Precision studies in neutron beta decay – improving the old and hunting for the new

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For collaborations between:

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Europäisches Graduiertenkolleg, Tübingen 21/06/2002

I. *Is the weak quark mixing done fairly? The CKM-matrix*

II. *V_{ud} via nuclear β-decays*

III. *V_{ud} via neutron decay*

1) *Neutron lifetime*
2) *Neutron β-asymmetry*
3) *Neutron results for V_{ud}*

IV. *Aimed improvement of precision of V_{ud} in neutron decay:*

1) *New run with PERKEO II*
2) *aSPECT*
3) *Neutron lifetime via magnetic storage of UCN*

V. *Radiative corrections*

VI. *Conclusions*

I. Cabibbo-Kobayashi-Maskawa matrix

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

- *near to diagonal:* $V_{ud} \cong 97.5\%,\ V_{cs} \cong 97.4\%,\ V_{tb} \cong 99.9\%$
- *accurate first row elements from semileptonic decays:*

$$V_{us} = 0.2196(23) \quad (\text{from } K_{e3} \text{ decays})$$

$$V_{ub} = 0.0036(9) \quad (\text{from } B \text{ decays})$$

- *Sensitive unitarity test via*

$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

- *Probes right-handed currents, scalar & tensor interactions...*
- *Challenge: accurate measurement of* V_{ud}

Semileptonic decay amplitude:

$$M = \frac{G_V}{\sqrt{2}} h^{\mu} l_{\mu} \quad \text{with} \quad l^{\mu} = \bar{u}\gamma^{\mu}(1-\gamma_5)U, \quad H_{\mu} = \bar{V}_{\mu}$$

$$H_{\mu} = f_1(q^2)\gamma_{\mu} + f_2(q^2)\frac{\sigma_{\mu\nu}q^{\nu}}{m_p} + f_3(q^2)\frac{q^{\mu}}{m_p} + \left[f_i \to g_i\gamma_5\right]$$

f_3, g_2 and g_3 negligible in Standard Model

Isospin breaking in vector formfactors $\propto \left(\frac{m_n - m_p}{m_p}\right)^2$

CVC, isospin symmetry: $f_1 = 1, \quad f_2 = \mu_p - \mu_n$

SM: 2 free parameters: $G_V, \quad \lambda = \frac{G_A}{G_V} = \frac{g_1}{f_1}$

- *Universality:* $\boxed{G_V = G_F V_{ud}}$ $\quad G_F = 1.16639(1) \times 10^{-5}\ \mathrm{GeV}^{-2}(\hbar c)^3$
- *Semileptonic decay rate:* $\tau^{-1} \propto G_V^2 |M_F|^2 + G_A^2 |M_{GT}|^2$

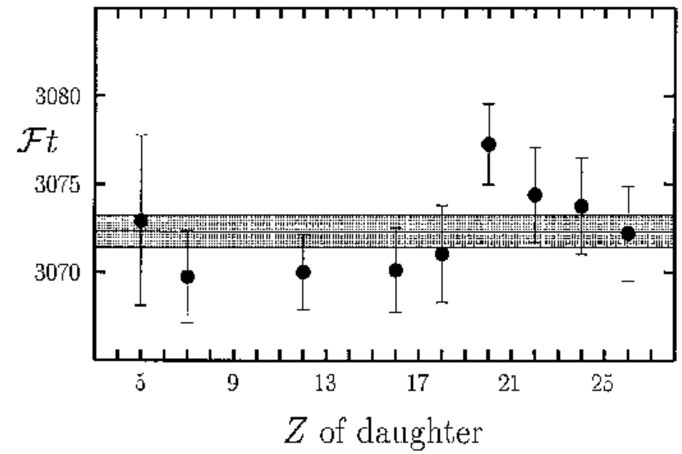
II. V_{ud} via nuclear β - decays

- *9 superallowed* $0^+ \to 0^+$ *transitions within I=1 multiplets* (^{10}C, ^{14}O, ^{26m}Al, ^{34}Cl, ^{38m}K, ^{42}Sc, ^{46}V, ^{50}Mn, ^{54}Co), $M_{GT}=0,\ |M_F|^2=2$

$$ft(1+\delta_R)(1-\delta_C) \equiv \mathcal{F}t = \frac{K}{2G_V^2(1+\Delta_R^V)} = const$$

$\Delta_R^V = 2.40(8)\%$, $\delta_R \cong 1.4\%$, $\delta_C \cong 0.4\%$ (*typical*)

$$V_{ud}^2 = \frac{K}{2G_F^2(1+\Delta_R^V)\langle \mathcal{F}t\rangle}$$



- *Result:* $V_{ud} = 0.9740 \pm 0.0005$ [Towner & Hardy, nucl-th/9809087]

± 0.001 [PDG 2000]

$$\sum_i V_{ui}^2 = 0.9968 \pm 0.0014 \to 2.2\sigma \text{ off unitarity}$$

- *Largest uncertainty contrib. from* Δ_R^V (± 0.0004) *and* δ_C (± 0.0003)

III. V_{ud} via neutron decay

- $|M_F|^2 = 1$ and $|M_{GT}|^2 = 3$, no correction δ_C

- Combination of two observables:

  1) neutron lifetime: $\tau_n^{-1} \propto G_V^2 (1 + 3\lambda^2)$

  2) β - asymmetry: $A = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$

$$V_{ud}^2 = \frac{K/\ln 2}{G_F^2 (1 + \Delta_R^V)(1 + 3\lambda^2) f^R \tau_n}$$

$f^R = 1.71482(15)$

- No nuclear structure dependent corrections

- Excellent experimental conditions

1) Neutron lifetime

- *In-beam experiments:*
  - Measure radioactivity of a neutron beam:

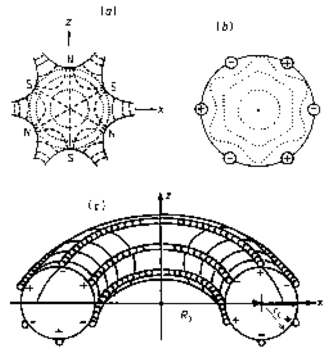
$$\frac{dN}{dt} = -\frac{N}{\tau_n} = -\frac{\rho V}{\tau_n}$$

