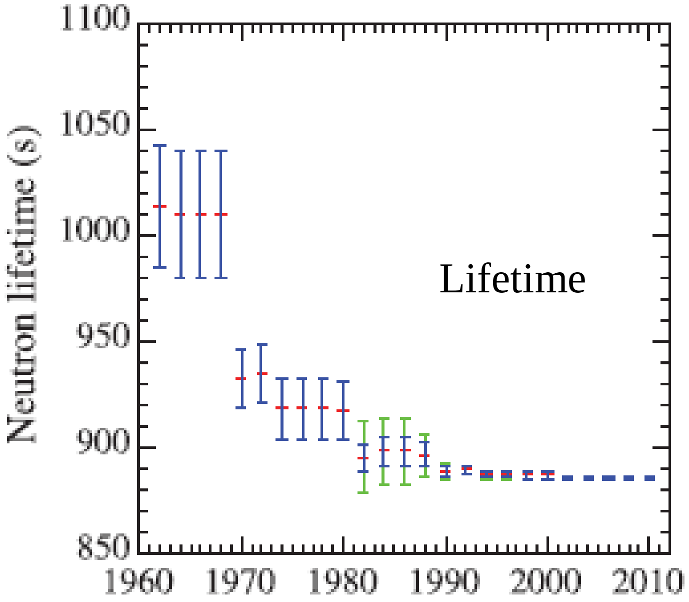
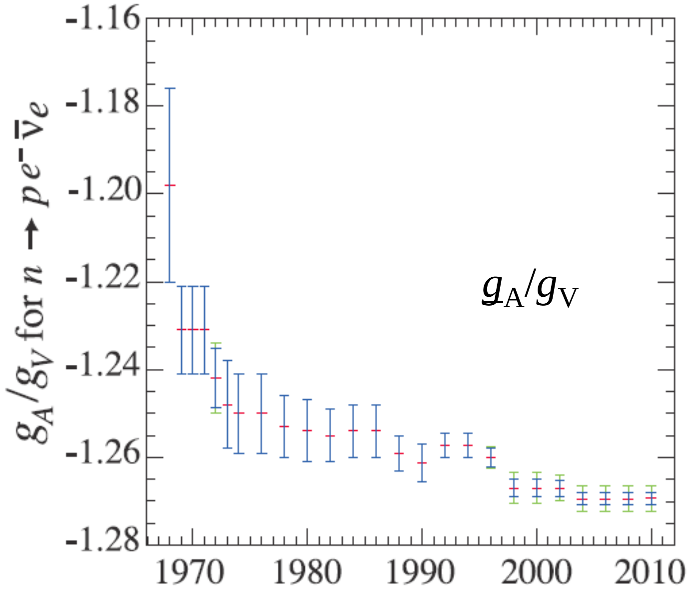
Neutron β-Decay

Dirk Dubbers
U. Heidelberg

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

History of world averages in neutron decay





1. Tremendous progress: lifetime error diminished by factor 200.
2. At all times, errors underestimated by factor ~3.

The public notices only the continuing 3 sigma discrepancy.

Difficult experiments: typically 1 of 10^7 neutrons decays in apparatus.

Every lost neutron may contribute to background.

Table of contents

Neutron β-decay

	quarks		leptons		
3rd:	b	t	τ	ν_τ	(high energy -
2nd:	s	c	μ	ν_μ	physics)
1st :	$d \longrightarrow u$		e	ν_e	neutron decay

Neutron decay involves all members of the first family

Neutron lifetime is long: $\tau \approx 15$ min

β-endpoint energy is low: $E_{\text{max}} = 782$ keV

Neutron β-decay theory on the *quark* level

Universality of the weak interaction:

$$\boxed{d \rightarrow u + e^- + \bar{\nu}_e}$$

The matrix element for β-decay (point-like) of the down quark *d* is:

$$\boxed{\mathcal{M}_{\text{quark}} = (G_F/\sqrt{2})[u\gamma_\mu(1-\gamma_5)d][e\gamma^\mu(1-\gamma_5)\nu_e]}$$

It is the same as for β-decay for instance of the lepton μ :

$$\mathcal{M}_{\text{muon}} = (G_F/\sqrt{2})[\nu_\mu\gamma_\lambda(1-\gamma_5)\mu][e\gamma^\lambda(1-\gamma_5)\nu_e]$$

with *P*-violating left-handed projection $(1-\gamma_5)\nu_e$ e.g. of spinor ν_e.

Fermi coupling constant $G_F/\sqrt{2} = \frac{1}{8}g_w^2/(m_W c^2)^2$

with weak coupling constant $g_w = e/\sin\theta_W \approx 0.65$

$$e = (4\pi\alpha)^{1/2} \approx 0.31$$

from muon decay $\boxed{G_F/(\hbar c)^3 = 1.166\,378\,8(7) \times 10^{-5}\ \text{GeV}^{-2}}$

now 15 times better (PSI): PRL **106**, 041803 (2011)

Neutron β-decay theory on the *nucleon* level

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

Neutron is a complicated strongly interacting object,
but matrix element needs only slight modifications:

$$\mathcal{M}_{\text{neutron}} = \frac{G_F}{\sqrt{2}} V_{ud} \left[p\left(\gamma_\mu (1 + \lambda\gamma_5) + \frac{\kappa_p - \kappa_n}{2M} \sigma_{\mu\nu} q^\nu\right) n \right] \left[e\gamma^\mu (1 - \gamma_5) \nu_e \right]$$

with:

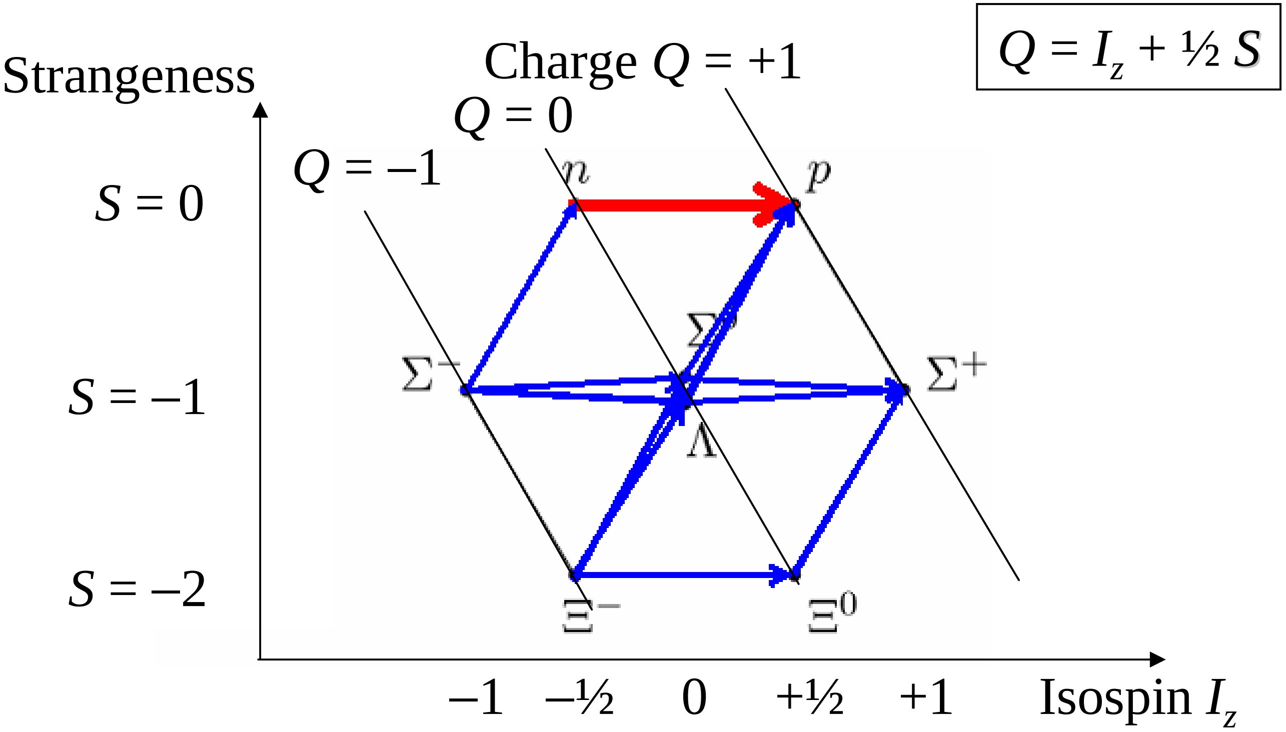
1. CKM matrix element $\boxed{V_{ud}}$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

2. ratio of axialvector to vector form-factors (in the limit $q^2 \to 0$)
$\boxed{\lambda = |g_A/g_V|\, e^{i\varphi}}$ real under time reversal invariance, $|\lambda|$ near 1 (PCAC)

