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named by B.P. Konstantinov

"Neutron lifetime measurements: status and prospects"

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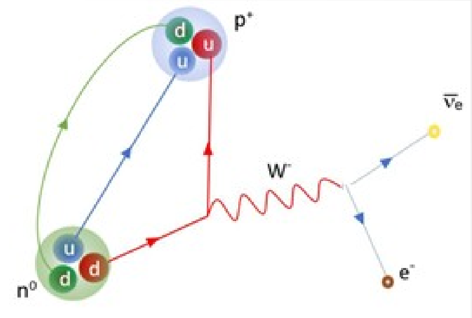
Neutron decay and Standard Model

Matrix element V_{ud} is responsible for the beta decay of the neutron
According requirement of unitarity the first row of V_{CKM} must satisfy

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$|V_{us}| = 0.2243 \pm 0.0008$$



Since $|V_{ub}|^2 = 1.7 \times 10^{-5}$ is negligibly small, it is ignored in this discussion

Precise values of V_{ud} have been obtained from superallowed nuclear, neutron, and pion beta decays

Superallowed $0^+ \rightarrow 0^+$ β transitions

$$\text{superallowed } \beta \text{ decays: } |V_{ud}|^2 = \frac{2984.43 s}{\mathcal{F}t(1+\Delta_R^V)}.$$

Here,

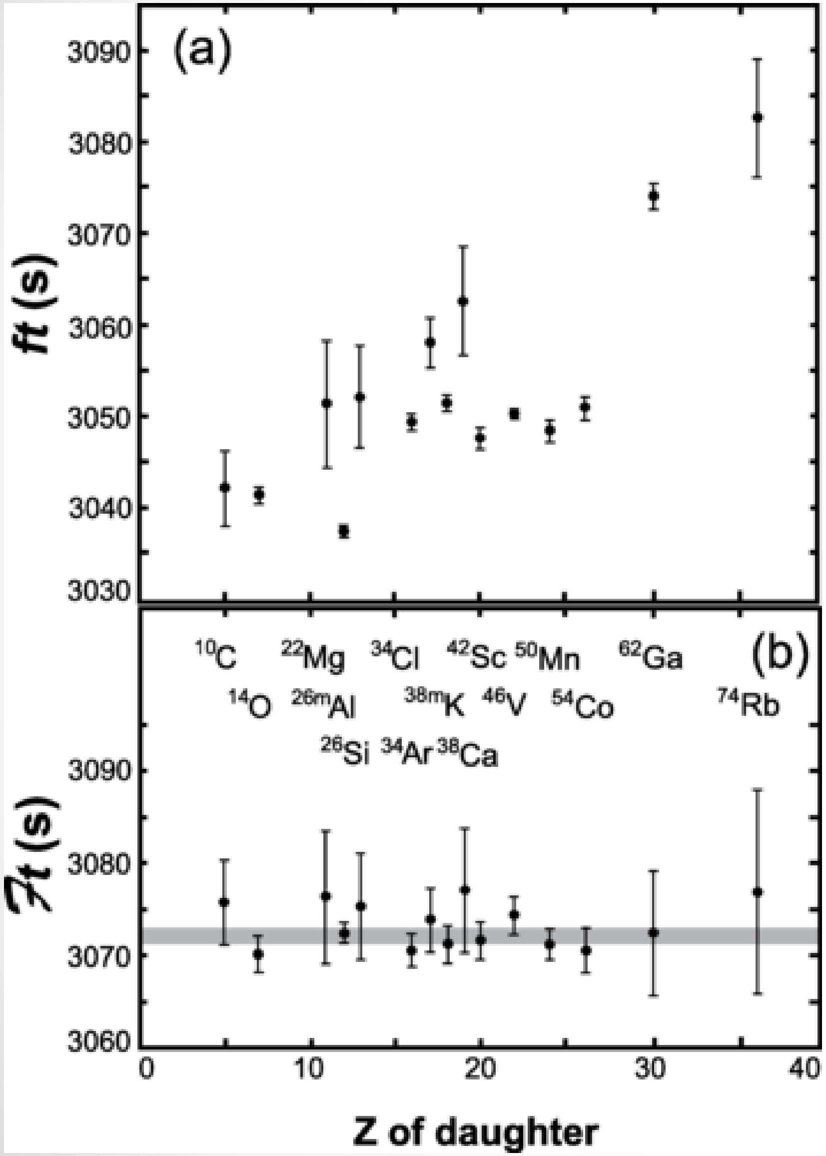
$$\mathcal{F}t = ft(1+\delta_R')(1+\delta_{NS}-\delta_C),$$

The ft value of any β transition is simply the product of the phase-space factor f, and the partial half-life of the transition, t.

where δ_R' is the outer correction that depends on the electron energy and the charge Z of the final nucleus and accounts for the Coulomb distortion and other QED effects;

δ_{NS} and δ_C are nuclear structure-dependent corrections that are independent of the electron energy.

Superallowed $0^+ \rightarrow 0^+$ β transitions



(a) In the top panel are plotted the uncorrected experimental ft values for the 15 precisely known superallowed transitions as a function of the charge on the daughter nucleus.
(b) In the bottom panel, the corresponding $\mathcal{F}t$ values are given; they differ from the ft values by the inclusion of the correction terms δ'_R, δ_{NS}, and δ_C.

The horizontal gray band gives one standard deviation around the average $\mathcal{F}t$ value. All transitions are labeled by their parent nuclei.

J. C. Hardy and I. S. Towner
Phys. Rev. C **102**, 045501 – Published 2 October 2020

Superallowed $0^+ \rightarrow 0^+$ β transitions

- Based on these 15 experimental data, Hardy and Towner recently updated the average

$$|V_{ud}|^2 = 0.97154(22)(54)_{\mathrm{NS}}/(1+\Delta_{\mathrm{R}}^{\mathrm{V}}),$$

J. C. Hardy and I. S. Towner, Phys. Rev. C 102, 4, 045501 (2020).

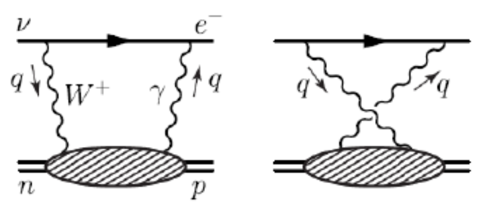
Δ_R^V denotes the so-called inner or universal electroweak radiative corrections (RC) to superallowed nuclear beta decays. Main problem that It is different in different approaches:

An approach to quantum loop corrections, specifically the gamma-W box diagram, gives

$$\Delta_R^V = 0.02467(22)$$

C.-Y. Seng *et al.*, Phys. Rev. Lett. **121**, 24, 241804 (2018)

Main source of uncertainty in inner RC: γW-box diagram



Sensitive to loop momentum q at ALL scales!

