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Measurement of the neutron lifetime with magnetically stored UCNs

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Outline

1. Motivations for precision measurements of τ_n
2. Present status
3. Neutron lifetime experiment
    - Principle of 3D storage with permanent magnets
    - Setup and experimental details
    - Spectra and data analysis
    - Preliminary result and error budget
4. Future plans

Summary

Motivations for precision measurements

1. The neutron decay rate is determined by the strength of the weak interaction.

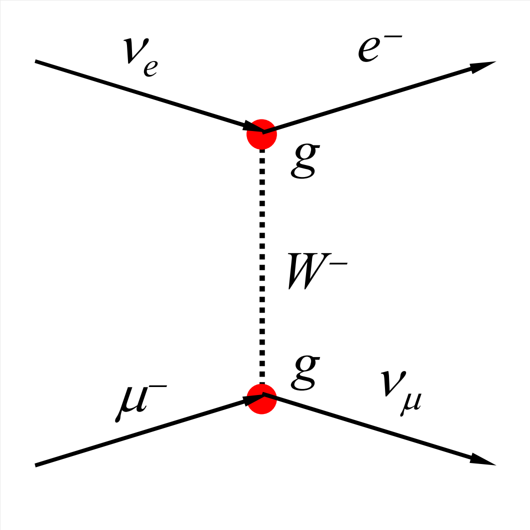
   Conversely, neutron decay is one out of four possible sources to determine the weak strength in processes involving the lightest quarks (V_{ud})

2. Neutron decay drives the primordial available “fuel” for the synthesis of light elements (^{4}He, D, ^{3}He, ^{7}Li).

   The neutron lifetime constitutes an input parameter to calculate the primordial ^{4}He abundance (one of the pillars of Big Bang theory).

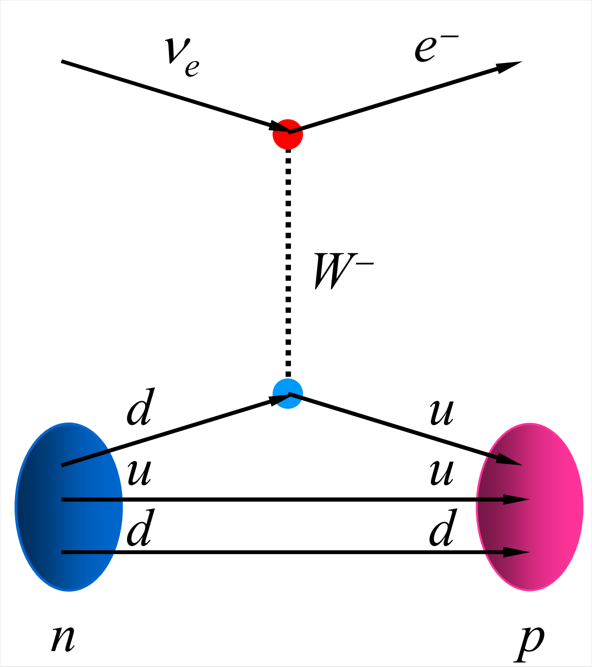
Weak universality and quark mixing

The strength of the weak interaction



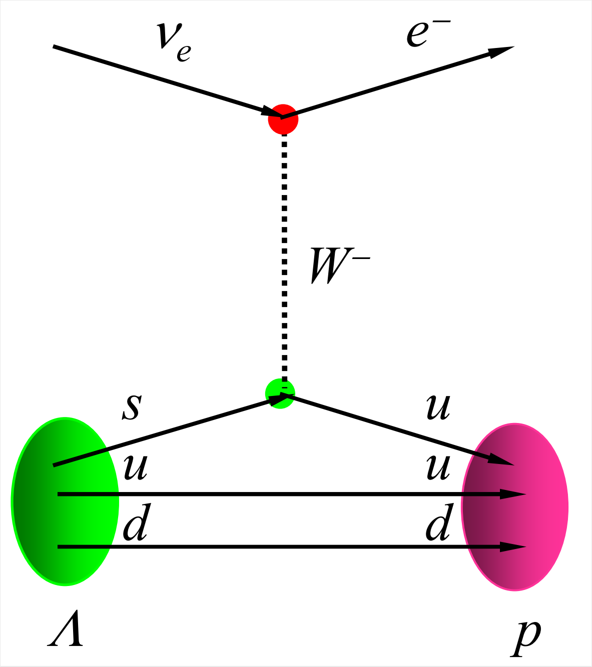
Pure leptonic

$$G_F \propto g^2$$



Semi-leptonic
(non strange)

$$G_V = G_F \cos\theta_C$$



Semi-leptonic
(strange)

$$G_\Lambda = G_F \sin\theta_C$$

$(\theta_C \approx 13^\circ)$

CKM unitarity and V_{ud}

$$V_{ud} = \cos \theta_C$$

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99995(61)$$

[J.C. Hardy and I.S. Towner PRC **79** (2009) 055502]

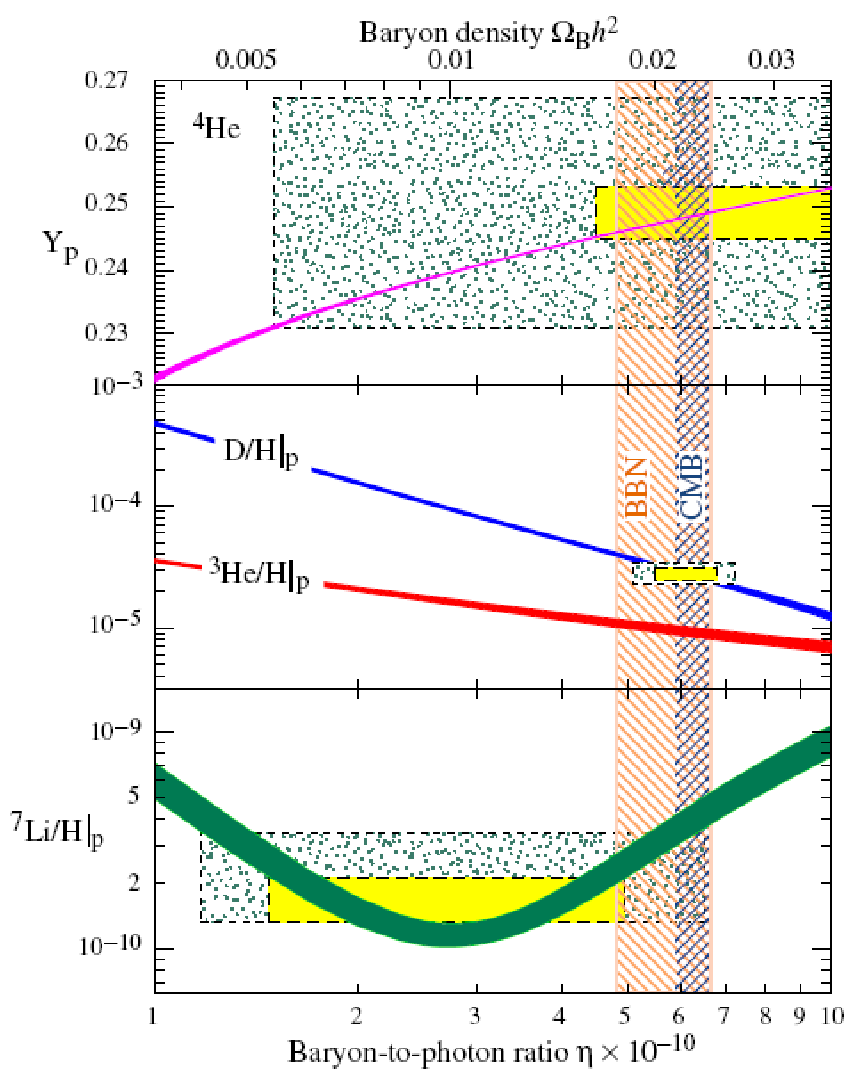
Deviations from unitarity provide signatures of physics beyond SM

