sense to let the neutron measurements play out before a substantial new effort is initiated on pion beta decay.

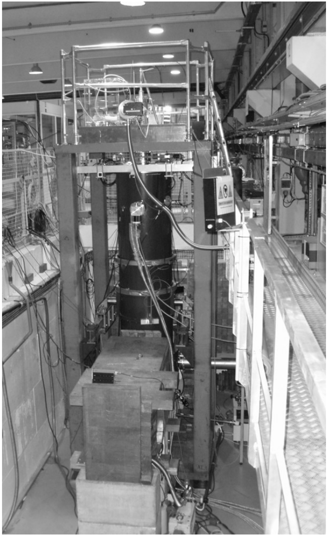
Additional slides

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