New neutron lifetime measurements with the big gravitational trap and review of neutron lifetime data

A.P. Serebrov, M.E.Chaikovskii

PNPI Scientific Research Center KI,
Gatchina, Russia

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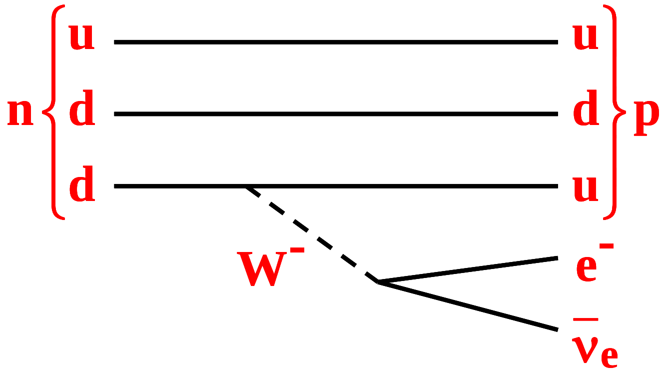
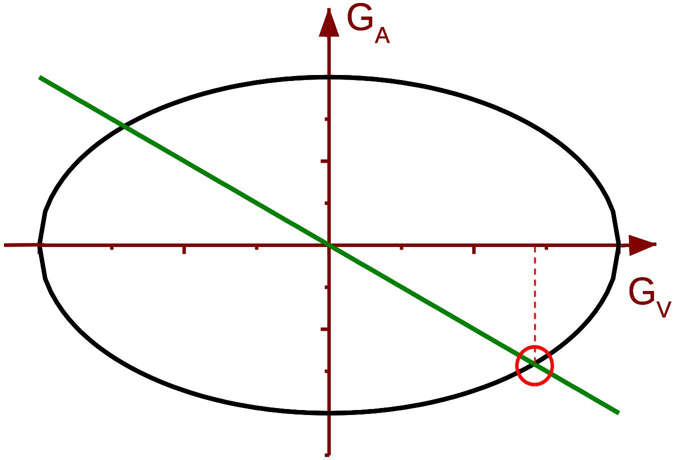
Neutron decay and Standard Model





CKM mixing matrix:

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

$$f\tau_n\left(1+\Delta_R\right)\left(1+\delta_R\right) = \frac{k}{\left|V_{ud}\right|^2 G_F^2\left(1+3\lambda^2\right)}$$

~1.5 %   ~2.4 %

$$\lambda = \frac{G_A}{G_V} \qquad A_0 = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$$

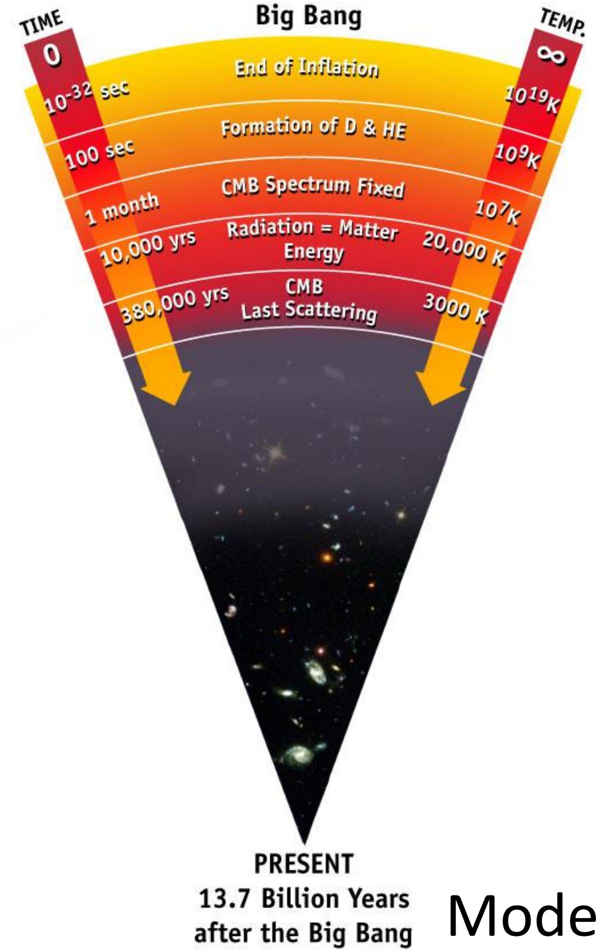
$$G_V = G_F \cdot V_{ud}$$

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

W.Marciano
A.Sirlin
PRL 96, 032002
(2006)

Required experimental accuracy for τ_n and A_0
Is about 10^{-3} and better.