A somewhat different approach

- $\Delta_R^V = 0.02426(32).$ A. Czarnecki, W. J. Marciano and A. Sirlin, Phys. Rev. D **100**, 7, 073008 (2019)

$\Delta_R^V = 0.02361(38)$ PDG (2018)

Currently the 15 most precisely measured superallowed 0+→0+ nuclear beta decays transitions lead to the dispersion relation based weighted average of

$V_{ud} = 0.97373(11)_{\mathrm{exp., nucl.}}(9)_{\mathrm{RC}}(27)_{\mathrm{NS}}$

V_{ud} has shifted significantly down compared to the 2018 PDG value of $V_{ud} = 0.97420(21)$

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2021) and 2021 update 1st December, 2021 8:58 am

Neutron lifetime

Neutron β decay is the simplest β decay to involve both the vector and axial-vector weak interactions. It is an attractive option for determining V_{ud} since its analysis does not require the application of corrections for isospin-symmetry-breaking δ_C, or for nuclear-structure-dependent radiative effects, δ_{NS}.
However, it has the distinct disadvantage that it requires a difficult correlation measurement in order to separate the vector-current contribution to its decay from the axial-vector one.

- **Measurements of the neutron lifetime, τ_n, and the ratio of axial-vector/vector couplings, $g_A \equiv G_A/G_V$, via neutron decay asymmetries combined with the inner radiative corrections can also be used to determine V_{ud} via the precise formula:**

$$|V_{ud}|^2 = \frac{5024.7\ \mathrm{s}}{\tau_n(1+3g_A^2)(1+\Delta_R^V)}$$

Δ_R^V **represents the same inner electroweak radiative corrections**

$$\tau_n^{\mathrm{ave}} = 879.4(6)\ \mathrm{s}\quad (1.6\ \mathrm{PDG\ scale\ factor})$$
$$g_A^{\mathrm{ave}} = 1.2756(13),\quad (2.6\ \mathrm{PDG\ scale\ factor})$$

$$|V_{ud}| = 0.9737(3)_{\tau_n}(8)_{g_A}(1)_{\mathrm{RC}},$$

superallowed 0+→0+ **$V_{ud} = 0.97373(11)_{\mathrm{exp.,\ nucl.}}(9)_{\mathrm{RC}}(27)_{\mathrm{NS}}$**

Standard Model
Superallowed $0^+ \rightarrow 0^+$ β transitions

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(6)(4).$$

where the first error is the uncertainty from $|V_{ud}|^2$ and the second error is the uncertainty from the average $|V_{us}|^2$

One finds about an overall 2 sigma deviation from unitarity. That deviation could be due a problem with $|V_{ud}|$ theory (RC or NS), the lattice determination of $f_+(0)$ or new physics.

Neutron lifetime end

Primordial Helium Abundance

Nucleosynthesis

Less than 1 second after the Big Bang, maintain the neutron:proton ratio in thermal equilibrium.

$$p + e^- \longleftrightarrow n + \nu$$

$$n + e^+ \longleftrightarrow p + \bar{\nu}$$

About 1 second after the Big Bang, the temperature becomes slightly lower than the energy equivalent of the neutron-proton mass difference, these weak reactions do not keep up with the rate of expansion of the Universe, and the neutron-proton ratio freezes at a value of about 1:6.

After 1 second, the only reaction that significantly changes the number of neutrons is the neutron decay shown on the right. Without further reactions keeping neutrons inside stable nuclei, the universe would consist of hydrogen alone.

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

Nucleosynthesis

At T_n the ratio of densities of neutrons and protons is fixed at

$$n_n/n_p|_{T=T_n} = \exp\left(-\Delta m/T_n\right),$$

where $$\Delta m = m_n - m_p \simeq 1.3\,\mathrm{MeV}$$

After the neutron freeze-out, proton number does not change while neutrons can decay with a lifetime n.

As the temperature further cools, protons and the remaining neutrons bind into deuterium via the reaction $$p + n \to D + \gamma.$$

Nucleosynthesis starts with the formation of deuterium and helium-4 at $T_{NS} \approx 100$ keV

$$\begin{aligned} Y_p = \frac{m_{^4\mathrm{He}}\, n_{^4\mathrm{He}}}{m_p n_p + m_n n_n} &\simeq \left.\frac{2}{1 + n_p/n_n}\right|_{T=T_{\mathrm{NS}}} \\ &\simeq \frac{2}{1 + e^{\Delta m/T_n} e^{t_{\mathrm{NS}}/\tau_n}} \simeq 25\%\,, \end{aligned}$$

$t_{\mathrm{NS}} \simeq 200$ s is the time at $T = T_{\mathrm{NS}}$.

Recent Primordial Helium Abundance Results from low metallicity galaxies

In astronomy, metallicity is the abundance of elements present in an object that are heavier than hydrogen and helium.

Citation	Y_P	N	Method
Izotov, Thuan, & Guseva (2014) [49]	0.2551 ± 0.0022	28	H II Region
Aver et al. (2015) [43]	0.2449 ± 0.0040	15	H II Region
Peimbert, Peimbert, & Luridiana (2016) [55]	0.2446 ± 0.0029	5	H II Region
Planck Collaboration (2018) [11]	0.239 ± 0.013		CMB
Cooke & Fumagalli (2018) [86]	$0.250^{+0.033}_{-0.025}$	1	Absorption Line
Valerdi et al. (2019) [56]	0.2451 ± 0.0026	1	H II Region
Fernández et al. (2019) [50]	0.243 ± 0.005	16	H II Region
Hsyu et al. (2020) [51]	$0.2436^{+0.0039}_{-0.0040}$	54	H II Region
This Work	0.2453 ± 0.0034	16	H II Region
Fields et al. (2020) [7]	0.2469 ± 0.0002		SBBN + CMB

