31st International Seminar on Interaction of Neutrons with Nuclei: Fundamental Interactions & Neutrons, Nuclear Structure, Ultracold Neutrons, Related Topics
(ISINN-31)

Modeling and Optimization of Experimental Setup Geometry for Measuring Ultracold Neutron Loss Factors Using Gravitational Spectroscopy

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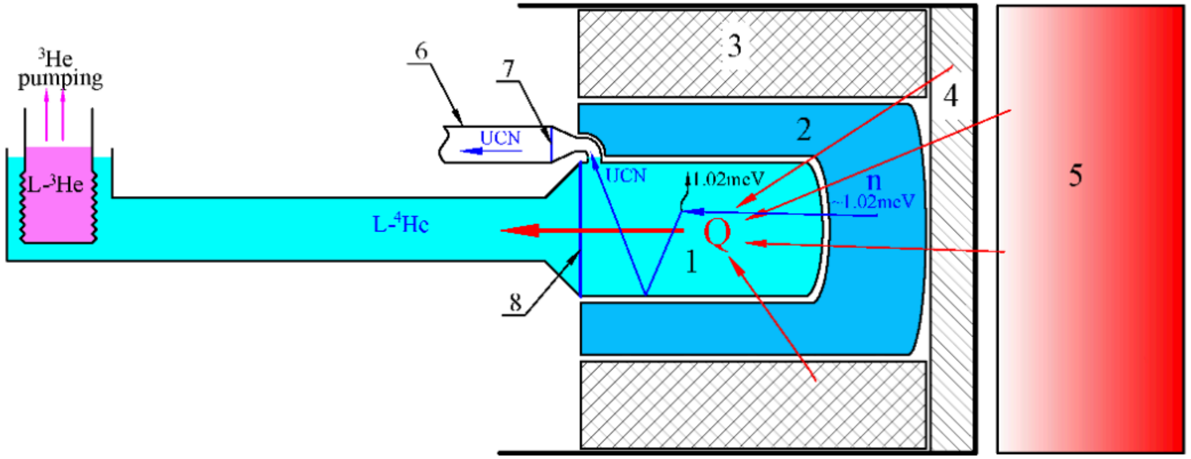
Motivation

Selecting a material with a high critical velocity allows for the expansion of the stored ultracold neutron (UCN) spectrum, including more energetic neutrons, which in turn will increase the density of ultracold neutrons and open up new experimental possibilities.

This research involves modeling and parameter calculations for upcoming experiments measuring UCN loss factors in different coatings. The main goals are optimizing the experimental geometry and determining optimal measurement parameters to ensure highly efficient follow-up experiments.



Schematic diagram of the planned ALSUN ultracold neutron source

Theoretical background

The ideal gas model is very suitable for describing UCN gas, but it has some significant features:

- UCNs are reflected from the walls of the trap mainly elastically and secularly (quasi-static (mechanical) equilibrium)
- Interaction of UCN with each other is negligibly small. The trajectories of neutrons in the trap are individual and do not depend on each other.
- The density of a gas in a closed volume decreases over time. This decrease is due to both interaction with the walls and β-decay.
- Since the speed of neutrons is very low, their motion is significantly affected by the gravitational interaction of neutrons with the Earth. UCN loses 1.02 neV per 1 cm of rise in the gravitational field of the Earth.

The loss probability μ is calculated assuming an isotropic velocity distribution of UCN impinging on the surface with Fermi potential U − iW

$$\overline{\mu^{+}}(y)=\frac{2\eta}{y^{2}}\left(\arcsin(y)-y\sqrt{1-y^{2}}\right)\theta(1-y)+\left(\frac{8y\left(y^{2}-1\right)^{\frac{3}{2}}}{3}-\frac{8}{3}y^{4}+4y^{2}-\frac{8}{6y^{2}}+\frac{\pi\eta}{y^{2}}\right)\theta(y-1)$$

$$\overline{\mu^{-}}(y)=\frac{8y}{3}\left[\left(y^{2}+1\right)^{\frac{3}{2}}-y\left(y^{2}+\frac{3}{2}\right)\right]$$

$$y=\frac{\vartheta}{\vartheta_{lim}}$$

$$\frac{W}{U}=\eta$$ – loss factor

See Ref.: R. Golub and J. Pendlebury, Rep. Prog. Phys. 42 (1979).