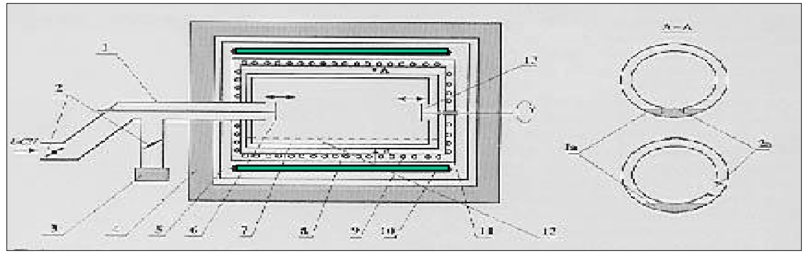
  - *Requires absolute determinations of* $\frac{dN}{dt}$, ρ *and* V

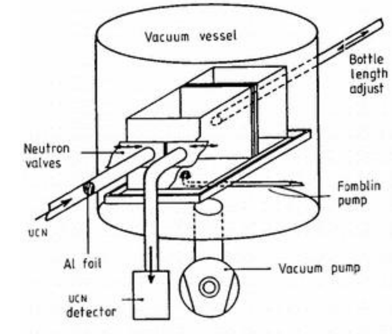
- *Storage experiments:*
  - Measure decay of trapped neutrons directly:

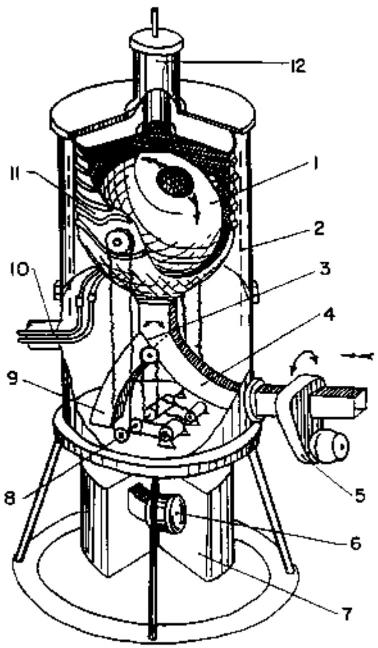
$$N(t) = N(t_0)\exp\left(-\frac{t}{\tau}\right)$$

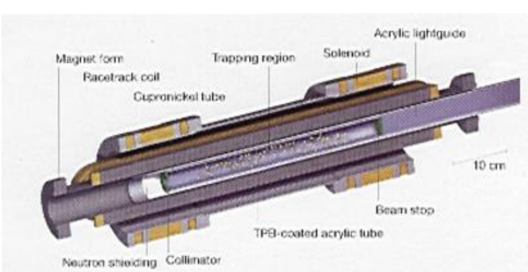
  - *No absolute determinations, but:* $\tau^{-1} = \tau_n^{-1} + \tau_{loss}^{-1}$