- Four possible sources to determine $|V_{ud}|$ from experiments:

  - Nuclear super-allowed pure Fermi ($0^+ \rightarrow 0^+$) transitions (Vector)
  - Nuclear *T=1/2* mirror transitions [O.N-C and N.Severijns, PRL **102** (2009) 142302]
  - Neutron decay
  - Pion beta decay (Vector)

Input for Big Bang Nucleosynthesis

Predicted BBN abundances using the PDG-2008 value for the neutron lifetime



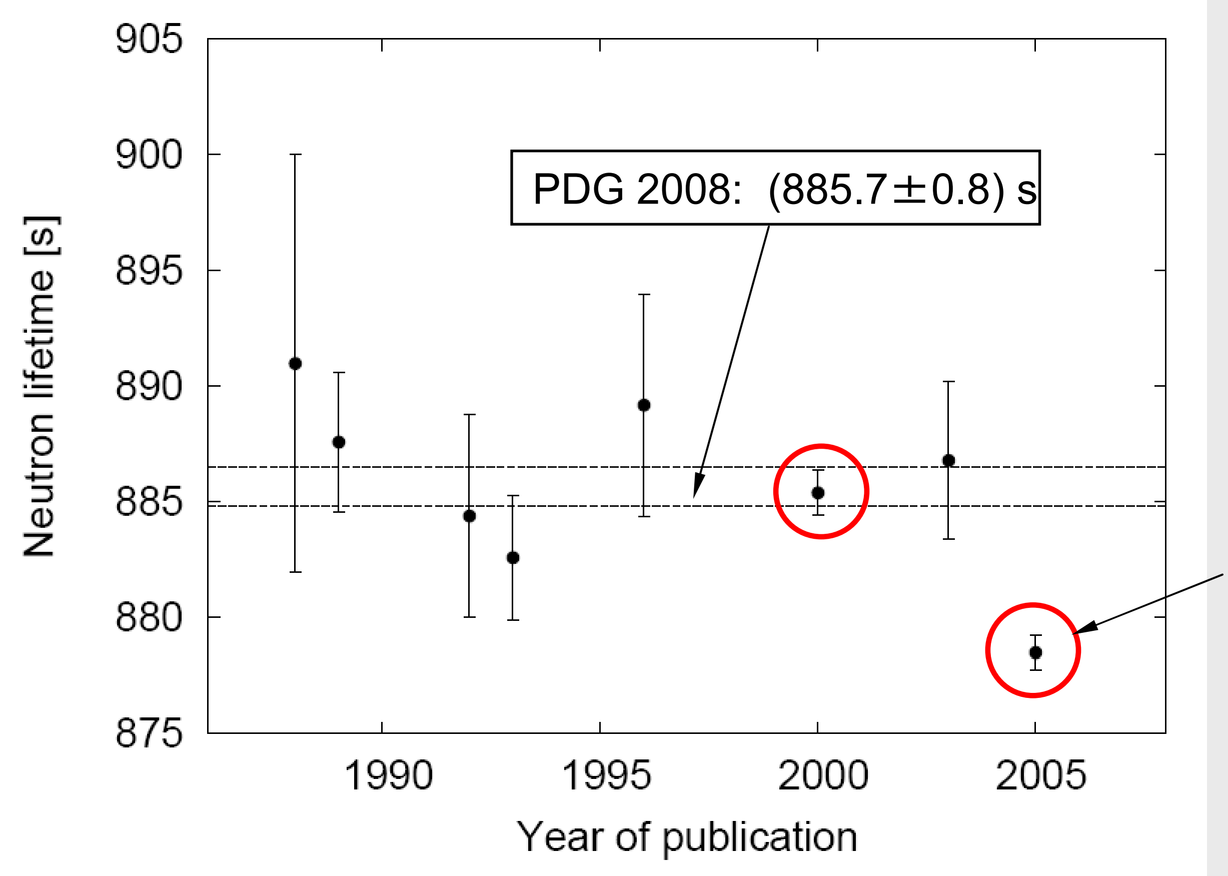
- As the universe expands, the temperature drop results in a departure from equilibrium conditions (neutron-proton inter-conversion breaks). Neutrons are free to decay.

- Nucleosynthesis begins effectively below the photo-dissociation threshold for deuterons (2.23 MeV).

- Nearly all surviving neutrons end up in bound ^{4}He nuclei. A sensitive parameter to determine Y_p is the neutron lifetime.

[B.D. Fields and S. Sarkar PDG-2008]