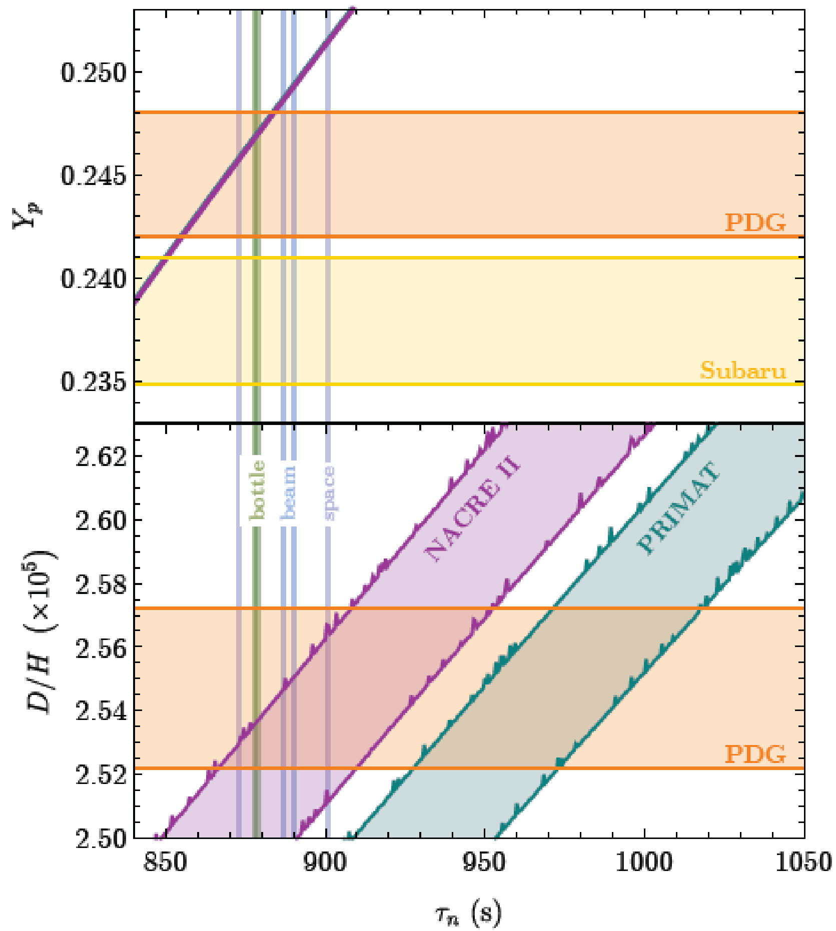
extremely metal-poor galaxies (EMPGs)

cosmic microwave background (CMB)

Big Bang Nucleosynthsis (BBN)

arXiv:2010.04180 **[astro-ph.CO]**

Recent Primordial Helium Abundance



Helium-4 mass fraction (Y_p) and relative deuterium abundance (D/H) versus neutron lifetime, τ_n. (The little spikes on the deuterium lines are due to numerics and are not physical.) The shaded regions for the theoretical calculations correspond the 1σ error bars on the CMB measuremnt of baryon-to-photn ratio, $\eta = (6.105 \pm 0.057) \times 10^{-10}$. ($D/H$ is lower for higher η.) The two different abundance predictions, NACRE II and PRIMAT,

Horizontal, orange shaded regions are observed primordial abundances given by PDG [3]. For helium-4, we also show a recent measurement by the Subaru telescope [13] in yellow. The vertical lines are averages of the neutron lifetime determined by beam, bottle, and space experiments.

One approach is employed by NACRE II [1] and used in many BBN analyses, e.g. in [28]. Another approach is to use theoretical calculations as an input for this temperature dependence. This is used in the BBN program PRIMAT

$$Y_p^{\rm PDG} = 0.245 \pm 0.003$$

arXiv:2210.12031v1 [hep-ph] 21 Oct 2022

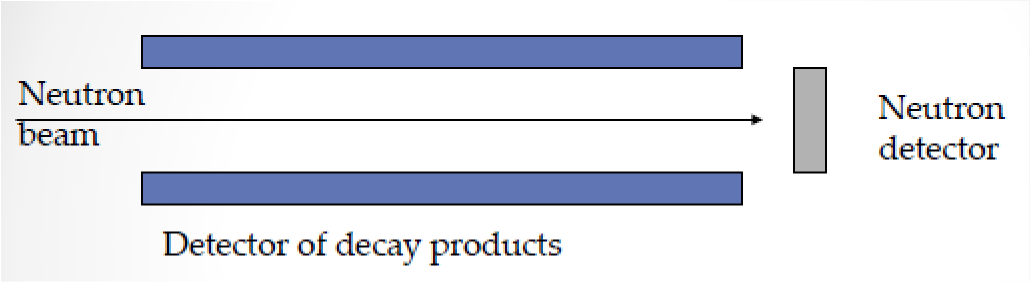
$$Y_p^{\rm Subaru} = 0.2379^{+0.0031}_{-0.0030} \,.$$

A. Matsumoto et al., (2022), arXiv:2203.09617 [astro-ph.CO].

Neutron lifetime experiments

1. Beam measurements of neutron lifetime

Accurate measurements of absolute value of neutron flux and collection of decay products



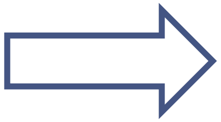
Unregistered decay products will increase neutron lifetime

