Neutron beta decay frontier in Europe

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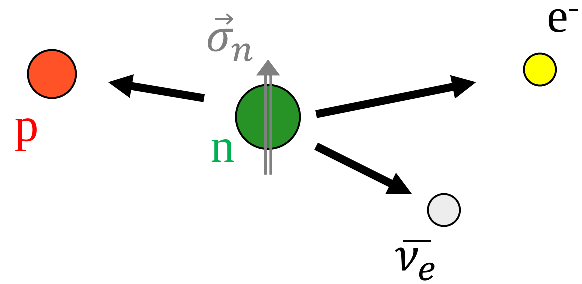
N.B.: I am mostly presenting other people's work. I thank for slides from K. Bodek, W. Heil, C. Schmidt, O. Zimmer, G. Konrad, D. Moser, S. Ivanov, D. Geisbauer, B. Märkisch. Errors are all due to my rearranging and compressing.

Observables in Neutron Beta Decay

Observables in neutron beta decay, as a function of generally possible coupling constants (assuming only Lorentz-Invariance):

Jackson et al., PR 106, 517 (1957), C.F. v.Weizsäcker, Z. f. Phys. 102,572 (1936), M. Fierz, Z. f. Phys. 105, 553 (1937)



$$d\Gamma \propto \rho(E_e)\cdot\left(1+3|\lambda|^2\right)\cdot\left\{1+a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu}+b\frac{m_e}{E_e}+\vec{\sigma}_n\cdot\left(A\frac{\vec{p}_e}{E_e}+B\frac{\vec{p}_\nu}{E_\nu}+D\frac{\vec{p}_e\times\vec{p}_\nu}{E_e E_\nu}\right)\right\}$$

Fierz interference term $b = 0$

Neutrino-Electron-Correlation $a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$

Beta-Asymmetry $A = -2\frac{|\lambda|^2+\mathrm{Re}\,\lambda}{1+3|\lambda|^2}$

Neutrino-Asymmetry B

Neutron lifetime $\tau_n^{-1} = \frac{2\pi}{\hbar} G_F^2 V_{ud}^{\ 2}\left(1+3|\lambda|^2\right)\int\rho(E_e)$

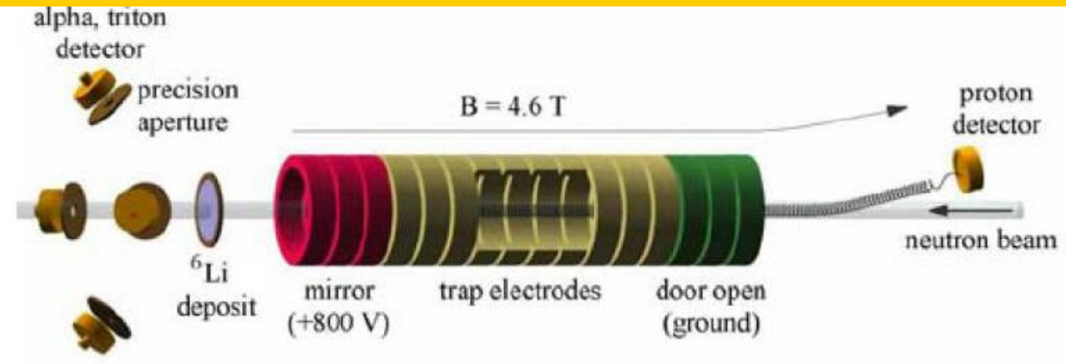
(Equations in SM, where $\lambda = g_A/g_V$)

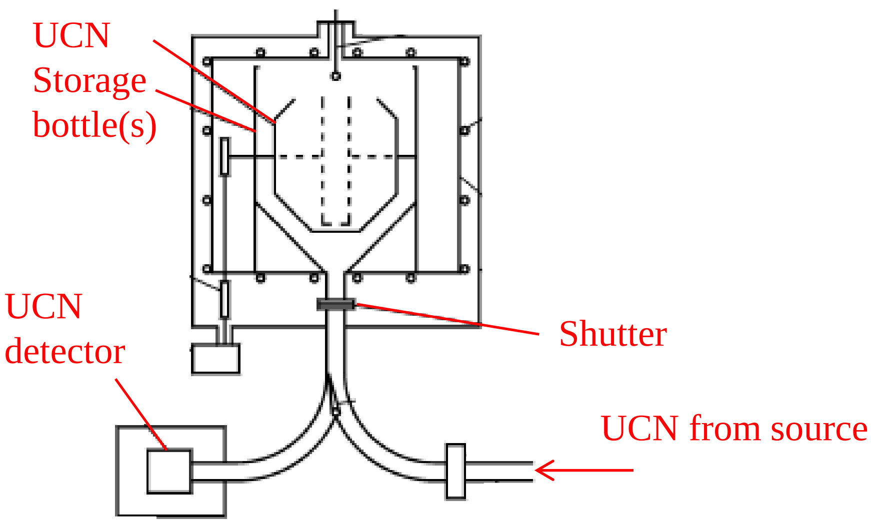
Neutron Lifetime Measurements

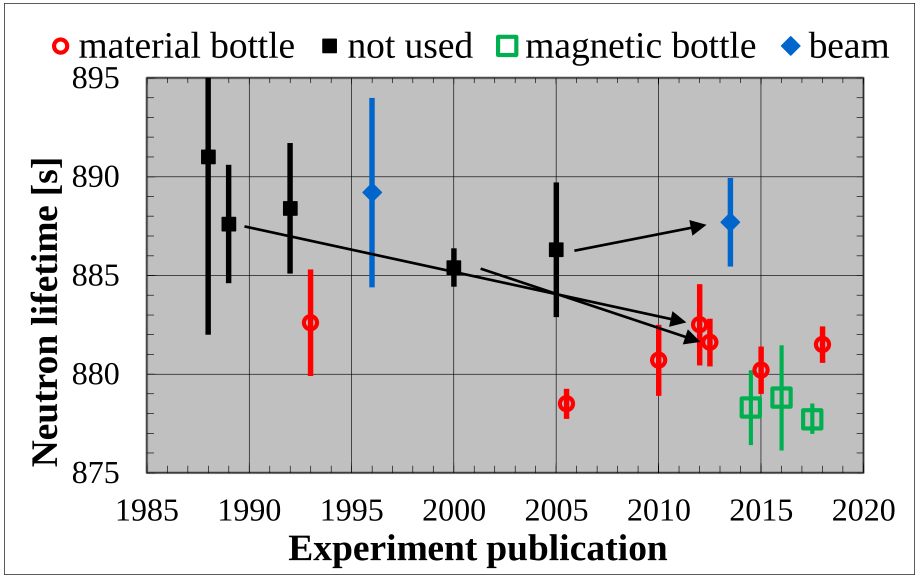
Beam: Decay rate: $\frac{dN}{dt} = \frac{N}{\tau_n}$

Bottle: Neutron counts : $N = N_0 e^{-\frac{t}{\tau_{eff}}}$

with $\frac{1}{\tau_{eff}} = \frac{1}{\tau_n} + \frac{1}{\tau_{wall}}$



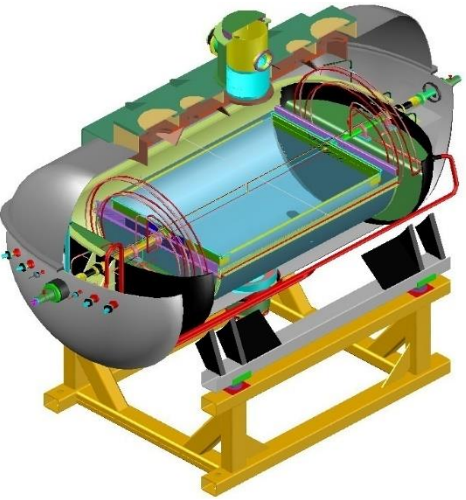




Many new experiments. In Europe…

- Improved material bottles (e.g. Big GRAVITRAP, Serebrov et al.)
- Magnetic bottles (e.g. UCNτ, C.-Y. Liu et al., LANL; τSPECT, W. Heil, M. Beck et al., TRIGA Mainz; HOPE, O. Zimmer et al., ILL Grenoble, PENELOPE, S. Paul et al., TU München; V. Ezhov et al. PNPI)
- Beam Lifetime (only at NIST)