3. small (~ 1%) weak magnetism, for Conserved Vector Current (CVC):
from anomalous magnetic moments $\kappa_p - \kappa_n = 1.793 - (-1.913) = 3.706$

β^--decays in baryon octet



$Q = I_z + ½\, S$

$\Delta I_z = ½$

for $\Delta S \neq 0$: $\Delta Q = \Delta S$

β-decay parameters are related to each other by $SU(3)_{\text{flavor}}$ symmetry

Table of contents

Neutron lifetime

$$\tau_n^{-1} = \frac{c}{2\pi^3} \frac{(m_e c^2)^5}{(\hbar c)^7} G_F^2 |V_{ud}|^2 (1 + 3\lambda^2) f$$

phase space factor $f = 1.6887(2)$

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

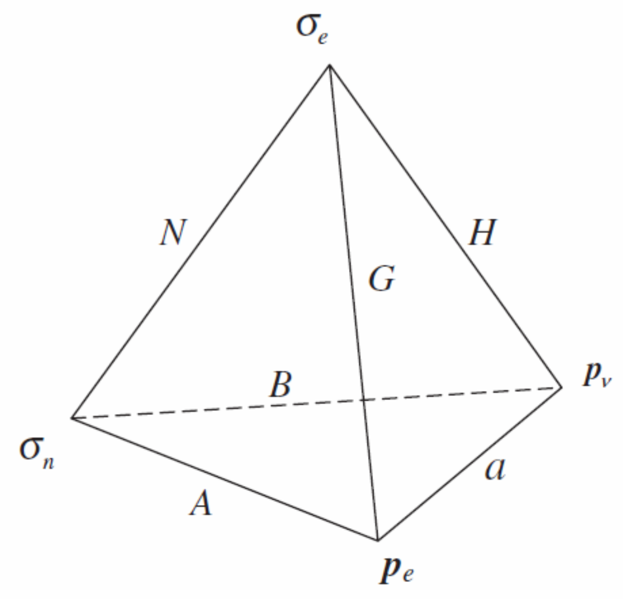
Lifetime depends on the quark mixing element V_{ud} and on $\lambda = g_A/g_V$.

(Error from radiative corrections)

Neutron decay correlations

4 Vectors are observable in n-decay: $n \rightarrow p + e + \nu_e$, namely:

$\boldsymbol{\sigma}_n,\ \boldsymbol{p}_p,\ \boldsymbol{p}_e, \boldsymbol{\sigma}_e \quad (\boldsymbol{p}_\nu = -\boldsymbol{p}_p - \boldsymbol{p}_e)$



6 scalar two-fold correlations:

$e-\nu$ correlation	$a\boldsymbol{p}_\nu \cdot \boldsymbol{p}_e$
β-asymmetry	$A\boldsymbol{\sigma}_n \cdot \boldsymbol{p}_e$
ν_e-asymmetry	$B\boldsymbol{\sigma}_n \cdot \boldsymbol{p}_\nu$
e^--helicity	$G\boldsymbol{\sigma}_e \cdot \boldsymbol{p}_e$
H-coeff.	$H\boldsymbol{\sigma}_e \cdot \boldsymbol{p}_\nu$
N-coeff.	$N\boldsymbol{\sigma}_e \cdot \boldsymbol{\sigma}_n$

4 scalar T-violating triple-correlations:

$D\boldsymbol{\sigma}_n \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu)$

$L\boldsymbol{\sigma}_e \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu)$

$R\boldsymbol{\sigma}_e \cdot (\boldsymbol{\sigma}_n \times \boldsymbol{p}_e)$

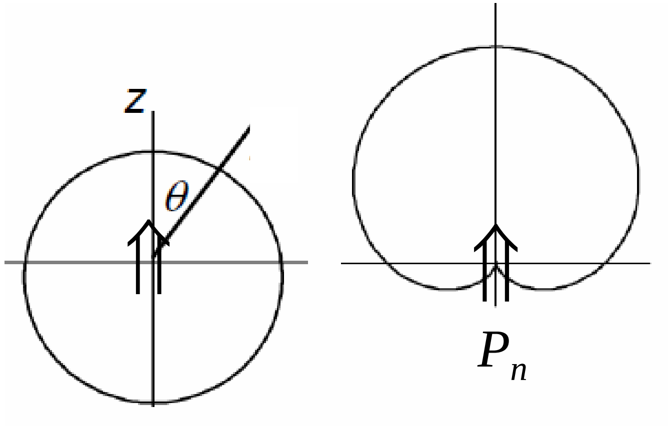
$V\boldsymbol{\sigma}_n \cdot (\boldsymbol{\sigma}_e \times \boldsymbol{p}_\nu)$ (+ 5 four-, five-fold)

Standard Model: All correlation coefficients depend only on $\lambda = g_A/g_V$

Example: β-decay asymmetry

Correlation between neutron spin $\langle \boldsymbol{\sigma}_n \rangle$
and electron momentum $\boldsymbol{p}_e$
leads to angular distribution:

$$d^2\Gamma \propto \left(1 + A\langle \boldsymbol{\sigma}_n \rangle \cdot \frac{c\mathbf{p}_e}{W_e}\right) d\Omega_e$$
$$= \left(1 + AP_n \frac{v_e}{c} \cos\theta\right) d\Omega_e$$



Electron Neutrino

with parity violating asymmetry parameter:

$$A = -2\frac{\lambda(\lambda + 1)}{1 + 3\lambda^2} \qquad (\lambda = g_A/g_V)$$

Neutron decay in standard model

In the standard model only 2 parameters are needed (V_{ud} and $\lambda = g_{\mathrm{A}}/g_{\mathrm{V}}$).
but many observables are accessible (ultimately 2 dozen).

Measured so far: τ, a, b, A, B, C, D, N, R, radiative decay (Khafizov et al., tomorrow)
Under preparation: bound β-decay, e^- helicity, weak magnetism, …

→ many tests beyond the Standard Model are possible

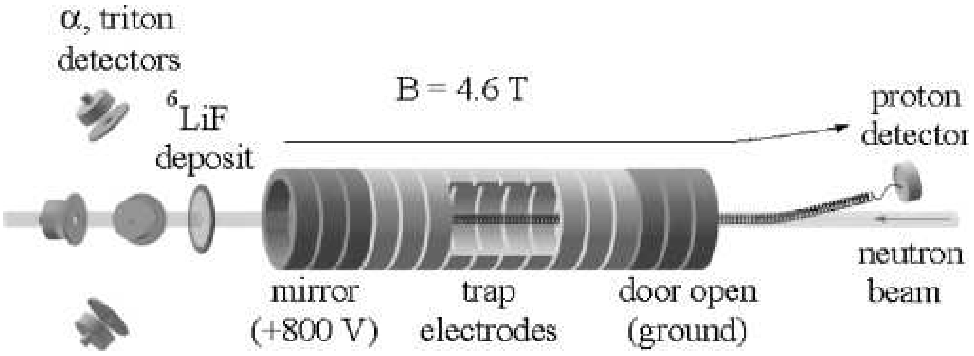
Details in DD and M.G. Schmidt:
"The neutron and ist role in cosmology and particle physics",
Rev. Mod. Phys. **83**, 1111 (2011)

Table of contents

1. Neutron decay in the standard model
2. Observables in neutron decay
3. Neutron lifetime experiments
4. Neutron decay correlation experiments
5. Upcoming neutron decay experiments
6. Comparison with other methods
7. Tests of the standard model with neutron decay

n-lifetime *in beam*

$$n_e = n_p = N_n / \tau_n$$



Measuring lifetime by counting neutrons
and trapped protons at NIST

Nico *et al.*, PR C **71**, 055502 (2005)
τ_n = (886.3 ± 3.5) s

n-lifetime *in trap*

$$N_n(T) = N_n(0)\exp(-T/\tau_{\text{storage}})$$

$$1/\tau_{\text{storage}} = 1/\tau_n + 1/\tau_{\text{loss}}$$

Storage of ultracold neutrons (UCN) confined by walls and by gravitation.