2. UCN storage measurement of neutron lifetime – relative measurement

Storage losses will decrease neutron lifetime

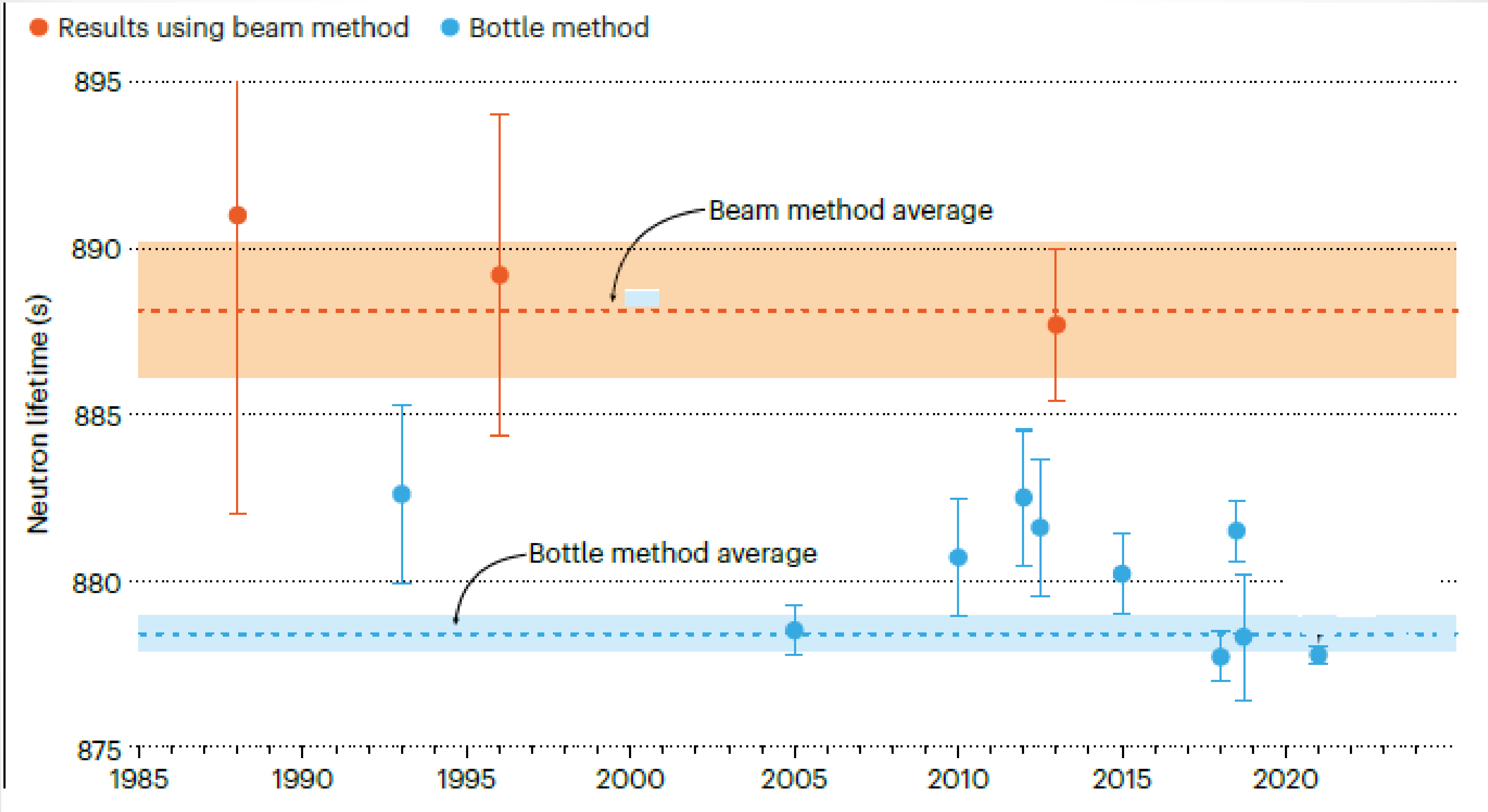
Material traps

Collisions with the walls - losses



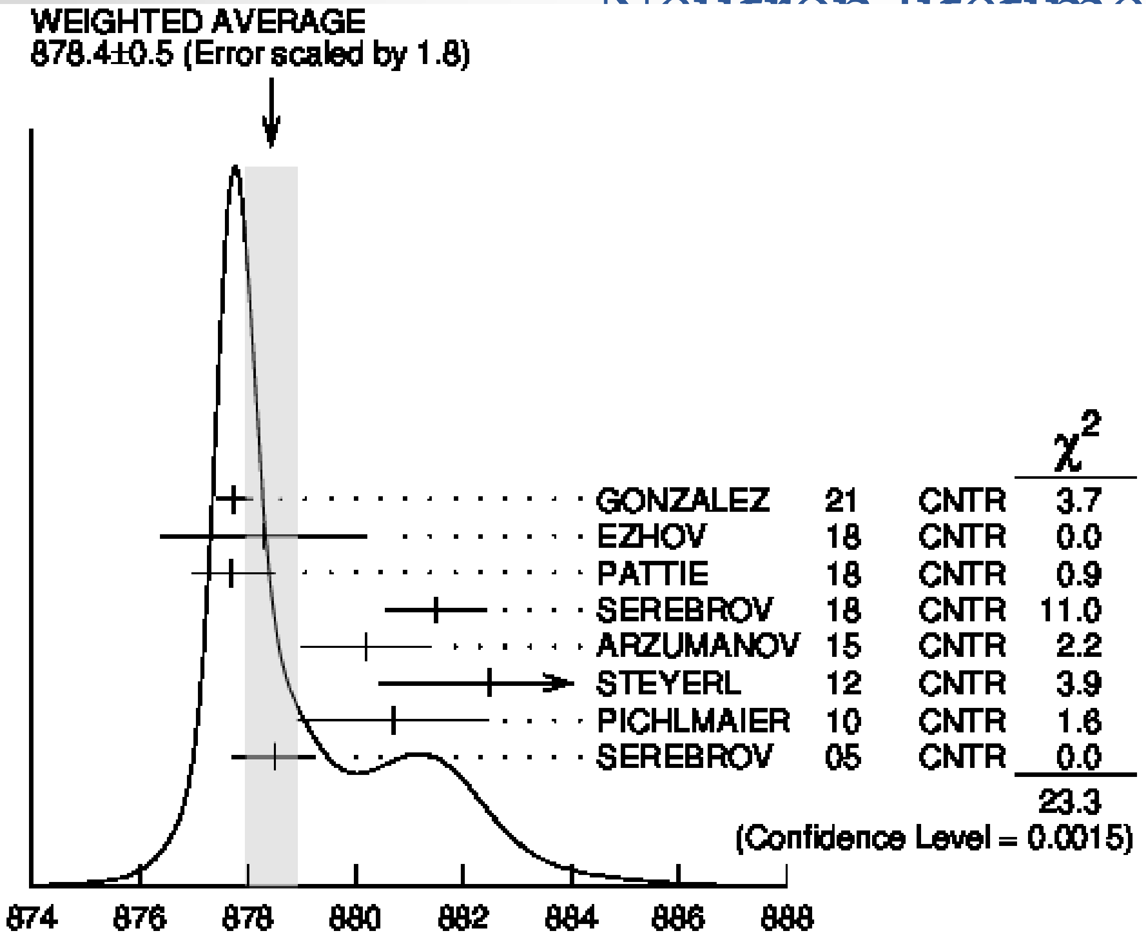
Magnetic traps

Neutron depolarization – losses
But these losses can be measured



Nature | Vol 598 | 28 October 2021

Neutron lifetime PDG



τ = 887,7 ± 1,2 ± 1,9 s – isn't included

We average seven of the best eight measurements, those made with ultracold neutrons (UCN's). If we include the one in-beam measurement with a comparable error (YUE 2013), we get 879.6 ±0.8 s, where the scale factor is now 2.0.

Possible dark decay channels

- Exotic decays that are completely dark, or with the dark fermion accompanied either by visible particles such as γ or e^+e^-, or by invisible pairs or dark photons.
- The disappearance of neutrons via neutron mirror-neutron oscillations and the role of neutron-antineutron oscillations in dark neutron decay.
- Fierz term of size $b = 1.44\%$ would enhance the branching ratio of dark decays, allowed by existing neutron data, to the level required to explain the neutron lifetime anomaly. This in turn, however, leads to some tension with the experimental limit on b from.