Neutron lifetime in material bottle - Big GRAVITRAP



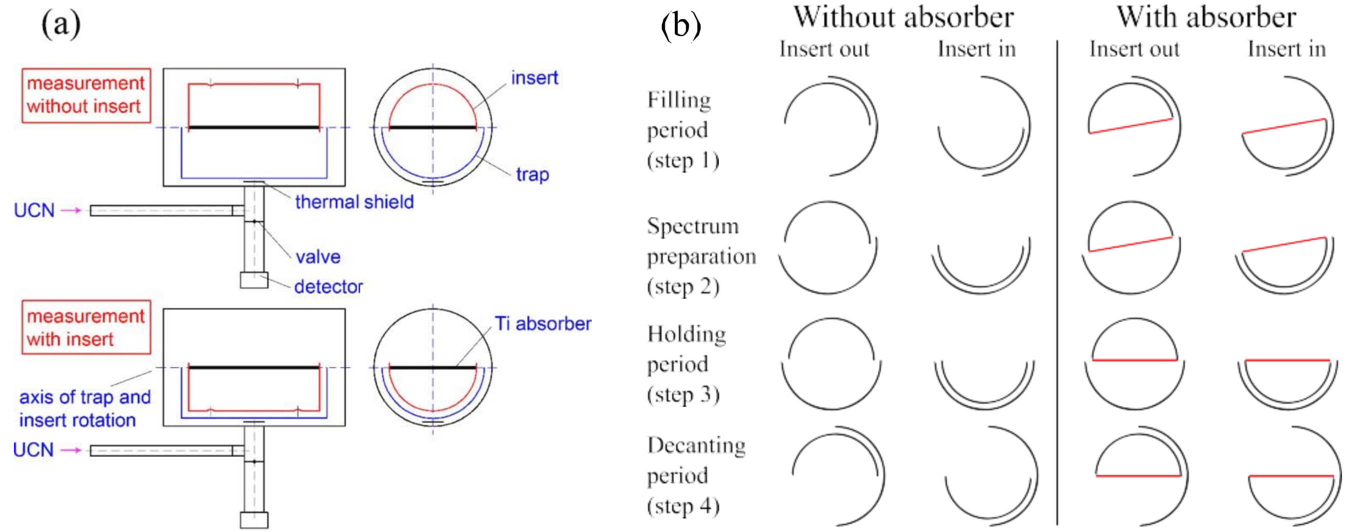


FIG. 1. Basic scheme of inner part of the apparatus (a) with conceptual scheme for the measuring procedures (b).

Idea: Measure Neutron count rate after storage:

$$N(t,E) = N_0 e^{-t/\tau_{st}(E)}$$

with storage lifetime $\tau_{st}^{-1}(E) = \tau_n^{-1} + \tau_{loss}^{-1}(E)$

and $\tau_{loss}^{-1}(E) = \mu(T,E)\nu(E) = \eta(T)\gamma(E)$

Loss coefficient — Effective collision frequency

If one measures two situations with different γ, and computes $\gamma_2(E)/\gamma_1(E)$, one gets

$$\tau_n^{-1} = \tau_1^{-1} - (\tau_2^{-1} - \tau_1^{-1})/\left[\frac{\gamma_2(E)}{\gamma_1(E)} - 1\right]$$

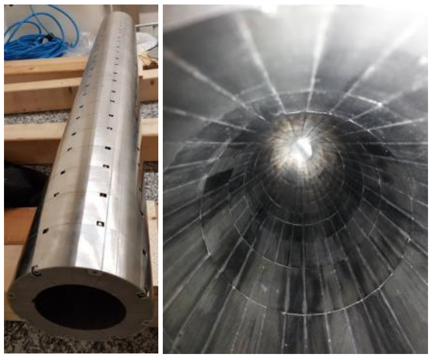
This can be done by varying trap geometry (better), or by varying neutron energy.

Result: $\tau_n = 881.5 \pm 0.7^{stat.} \pm 0.6^{syst.}$ (Phys. Rev. C 97, 055503 (2018))