Neutron decay and cosmology



$$(f\tau_n)^{-1} = \frac{G_F^2}{2\pi^2}(1+3G_A^2)m_e^5\lambda_0$$

$$\Gamma = (7/60)\pi(1+3G_A^2)G_F^2T^5$$

$$\rho_\gamma = (\pi^2/30)g_*T^4$$

$$H \approx \left[(8/3)\pi G\rho_\gamma\right]^{1/2}$$

$$T_f \approx 1\ \mathrm{MeV}$$

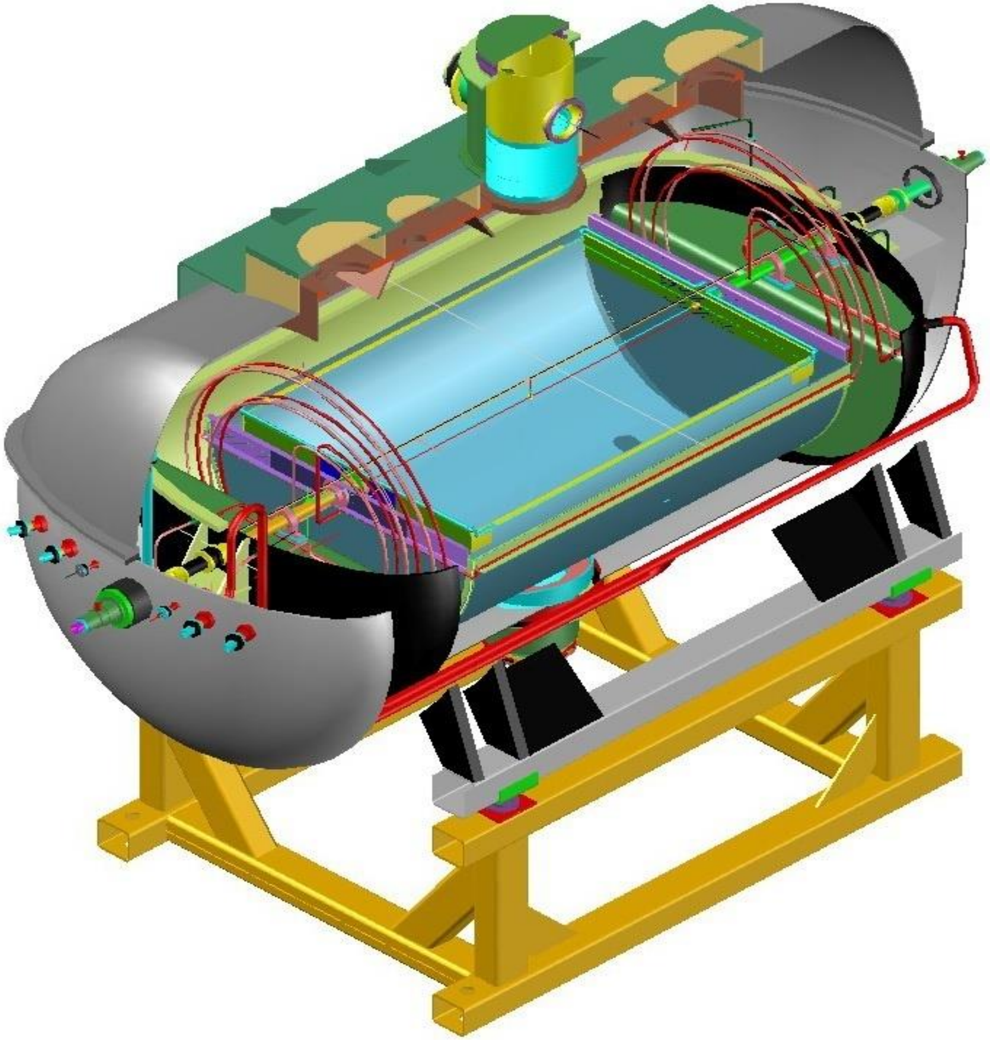
Weak interactions freeze-out temperature depends on τ_n

n/p ratio changes only by β-decay

Survived neutrons form ^{4}He nuclei

Models of Big-Bang nucleosynthesis is sensitive to τ_n

New setup - *Big Gravitational Trap*



Calculation of neutron lifetime

Amount of neutrons in the trap

$$N(t,E) = N_0 \exp(-t/\tau_{st}(E))$$
$$\tau_{\mathrm{st}}^{-1}(E) = \tau_{\mathrm{n}}^{-1} + \tau_{loss}^{-1}(E)$$
$$\tau_{st} = (t_2 - t_1)/\ln(N_1/N_2)$$

Losses in the trap

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

Calculation of neutron lifetime τ_n requires measurements of two different storage times τ_1 and τ_2 corresponding to different effective collision frequencies γ_1 and γ_2:

$$\tau_2^{-1} = \tau_n^{-1} + \eta\gamma_2 \quad \tau_1^{-1} = \tau_n^{-1} + \eta\gamma_1$$

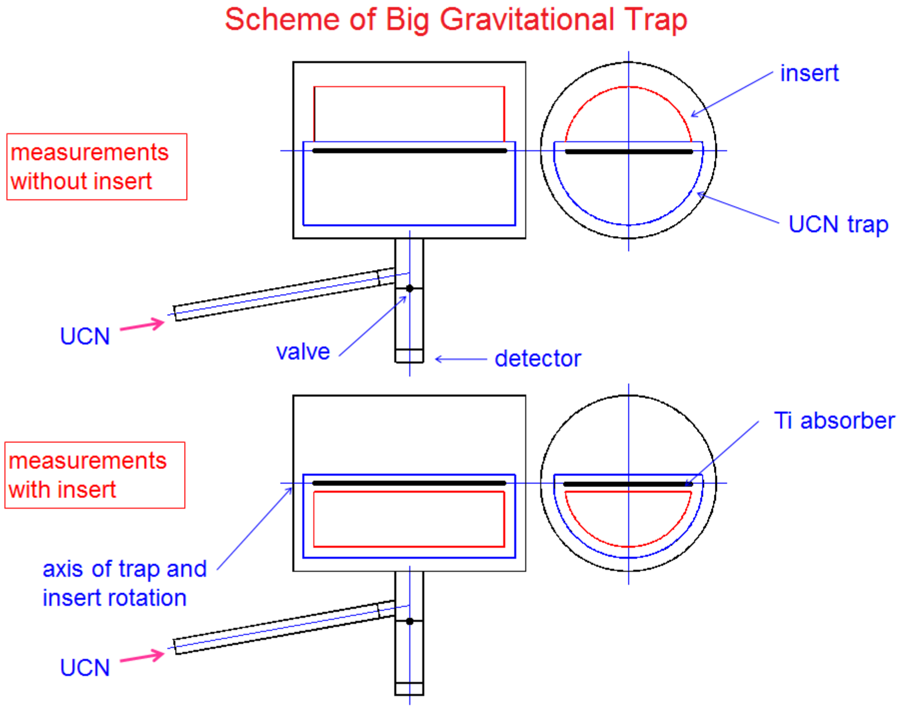
Effective collision frequency have to be calculated using Monte Carlo simulation

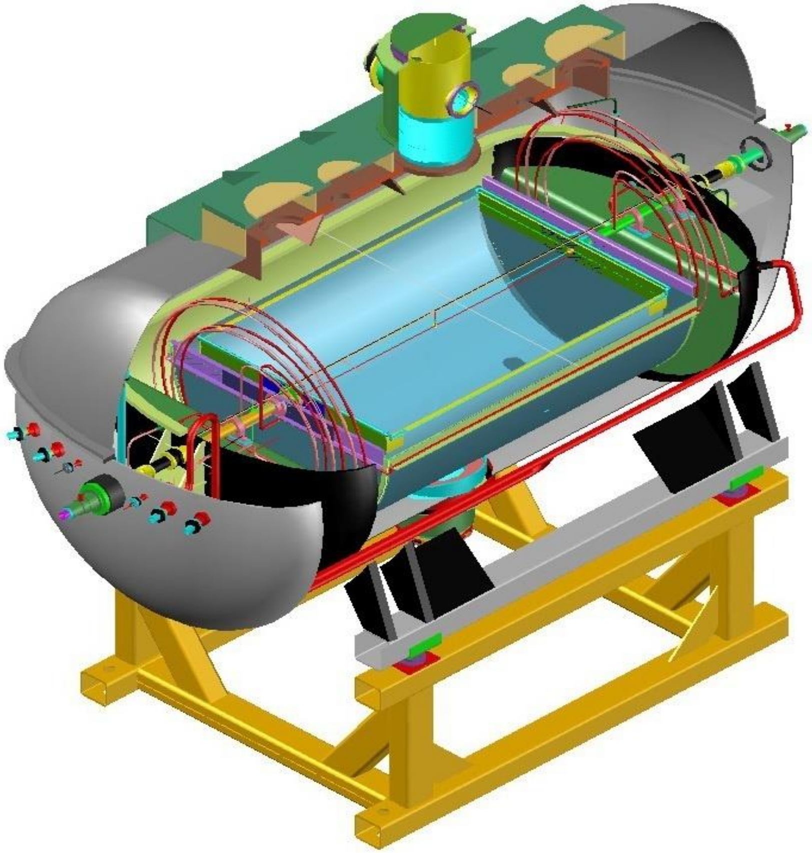
$$\eta = (\tau_1^{-1} - \tau_2^{-1})/(\gamma_1 - \gamma_2)$$