Magnetic trap

Magnetic trapping permits to exclude UCN collisions with a wall

Reflection of UCN by magnetic barrier

V.V. Vladimirskii, Sov. Phys. - JETP 12, 740, 1961

$$U = -\vec{\mu} \cdot \vec{B}$$

$$F = -\nabla U = \nabla(\vec{\mu} \cdot \vec{B}) = \pm \mu \nabla \left| \vec{B} \right|$$

+ for $\vec{\mu} \uparrow\uparrow \vec{B}$ and

– for $\vec{\mu} \uparrow\downarrow \vec{B}$

Magnetic field 1 T reflects neutrons up to 3.4 m/s

Depolarization

- Adiabatic condition

$$\frac{\dot{H}}{\gamma H} = \frac{(\vec{v} \cdot \vec{\nabla})H}{\gamma H} \ll 1\,,$$

$$P = e^{-\pi\omega\tau}\,,$$

$$\text{where } \tau = H/\dot{H}.$$

- Magnetic field in trap is too inhomogeneous
- Main task to exclude zero points of magnetic fields

The magnetic moment precession frequency around the driving field should be much greater than the rotation frequency of the magnetic field (in neutron reference) due to neutron moving in a non uniform magnetic field

It is impossible to exclude UCN depolarization

- If anybody satisfies adiabatic condition with accuracy, for example, 10^{-6} it'll mean that 1 UCN from 10^{6} will be depolarized!!!
- So one have to measure losses due to depolarization in his experiment with magnetic storage

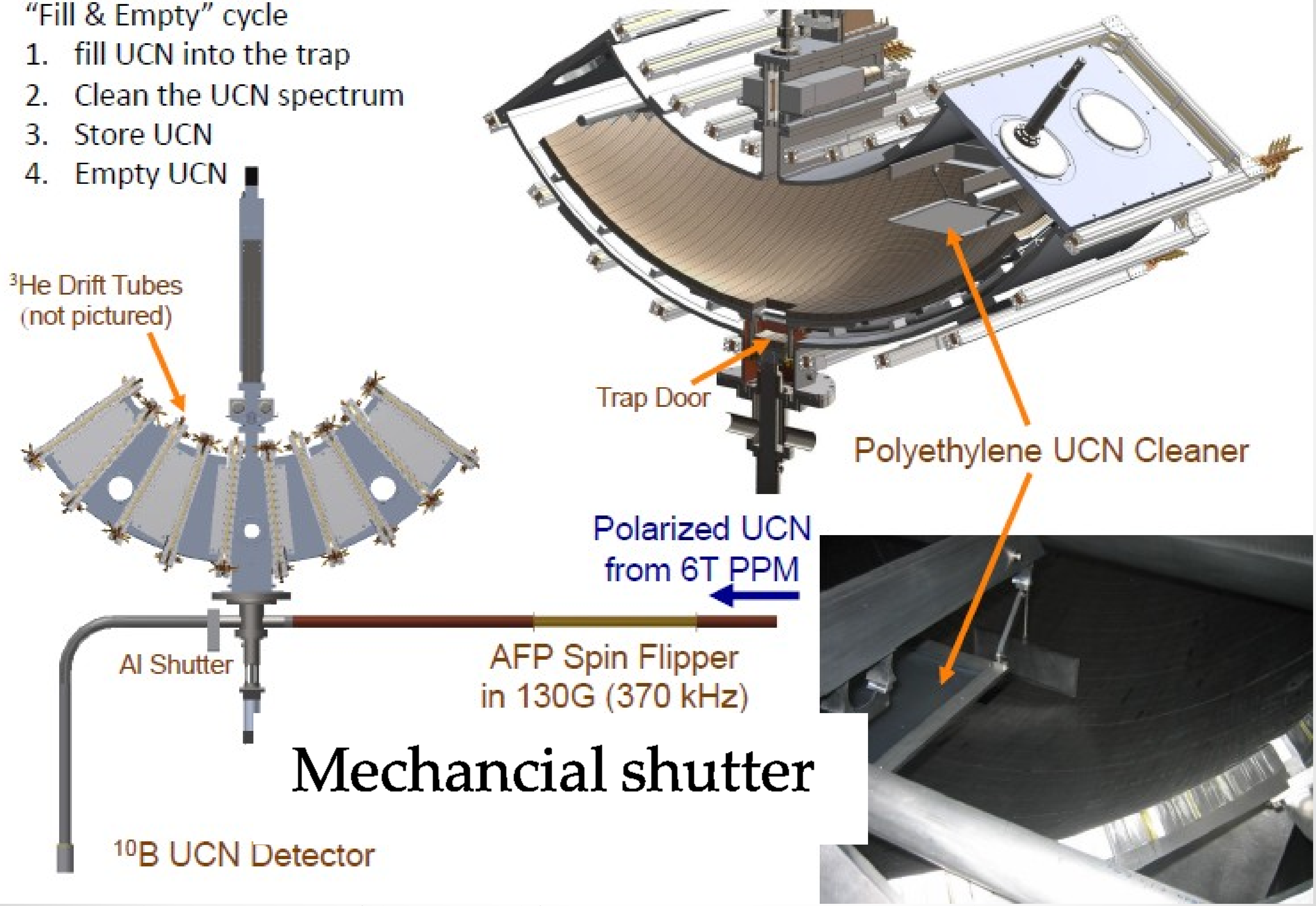
Main advantage of magnetic trapping in comparing with UCN storage in material trap is the possibility to detect UCN losses during storage time

- Today there are two types of UCN magnetic traps used in neutron lifetime experiments
  - Mechanical shutter
  - Magnetic shutter

Operation of the UCNτ Experiment

"Fill & Empty" cycle

1. fill UCN into the trap
2. Clean the UCN spectrum
3. Store UCN
4. Empty UCN



R. Pattie et al., Measurement of the neutron lifetime using a magneto-gravitational trap, Science 10.1126/science.aan8895 , 2018.

Table 2. Systematic uncertainties.

Effect	Upper bound (s)	Direction	Method of evaluation
Depolarization	0.07	+	Varied external holding field
Microphonic heating	0.24	+	Detector for heated neutrons
Insufficient cleaning	0.07	+	Detector for uncleaned neutrons
Dead time/pileup	0.04	±	Known hardware dead time
Phase space evolution	0.10	±	Measured neutron arrival time
Residual gas interactions	0.03	±	Measured gas cross sections and pressure
Background shifts	<0.01	±	Measured background as function of detector position
Total	0.28		(uncorrelated sum)

Effect	Correction	uncertainty
UCN event definition	...	± 0.13
Normalization weighting	...	± 0.06
Depolarization	...	$+0.07$
Uncleaned UCN	...	$+0.11$
Heated UCN	...	$+0.08$
Al block	$+0.06$	± 0.05
Residual gas scattering	$+0.11$	± 0.06
Uncorrelated sum	$0.17^{+0.22}_{-0.16}$ s	

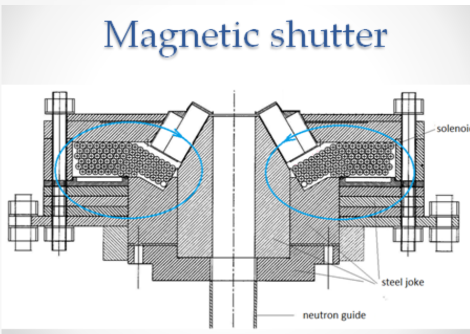
TABLE II. Systematic corrections with uncertainties to τ_n in seconds. The total is an uncorrelated combination of all systematic corrections. The non-zero corrections here are applied to the final result. Only the UCN event definition and normalization effects can decrease the measured τ_n.