S. Ivanov, A.P. Serebrov et al. (PNPI Gatchina et al.)

Neutron lifetime in magnetic trap - $\tau SPECT$

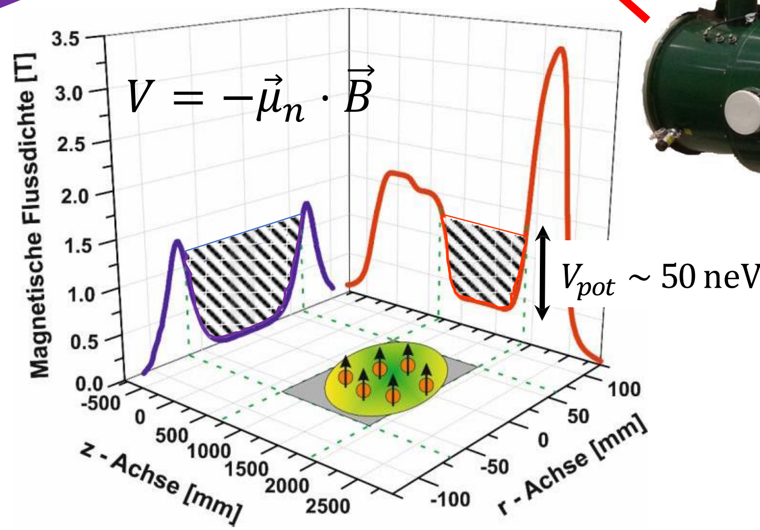
Octupole magnet
Halbach-configuration



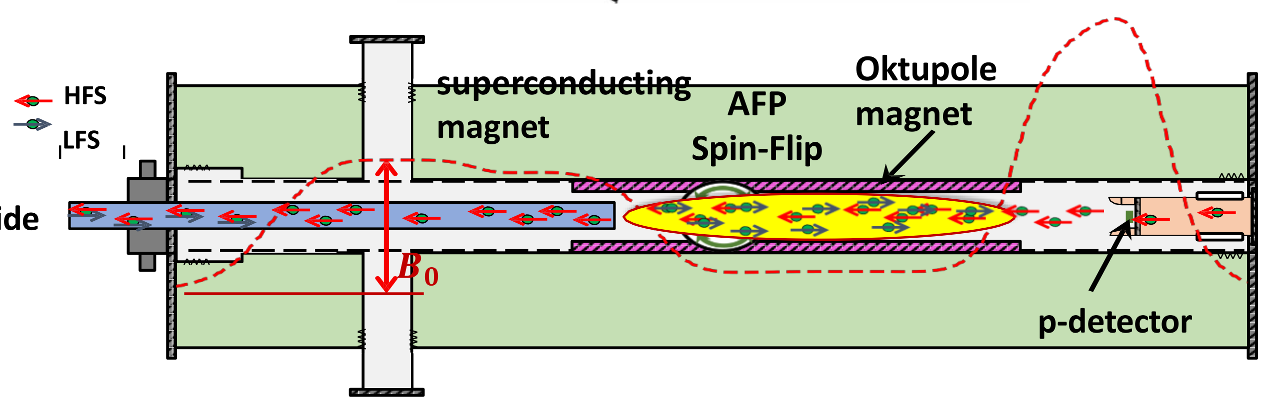
permanent magnets Sm_2Co_{17}

radial

axial

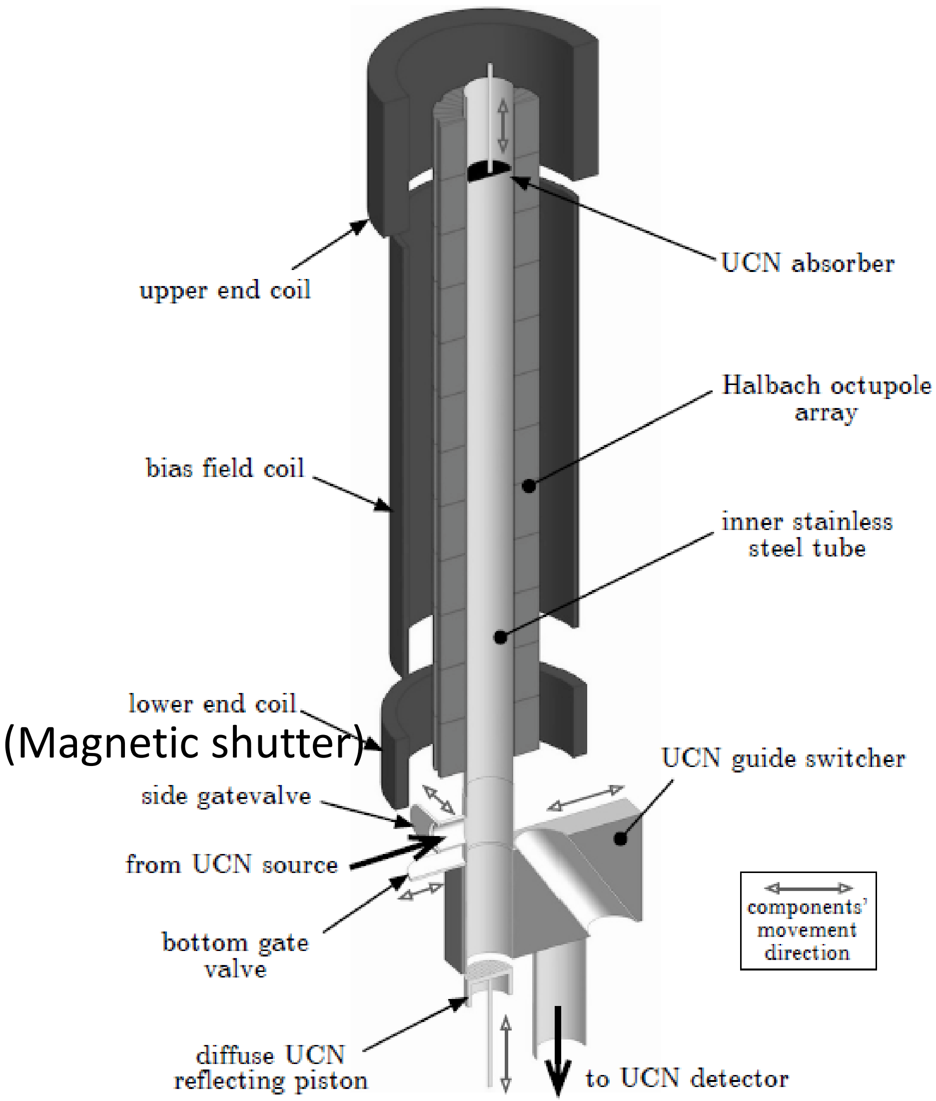


aSPECT superconducting magnet (see later)



Goal:
$\Delta\tau_n \leq 2$ s (soon)
$\Delta\tau_n \leq 0.3$ s
(2023?)

Neutron lifetime in magnetic trap (2) - HOPE



Measurement procedure: Start with well established "fill and empty" method. Use lower end coil as magnetic shutter.

Feature: Full-bore access from top and bottom:

- insertion of diffusive paddle and absorber
- monitoring of depolarisation
- detection of marginally trapped neutrons
- later proton detection possible at top

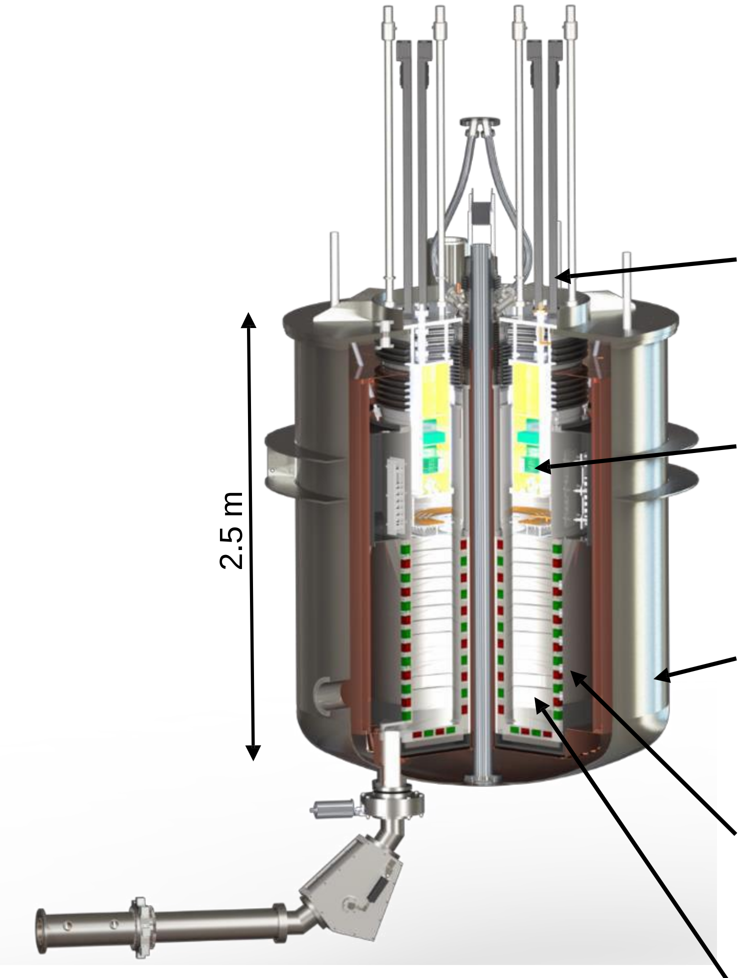
Couple experiment to superfluid-helium UCN source **SUN-2** at ILL
(pessimistic estimate: 3000 UCN/fill)

$\delta\tau_n$ ~ 0.7 s in 50 days (statistical)

Experiments @ PF2 performed in fall 2014
($\delta\tau = 52.7$ s in about 1 day)
Experiments @ SUN-2 in preparation **L. Babin**

Oliver Zimmer (ILL Grenoble) et al.