Theoretical background

1. Filling Ves.1:

$$\frac{dN_{1fill}}{dt} = N_s - N_{1fill} \cdot (\frac{1}{\tau_{f1}} + \frac{1}{\tau_{t1}})$$

$$N_{1fill}[0] = 0$$

2. Storage Ves.1:

$$\frac{dN_{1storage}}{dt} = -N_{1storage} \cdot \frac{1}{\tau_{1t}}$$

$$N_{1storage}[t_{1close}] = N_{01close}$$

3. Empt. Ves.1:

$$\frac{dN_{1empty}}{dt} = -N_{1empty} \cdot (\frac{1}{\tau_{e1}} + \frac{1}{\tau_{t1}})$$

$$N_{1empty}[t_{1open}] = N_{01open}$$

N_s - Neutrons from source.
τ_{f1} - vessel1 fill time constant
τ_{t1} - vessel1 total loss time constant

4. Filling Ves.2:

$$\frac{dN_{2fill}}{dt} = N_1^{empty} \cdot \frac{1}{\tau_{e1}} - N_{2fill} \cdot (\frac{1}{\tau_{f2}} + \frac{1}{\tau_{t2}})$$

$$N_{2fill}[t_{fillstarts}] = 0$$

$$N_{1empty}[t_{fillstarts}] = N_{01open}$$

5. Storage Ves.2:

$$\frac{dN_{2storage}}{dt} = -N_{2storage} \cdot \frac{1}{\tau_{t2}}$$

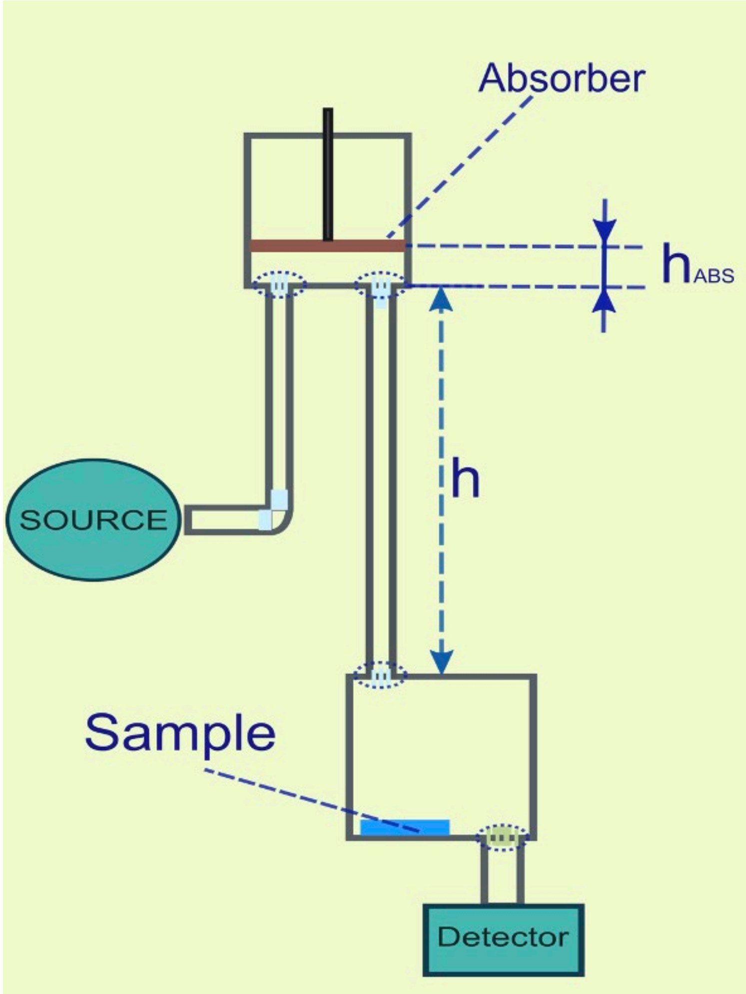
$$N_{2storage}[t_{2close}] = N_{02close}$$