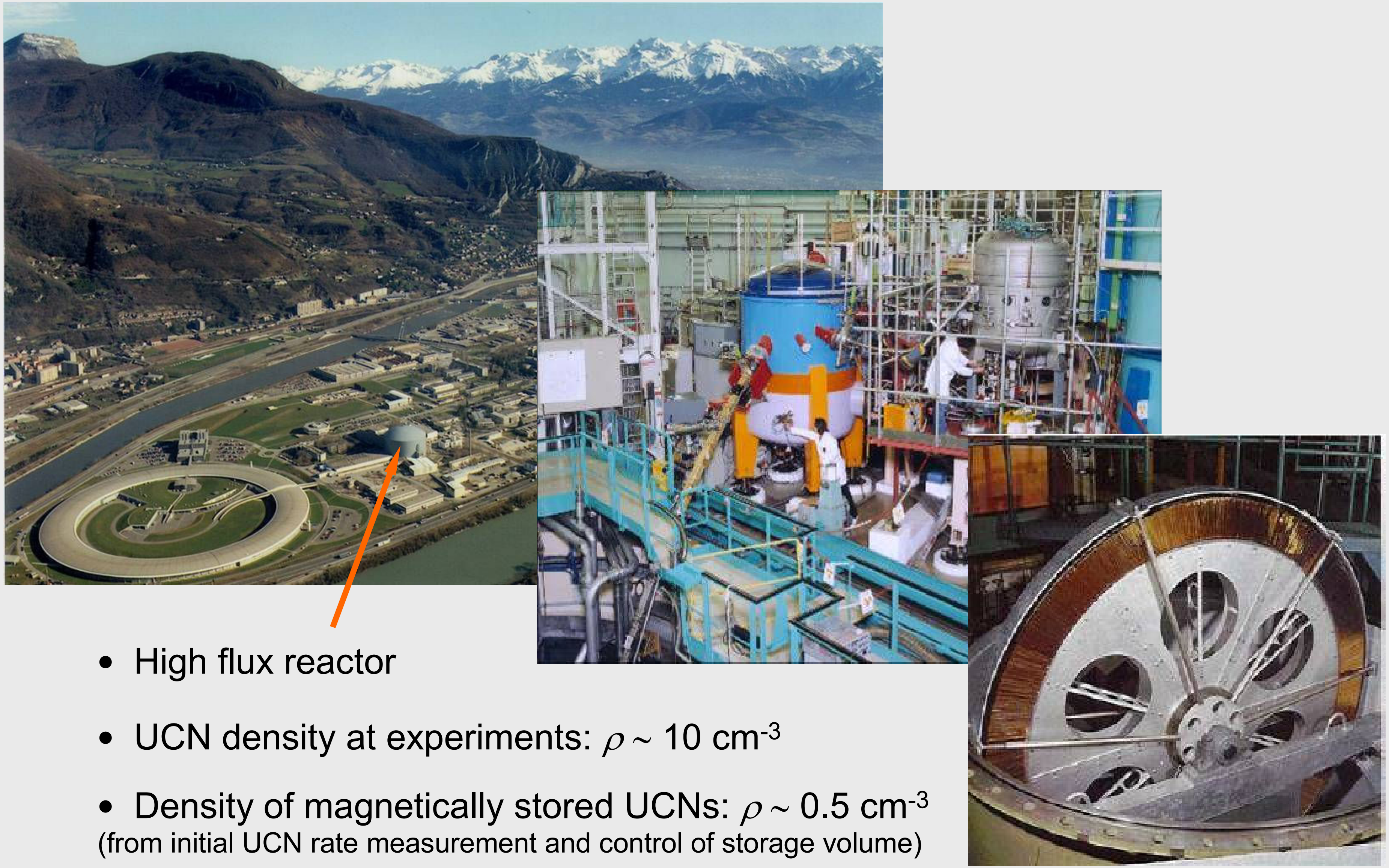
Present status



A.Serebrov *et al.*, PLB **605** (2005) 72
PRC **78** (2008) 035505

- All recent storage experiments (including the two most precise) used <u>material</u> storage of UCN (although not under the same conditions).
- Other trapping techniques, with different potential sources of systematic effects, are needed.

The UCN source at ILL-Grenoble



- High flux reactor
- UCN density at experiments: $\rho \sim 10\ \mathrm{cm}^{-3}$
- Density of magnetically stored UCNs: $\rho \sim 0.5\ \mathrm{cm}^{-3}$

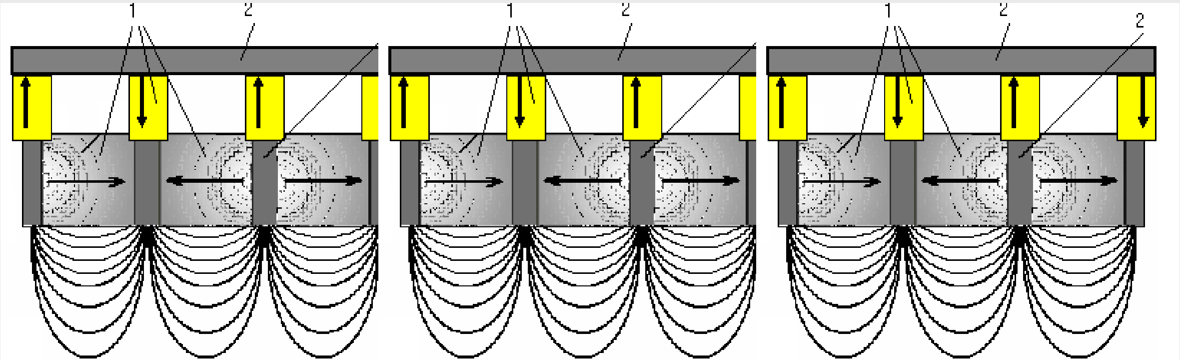
(from initial UCN rate measurement and control of storage volume)

Principle of 3D magnetic trapping

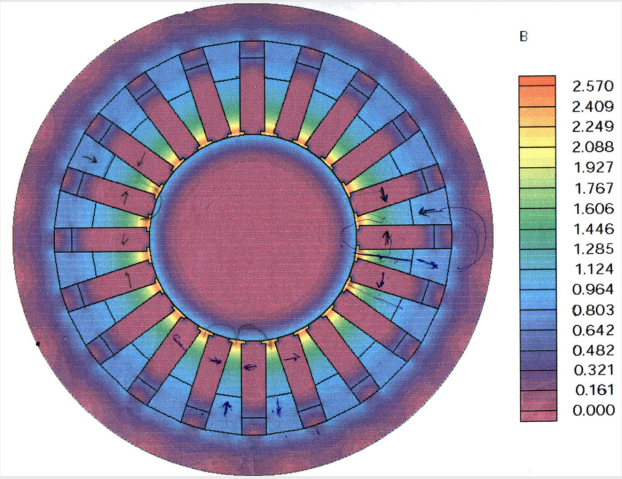
- For μ_n = -60.3 neV/T, a 2T field generates a 120 neV barrier.
- Force due to field gradient, $F = -\mu\,(dB/dz)$, repels only one spin state.
- Use permanent magnets.