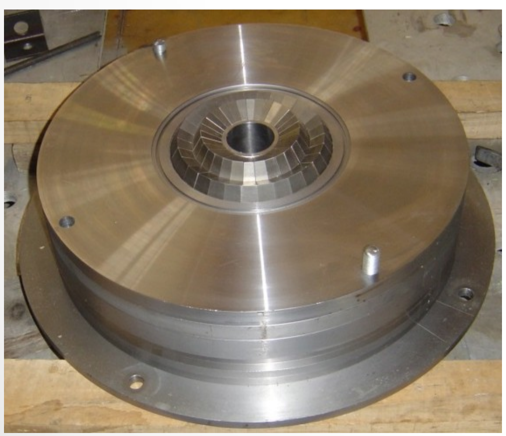
V.F. Ezhov et. al. *JETP Letters, 2018, Vol. 107, No. 11, pp. 671–675*

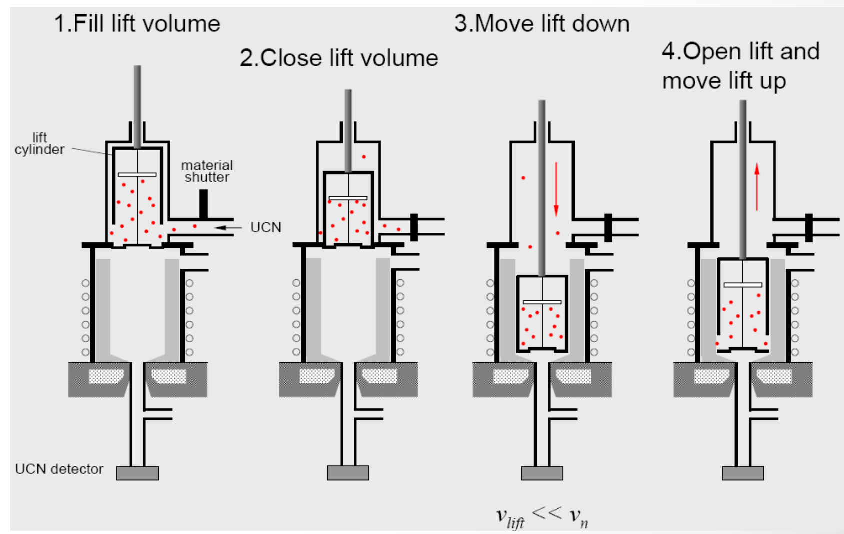
Magnetic shutter in lower part of trap permits to collect depolarized UCN during storage time.

$\tau_n = (878.3 \pm 1.6 \pm 1.0)$ s

Trap is filled using elevator in upper part of trap. There are an absorber inside elevator for preliminary preparation of UCN spectrum. Final cleaning proceeds inside the trap throw magnetic shutter in lower part of trap







V.F. Ezhov, et al, Technical Physics Letters, Vol. 44, No. 7, pp. 602–604, 2018.

Control of the depolarized (or spin flipped) UCN

- To control the spin flipped UCN the inner trap walls are covered with thin layer of fomblin that barrier is higher than magnetic one and reflects spin flipped UCN. After some collisions (order of 10-th) the spin flipped UCNs penetrate through the magnetic barrier of solenoid and are detected by the UCN detector installed below the solenoid. Hence this intensity may be used as the detector of UCN losses during storage time.

Magnetic shutter – main characteristics

- Magnetic shutter is **transparent for depolarized neutrons and neutrons that energy exceeds the energy of shutter magnetic barrier**, so it permits to control UCN losses during storage time as connected with depolarization, so with small UCN heating
- Shutter magnetic barrier has to be **less then magnetic barrier of the wall**
- Filling trap with **unpolarized** UCN gives monitor for each filling cycle
- **Artificial depolarization permits** to measure efficiency of depolarized neutron collection

Main properties of “ideal” experimental setup for neutron lifetime measuring

1. **On-line control of UCN losses**
2. **Measuring of efficiency of UCN losses detection**
3. **Result have to be independent from transformation of neutrons spectra during storage. (Small UCN heating?)**
    1. **Fluctuation of magnetic field (thermal and vibration)**
4. **Control of UCN spectra cleaning**
5. **Monitoring of filling directly in trap. (for an example, mechanical filling shutter can have slightly different position in each cycle)**
6. **Storage time independence of vacuum**
7. **It’s necessary to have minimum three point of different storage time at decay curve.**

1 – 5 problems can be solved using magnetic shutter

Transformation of neutrons spectra during storage

Small UCN heating?

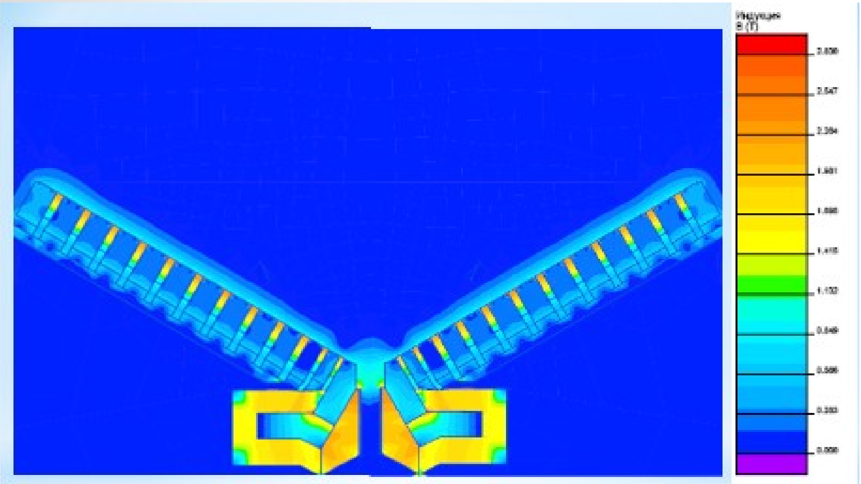
- To exclude this effect the magnetic barrier in magnetic shutter have to be less then magnetic barrier of the wall. So in case of small heating during storage such neutrons will be reflected by barrier of the wall and leave the trap through magnetic shutter and fall down to detector. As a result they will be taken into account as losses in trap. They will be equal to depolarized neutrons.