Serebrov *et al.*, PL B **605**, 72 (2005)
$\tau_n = (878.5 \pm 0.8)$ s

Pichlmaier *et al.*, PL B **693**, 221 (2010)
$\tau_n = (880.7 \pm 1.8)$ s

L. Bondarenko *et al.*, tomorrow afternoon

A. P. SEREBROV *et al.*

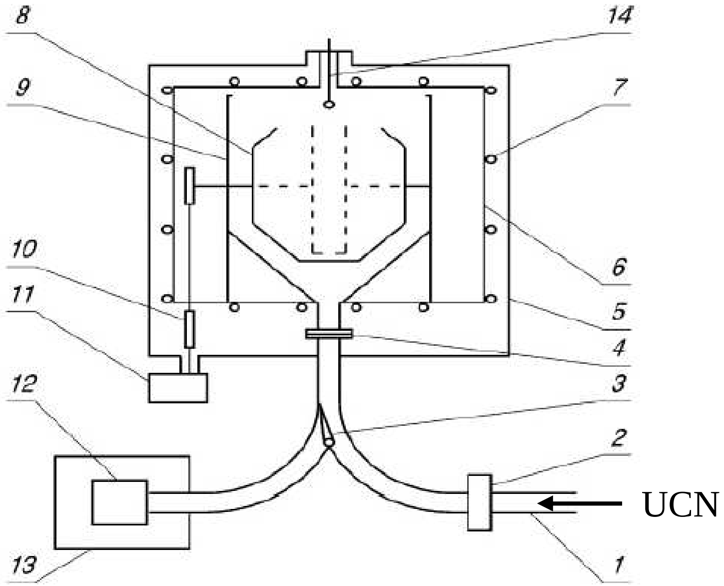
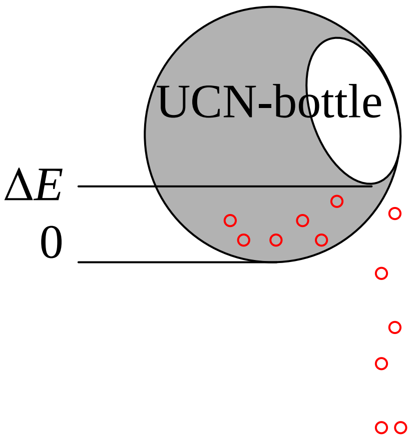


FIG. 1. Schematic of the gravitational UCN storage system: 1—input neutron guide for UCN, 2—inlet valve, 3—selector valve (shown in the position in which the trap is being filled with neutrons), 4—foil unit, 5—vacuum volume, 6—separate vacuum volume of the cryostat, 7—cooling system for the thermal shields, 8—UCN storage trap (with the dashed lines depicting a narrow cylindrical trap), 9—cryostat, 10—trap rotation drive, 11—step motor, 12—UCN detector, 13—detector shield, and 14—vaporizer.

n-lifetime in variable trap

The UCN loss rate γ is only due to wall collisions.

Vary γ by some means and extrapolate to zero.



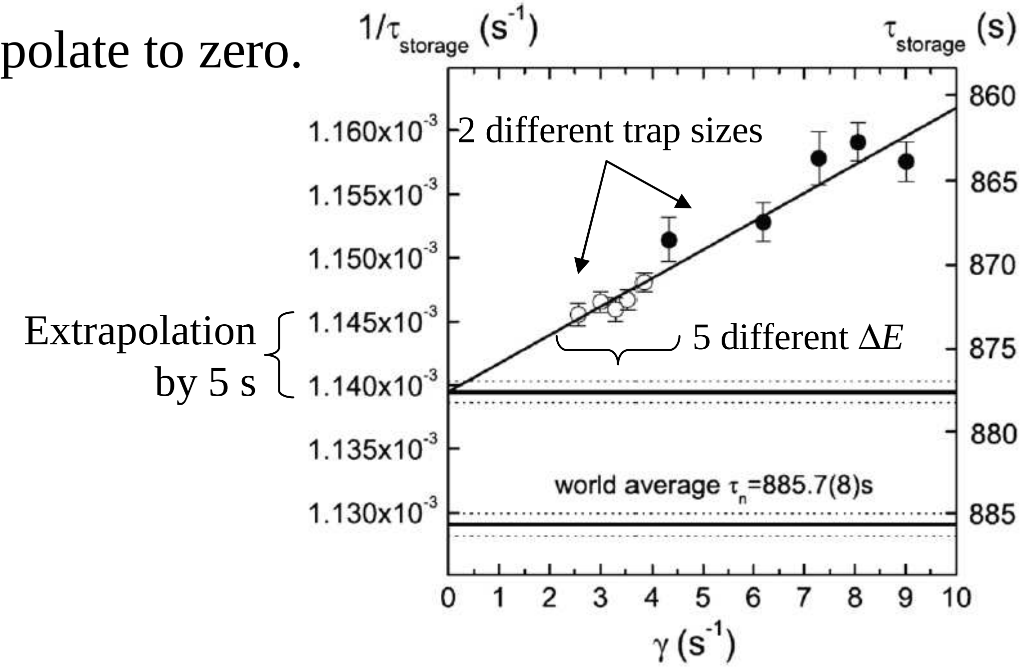
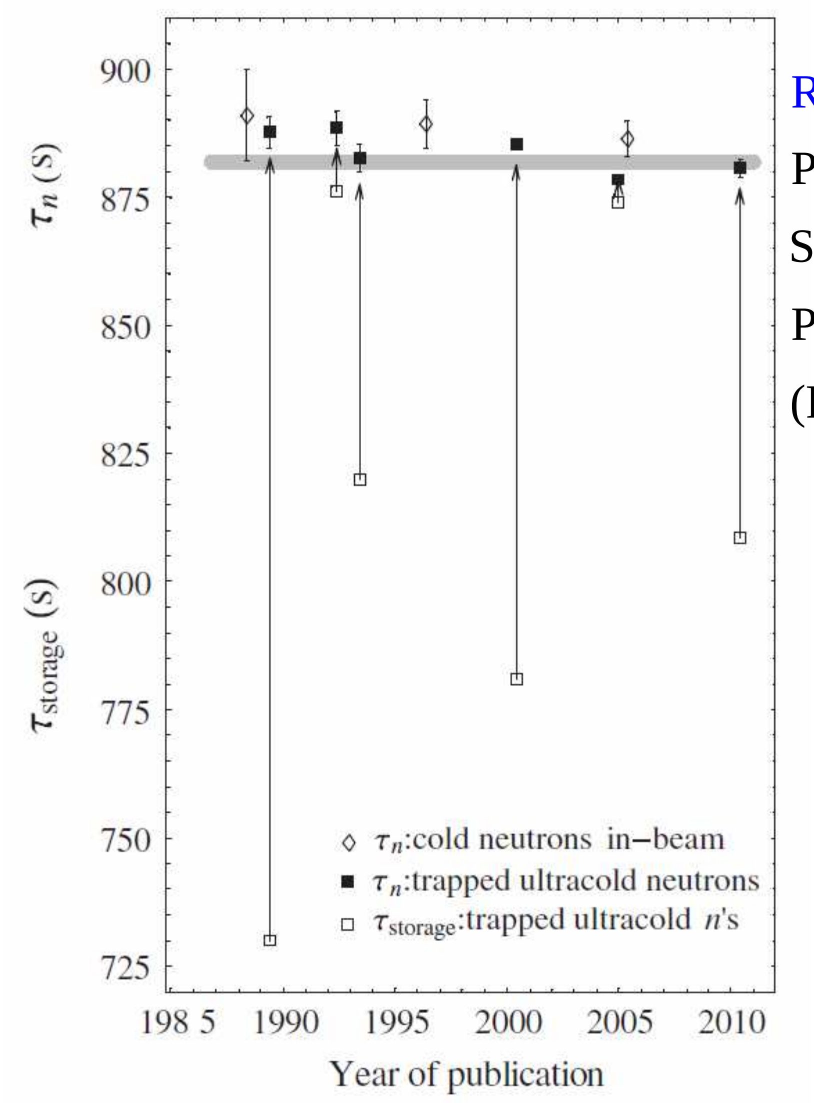


FIG. 19. Neutron lifetime from the latest UCN storage experiment. Shown is the UCN disappearance rate $1/\tau_{\text{storage}}$ vs the (normalized) loss rate $\gamma \propto 1/\tau_{\text{loss}}$; see Eq. (6.27). For $\gamma = 0$, the linear fit gives $\tau_{\text{storage}} = \tau_n = 878.5 \pm 0.8$ s. Open dots are for the larger trap, full dots for the smaller trap, each for five different UCN energy bands. The extrapolation is over $\Delta\tau = 5$ s. Shown is also the PDG 2010 average. From Serebrov *et al.*, 2005 and 2008b.