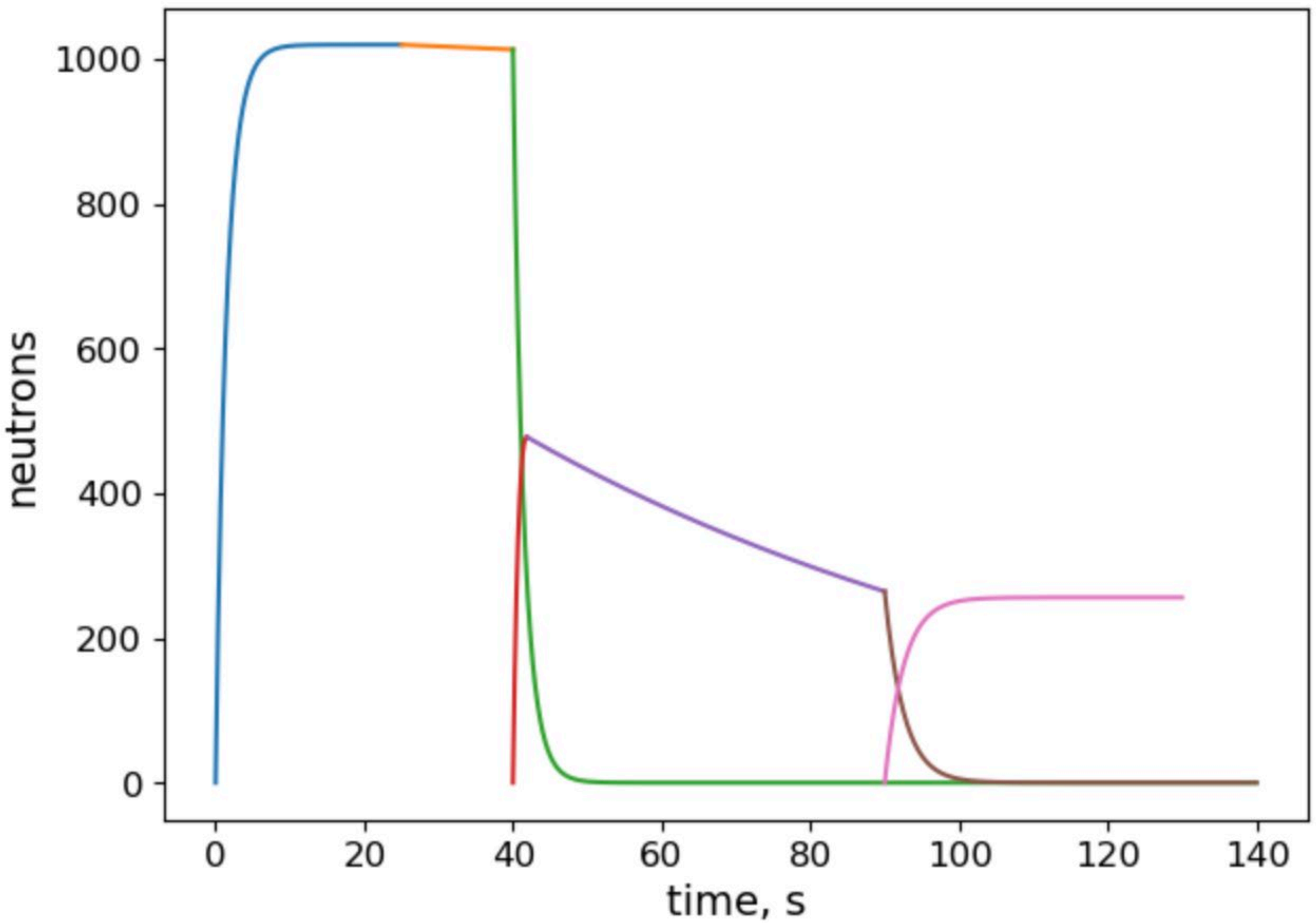
6. Empt. Ves.2:

$$\frac{dN_{2empty}}{dt} = -N_{2empty} \cdot (\frac{1}{\tau_{e2}} + \frac{1}{\tau_{t2}})$$

$$N_{2empty}[t_{2open}] = N_{02open}$$

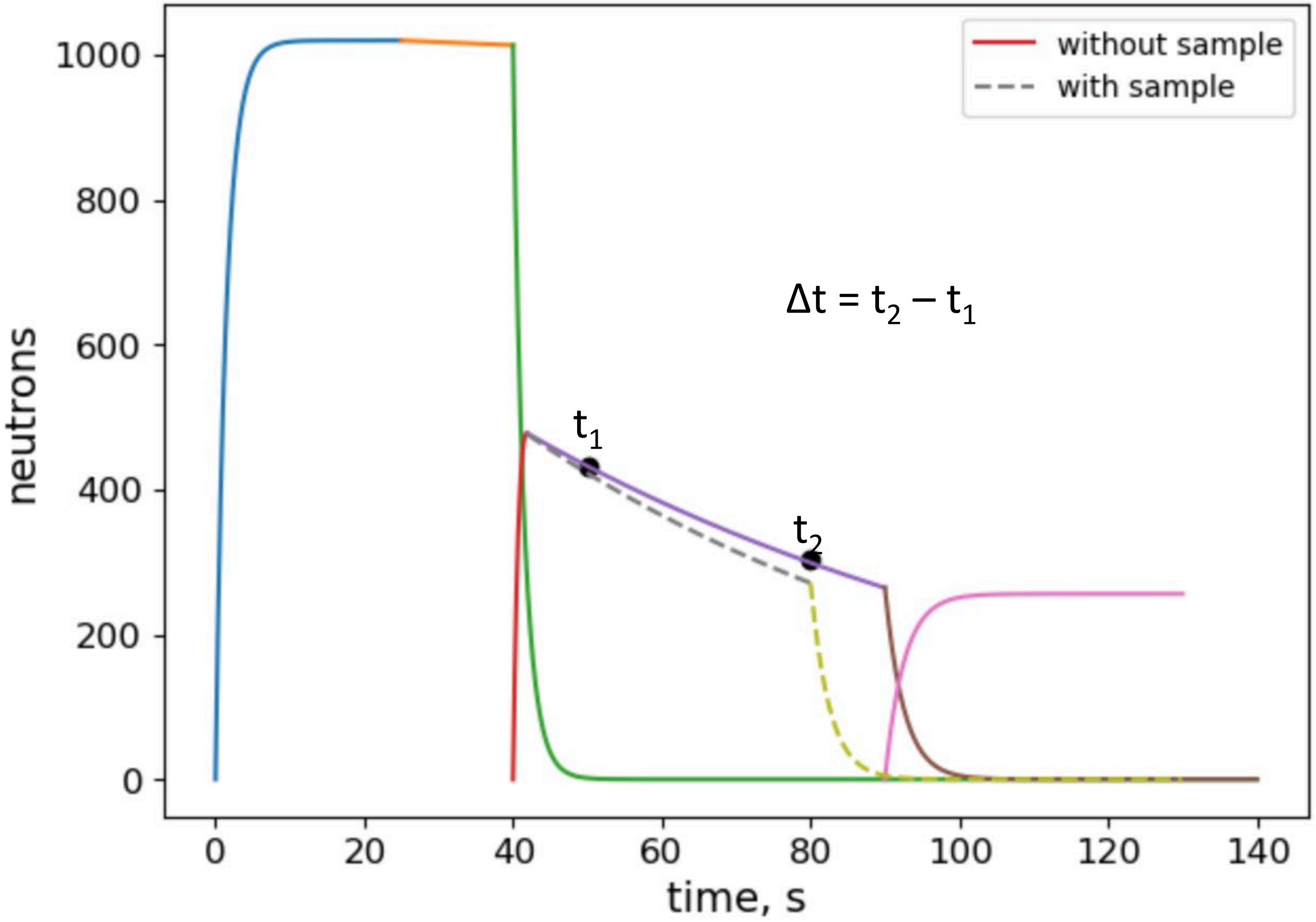
N_{01open} - Number of neutrons in ves 1. when emtying ves. 1 starts (it is the time when filling ves. 2 starts)
$t_{fillstarts}$ - time when filling ves. 2 starts
τ_{f2} - ves.2 fill time constant
τ_{t2} - ves.2 total loss time constant
N_{2close} - Number of neutrons when storage in ves.2 starts