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

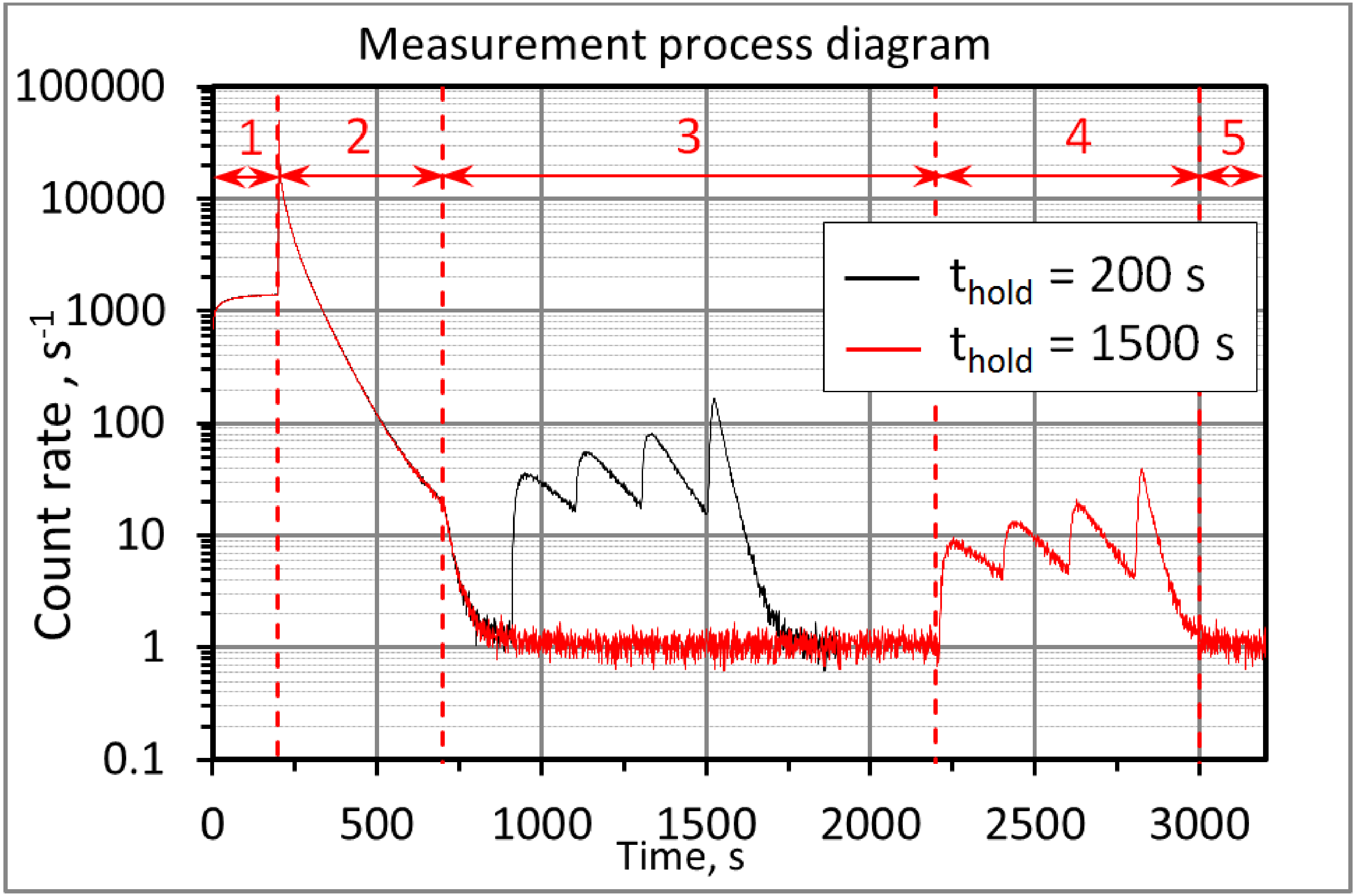
Neutron lifetime obtaining by extrapolation to an infinite trap with zero collision frequency

Basic scheme of the UCN trap





Trap – length 2 m; radius – 0.7m
Insert – length 1.8m; radius – 0.6m

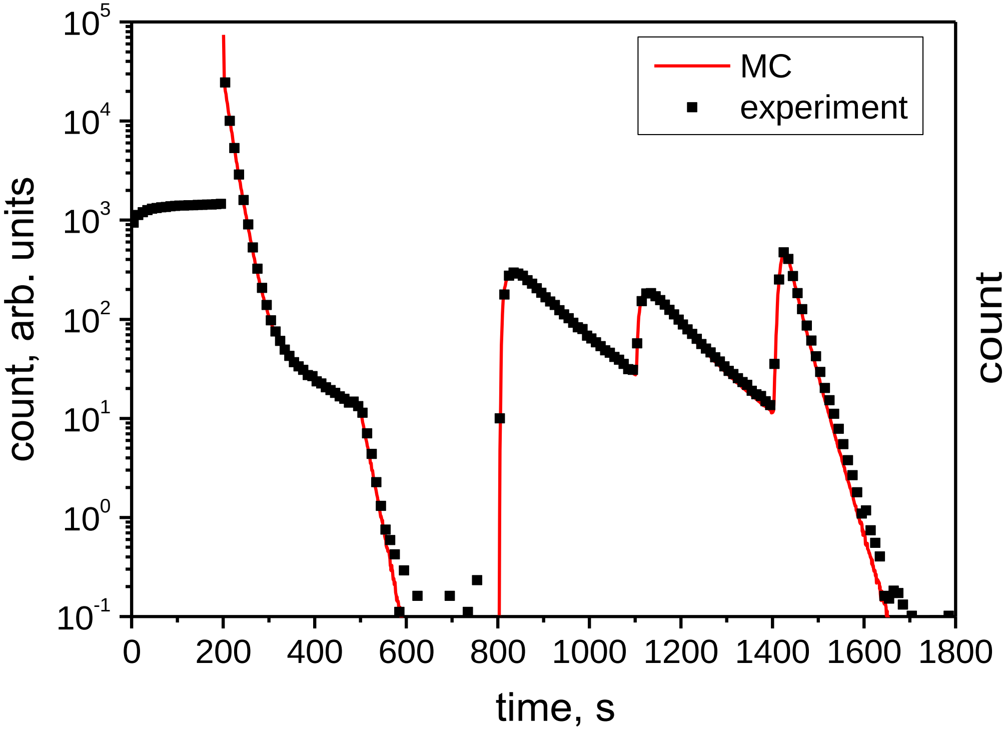


1 – filling the trap with UCN; 2 – extracting above-barrier neutrons; 3 – hold neutrons UCN in the trap; 4 – unload neutrons to detector; 5 –background measuring