(More on γ in Lychagin's talk this afternoon)

History of *n*-lifetimes



Results: error scaled up by:

PDG 2001-2010 $\tau_n = (885.7 \pm 0.8)$ s $S = 1$

Serebrov 2005 $\tau_n = (878.5 \pm 0.8)$ s

Pichlmaier *et al*. 2010 $\tau_n = (880.7 \pm 1.8)$ s

(PDG 2011 $\tau_n = (881.7 \pm 1.4)$ s $S = 2.6$)

Table of contents

n-correlations in-beam

H. Abele, TU Vienna: "The neutron ABC"
with PERKEO:

1. β-asymmetry
Mund *et al*., submitted to PRL
arxiv 1204.0013 [hep.exp] (2012)

$$A = -\,0.1200 \pm 0.0006$$

2. Neutrino asymmetry
Schumann *et al*., PRL 99, 191803 (2007)

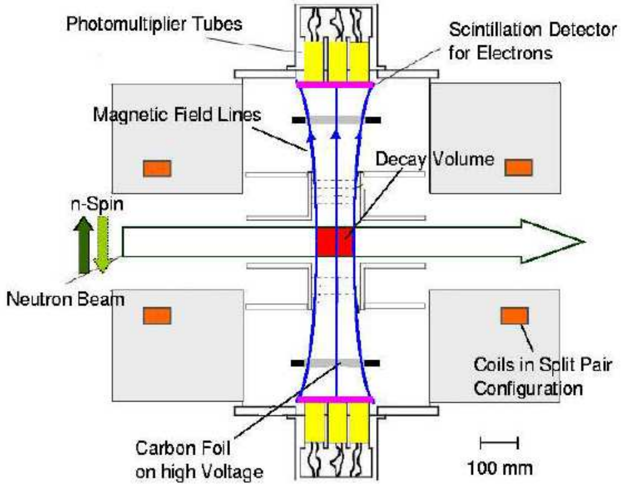
$$B = +\,0.983 \pm 0.005$$

3. Proton asymmetry
Schumann *et al*., PRL 100, 151801 (2008)

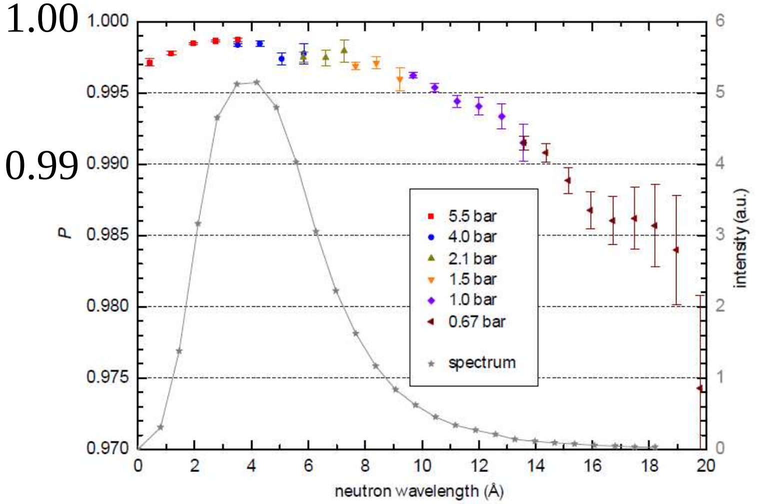
$$C = -\,0.239 \pm 0.003$$

n-polarization $P_n = 0.997 \pm 0.001$

(Here all errors rounded to 1 digit)

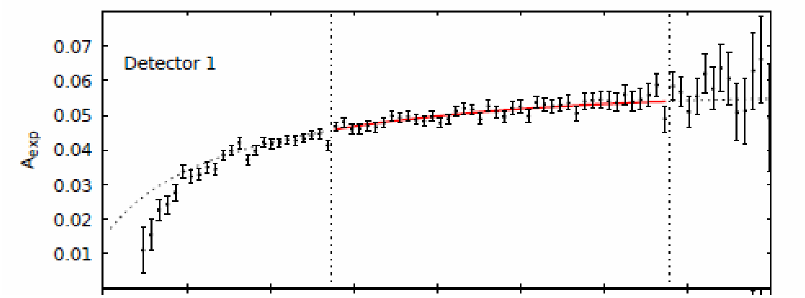


Neutron polarization

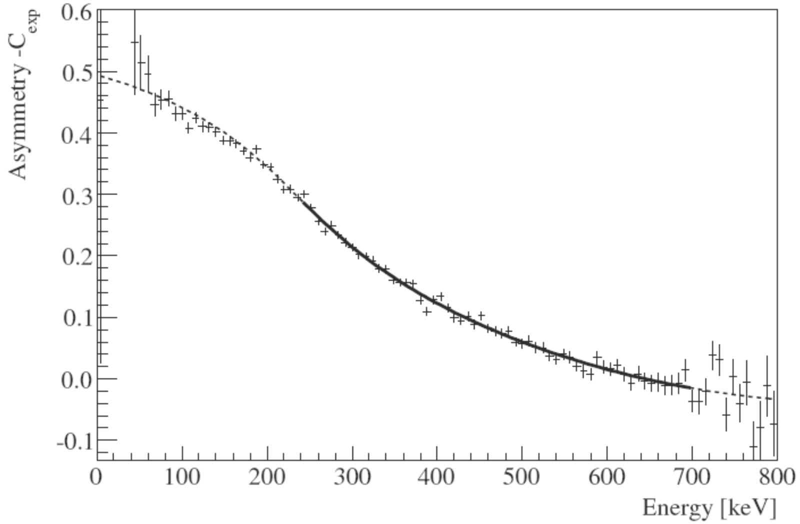


Typical asymmetry spectra

β-asymmetry A

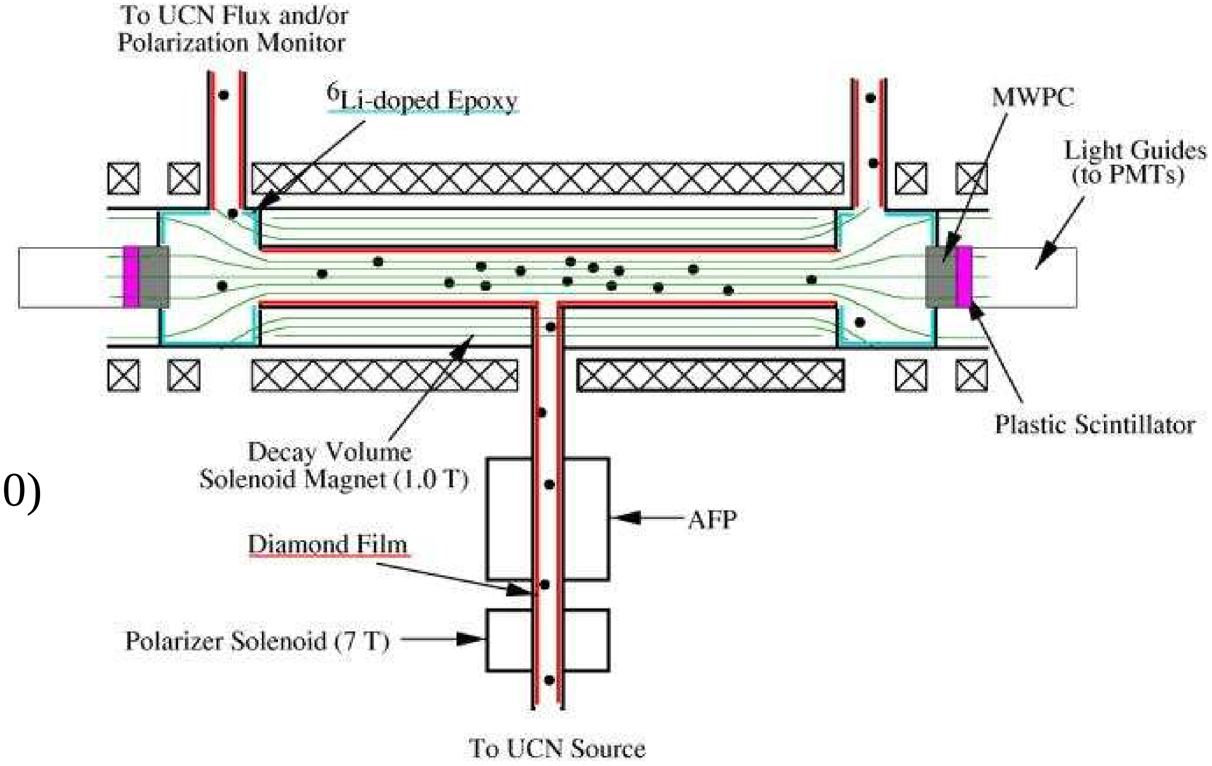


Proton asymmetry C



Electron enery E_e

β-asymmetry A in-trap



↑ UCN

LANSCE/Los Alamos

Liu *et al.*, PRL **105**, 181803 (2010)

$A = -0.1197 \pm 0.0016$

$$P_n = 1.00^{+0}_{-0.0052}$$

Neutrino asymmetry *B*

Kuznetsov *et al.*, PRL **75**, 7942 (1995)

$B = 0.9821 \pm 0.0025$

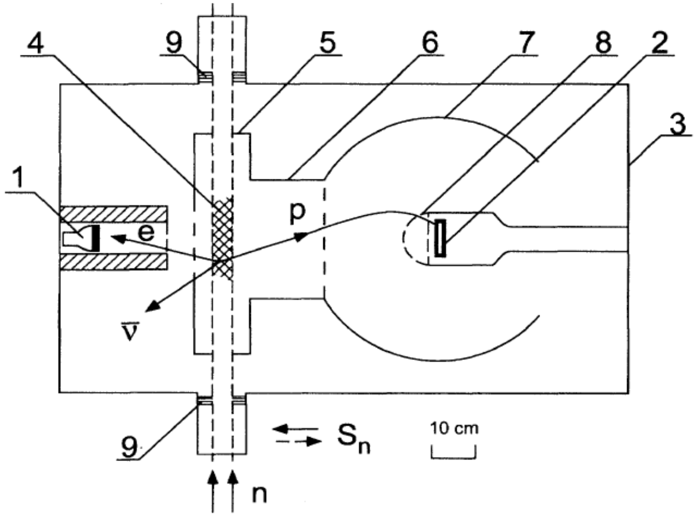


FIG. 2. Experimental apparatus. (1) Electron detector, (2) proton detector, (3) vacuum chamber, (4) decay region, (5) cylindrical electrode, (6) TOF electrode, (7) spherical electrode, (8) spherical grid, and (9) LiF diaphragm.