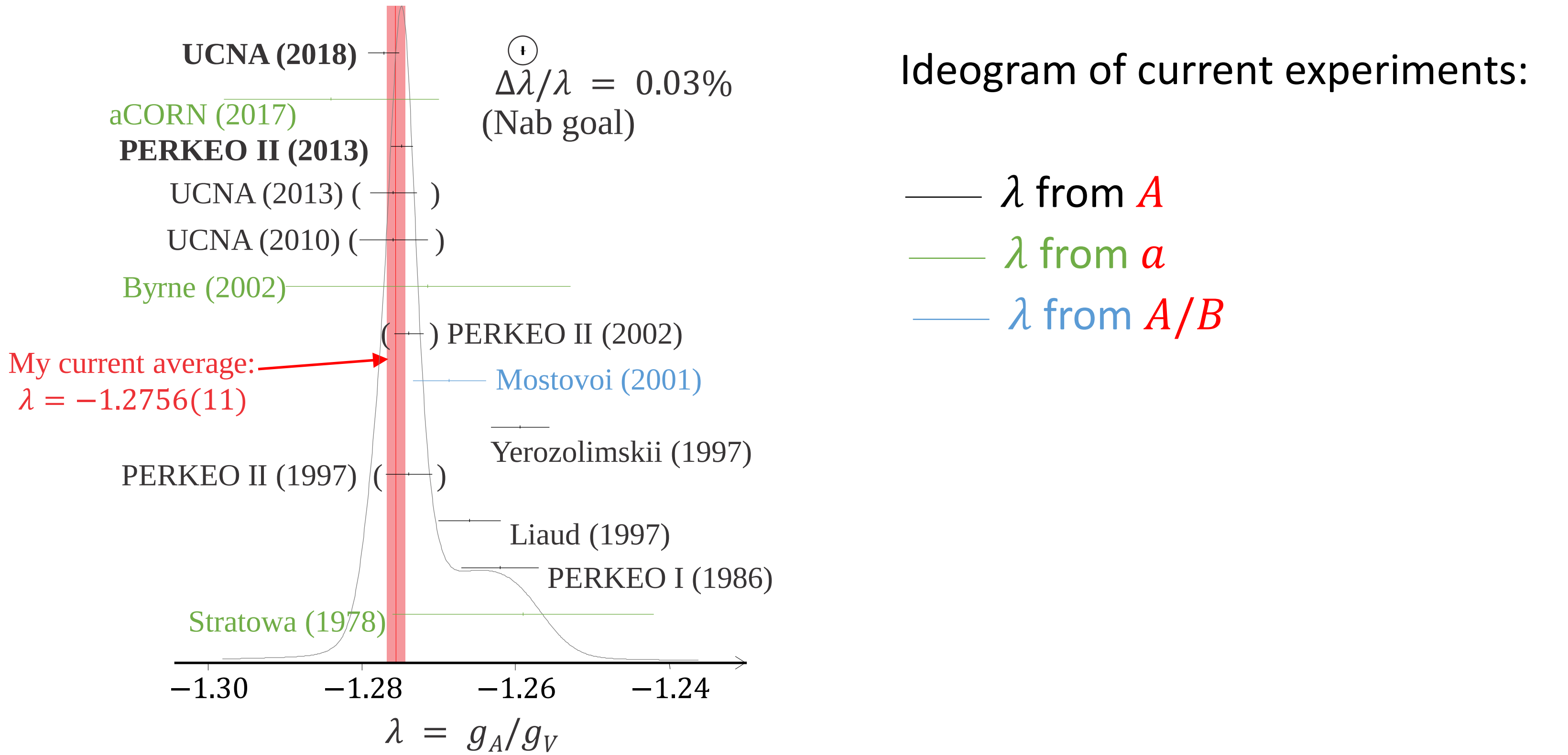
Neutron lifetime in magnetic trap (3) – PENELOPE



- Will be located at the Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II)
- Magneto-gravitational trap for ultra-cold neutrons
- Filling: Insert UCN, Ramp up magnetic field, remove high field seekers (spin-down neutrons) with absorber)
- Aiming for a precision of ± 0.1 s
- Measuring protons (during storage) and neutrons (after storage)

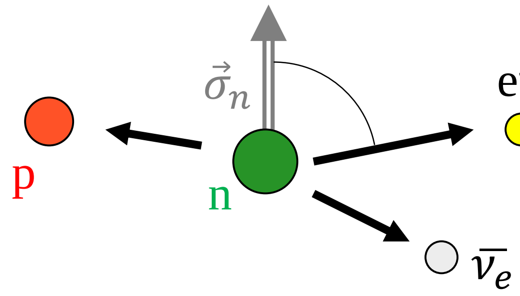
Determination of ratio λ of V,A coupling constants

Determination of ratio $\lambda = g_A/g_V$ from $A = -2(\mathrm{Re}\,\lambda + |\lambda|^2)/(1+3|\lambda|^2)$ or $a = (1-|\lambda|^2)/(1+3|\lambda|^2)$ from experiment:



(There is a shift to the left, since 20 years, confirmed with increasing accuracy over the years)

The Beta Asymmetry – general idea

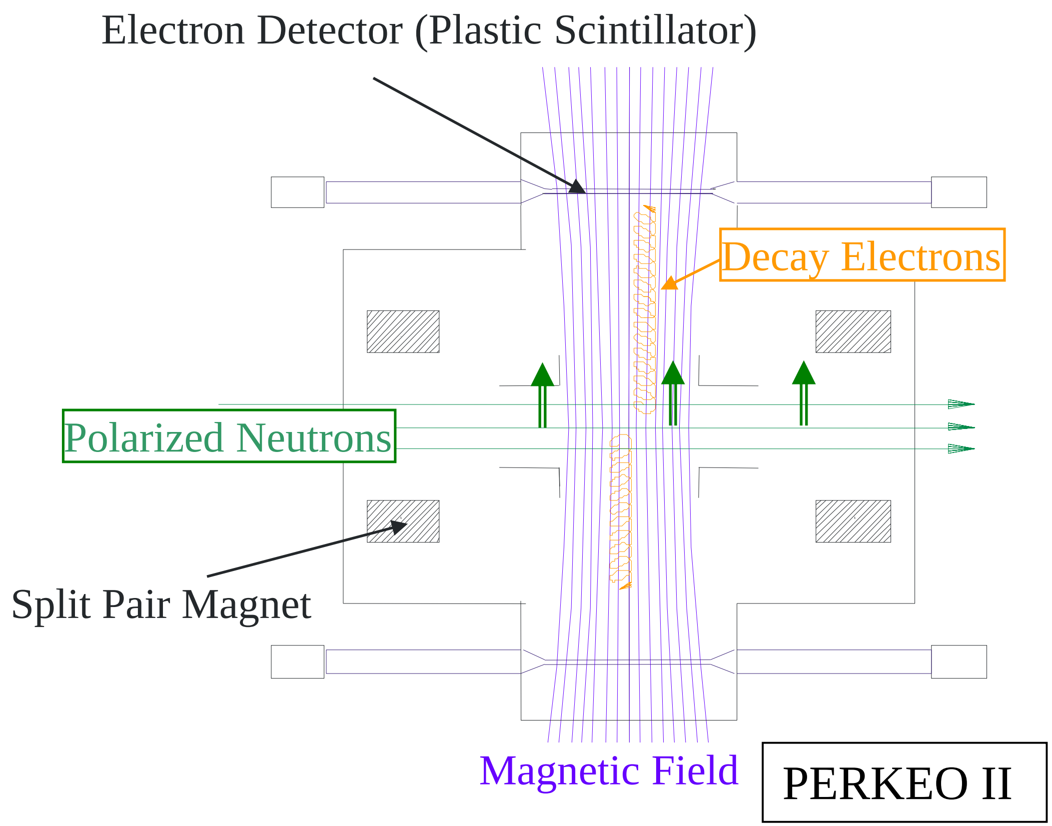


$$d\Gamma \propto \varrho(E_e)\left(1 + b\frac{m_e}{E_e} + A\vec{\sigma}_n \cdot \frac{\vec{p}_e}{E_e}\right)$$

Experimental Reality:

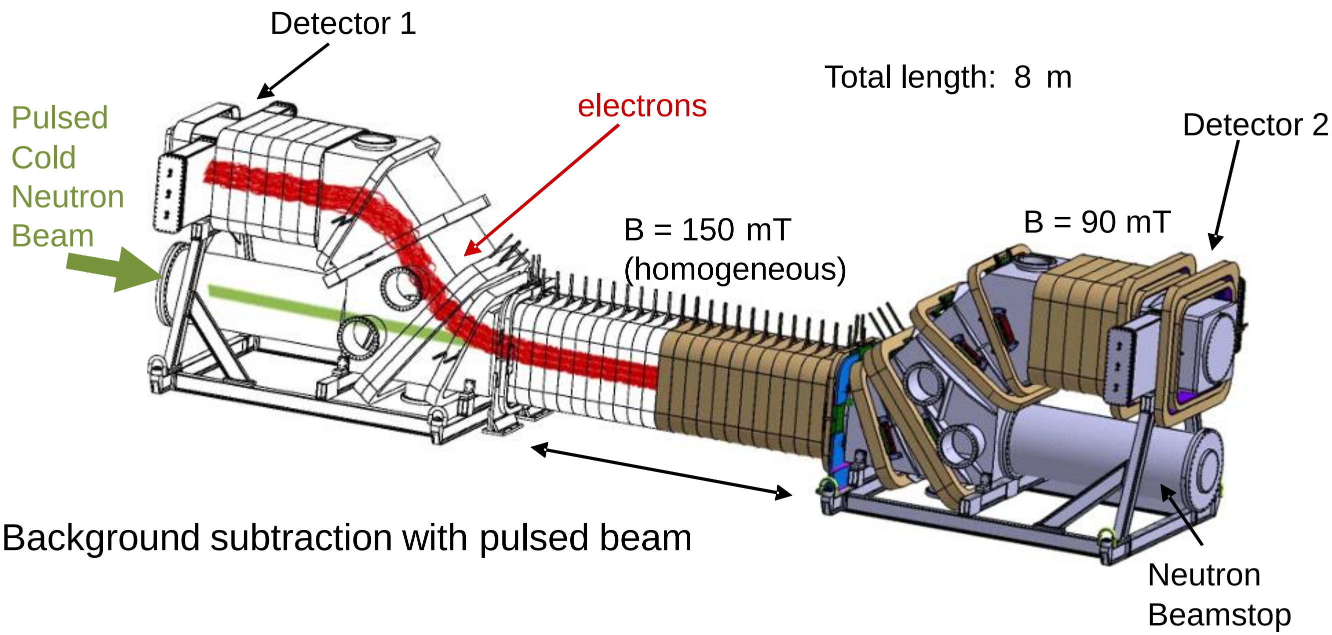
- Flip neutron spin, don't compare detectors!
- Two detectors still needed to suppress electron backscattering.

$$\frac{N_{\text{up}} - N_{\text{down}}}{N_{\text{up}} + N_{\text{down}}} = A\frac{v}{c}\langle\cos(p_e, \sigma_n)\rangle Pf$$

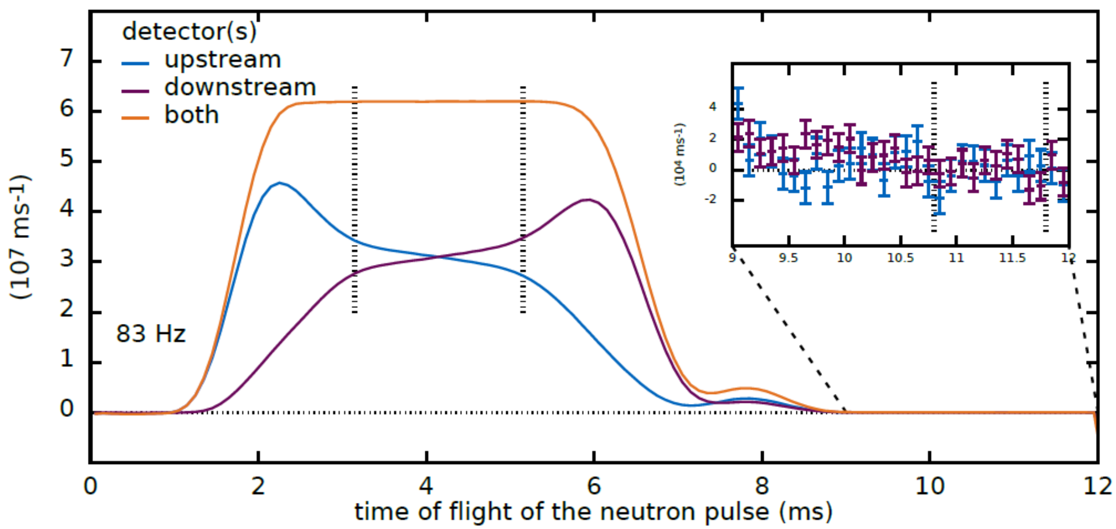


Perkeo 2 - Beam time	Result	Publication
1995	A = -0.1189(12)	Phys. Lett. B 407, 212 (1997)
1997	A = -0.1189(7)	Phys. Rev. Lett. 88, 211801 (2002)
2004	$A = -0.11926^{+47}_{-53}$	Phys. Rev. Lett. 110, 172502 (2013)

The Beta Asymmetry – PERKEO III



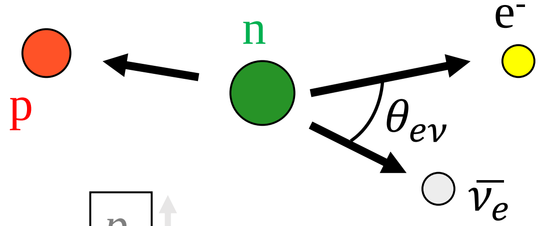
Background subtraction with pulsed beam



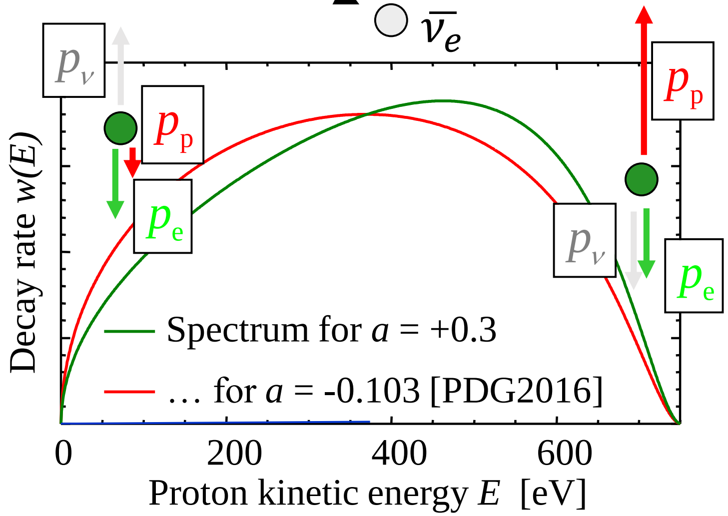
NB: At PPNS Grenoble, 2018, B. Märkisch presented a result with $\Delta A = 2.1 \cdot 10^{-4}$. The number is unpublished so far, and was not part of the slides I was given.

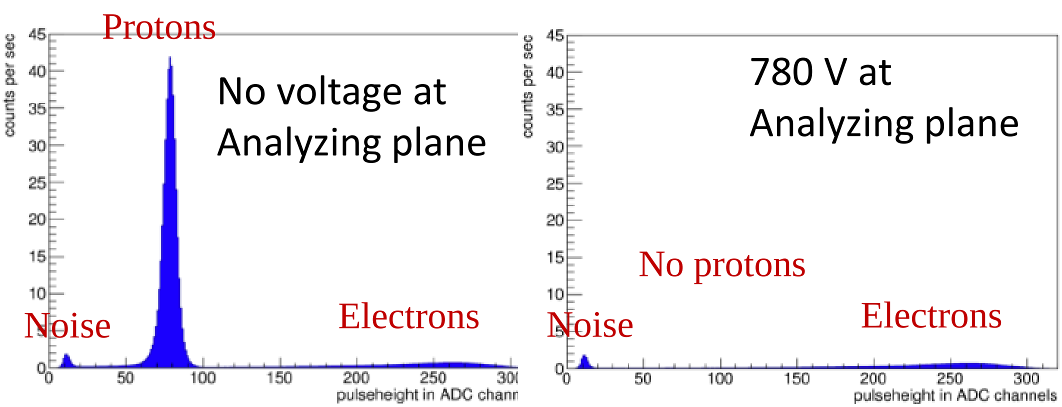
B. Märkisch (TU München), D. Dubbers (U Heidelberg), H. Abele (TU Wien) et al.