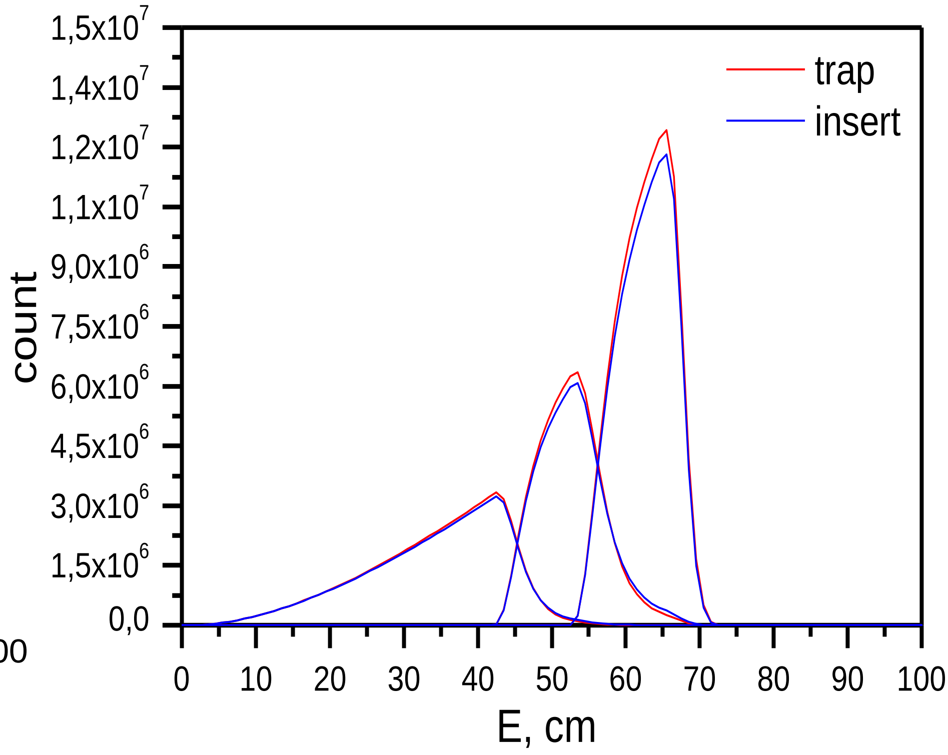
Monte Carlo simulation

Simulation of the neutron path from neutron guide to detector

Experimental and simulated count rates

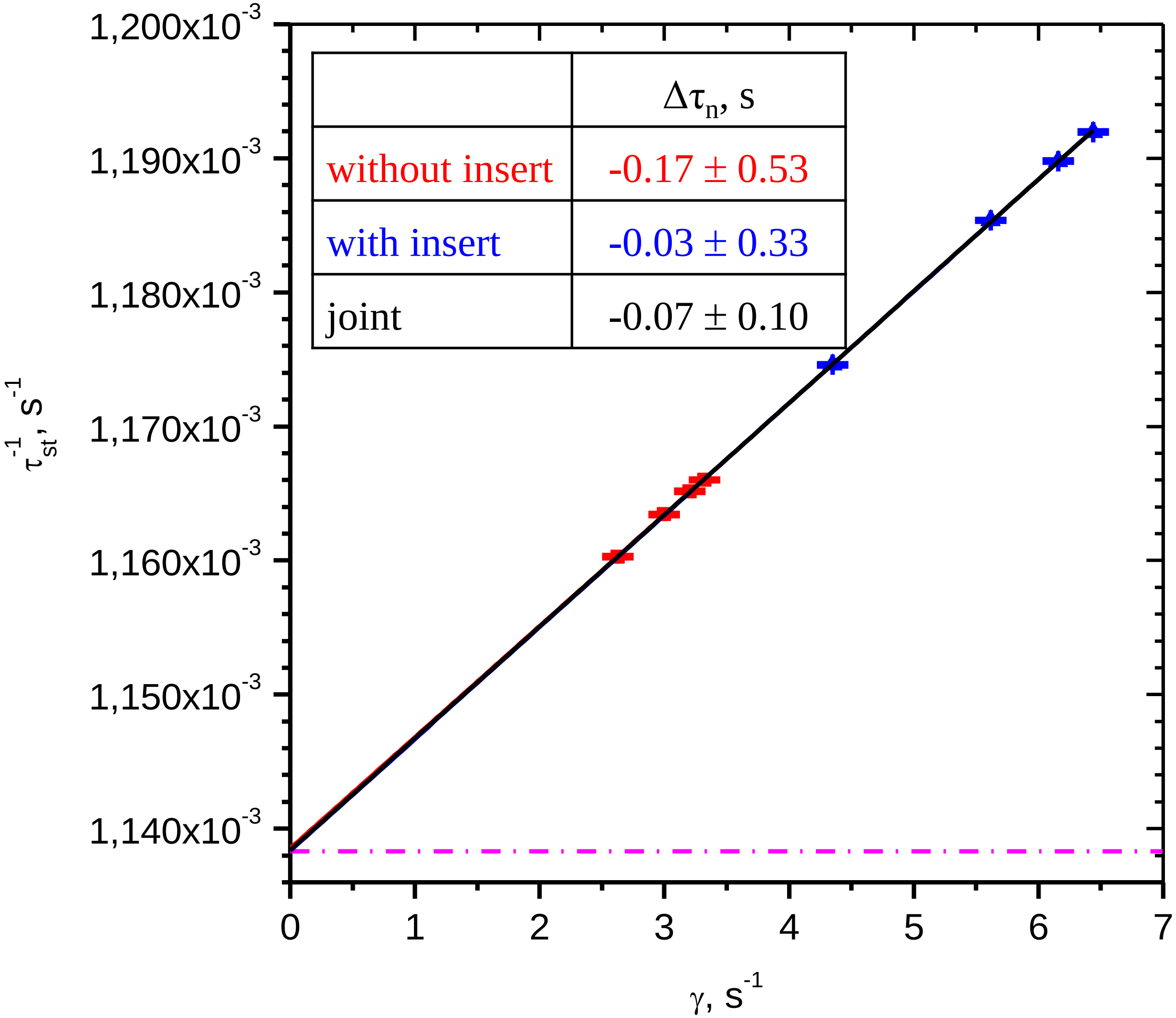


Energy spectrum in the emptyings



MC simulations is required to calculate mean effective collision frequencies for each measured mean storage time