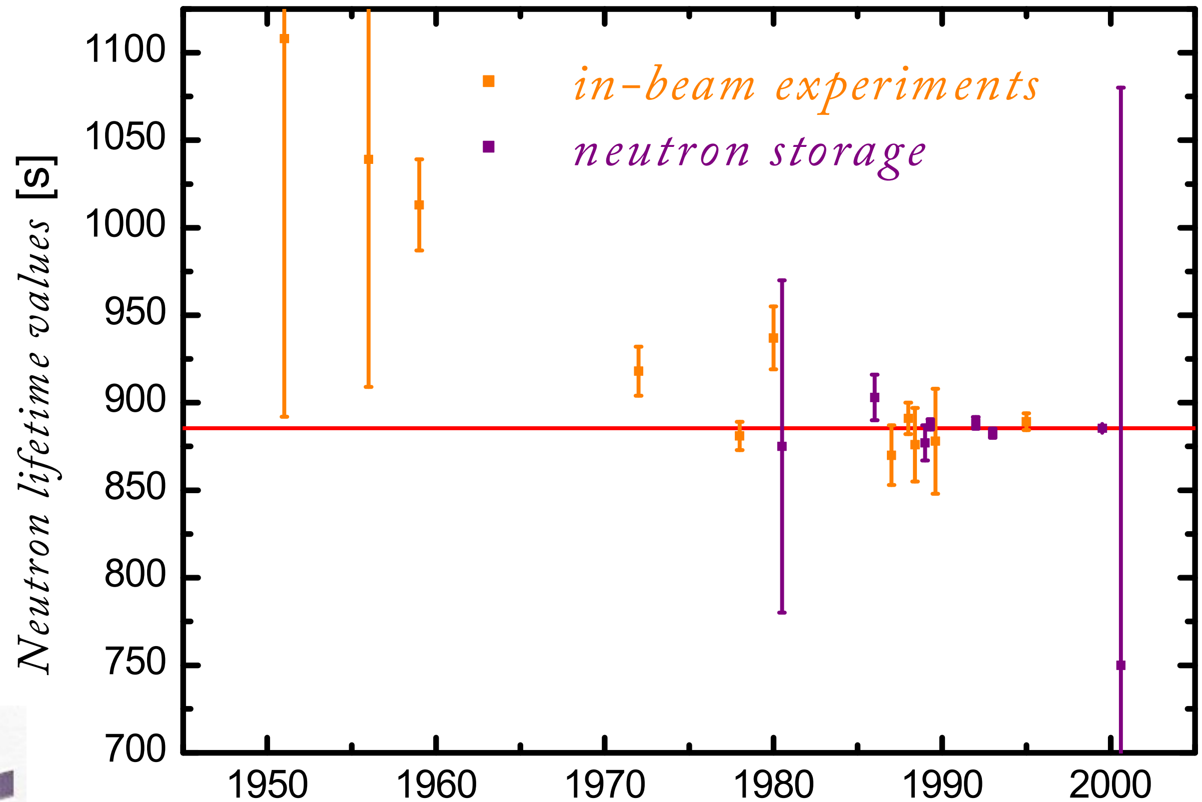




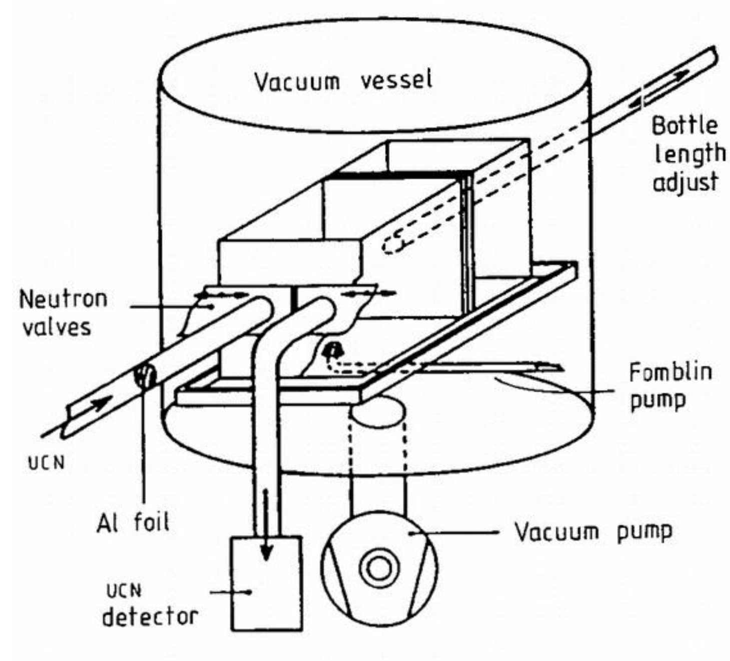








World average: τ_n = 885.7(7) s [PDG 2001]

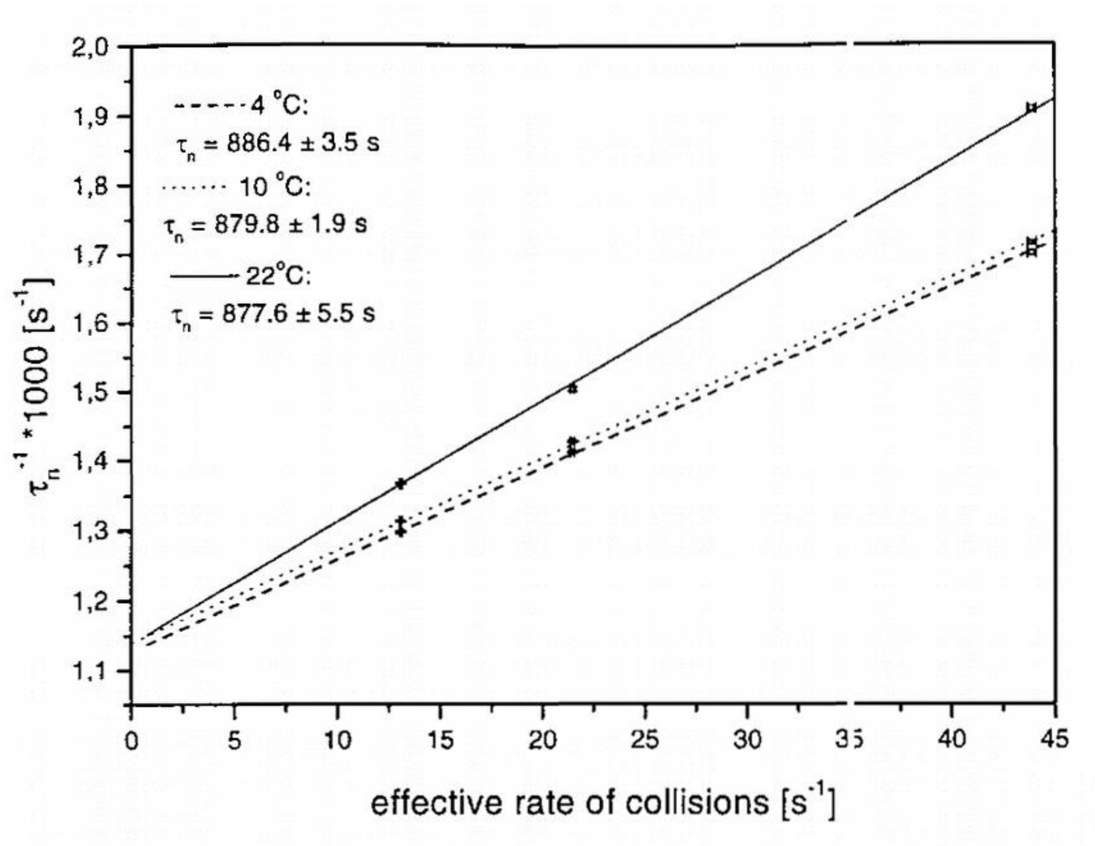


- *Liquid surfaces (Fomblin)*
- *Modulation of losses via well-defined variation of the ratio surface/volume*
- *Extrapolation: volume* $\rightarrow \infty$
- *Result:*

$$\tau_n = 887.6 \pm 3\ s$$

[W. Mampe *et al.*, NIM A284 (1989) 111]

Data from *MAMBO II*:



– *Preliminary result:*

$$\tau_n = 881.0 \pm 3\ s$$

typically (Fomblin) :

$$\tau_n - \tau = 100 - 150\ s$$

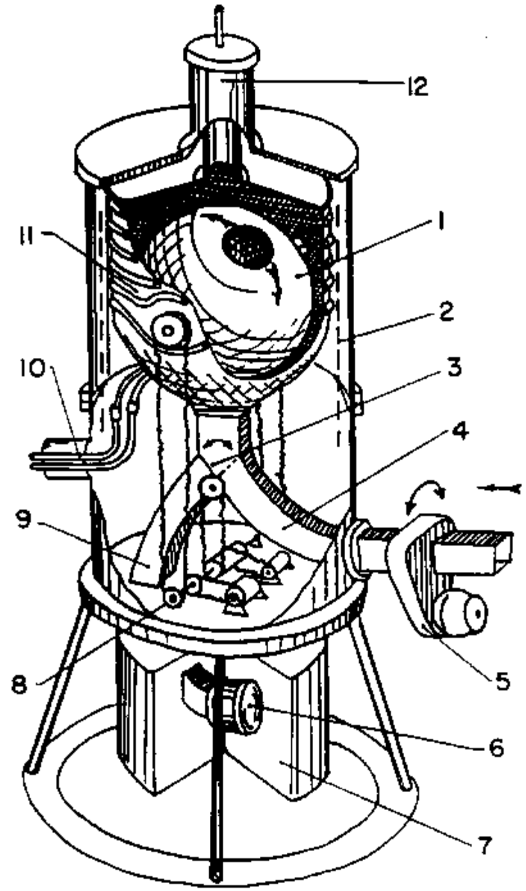
[A. Pichlmaier *et al.*, NIM A 440 (2000) 517]