aSPECT @ ILL Grenoble



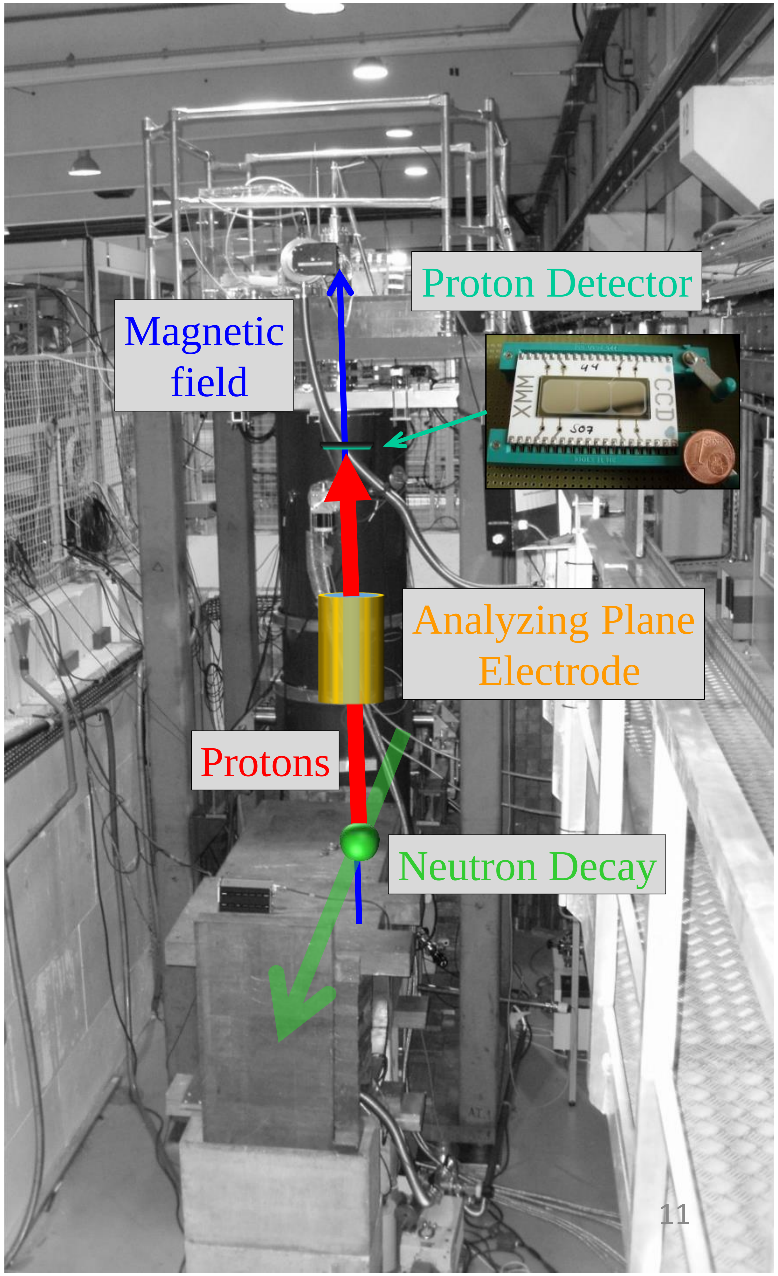
$$d\Gamma \propto \left(1 + a\frac{p_e}{E_e}\cos\theta_{ev}\right)$$





Preliminary result (PPNS Grenoble, 2018): $a = -0.10603(91)$

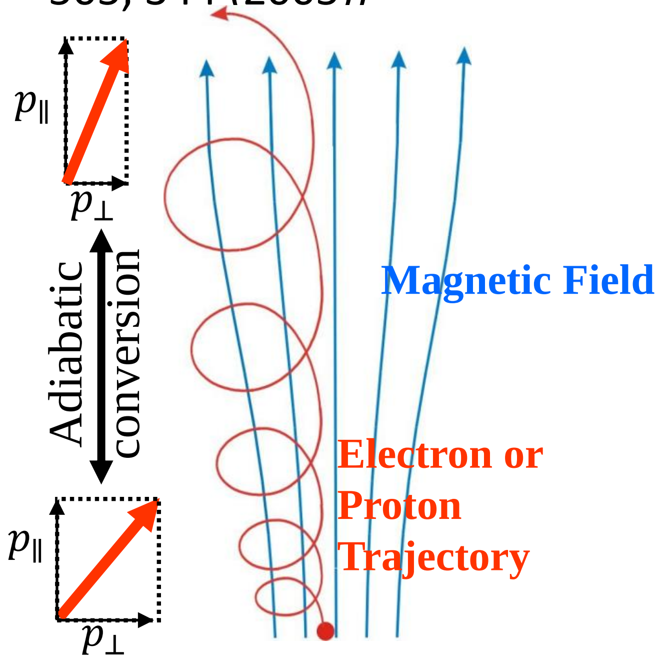
W. Heil, M. Beck, C. Schmidt (U Mainz) et al.

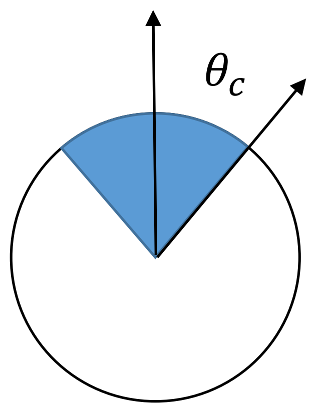


The Beta Asymmetry – next step (PERC)

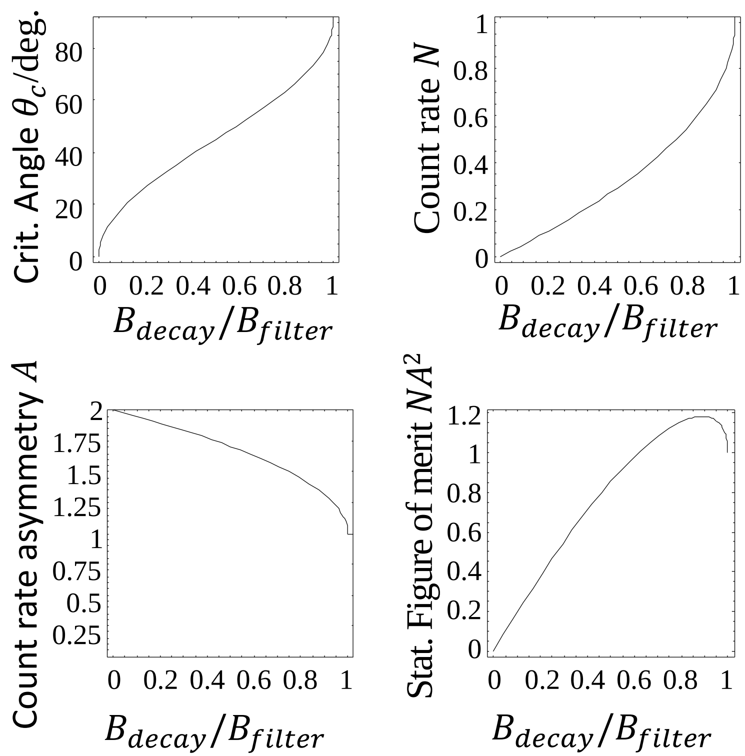
Motivation:

- Use idea from PERKEO III to reduce beam-related background (pulsed beam)
- Increase count rate by looking at decay volume in neutron guide
- Increase sensitivity through use of magnetic filter (see also A. Serebrov, Nucl. Inst. Meth. 505, 344 (2005))