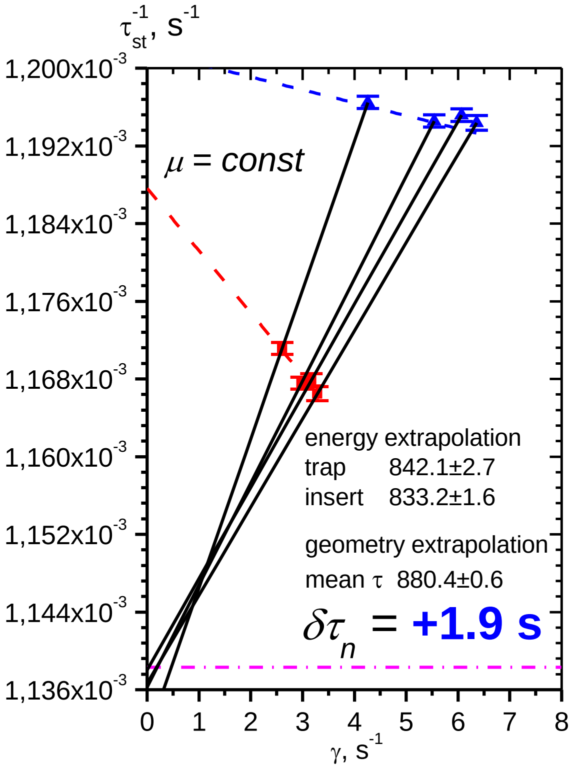
Extrapolation to neutron lifetime

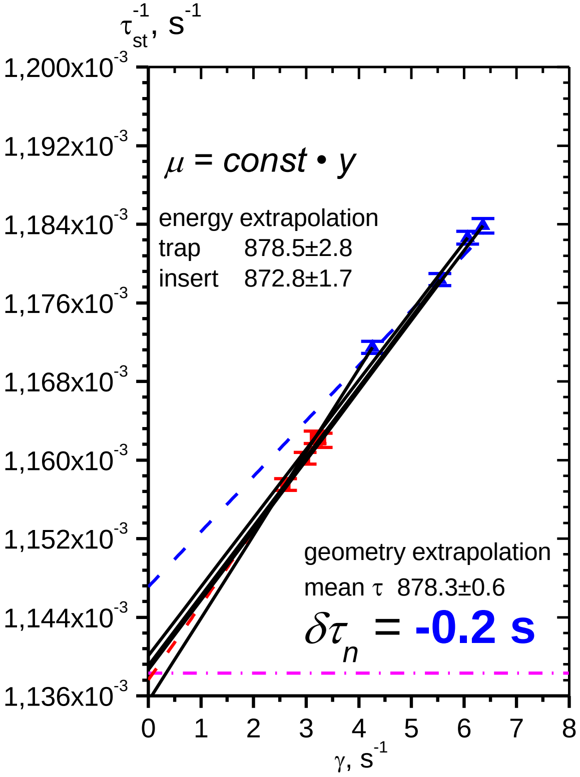


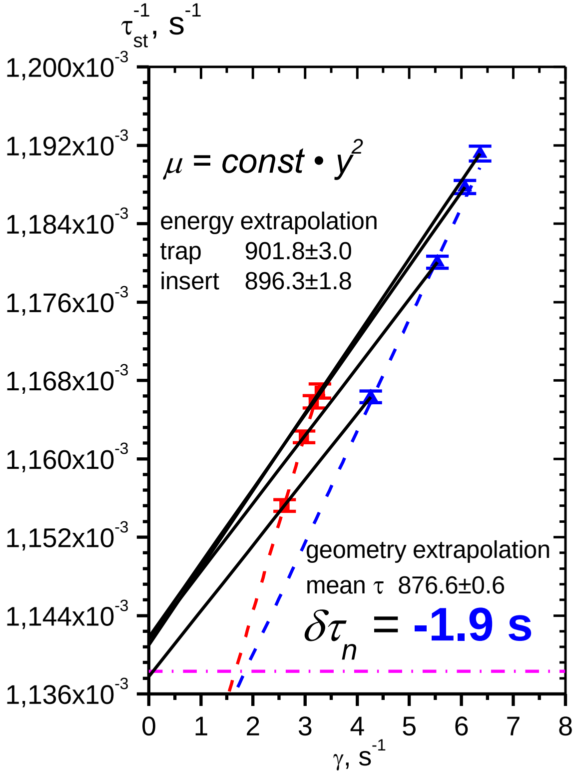
	$\Delta\tau_n$, s
without insert	-0.17 ± 0.53
with insert	-0.03 ± 0.33
joint	-0.07 ± 0.10

MC simulation of the measurement process. Lifetime reconstructed from count rates is in perfect agreement with built in decay parameter.