- *Surfaces from frozen oxygen → best storage time ever obtained with a material bottle*

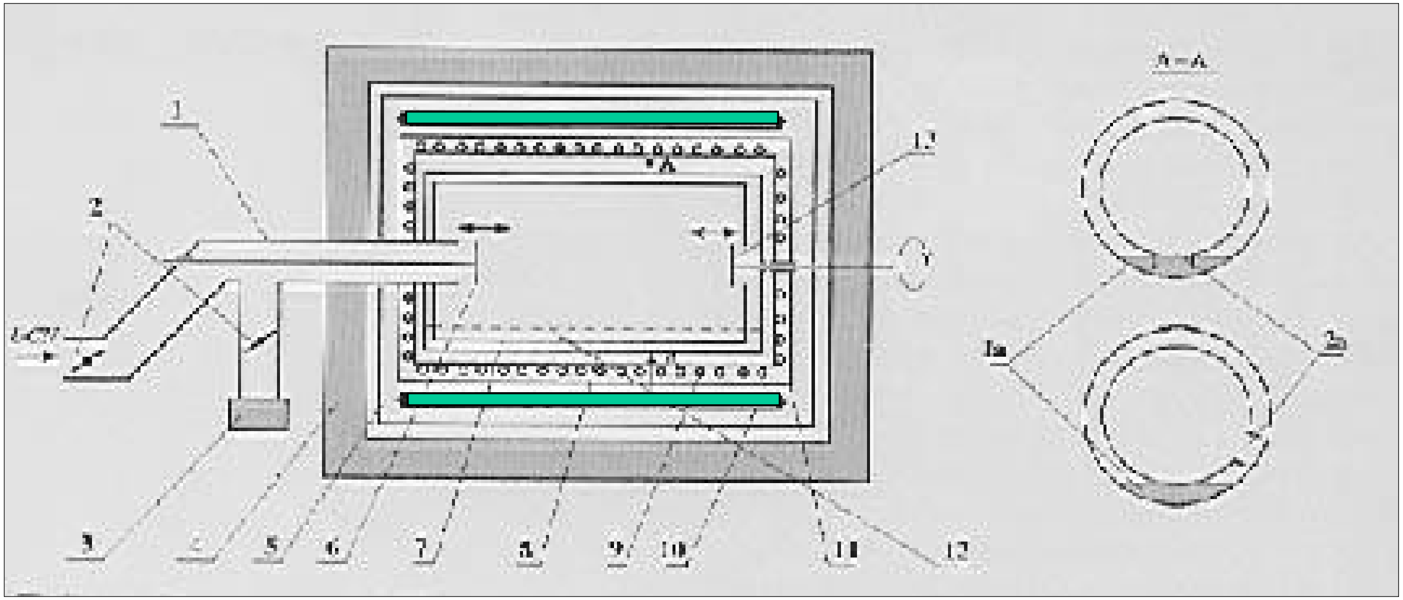
$$\tau_n - \tau = 23\ s$$

- *S/V – variation + extrapolation*
- *Measurements for different UCN-velocity-spectra*
- *Result:*

$$\tau_n = 888.4 \pm 3.1\ s$$



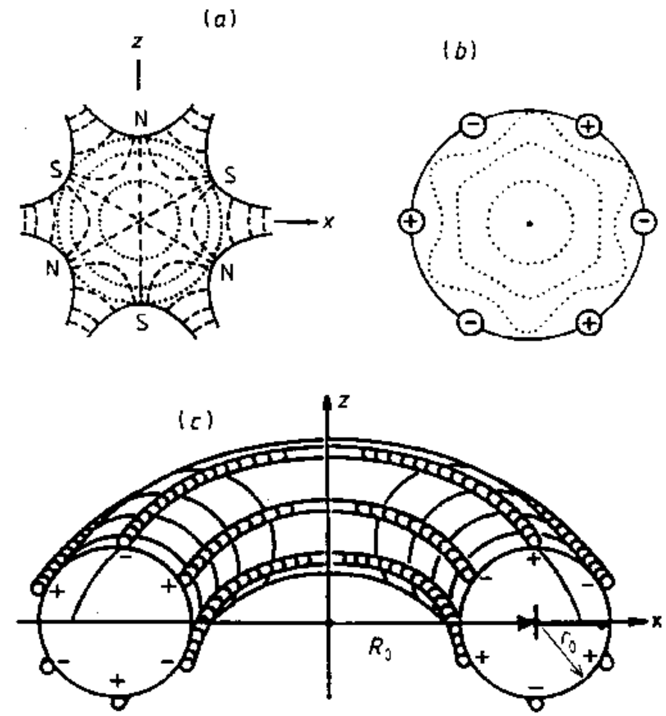
[V. Nesvizhevsky, A. Serebrov *et al.*, JETP 75 (1992) 405]



- *Liquid surfaces*
- *Detection of upscattered neutrons (monitoring of losses)*
- ***Result:*** $\tau_n = 885.4 \pm 0.9_{stat} \pm 0.4_{syst}\ s$