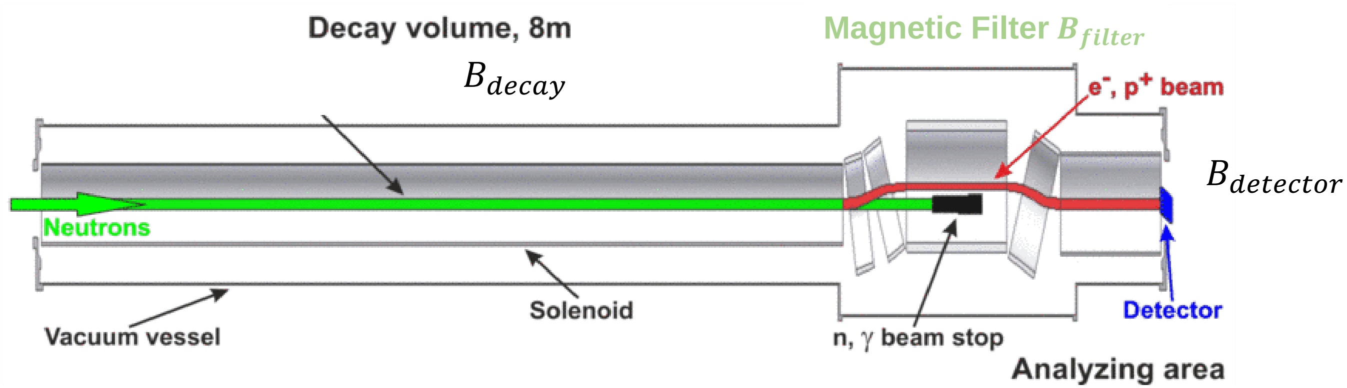
For asymmetry $d\Gamma \propto (1 + A\cos\theta)$



If $B_{filter} > B_{decay}$, detector behind filter detects only particles with angle to field θ less than crit. angle θ_c with $\sin\theta_c = \sqrt{\frac{B_{decay}}{B_{filter}}}$

See D. Dubbers et al., Nucl. Instr. Meth. A 596, 238 (2008)

The PERC facility @ FRM II



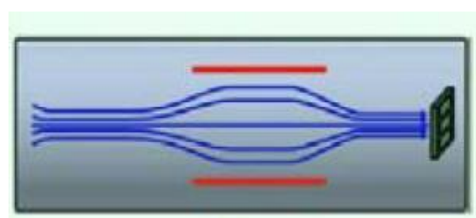
Active volume in a 8 m long neutron-guide, $B_{decay} \leq 1.5$ T:
(statistics, phase space density (S/B !), smaller detectors)

Magnetic Filter, $B_{filter} \leq 6$ T (can select $B_{filter}/B_{decay} = 2 \ldots 12$): phase space selection, systematics
(choice of solid angle, backscatter suppression)

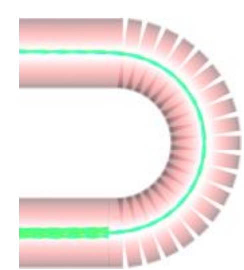
Source for specialized spectrometers

Electron or proton detector (Plastic scintillator, silicon)

MAC-E filter
(as in "aSPECT" – see later)



R×B spectrometer
(NOMOS)



B. Märkisch (TU München), D. Dubbers (U Heidelberg), H. Abele (TU Wien) et al.

Status of PERC

Focus on *non-coincident* measurements due to high count rates:

Polarised neutrons

β-asymmetry A — $\Delta A/A \sim 5 \cdot 10^{-4}$

Proton asymmetry C — $\Delta C \sim 3 \cdot 10^{-4}$

Neutrino asymmetry B — $\Delta B \sim 1 \cdot 10^{-3}$

Weak magnetism f_{WM} — $f_{WM} > 3\sigma$
from β-asymmetry or polarised spectra

> NB from Stefan: I showed an incorrect sensitivity goal for A. Bastian has given my a corrected number, and has confirmed the information for B and C. I am still unsure about the goal for a.

Status:

New beam line at FRM II, Garching, under construction

Superconducting Magnet delivery Q1/2019

Commissioning in 2020/2021.

PERC may move to European Spallation Source (ESS) if fundamental physics beamline (ANNI) gets funding.

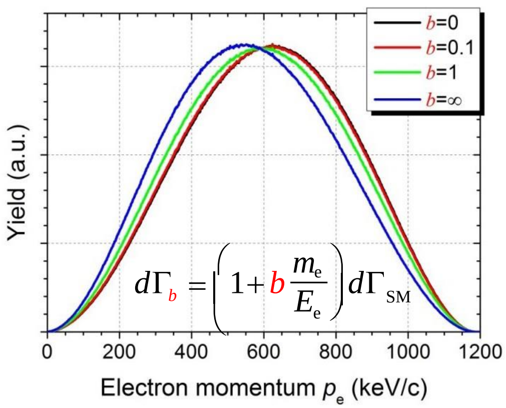
Unpolarised neutrons

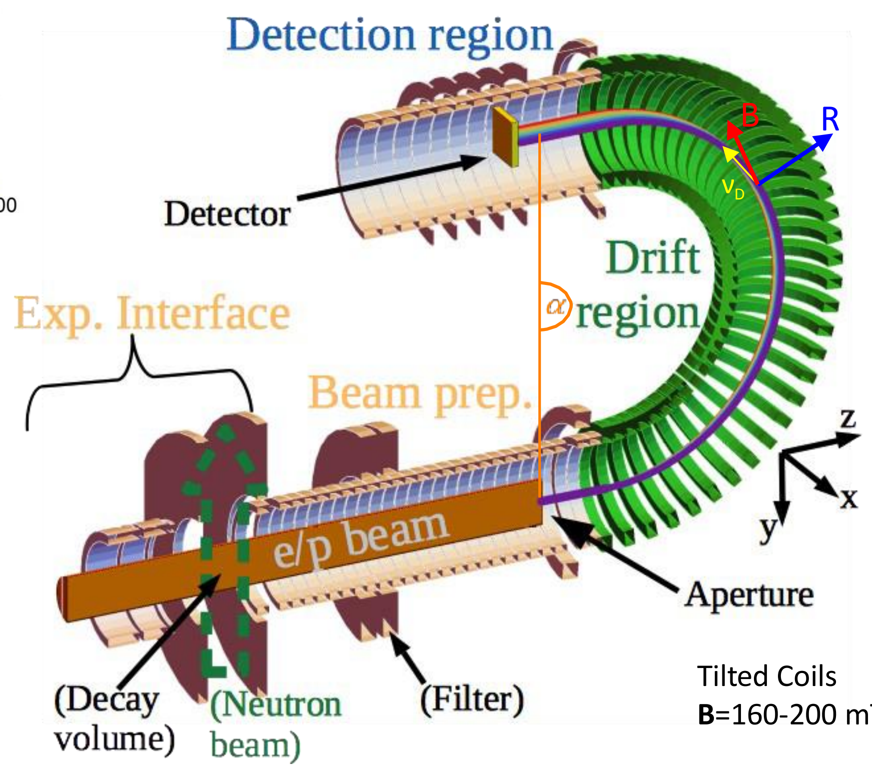
- Correlation a — $\Delta a \sim 5 \cdot 10^{-3}$
  from proton spectrum
- **Fierz term** b — $\Delta b \sim 1 \cdot 10^{-3}$
  from electron spectrum or β-asymmetry
- Electron helicity h

PERC Cryostat (12m)

B. Märkisch (TU München), D. Dubbers (U Heidelberg), H. Abele (TU Wien) et al.

NoMoS (**N**eutron Decay Pr**o**ducts **Mo**mentum **S**pectrometer)