• Uncleaned UCN

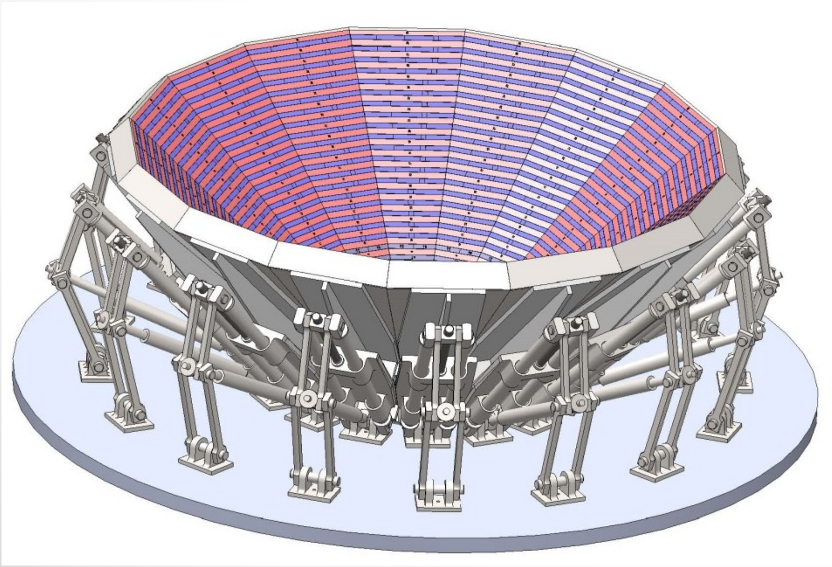
- (Wall magnetic barrier higher then shutter one) – it means that uncleaning UCN – will be registered by detector during storage time as losses too.

New trap under construction

B. A. Bazarov et al, Technical Physics Letters 42(7), 663-666, (2016)



Calculated map of magnetic field for a new trap



Increasing of volume is about 15 times
Increasing of stored UCN energy in 2 times due to increasing shutter magnetic barrier value

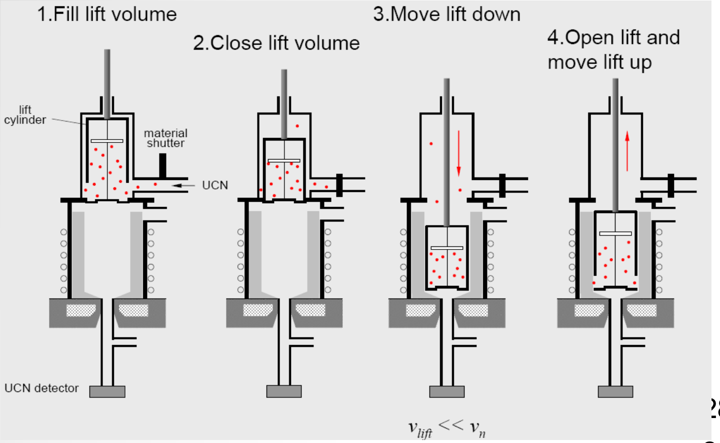
Waited accuracy about 0.2 s.

Vacuum chamber and filling system for new trap (ILL, Level D)