Simulation with alternative loss probability functions

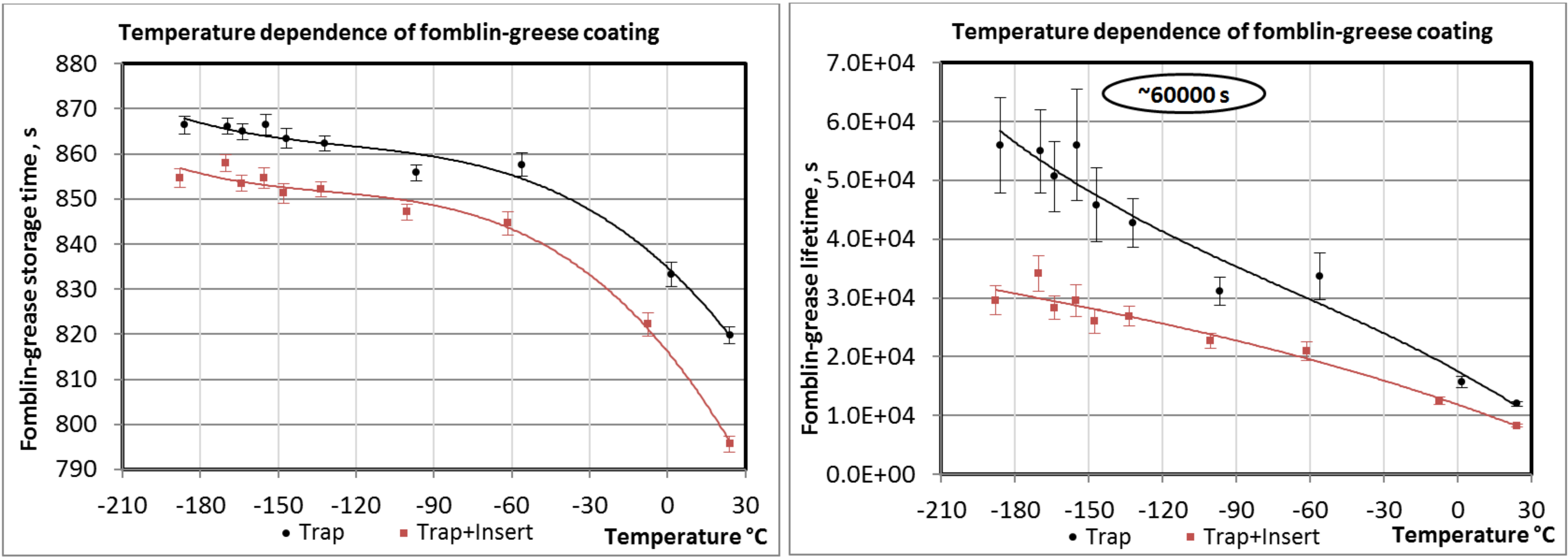






MC simulation is applied for estimation of systematic errors

Storage time temperature dependence for copper trap coated with fomblin grease

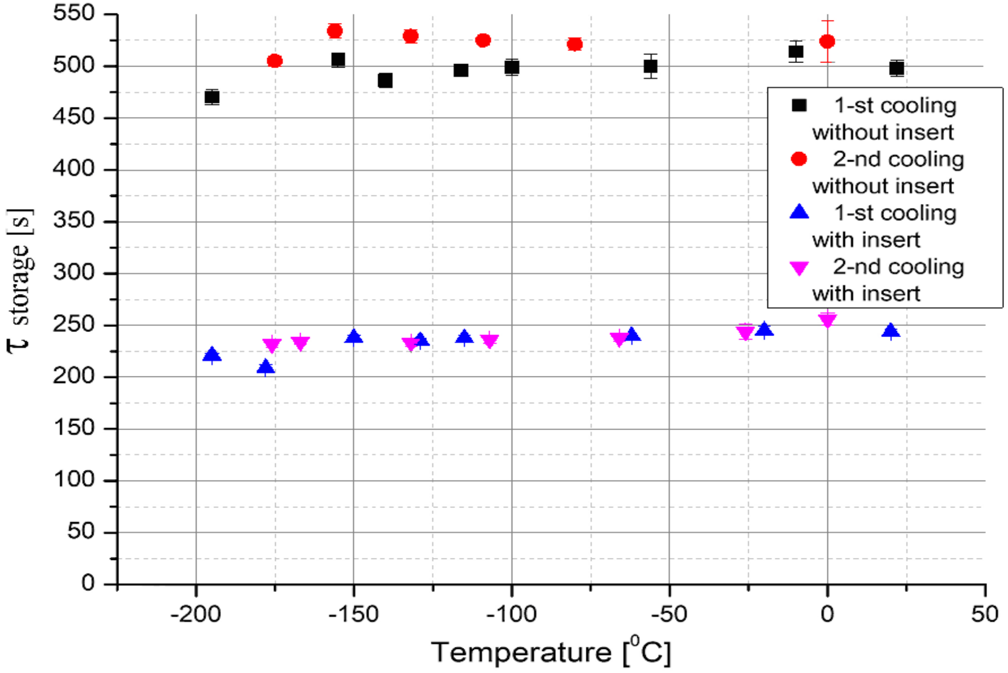


At 80 K the loss probability of fomblin is only 1.5% of neutron decay probability

Fomblin grease covering stability during freezing.

Test experiment with Titanium Trap

Titanium has high neutron capture probability $b_{coh} < 0$ and hence any changes in trap covering strongly affect the results of storage time measurements during the cooling and heating.



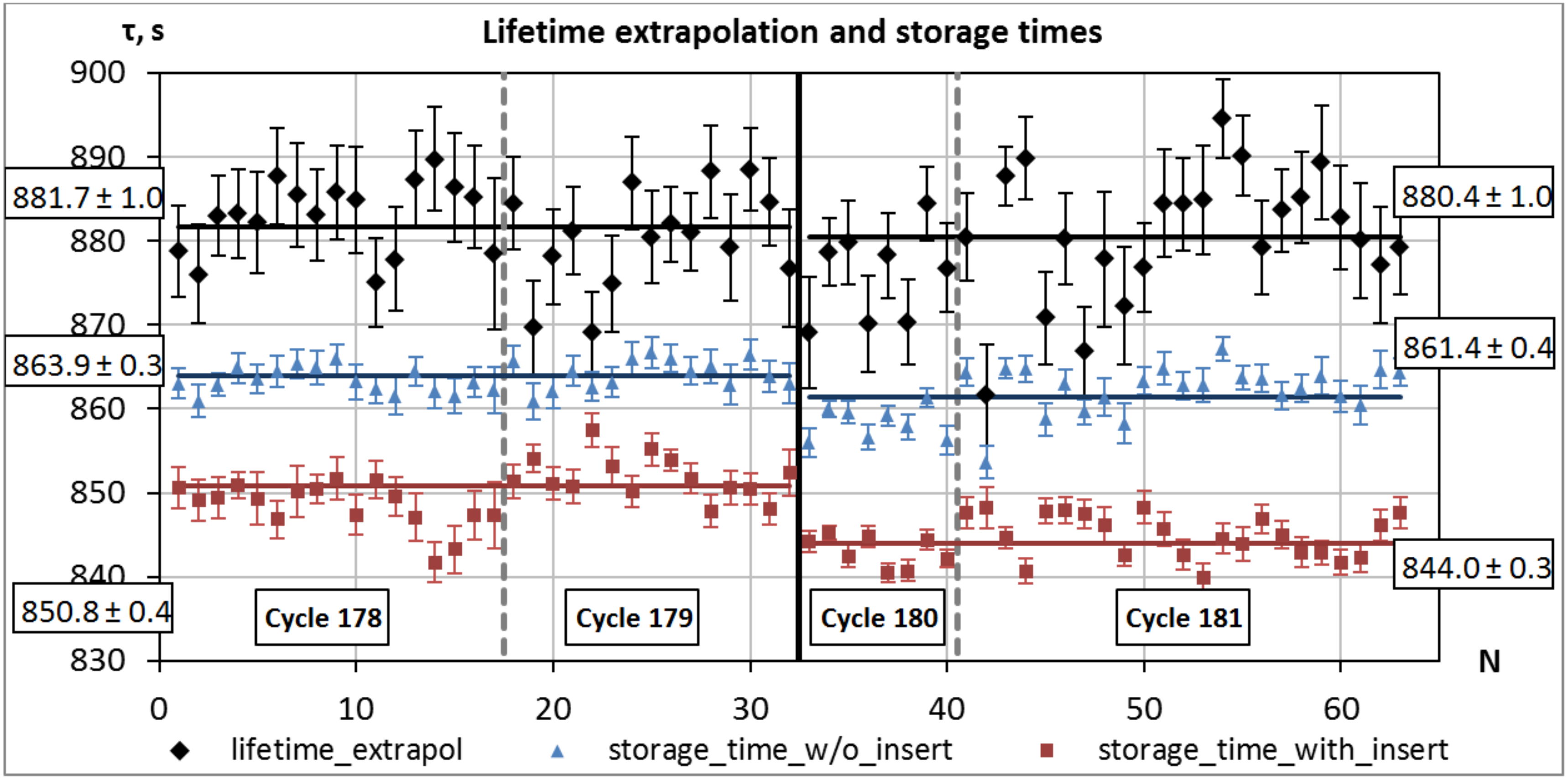
Storage time temperature dependence in experiment with Ti absorber.