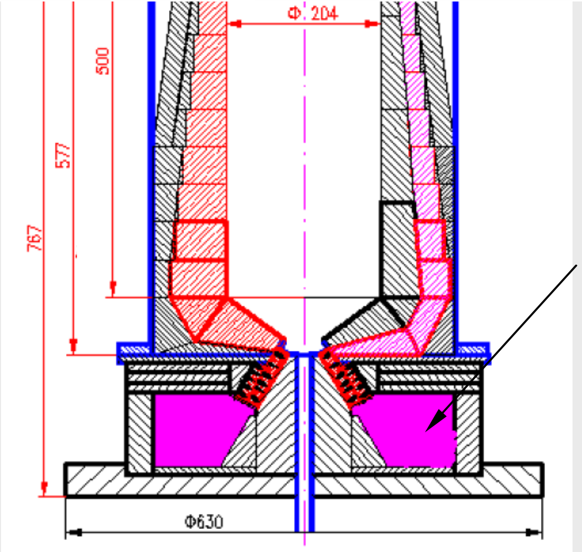
- **Step 1: 1D confinement**

1 – permanent magnets
2 – magnetic poles



- **Step 2: 2D confinement**





Add magnetic shutter

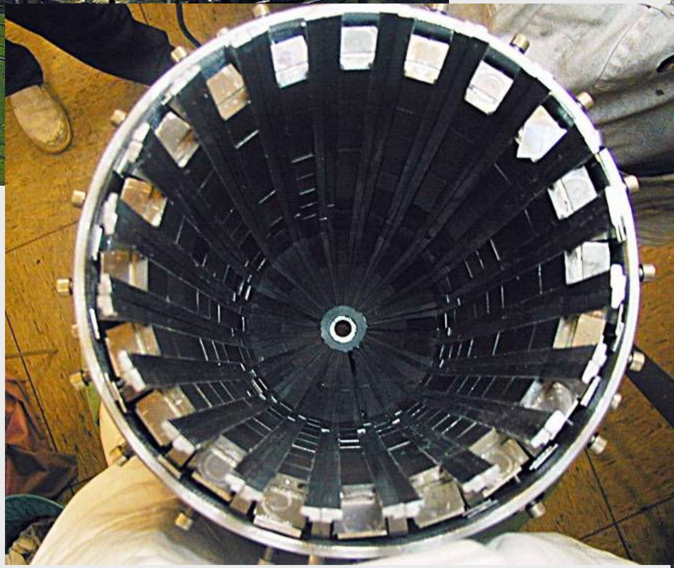
…in real life

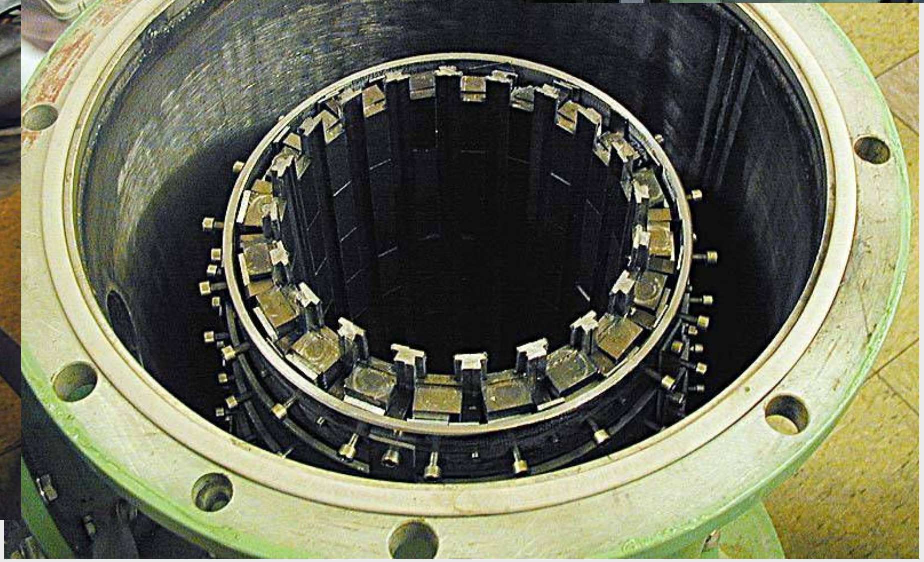
- 20 segments; 560 NdFeB magnets; FeCo poles
- inner walls covered with Fomblin oil

(reflect “wrong” spin neurons during filling and depolarized neutrons during storage)

- field gradient near wall: 2 T/cm
- 15 l total- (9 l storage-) volumes

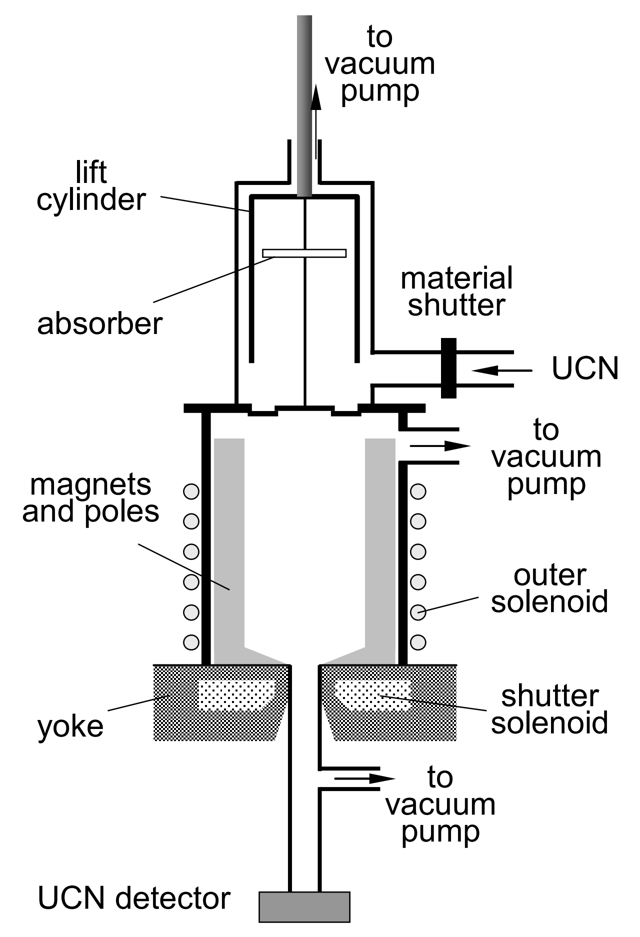
(trappers team)





Experimental setup

Main elements:
lift, trap, solenoid, shutter, detector



Lift: Fomblin coated Al cylinder + PE disk
Trap: Fomblin coated magnets and poles

[V.F. Ezhov *et al.*, NIM A **611** (2009) 167]