- The vessels are cylindrical in shape: D = 30 cm.
- The height of the absorber (polyethylen) is variable (h_{abs} = 5-10 cm.)
- Valves – 8 cm in diameter.

Coatings	U, nEV	v_{lim}, m/s	$\eta \cdot 10^{-4}$
Wall Ni58	~335	8.0	~ 3.0



$$\tau_{noSamp} = \frac{t_2 - t_1}{\ln(N_1/N_2)}$$

$$\tau_{withSamp} = \frac{t_2 - t_1}{\ln(N_1/N_2)}$$

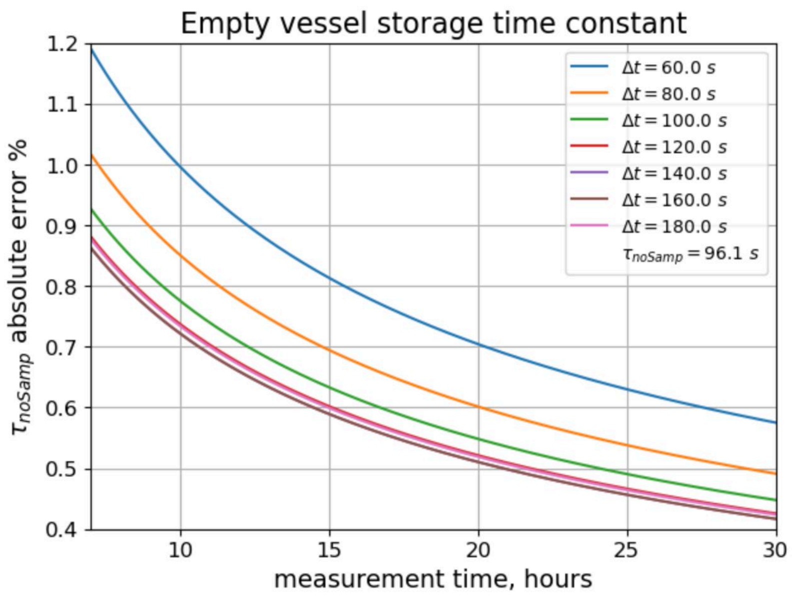
$$\frac{1}{\tau_{Samp}} = \frac{1}{\tau_{noSamp}} - \frac{1}{\tau_{withSamp}}$$