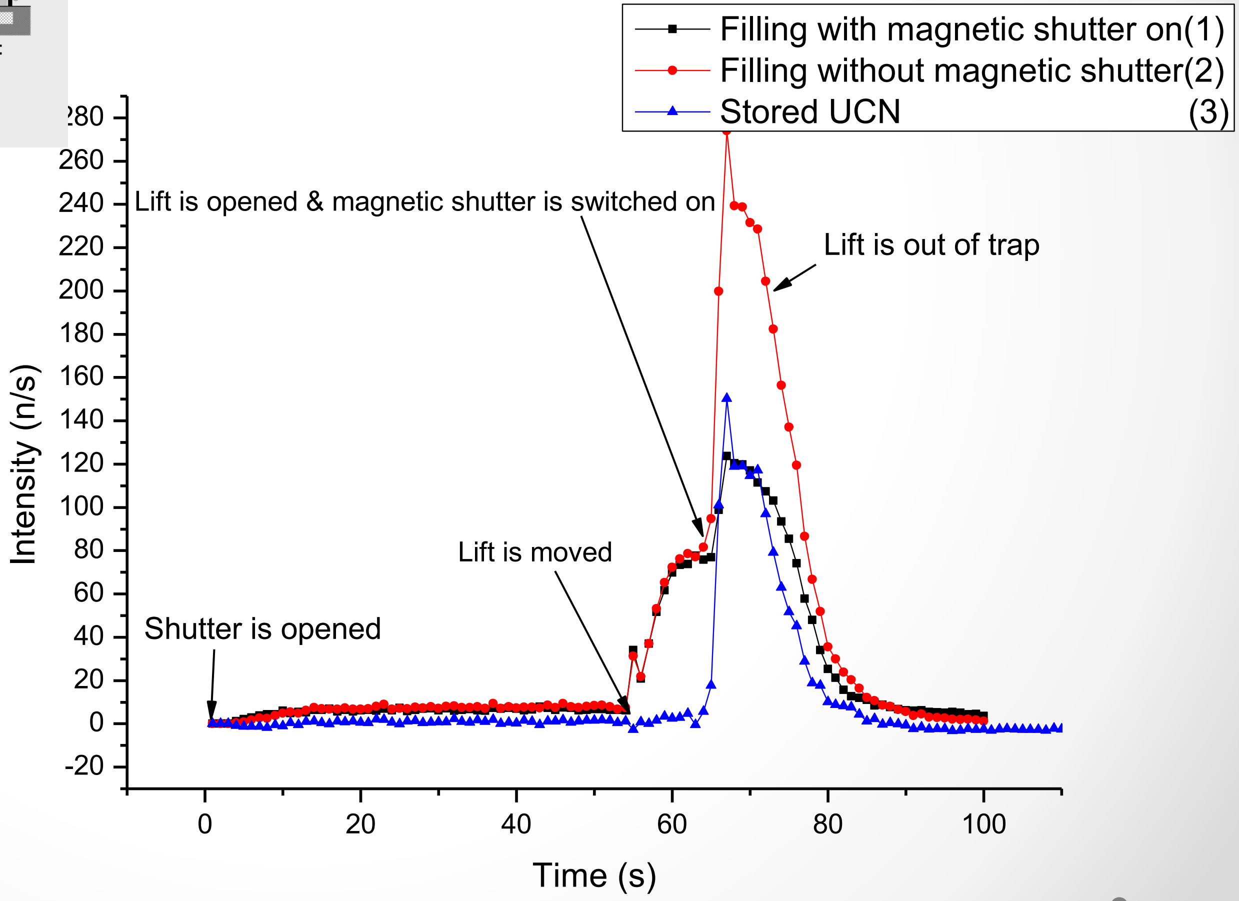
…

Thank you for attention

Monitor of trap filling



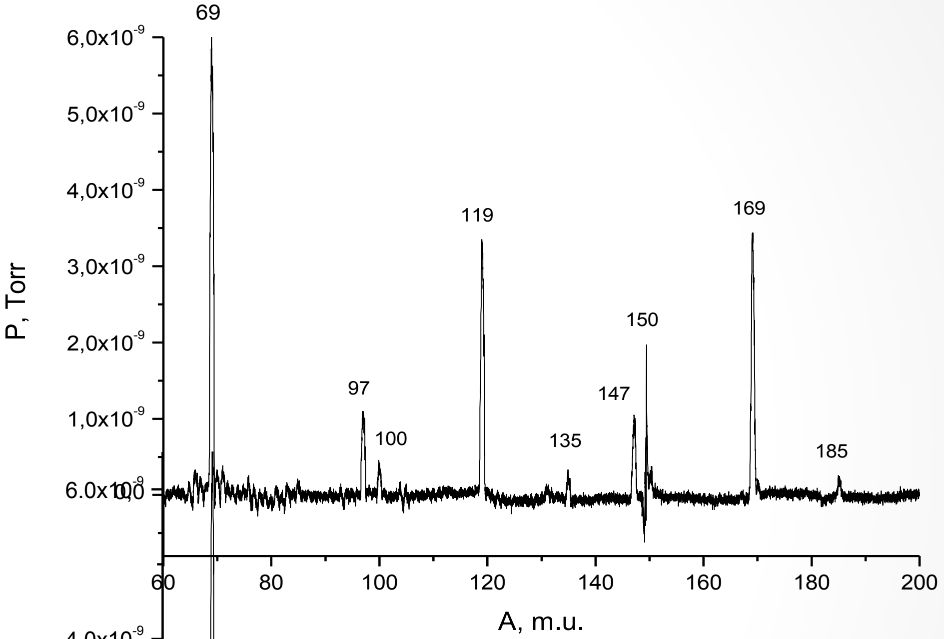
Trap is filling with **unpolarized** UCN. In this case half of UCN will be detected just during the filling

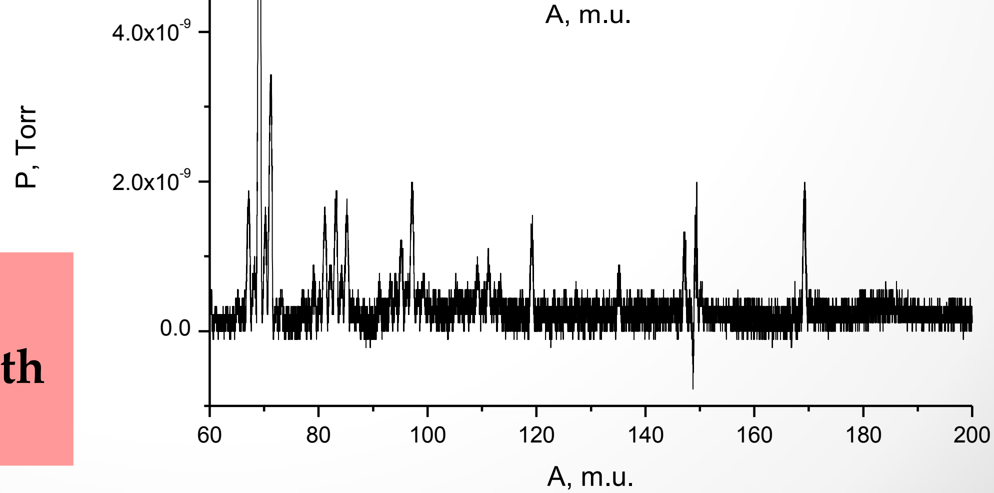


Fomblin vapor scattering?

Calibration

Fomblin spectrum under 98 C



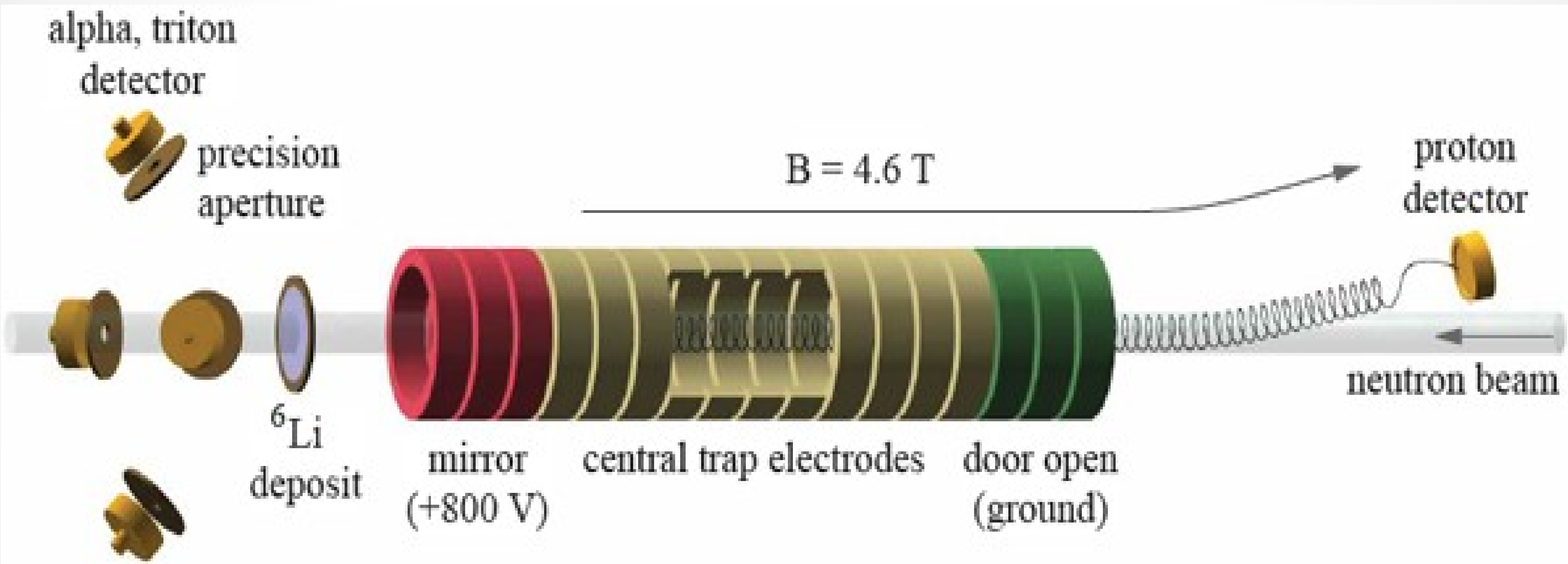


Spectrum of the rest vapor in the trap that wall covered with fomblin

Improved Determination of the Neutron Lifetime

Phys. Rev. Lett. 111, 222501 – Published 27 November 2013

A. T. Yue, M. S. Dewey, D. M. Gilliam, G. L. Greene, A. B. Laptev, J. S. Nico,
W. M. Snow, and F. E. Wietfeldt



$$\tau = 887{,}7 \pm 1{,}2 \pm 1{,}9\ \text{c}$$