Electron-neutrino correlation *a*

In pile (TRIGA)

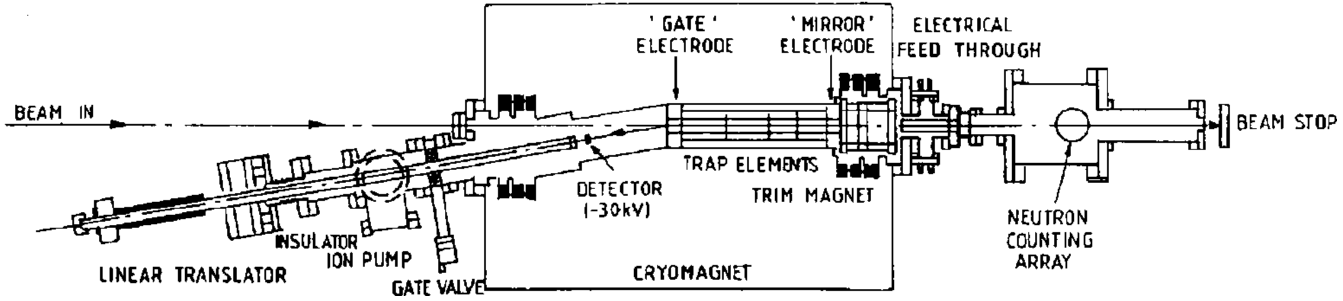
Stratowa *et al.*, PR D **18**, 3970 (1978)

$a = -0.1017 \pm 0.0051$

p-trap

Byrne *et al.*, JPh G **38**, 1325 (2002)

$a = -0.1054 \pm 0.0055$



Electron spin – neutron spin correlation *N*

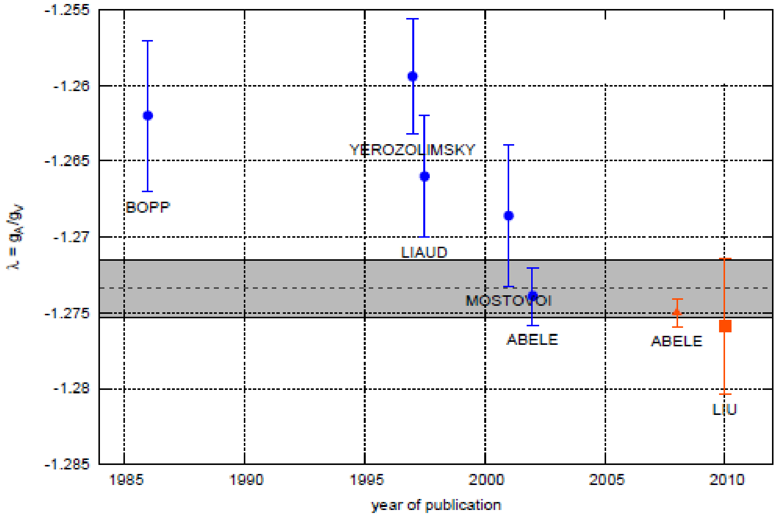
Kozela *et al.*, PRL **102**, 172301 (2009)

$N = 0.056 \pm 0.012$

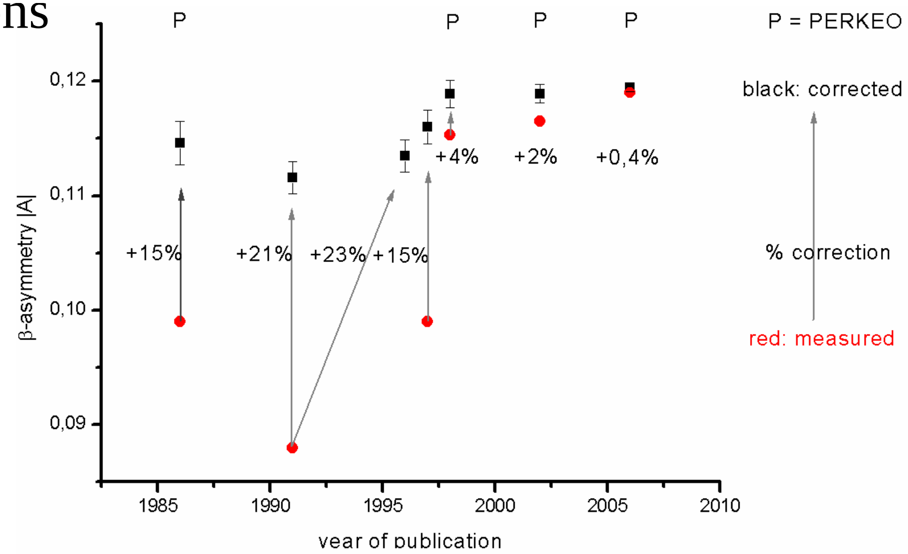
See *R*-coeff. below

History of β-asymmetry A

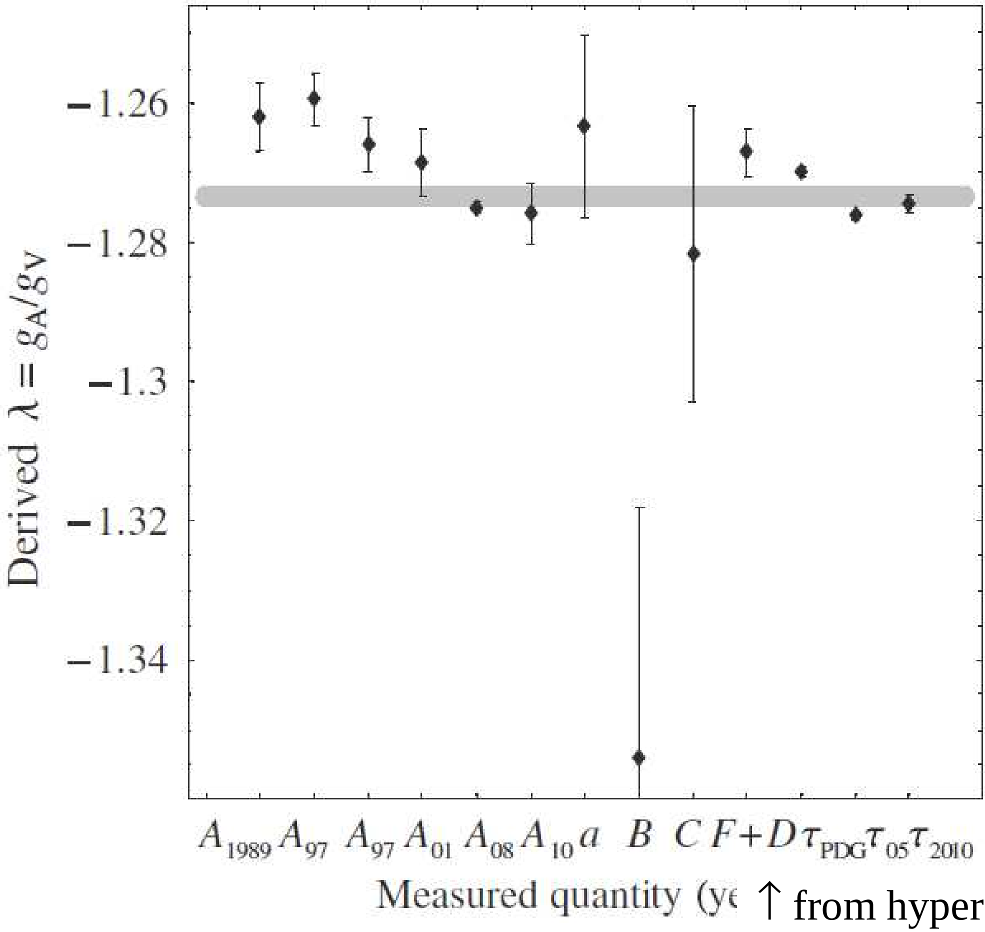
History of errors



History of corrections



$\lambda = g_A/g_V$ from various sources



← with V_{ud} from nuclei

↑ from hyperon decays (baryon octet)