Trap filling sequence

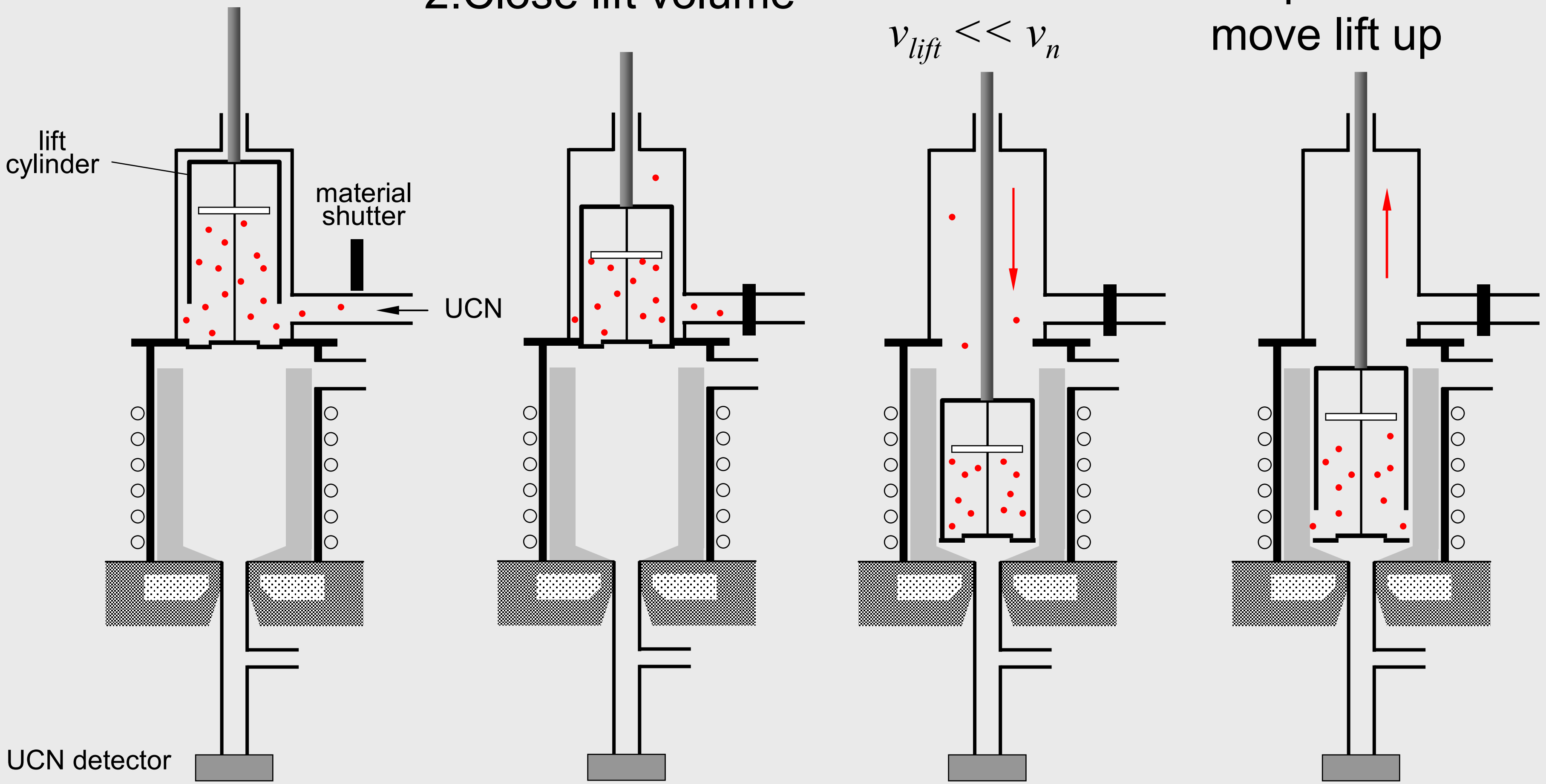
1.Fill lift volume

2.Close lift volume

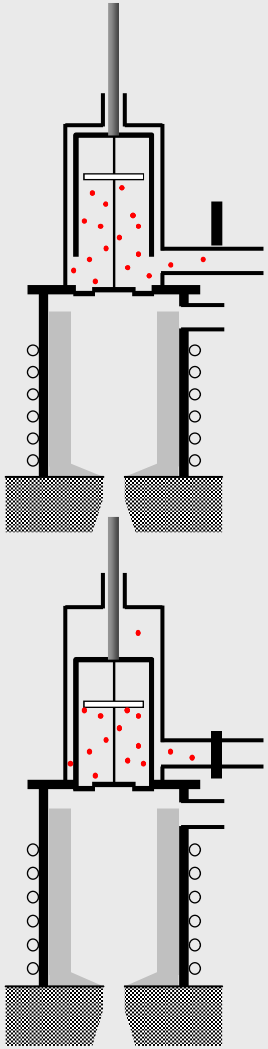
3.Move lift down

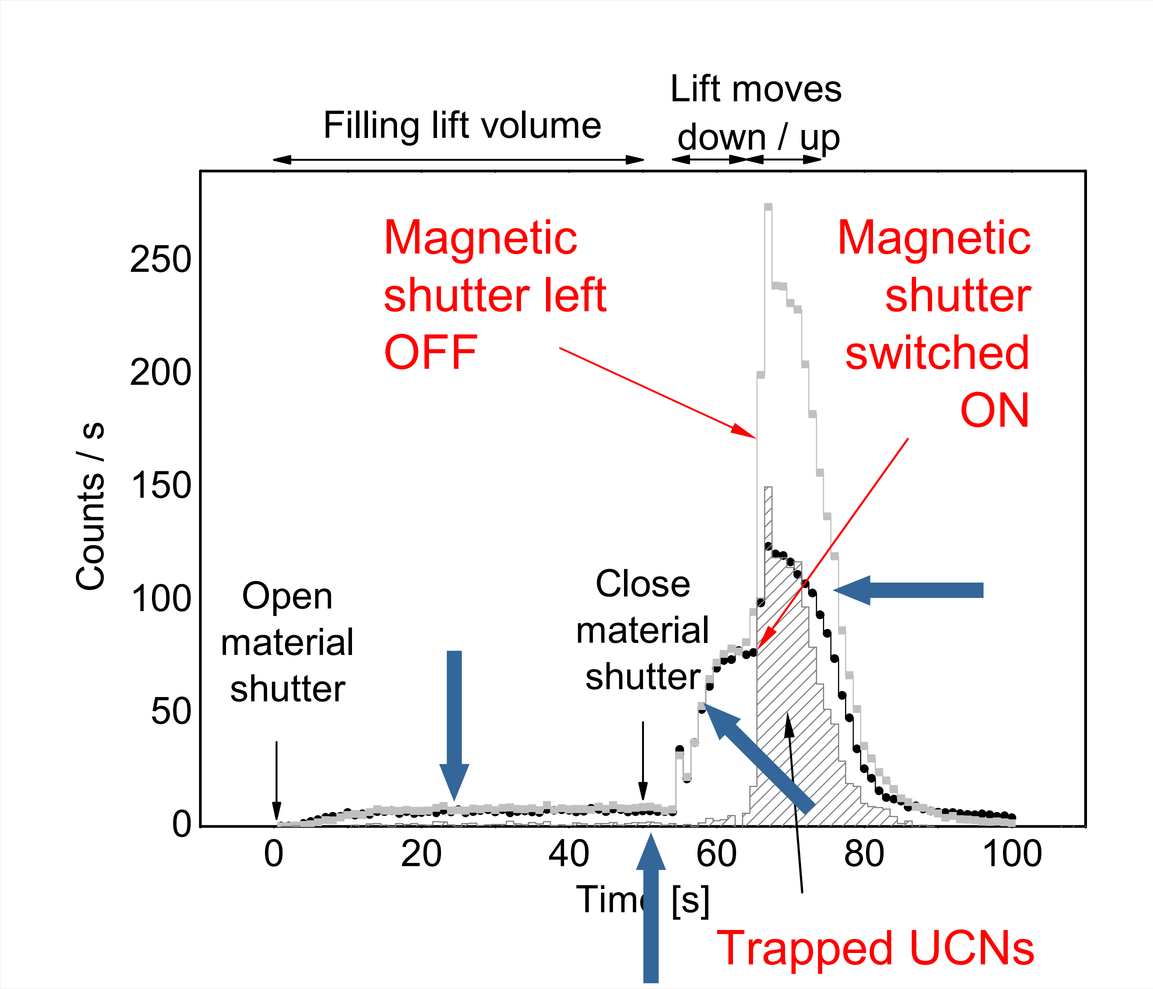
$v_{lift} << v_n$

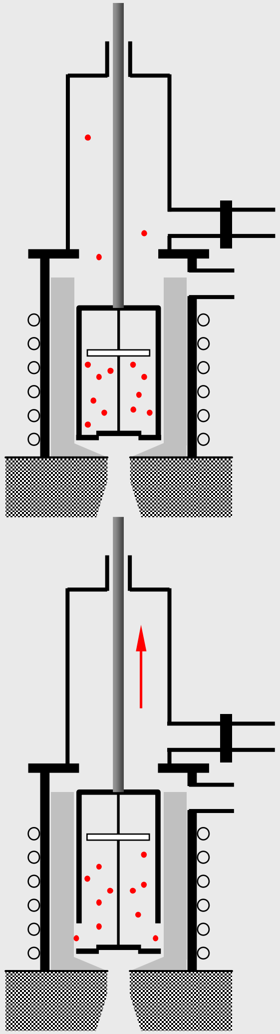
4.Open lift and move lift up



Monitoring the trap filling

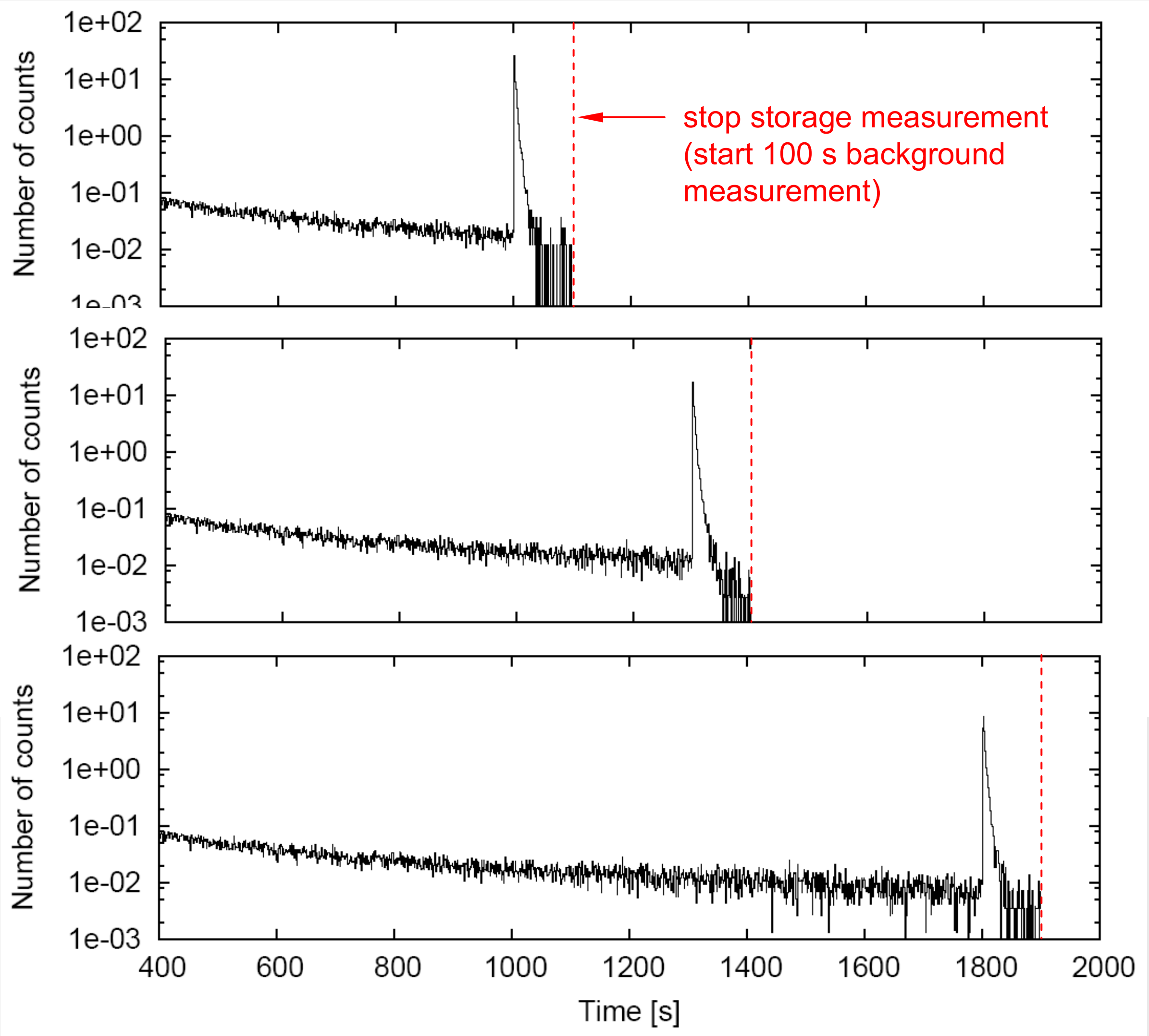