Tilted Coils
B=160-200 mT

$$\vec{v}_d \propto \frac{R \times B_3}{qR^2 B_3^2}$$

$$D(p,\theta) = \int_T v_d \, dt = \frac{p}{qB_3} \cdot \alpha \cdot \frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

+ adiabatic transport
+ small distortion by θ
+ high resolution

R×B Magnet is planned to be available at the end of 2020.
Nomos is planned to be used to determine a and b to 0.1% level

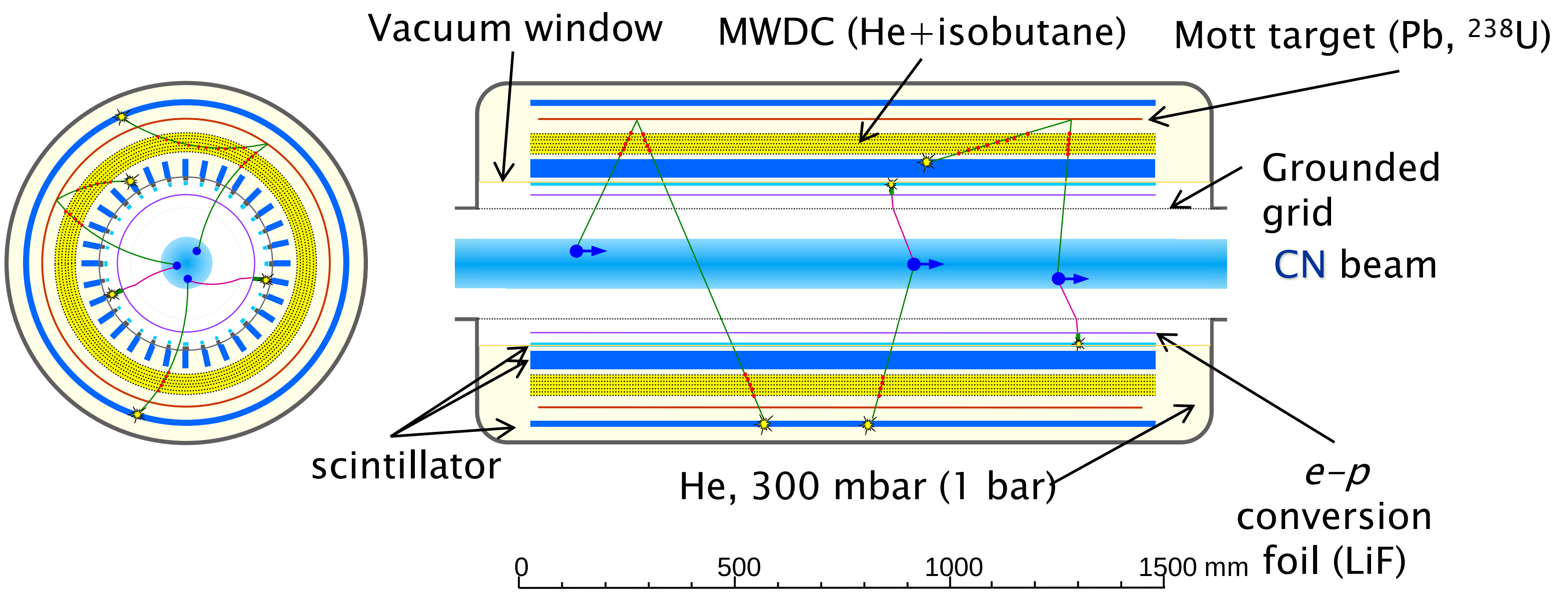
G. Konrad (SMI Wien) et al.

BRAND – Search for BSM physics through measurement of transverse electron polarization

Note that there is another workshop, "Theoretical issues and experimental opportunities in searches for time reversal invariance violation using neutrons" - Amherst, 6-8.12.2018

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto (1 + a\frac{\vec{p}_e}{E_e}\frac{\vec{p}_\nu}{E_\nu} + b\frac{m_e}{E_e} + \vec{\sigma}_n\left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right]$$
$$+\vec{\sigma}_e\left[H\frac{\vec{p}_\nu}{E_\nu} + L\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} + \mathrm{N}\vec{\sigma}_n + R\vec{\sigma}_n \times \frac{\vec{p}_e}{E_e}\right]$$
$$+\vec{\sigma}_e\left[S\vec{\sigma}_n\frac{\vec{p}_e}{E_e}\frac{\vec{p}_\nu}{E_\nu} + U\frac{\vec{p}_\nu}{E_\nu}\left(\vec{\sigma}_n \cdot \frac{\vec{p}_e}{E_e}\right) + V\frac{\vec{p}_\nu}{E_\nu} \times \vec{\sigma}_n\right]$$

BRAND needs to measure transverse electron polarization.



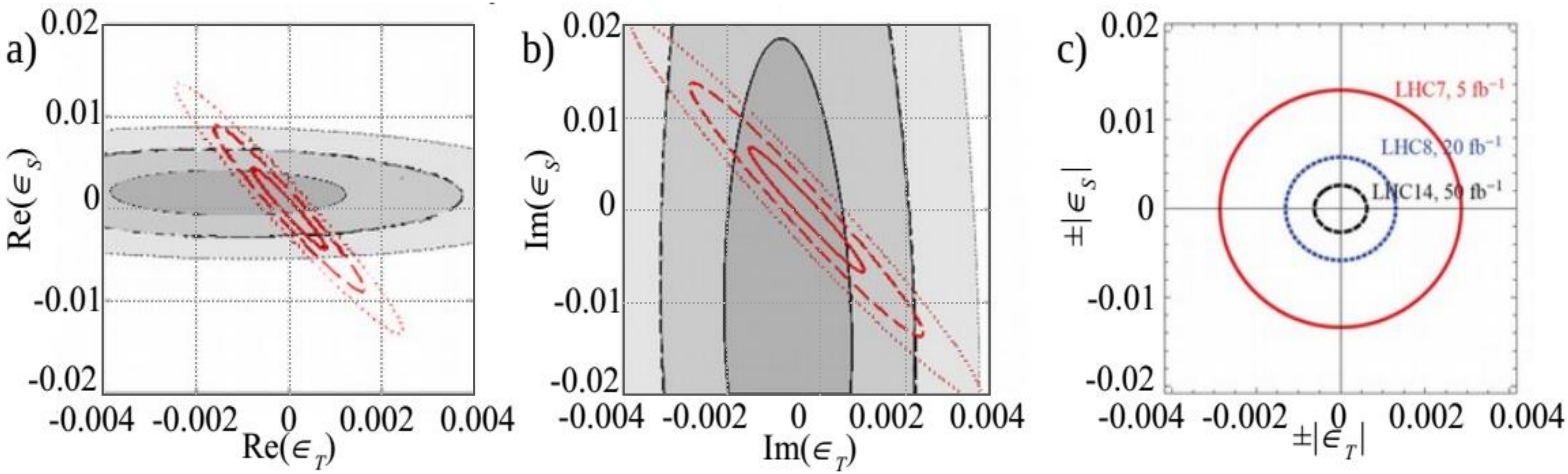
K. Bodek (U Krakow) et al.

BRAND, cont.

Impact of *H, L, N, R, S, U* and *V* measurement assuming accuracy of 5×10^{-4}

- Translated into EFT parameters

M. Gonzalez-Alonso et al., Ann. Phys. 525 (2013)



4×10^{-3} → 2×10^{-3} → 1×10^{-3} → 5×10^{-4}

nTRV (PSI) | BRAND I (ILL) | BRAND II (ILL) | BRAND III (ESS)

K. Bodek (U Krakow) et al.

Summary

I hope I did not present too much details. The take-away is:

- Many active groups in neutron beta decay, many experiments are done at the same time.
- Goal for new neutron lifetime measurement down to 0.1 s
- Goal for correlation coefficient measurements in the order of 10^{-3}