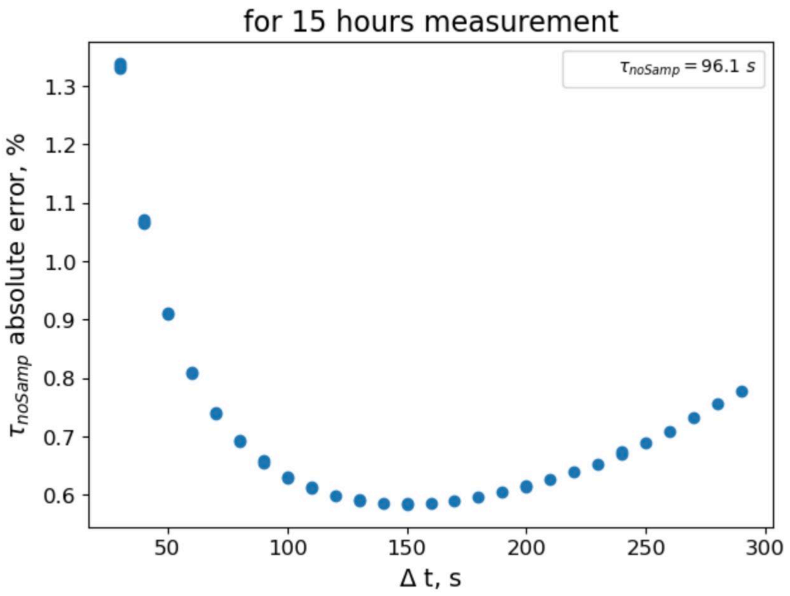
$$\frac{1}{\tau_{Samp}} \approx \overline{\mu(\vartheta)\cdot\nu(\vartheta)}$$

$\nu(\vartheta) \approx \frac{S\cdot\vartheta}{4V}$ – collision frequency

$$\overline{\mu(\vartheta)} \approx \frac{1}{\tau_{Samp}\cdot\nu(\vartheta)}$$

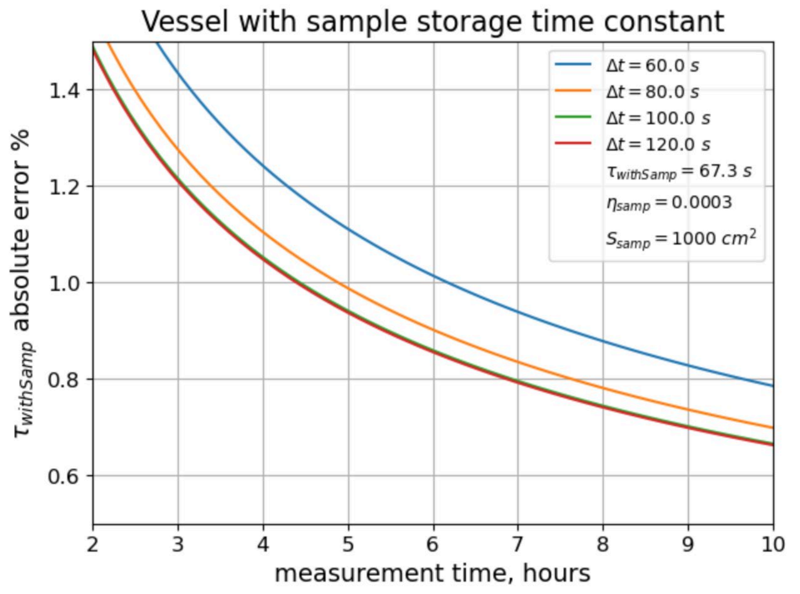
Optimization of neutron drain time selection