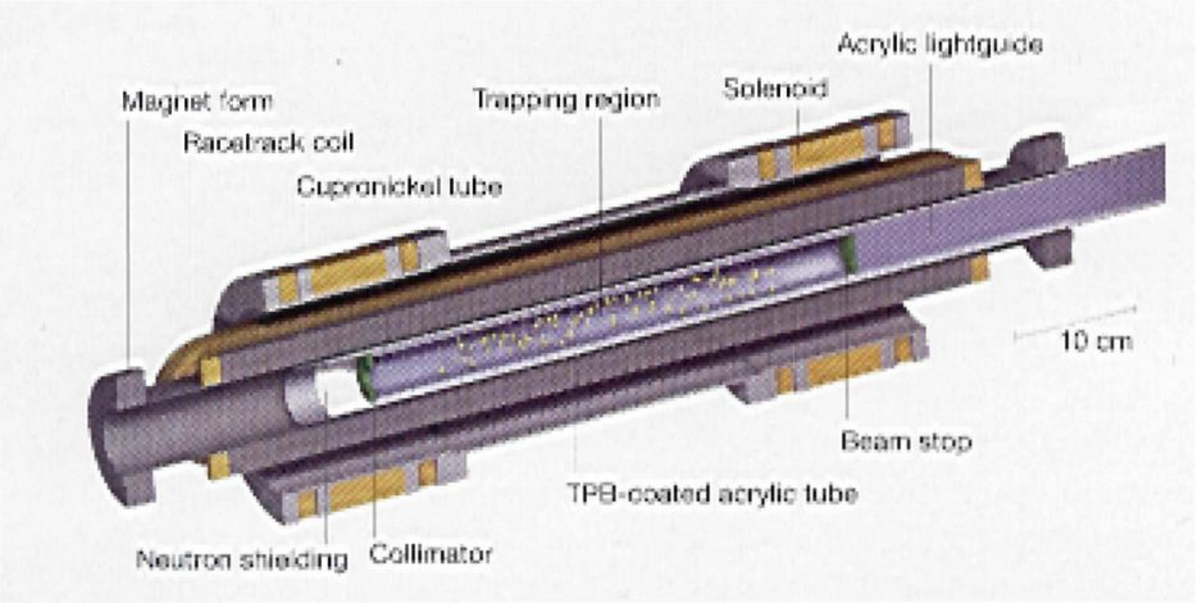
[S. Arzumanov, L. Bondarenko *et al.*, NIM A 440 (2000) 511]

- *Magnetic trapping* of very cold neutrons
- (spin component with $\mu \cdot B < 0$)
- Result:



$$\tau_n = 876.7 \pm 10\ s$$

[F. Anton, W. Paul *et al.*, NIM A 284 (1989) 111]



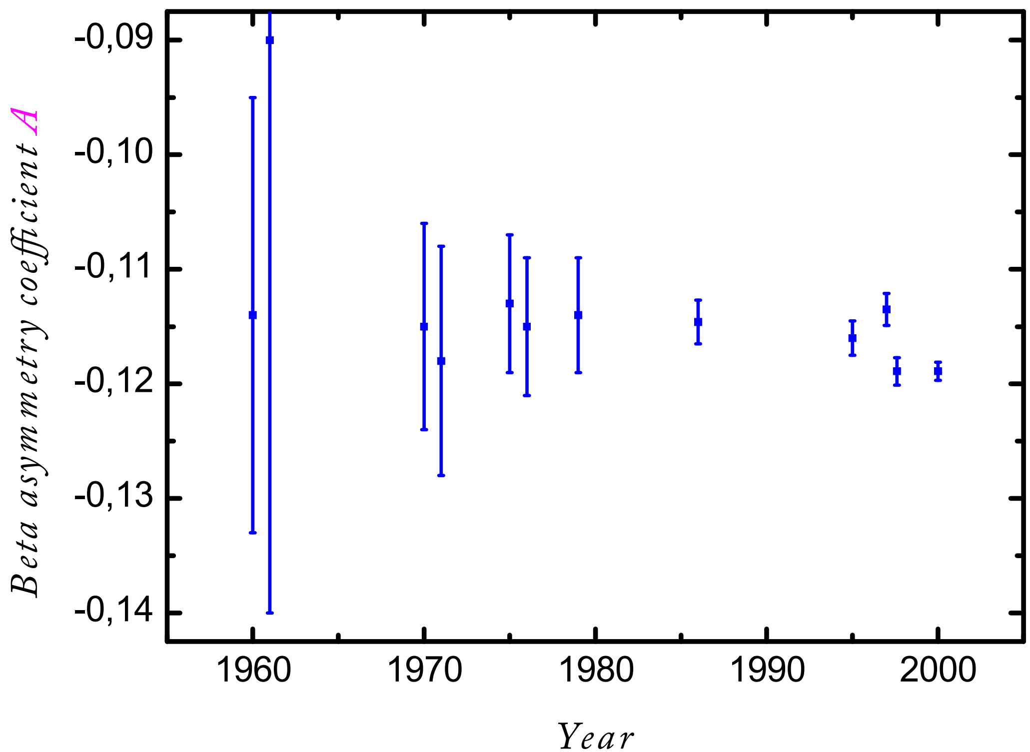
- *Production of UCN in a 3-D magnetic trap (inelastic n-scattering in superfluid ^4He)*
- *In-situ detection of charged particles ($N(t)$) (scintillation in the Helium)*
- *requires ultrapure ^4He at 150 mK !*
- *First result:*

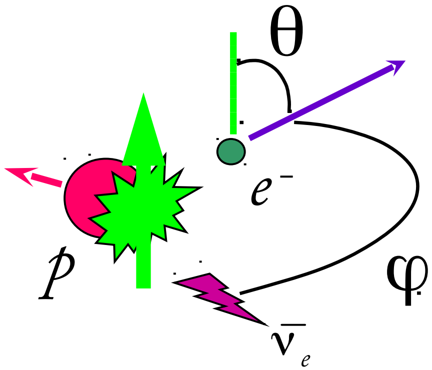
$$\tau_n = 750^{+330}_{-200}\ s$$

[P.R. Huffman *et al.*, Nature 403 (2000) 62]

2) Neutron β - asymmetry

(Wu-experiment with neutrons)