→ The detection of “wrong” spin neutrons during filling provides a normalization for every cycle

Normalized time spectra



Storage time

1000 s

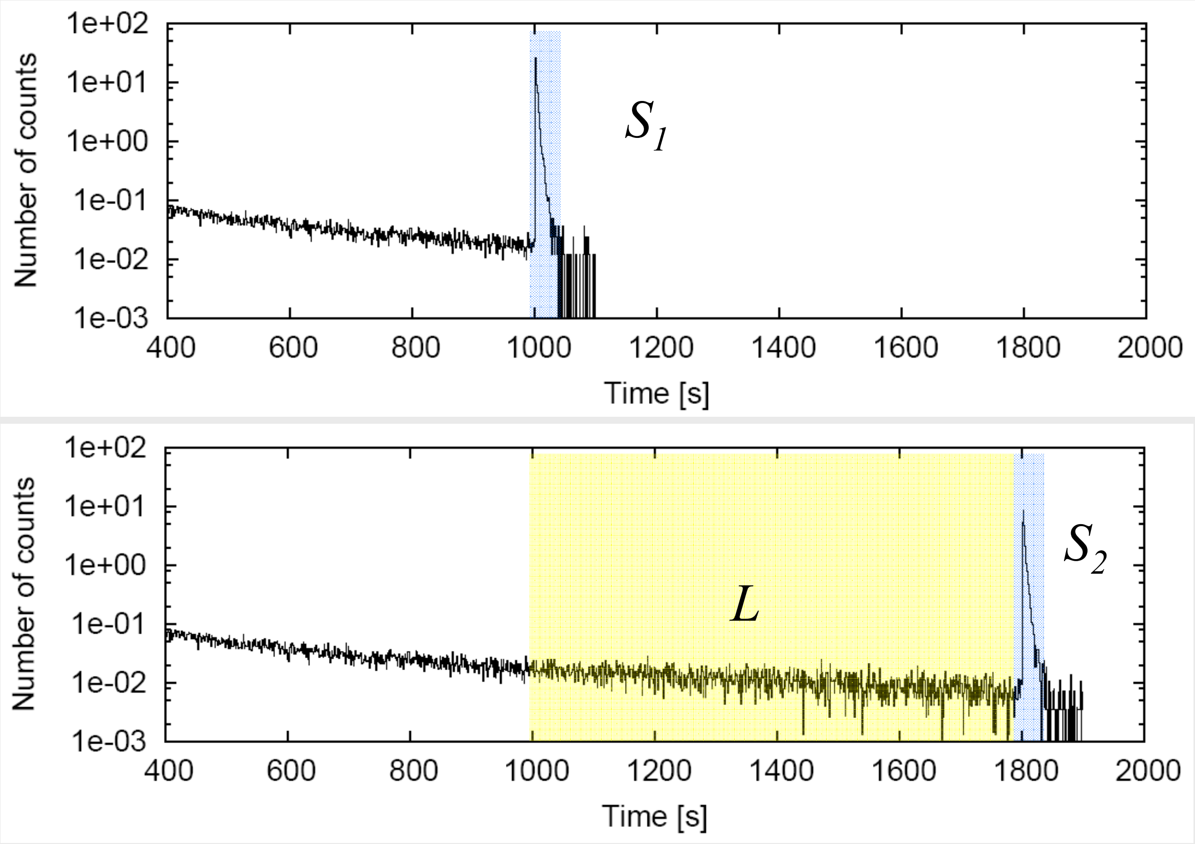
1300 s

1800 s

→ Continuous monitoring of “leaking” neutrons (which are depolarized in the trap, reflected by the Fomblin coated walls and detected)

Principle of data analysis

If the neutron lifetime would be infinitely long
and all depolarized leaking neutrons were detected…