PRL 92, 251803 (2004)

Time reversal violating *D* and *R* coefficients

Triple correlation $D\boldsymbol{\sigma}_n \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu)$

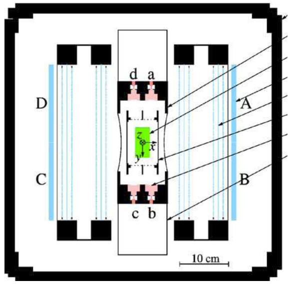
Soldner *et al.*, PL B **581**, 49 (2004)
$D = -.0003 \pm 0.0007$

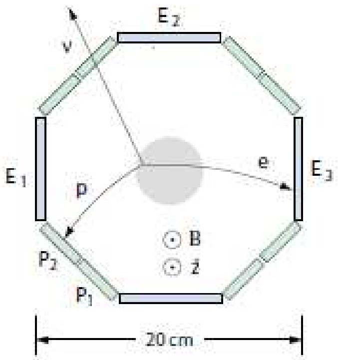
Mumm *et al.*, PRL **107**, 102301 (2011)
$D = -.0001 \pm 0.0002$

In $\lambda = |g_A/g_V|e^{i\varphi}$:
$\varphi = 180.01° \pm 0.03°$

Triple correlation $R\boldsymbol{\sigma}_e \cdot (\boldsymbol{\sigma}_n \times \boldsymbol{p}_e)$

Kozela *et al.*, PRL **102**, 172103 (2009)
$R = -.006 \pm 0.013$





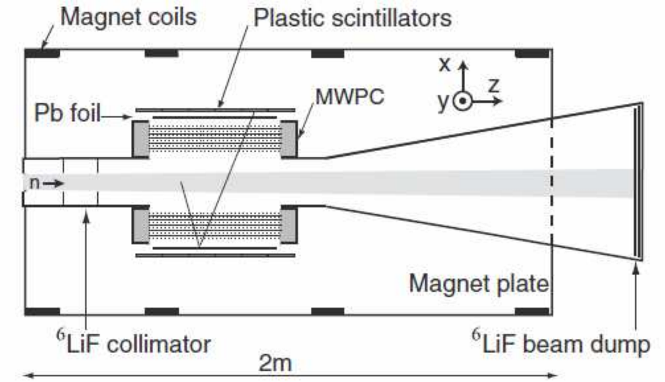
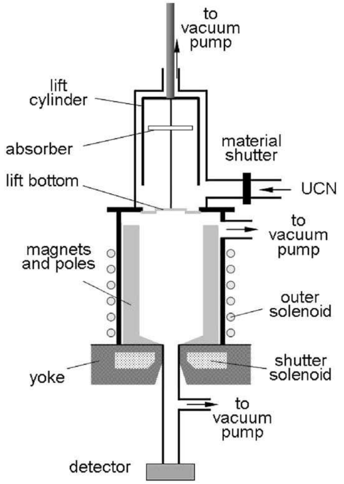


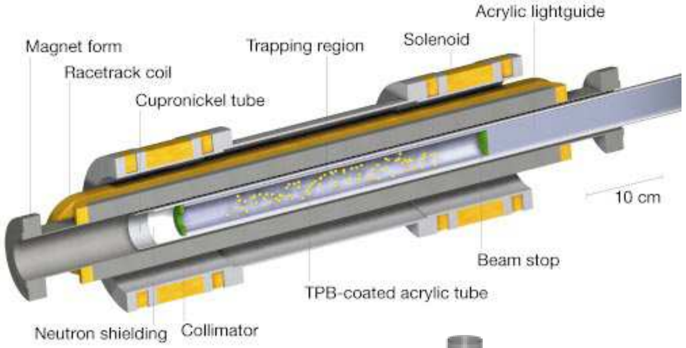
Table of contents

Upcoming lifetime experiments

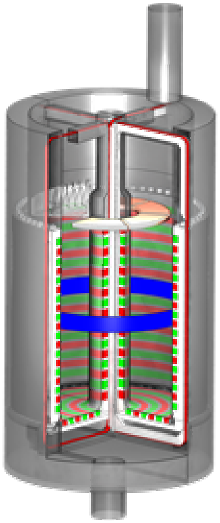


All with trapped ultracold neutrons (UCN):

Permanent-magnet UCN trap PNPI/ILL
Ezhov et al., NIM A **611**, 167 (2009)



Superconducting magnet trap, UCN in ^{4}He, NIST
O'Shaughnessy et al., NIM A **611**, 171 (2009)

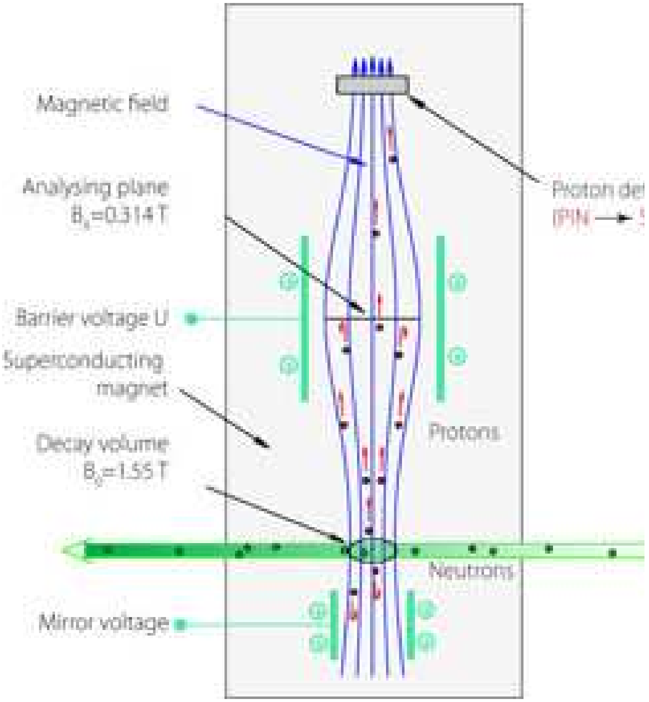


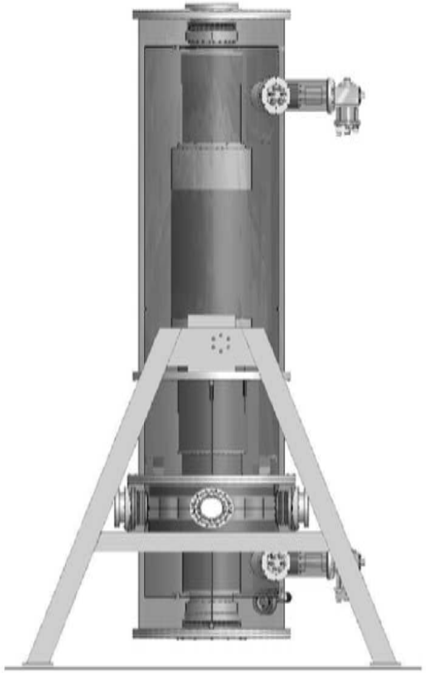
Superconducting magnet UCN trap, TU-Munich/FRM II

Zimmer et al., NIM A **440**, 548 (2000)
Materne et al., NIM A **611**, 176 (2009)

+ Ino's talk this morning

Upcoming correlation experiments



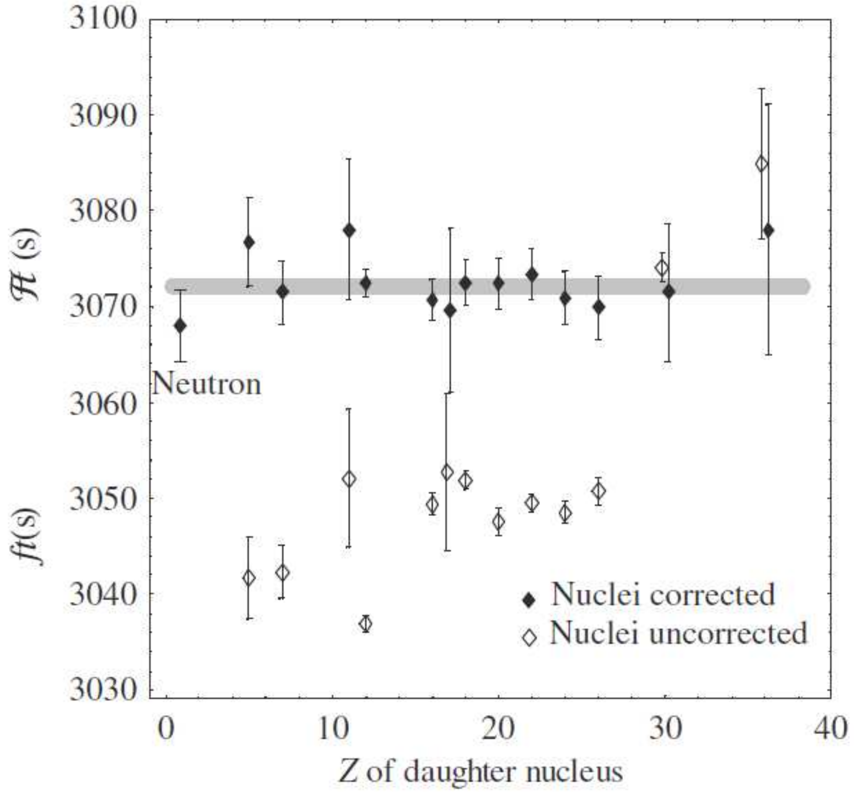


*a*SPECT/U. Mainz

Baeßler *et al.*, EPhJ A **38**, 17 (2008)