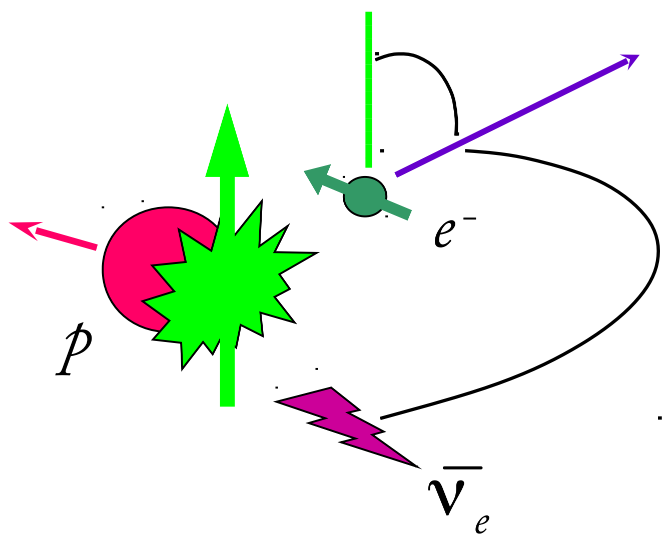
$$dW \propto 1 + \frac{v}{c} P_n A \cos\theta$$

$\lambda = -1.2715 \pm 0.0021$ [PDG 2000]

Angular correlations:

Differential decay probability:

$$dW \propto 1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} + \ldots + R\frac{\vec{p}_e \times \vec{P}_e}{E_e} \right) \cdot \vec{P}_n$$



- *In general*: a, b, A, B, D, R, τ_n *are functions of* $L_{V,A,S,T}$ *and* $R_{V,A,S,T}$

- *Within the standard model*:

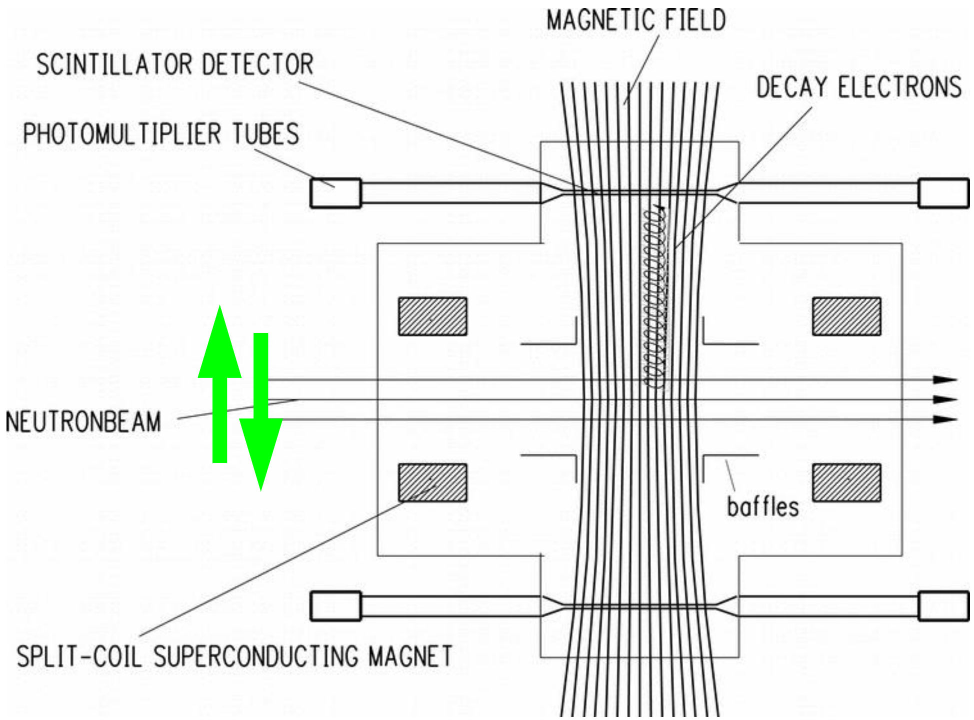
$$a = \frac{1-\lambda^2}{1+3\lambda^2}, \qquad A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2},$$

$$B = 2\frac{\lambda-\lambda^2}{1+3\lambda^2}, \qquad b = D = R = 0,$$

$$\tau_n^{-1} \propto g_V^2\left(1+3\lambda^2\right) \qquad \textit{with} \qquad \lambda := \frac{g_A}{g_V}$$

$\Rightarrow$ *determination of the weak couplings* g_A *and* g_V

The spectrometer PERKEO II (Heidelberg – ILL)



Effect	Correction	Error
Polarization analysis		
Polarization efficiency	1.1%	0.3%
spinflip efficiency	0.3%	0.1%
Data set		
Statistics		0.45%
Background	(0.5%)	0.25%
Detector response		
Linearity		0.2%
Width and pedestal		0.1%
Drifts		0.06%
Edge effect	(-0.24%)	0.1%
Hemisphere integration		
Mirror effect	0.09%	0.02%
backscattering	0.2%	0.17%
Radiation corrections	0.09%	0.05%
Sum	**2.04%**	**0.68%**

[H. Abele, S. Baeßler, D. Dubbers *et al.*, PLB 407 (1997) 212]: $A = -0.1189(12)$

[J. Reich, H. Abele, D. Dubbers *et al.*, NIMA 440 (2000) 535]
// [H. Abele, S. Baeßler. D. Dubbers *et al.*, to appear in PRL]: $A = -0.1189(8)$

combined: $A = -0.1189(7) \rightarrow \lambda = -1.2739 \pm 0.0019$

3) Neutron results for V_{ud}

PDG 2000 (4 *recent values of* A + *world av. of* τ_n):

$$V_{ud} = 0.9728 \pm 0.0012$$

$$\rightarrow \quad \sum_i V_{ui}^2 = 0.9946 \pm 0.0025 \rightarrow 2.2\sigma \textit{ off unitarity}$$

PERKEO II results alone + *world av. of* τ_n:

$$V_{ud} = 0.9713 \pm 0.0013$$

$$\rightarrow \quad \sum_i V_{ui}^2 = 0.9917 \pm 0.0028 \rightarrow 3.0\sigma \textit{ off unitarity}$$