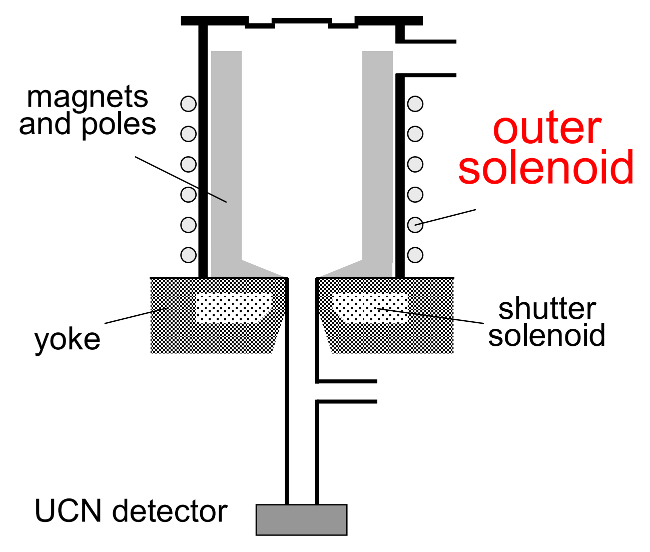
…then $S_1 = L + S_2$

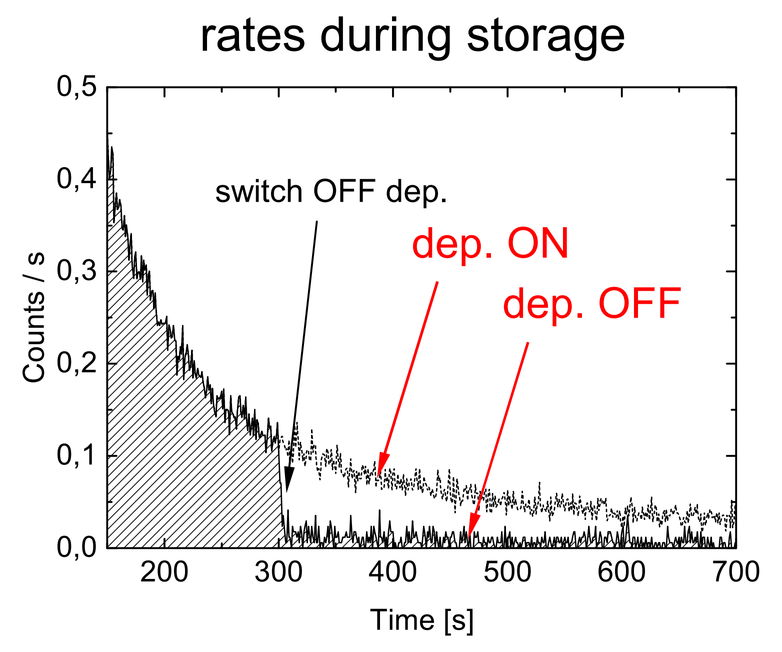
BUT…

- Neutrons which are depolarized in the trap, might be lost by collisions with the walls. Only a fraction ε will be detected during the storage time.

Tuning the leaking neutrons

- Leaks are very small under optimized trapping conditions → difficult to control.
- To optimize the trapping, the outer solenoid produces an additional field such as to eliminate trap imperfections (zero field regions) avoiding then leaks due to depolarization.
- Conversely, the outer solenoid can be tuned with the opposite field such as to increase trap imperfections and hence also leaks ("forced depolarization").



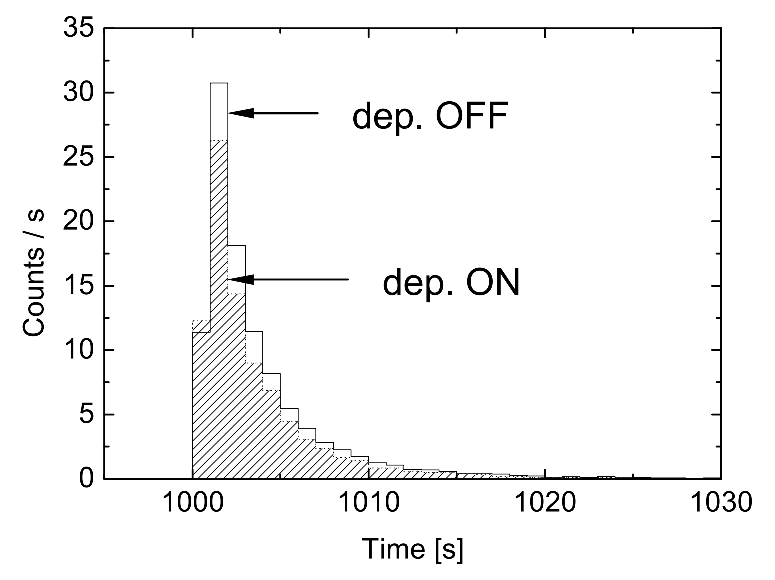


→ Intensity of leaks can be tuned

Determination of the "efficiency"

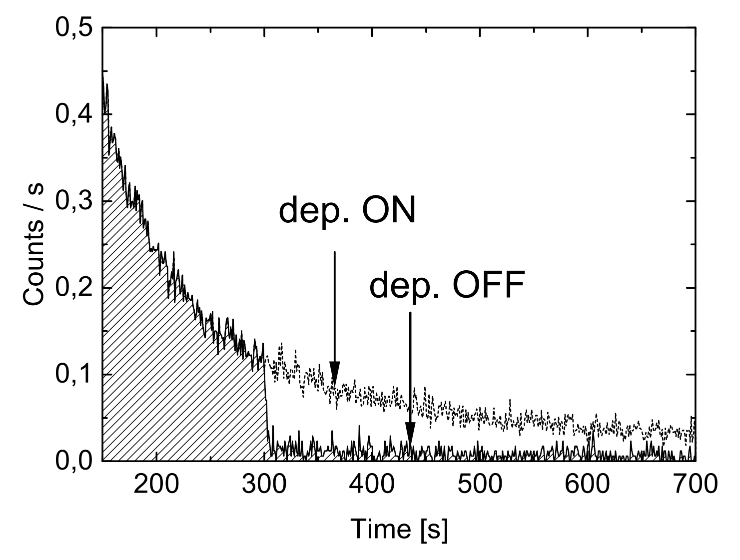
- The efficiency of leakage detection can be obtained from the measured rates, with/without the forced depolarization active.

Rates after storage time 1000 s



→ Missing UCNs: N_{mis}

Rates during storage



→ Detected depolarized UCNs: N_{dd}

Efficiency: $\varepsilon = N_{dd} / N_{mis}$

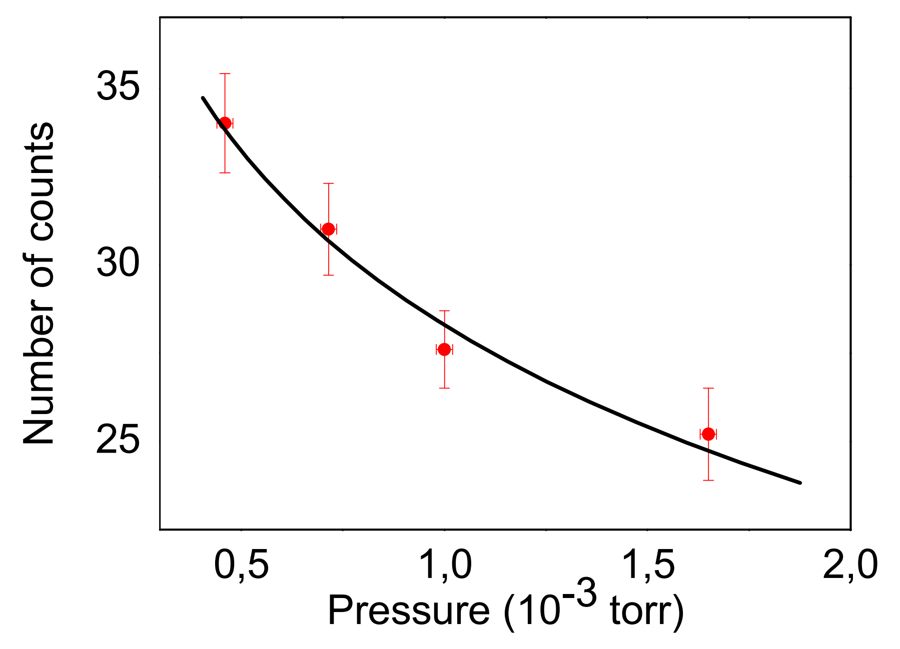
(convoluted with the neutron decay)