1) The covering is stable and repeating cooling and heating does not damage it in any significant way. It means that uncovered area does not grow after cooling.

2) Uncovered area does not exceed 0.1% of the total trap area, as result maximal possible systematic for Cu trap with Cu insert is about 0.5s.

Diagram of measurements

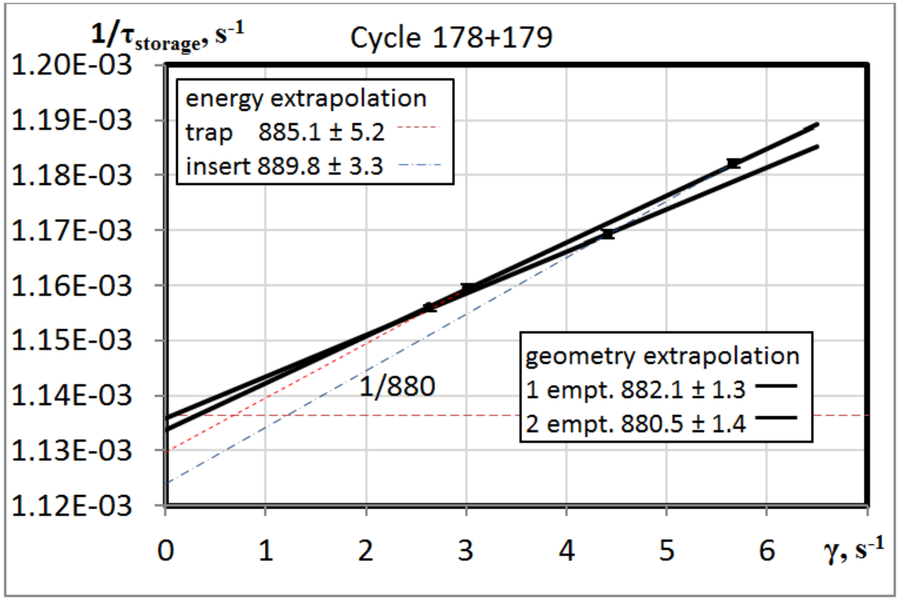
Four reactor cycles of data collecting



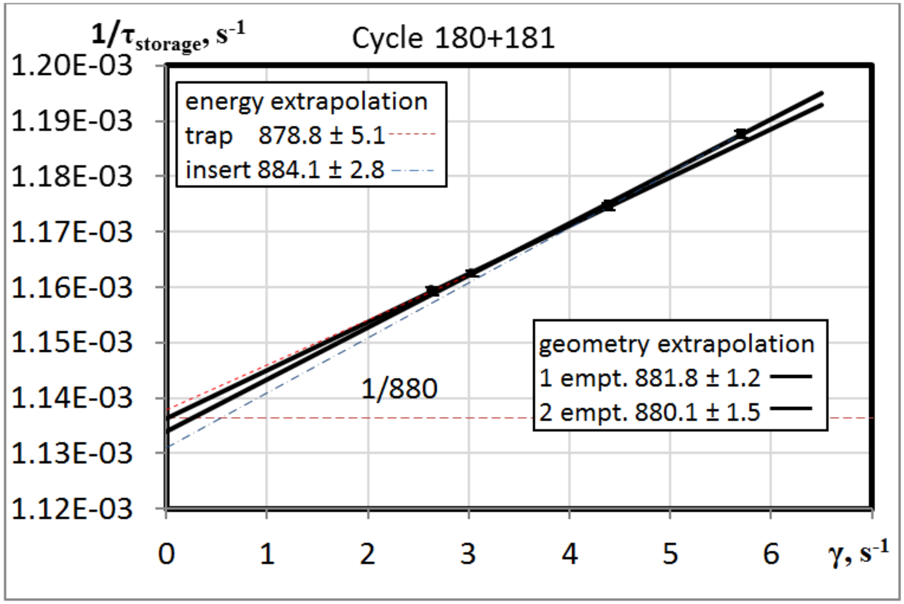
After reactor cycle 179 the Ti absorber was installed to speed up eliminating of above-barrier neutrons

Results of measurements

Without absorber



With absorber



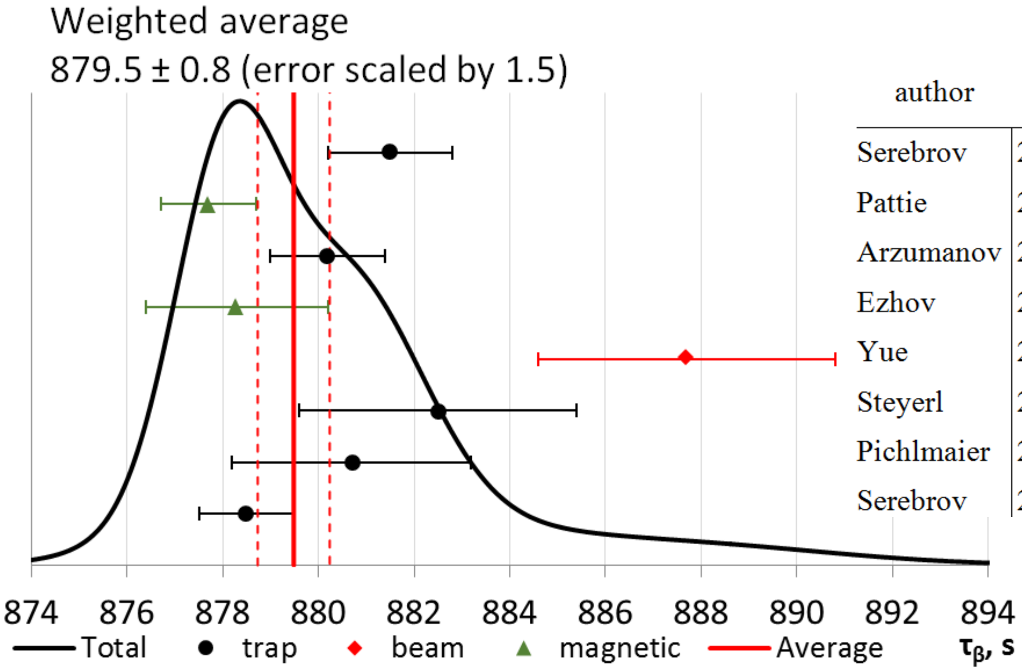
Cycle	Lower energies	Higher energies	Averaged
178+179	880.5±1.4	882.1±1.3	881.4±0.9
180+181	880.1±1.5	881.8±1.2	881.1±0.9
Averaged	880.3±1.0	881.9±0.9	881.3±0.7