IV. Next steps to improve on V_{ud}

1) New run with PERKEO II

- 4 times stronger beam at ILL

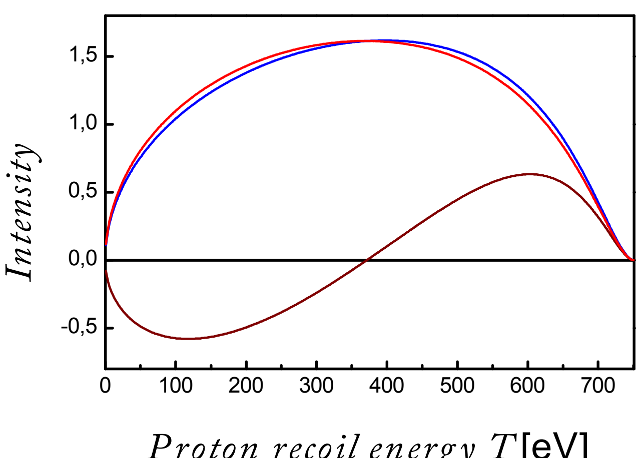
  (Supermirror guide set up by Heidelberg group)

- Neutron polarization analysis with pol. ^{3}He [O. Zimmer, P. Hautle, W. Heil *et al.*, PL B 455 (1999) 62]

$$\bar{\nu}_e - e^-$$

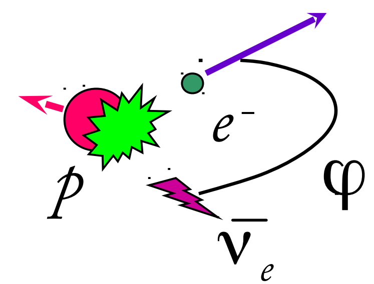
2) Measurement of $\bar{\nu}_e - e^-$ angular correlation coefficient a with aSPECT

Proton recoil spectrum is sensitive to λ:



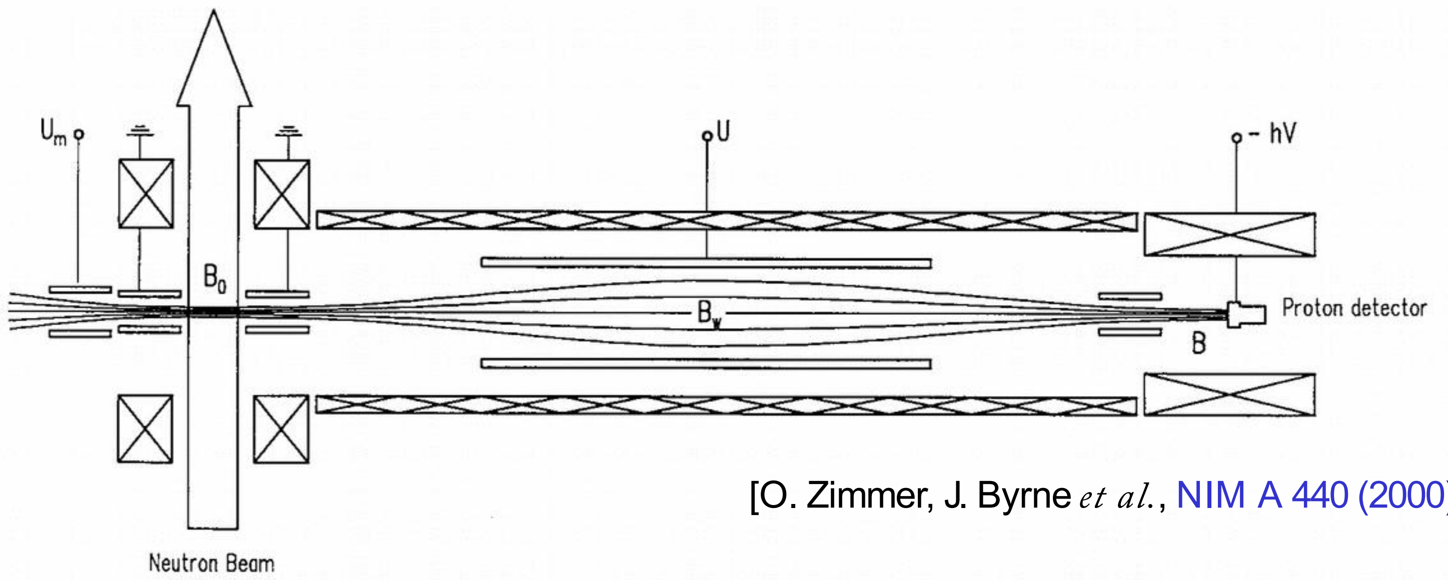
$$W(T) = g_1(T) + a\, g_2(T)$$

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



$$dW \propto 1 + \frac{v}{c}\, a \cos\varphi$$

The proton recoil spectrometer aSPECT (Mainz – München – Sussex)



[O. Zimmer, J. Byrne *et al.*, NIM A 440 (2000) 548]