$\varepsilon = 0.90 \pm 0.02$

Effect of residual gas pressure

(degrade vacuum in order to measure some effect)

Number of trapped UCNs after 2200 s storage

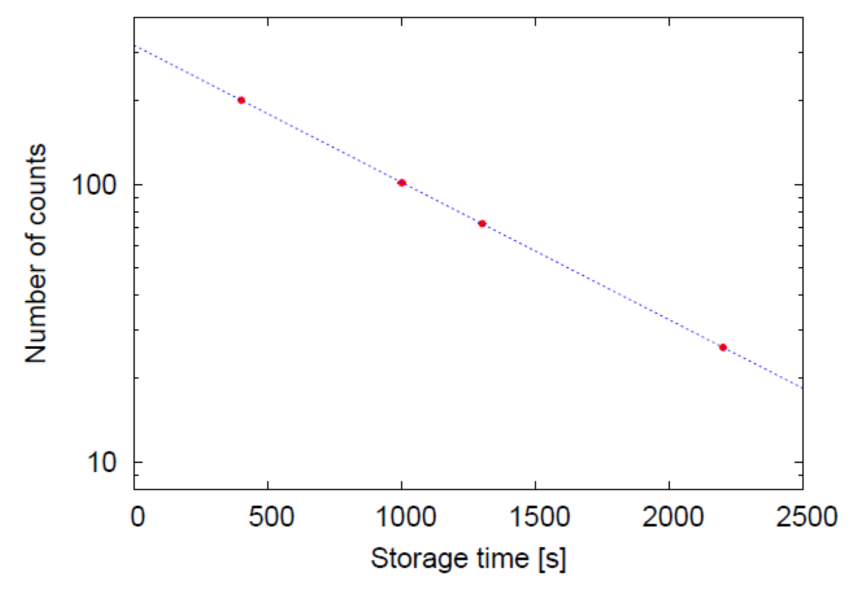


Assuming losses due to interactions with residual gas $\propto p$: σ = 0.15(4) $(\text{s torr})^{-1}$

For a precision < 1s : $p < 7.5 \times 10^{-6}$ torr; In practice $p \approx 1.2 \times 10^{-6}$ torr

Result and error sources

- Since ε is determined from data, there is only one free parameter: τ_n



τ_n = 877.9 ± X.X(stat) ± ?.?(syst) [s]

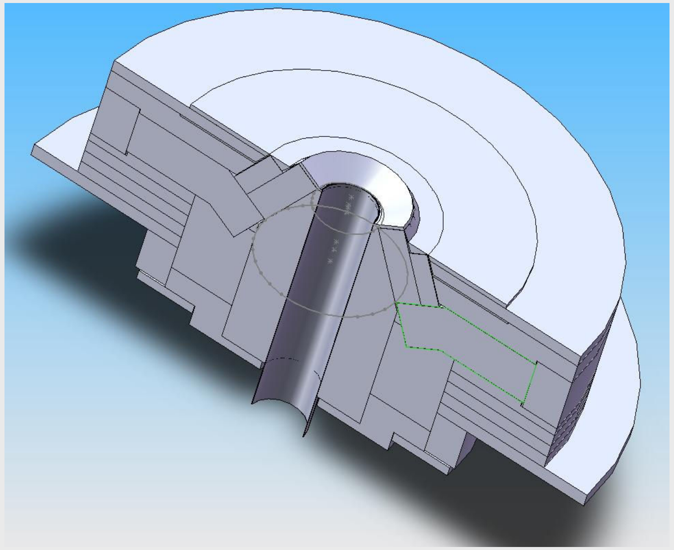
Source
Storage
Background
Leaks FD "ON"
Leaks FD "OFF"
Storage 1800s FD "ON"
Storage 1800s FD "OFF"

Independent measurements for the determination of ε need to be long enough in order not to be a dominant source of error.

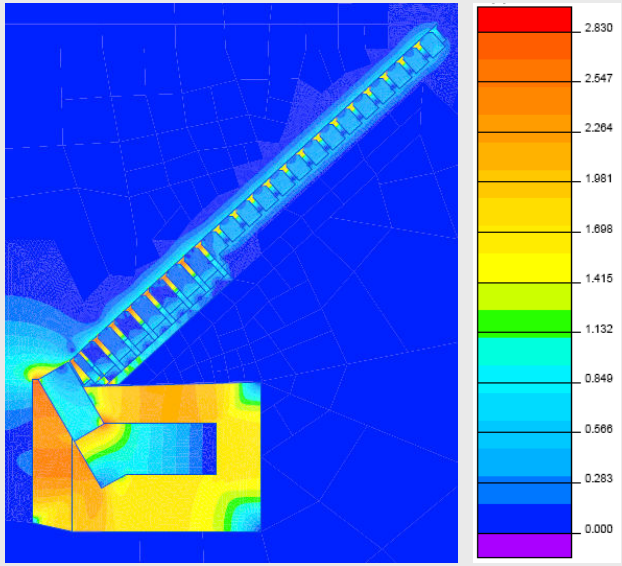
Future plans

- Construction of a new trap with a 90 l storage volume
- 60 segments disposed on a Ø80x40cm^{2} cone, Ø6cm guide
- NdFeCo magnets and FeCoNi poles
- Fill trap from top with adapted “lift”
- Use forced depolarization to change trapping conditions (leaks)
- Add spin analysis system with UCN detection
- Project funded (France/Russia); parts to be shipped to ILL in 2010

Construction of new shutter (completed)



Field maps calculations for new trap (completed)



Summary

- The use of permanent magnets has provided so far the most sensitive value for the neutron lifetime with magnetically stored UCNs.

- Key features of the trap for the measurement of the neutron lifetime are:
    - filling of the trap from top with a slow lift
    - continuous monitoring of leaking neutrons
    - tuning leaks by depolarizing neutrons inside the trap

- A final value of the neutron lifetime is expected to be issued soon from measurements performed with the prototype trap.

- An improved setup is under construction which will enable to reach a statistical precision below 1s (and hopefully solve the existing puzzle).

People and institutions

Present Russian-French collaboration

V.Ezhov[1], A.Z.Andreev[1], G.Ban[2], B.A.Bazarov[1], P.Geltenbort[3], A.G.Glushkov[1], M.G.Groshev[1], V.A.Knyazkov[1], N.A.Kovrizhnykh[4], O.Naviliat-Cuncic[2], V.L.Ryabov[1]

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