Table of systematic errors

Systematic effect	Value, s
Uncertainty of γ function calculating (MC)	0.1
Uncertainty of shape of function μ(E)	0.3
Uncertainty of trap dimensions (3 mm for diameter 1200 mm)	0.15
Uncertainty of trap angular position (2^o)	0.1
Uncertainty of difference for trap and insert coating	0.5
Residual gas correction	+0.2
Total	0.6

The new result of measurements with big gravitational trap is:

$$\tau_n = 881.5 \pm 0.7_{stat} \pm 0.6_{syst} \; s$$

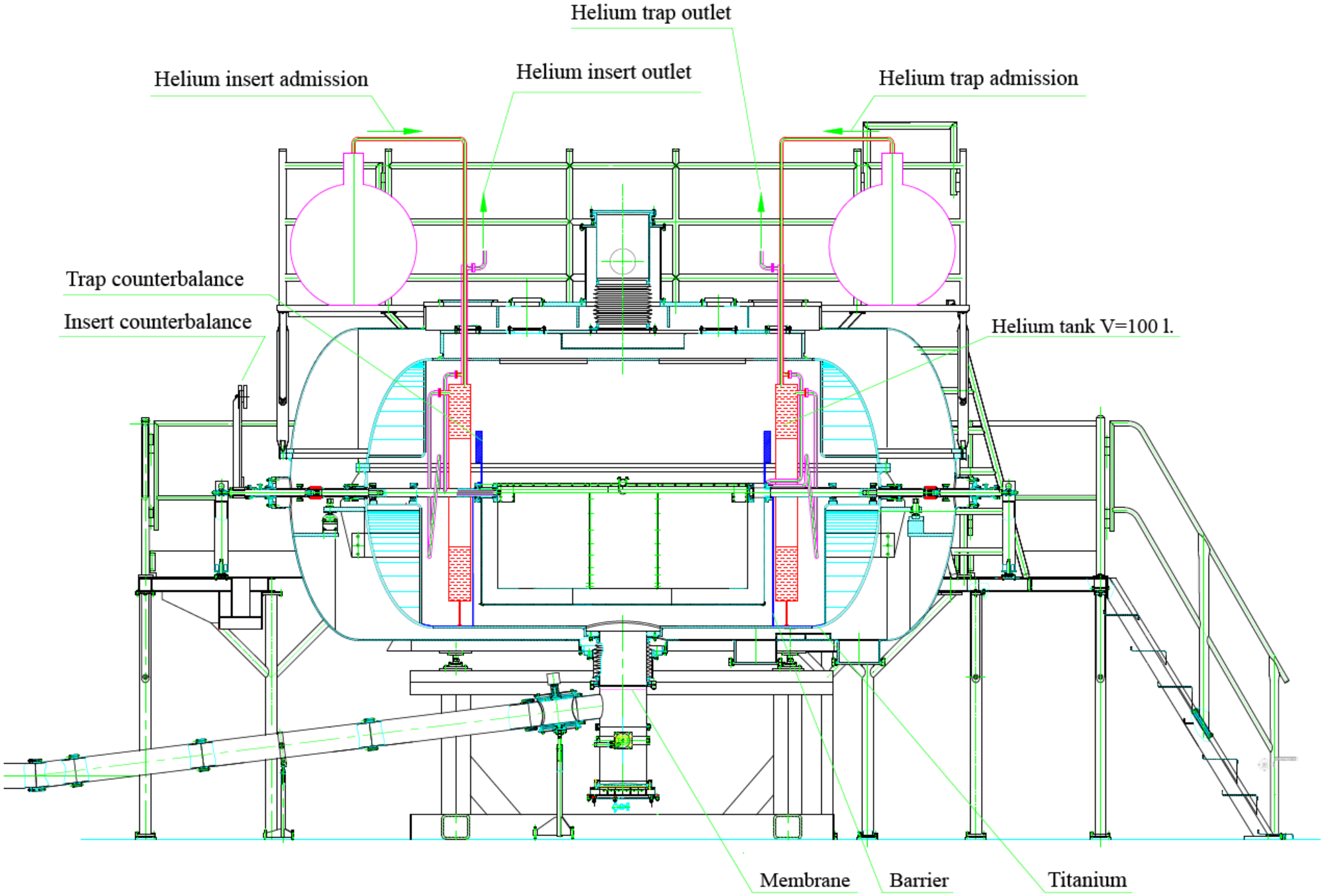

Weighted average
879.5 ± 0.8 (error scaled by 1.5)

author	year	value	error			χ^2
			stat	sys	Σ	
Serebrov	2017	881.5	0.7	0.6	1.3	2.4
Pattie	2017	877.7	0.7	0.3	1.0	3.2
Arzumanov	2015	880.2	1.2		1.2	0.4
Ezhov	2014	878.3	1.9		1.9	0.4
Yue	2013	887.7	1.2	1.9	3.1	7.0
Steyerl	2012	882.5	1.4	1.5	2.9	1.1
Pichlmaier	2010	880.7	1.3	1.2	2.5	0.2
Serebrov	2004	878.5	0.7	0.3	1.0	1.0

The results of storage measurements with material and magnetic trap are in agreement within two standard deviations.
Further improvement of storage experiments required .

Thank you for attention

The Big Gravitational Trap with Fomblin grease coating at the temperature about 10 K



Helium trap outlet

Helium insert admission

Helium insert outlet

Helium trap admission

Trap counterbalance

Insert counterbalance

Helium tank V=100 l.

Membrane

Barrier

Titanium