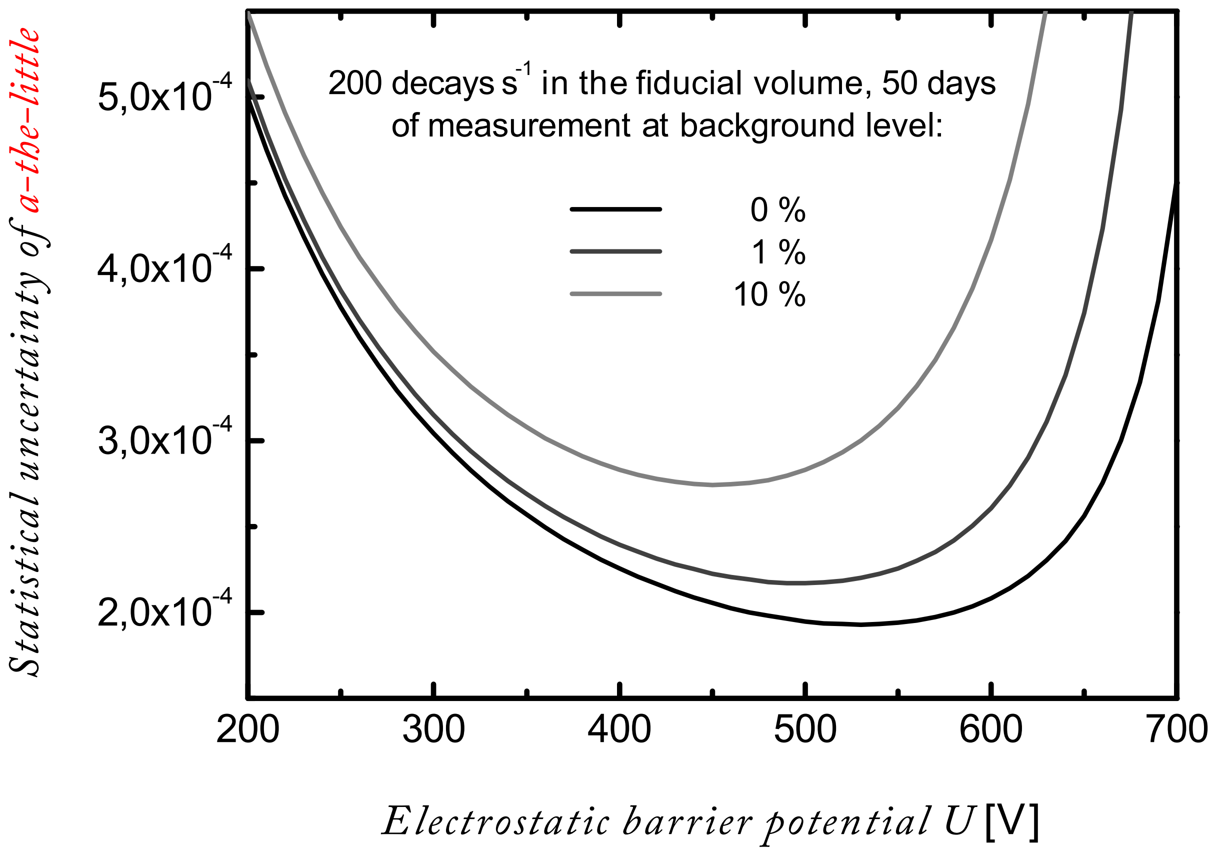
Present knowledge:

$$a = -0.102 \pm 0.005 \Rightarrow |\lambda| = 1.259 \pm 0.017$$

Aim of aSPECT:

$$\sigma(\lambda) \leq 10^{-3} \quad \Leftrightarrow \quad \sigma(a) \leq 3 \times 10^{-4}$$

Statistical precision



3) Magnetic storage of ultracold neutrons (TU München, PNPI)

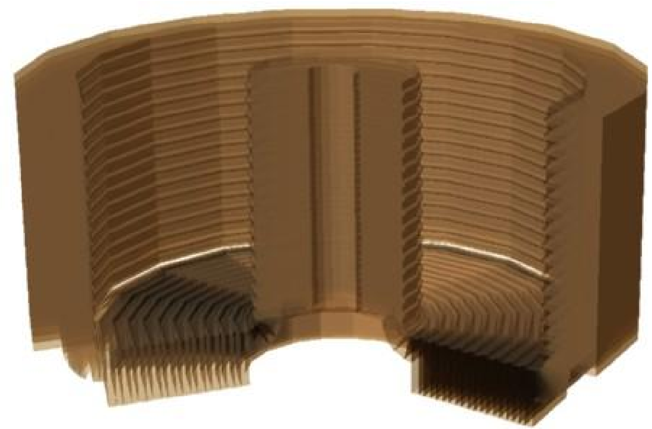
Strategy:

- *Magneto-gravitational trapping of UCN, avoiding wall collisions*
- *No losses due to depolarisation (?), but:*
- *Control of losses*

$$\tau^{-1} = \tau_n^{-1} + \tau_{los\ s}^{-1}$$

- *In-situ measurement of N(t) using proton detectors*

[O. Zimmer, JP G 26 (2000) 67-77]



Setup of the trap with permanent magnets

[F.J. Hartmann, I. Altarev, S. Paul *et al.*, TU München, E18]

A i m $\sigma(\tau_n)$ *s* << 1

- *UCN density at FRM II: 10^4 cm^{-3} (at ILL: 50 cm^{-3})*

V. Radiative corrections

- *Model-independent rc's:*
  - *Changes spectra and asymmetries (~ 1 % effects)*
  - *Reliably calculated*

[F. Glück, PR D 47 (1993) 2840]
// [F. Glück, PL B 436 (1998) 25]

- *Model-dependent rc's:*
  - *Can be absorbed into G_V and λ*

    (neglecting terms of order $\propto \alpha \frac{E_e}{m_n} \ln \frac{m_n}{E_e} \cong 10^{-5}$ *)*
  - *Very important for CKM unitarity test, but less reliably known*

$$\Delta_R^V = \Delta_{R,med}^V + \Delta_{R,asymp}^V = 2.40 \pm 0.08\ \%$$

$$\cong 0.2\% + 2.2\%$$

(m e.g. $\cong 0.24$ GeV, $p \geq 4$ GeV)

[W.J. Marciano, A. Sirlin, PRL 56 (1986) 22] //
[A. Sirlin, in Prec. Tests of the Standard Electroweak Model, World Sc. 1994]

VI. Conclusions

- Both $0^+ \to 0^+$ superallowed nuclear β - decays and neutron β - decay seem to violate CKM unitarity (by 2.2σ resp. 3σ).

- Nuclear β - decays have reached theoretical limit set by model-dependent radiative correction Δ_R^V. Problems with correction δ_C, further investigated both theoretically and experimentally.

- Neutron decay has smaller theoretic uncertainties. New experiments:

  β - asymmetry with PERKEO II,

  antineutrino – electron angular correlation with aSPECT,

  neutron lifetime via magnetic storage of UCN

  will improve precision of V_{ud} beyond limit set by Δ_R^V.

$\Rightarrow$ New, reliable calculation of Δ_R^V needed!