Table of contents

Comparison with nuclear *Ft*-values



$$ft = \frac{2\pi^2(\hbar c)^7}{c(mc^2)^5}\,\frac{\ln 2}{G_F^2|V_{ud}|^2}$$

$$\mathcal{F}t = 3071.81 \pm 0.83 \text{ s} \quad (\text{nuclear } \mathcal{F}t)$$

$$\mathcal{F}t_{n\text{-Vector}} = f^R\tfrac{1}{2}(1+3\lambda^2)\tau_{\mathrm{n}}\ln 2 = 3068 \pm 3.8 \text{ s}$$ (neutron *Ft*)

Comparison with muon decay data

Neutron-decay:

coefficient: $A \quad B \quad C \quad a \quad D \quad N \quad R$

relative error: $(4, 30, 9, 40, 6, 120, 80)\times 10^{-4}$

Comparable to muon-decay parameters:

coefficient: $\rho \quad \eta \quad \xi \quad \delta \quad x \quad y$

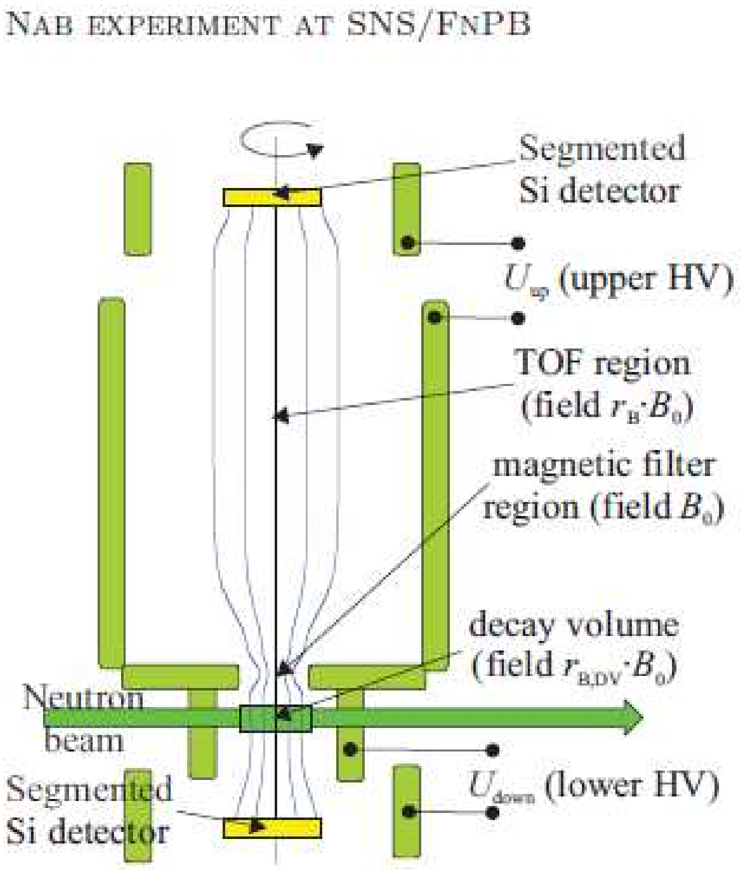
relative error: $(4, 34, 35, 6, 80, 80)\times 10^{-4}$

N*ab*

For *e*-ν correlation and Fiertz term *b*:

N*ab*/SNS

Počanić *et al.*, NIM A **611**, 211 (2009)

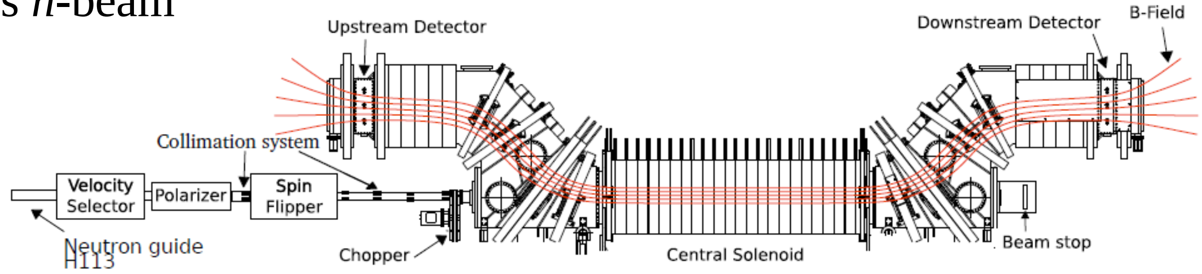


Perkeo III

B. Märkisch *et al.*, NIM A **611**, 216 (2009):

n-decay rate 50 000 sec^{-1}

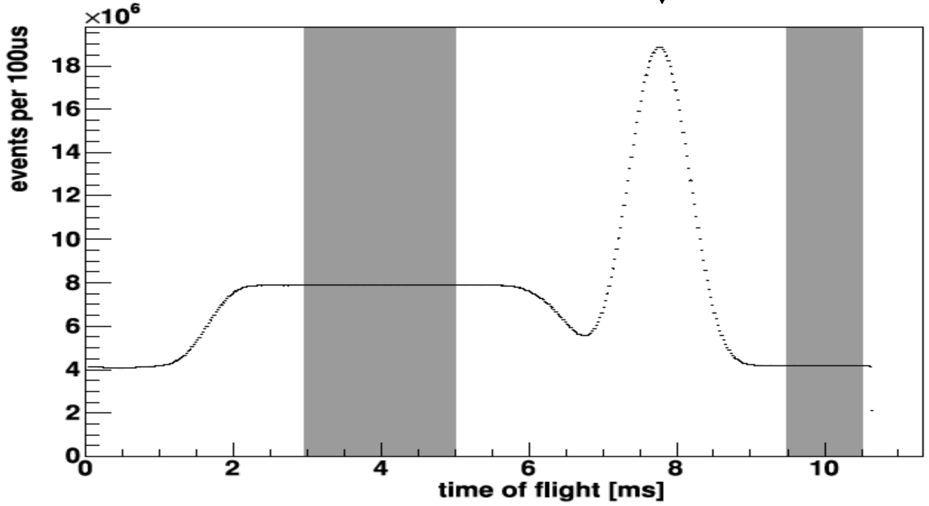
for unpolarized, continuous n-beam



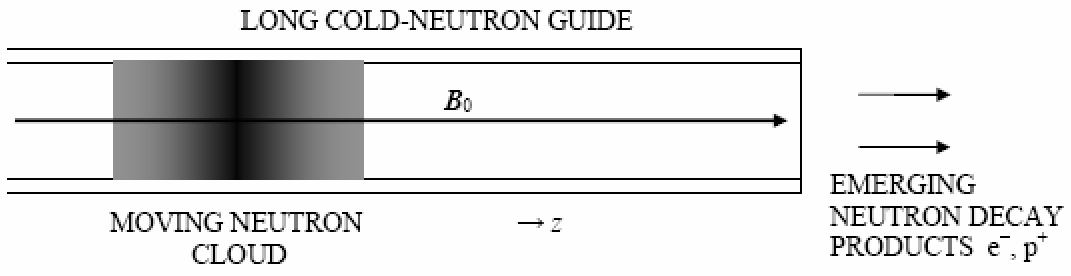
e^- gate

With pulsed neutron beam:

e^- countrate



PERC

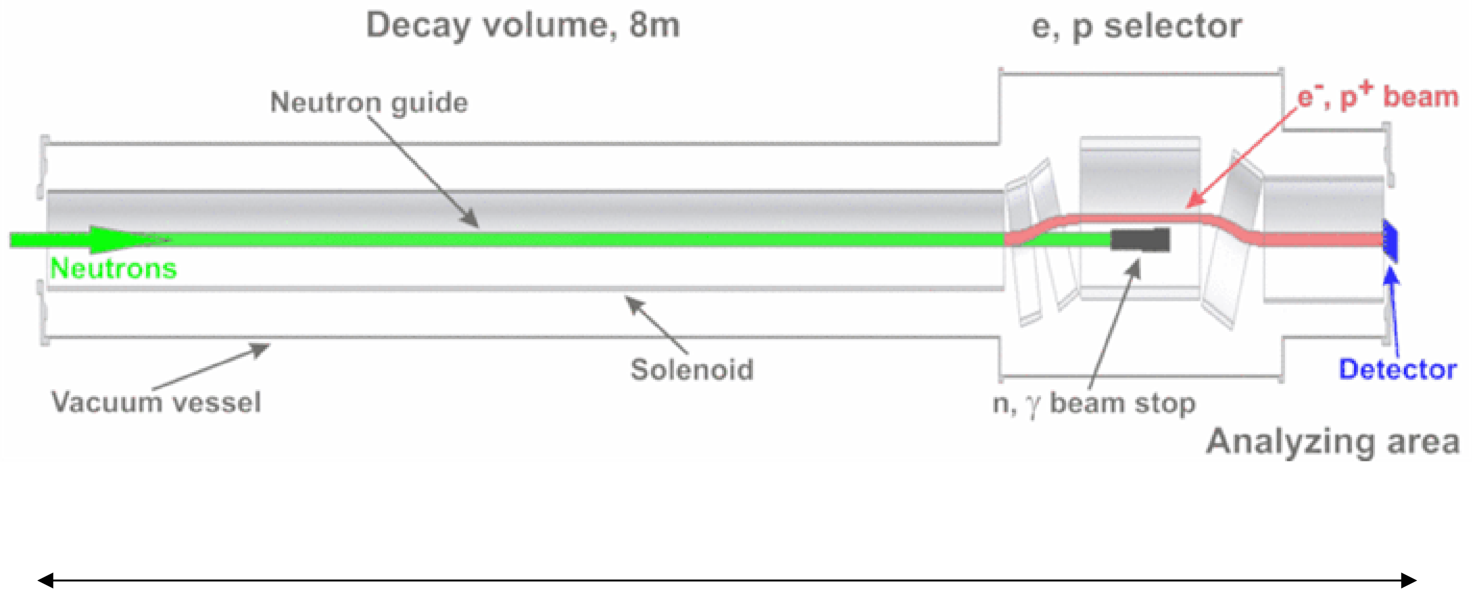


PERC = Proton-Electron-Radiation-Channel

10^6/s neutron decays per meter length within long neutron guide, magnetic extraction of decay products (FRM-II).

Under construction, Heidelberg-Vienna-Mainz-ILL-Munich

PERC apparatus



12 m

D. Dubbers *et al.*
NIM. A **596**, 238 (2008)

Table of contents

1. Is Standard Model really $V - A$?

Possible weak-interaction Hamiltonians:

- Scalar×Scalar (S),
- Vector×Vector (V),
- Tensor×Tensor (T),
- Axial vector×Axial vector (A),
- Pseudoscalar×Pseudoscalar (P).

From all available data :

$\left|g_S / g_V\right| < 7\%$ and $\left|g_T / g_A\right| < 8\%$ (95% C.L.)

Severijns *et al.*,
RMP **78**, 991 (2006)

Limits on Fierz interference terms

Fierz: number of n-decays $N = N_0(1+\frac{m_e}{W_e}b)$

$b = 0$ in standard model

β-Asymmetry $A_0 = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$

$$A = \frac{A_0}{1+(m_e/W_e)b}$$

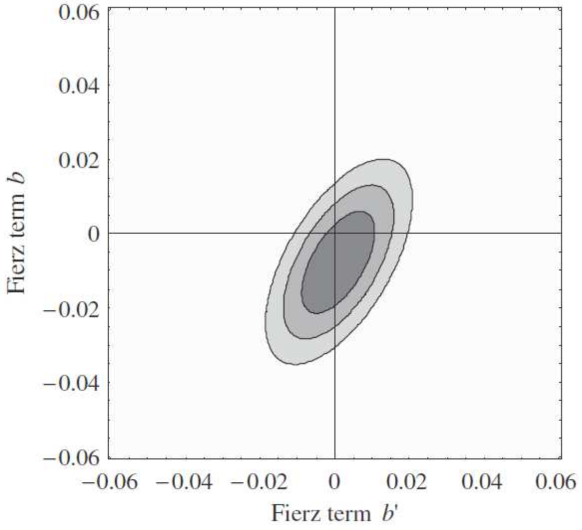
W_e = total
e^- energy

From neutron β-asymmetry spectrum:

$|b| < 0.19$, 95% C.L.

Two Fierz terms b, b' in neutrino asymmetry B:

$$B' = \frac{B + (m_e/W_e)b'}{1 + (m_e/W_e)b}$$

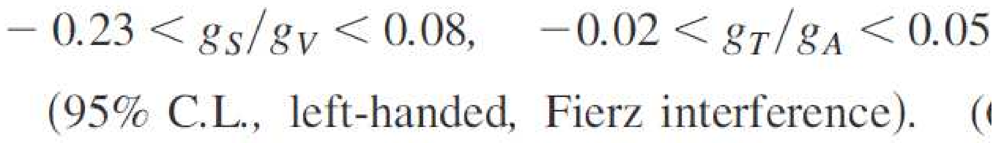


Fierz limits from all data

Limits on Scalar and Tensor amplitudes

From all *n*-decay data *A*, *B*, *C*, τ:

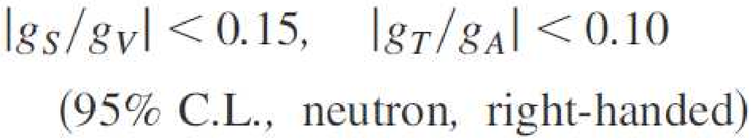
Left-handed *S*, *T*   (from *n*-Fierz interference terms *b*, *b'*)



$$-0.23 < g_S/g_V < 0.08, \quad -0.02 < g_T/g_A < 0.05$$

(95% C.L., left-handed, Fierz interference).

Right-handed *S*,

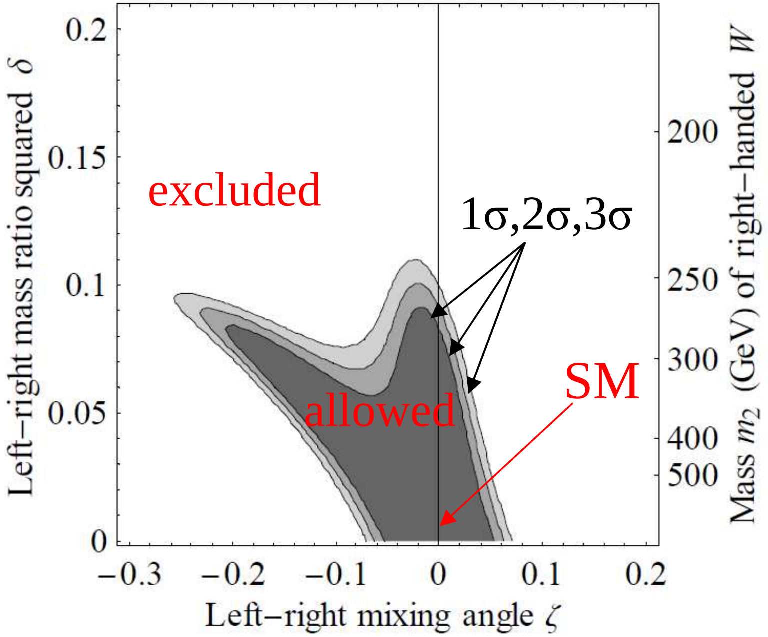


$$|g_S/g_V| < 0.15, \quad |g_T/g_A| < 0.10$$

(95% C.L., neutron, right-handed)

Dubbers and Schmidt
RMP **83**, 1111 (2011)
Reprints: send me an email with your post address

2. Is Standard Model really 100% left-handed?



Limits from neutron decay

Mass of right-handed W_R-boson: Neutron limit: > 250 GeV/c^2,
(both 90% CL) High-energy limit: > 715 GeV/c^2

3. Is CKM-matrix unitary?

With nuclear V_{ud}

1^{st} row : $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999 \pm 0.0006$

With neutron V_{ud}

1^{st} row : $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.0000 \pm 0.0026$

High-energy results

2^{nd} row : $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.101 \pm 0.074$

1^{st} column : $|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1.002 \pm 0.005$

2^{nd} column : $|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1.098 \pm 0.074$

Unitarity bound constrains low-energy effective Lagrangian to $\Lambda > 11$ TeV at 90% C.L

Cirigliano *et al.*,
NP B **830**, 95 (2010)

Summary

Many observables in neutron decay

Many tests of the standard model possible

Many upcoming experiments