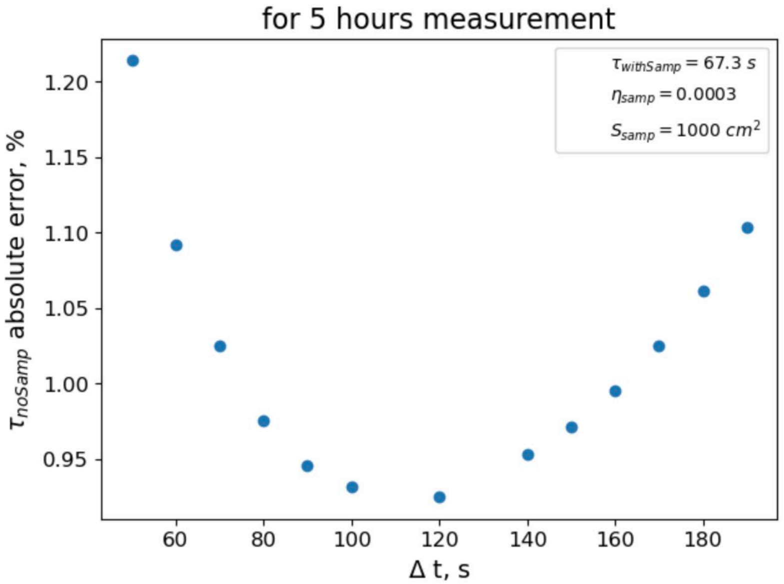


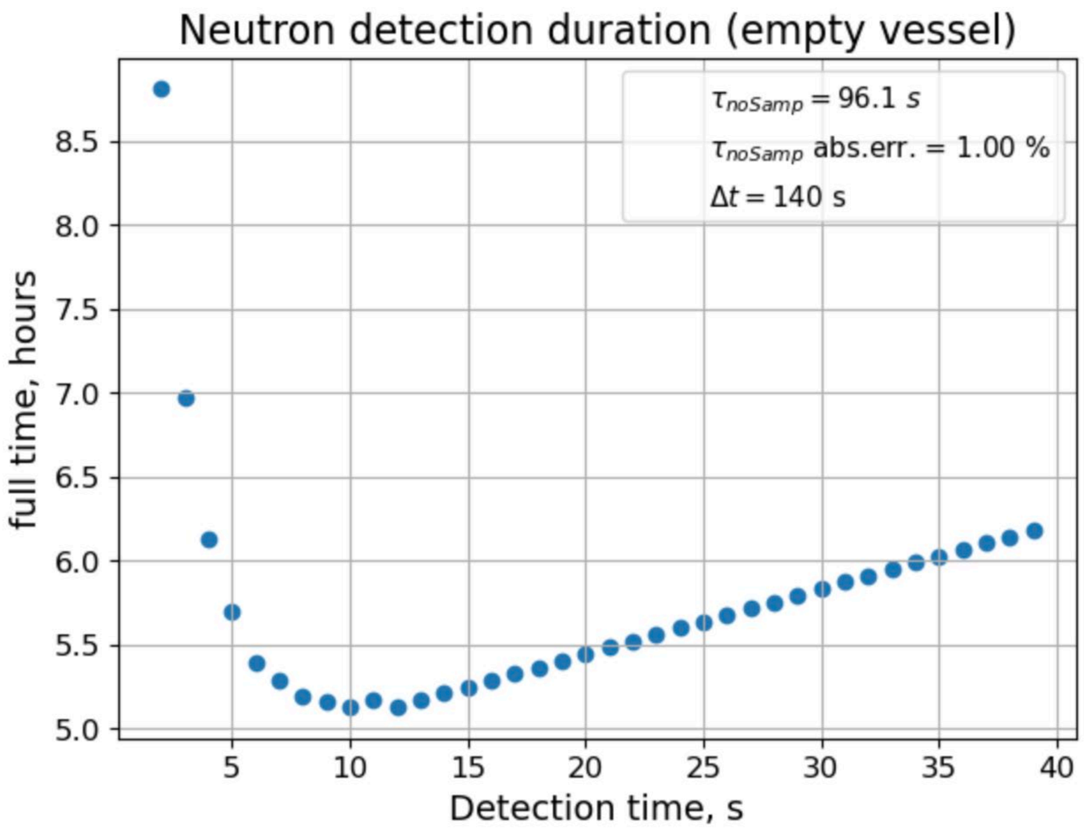


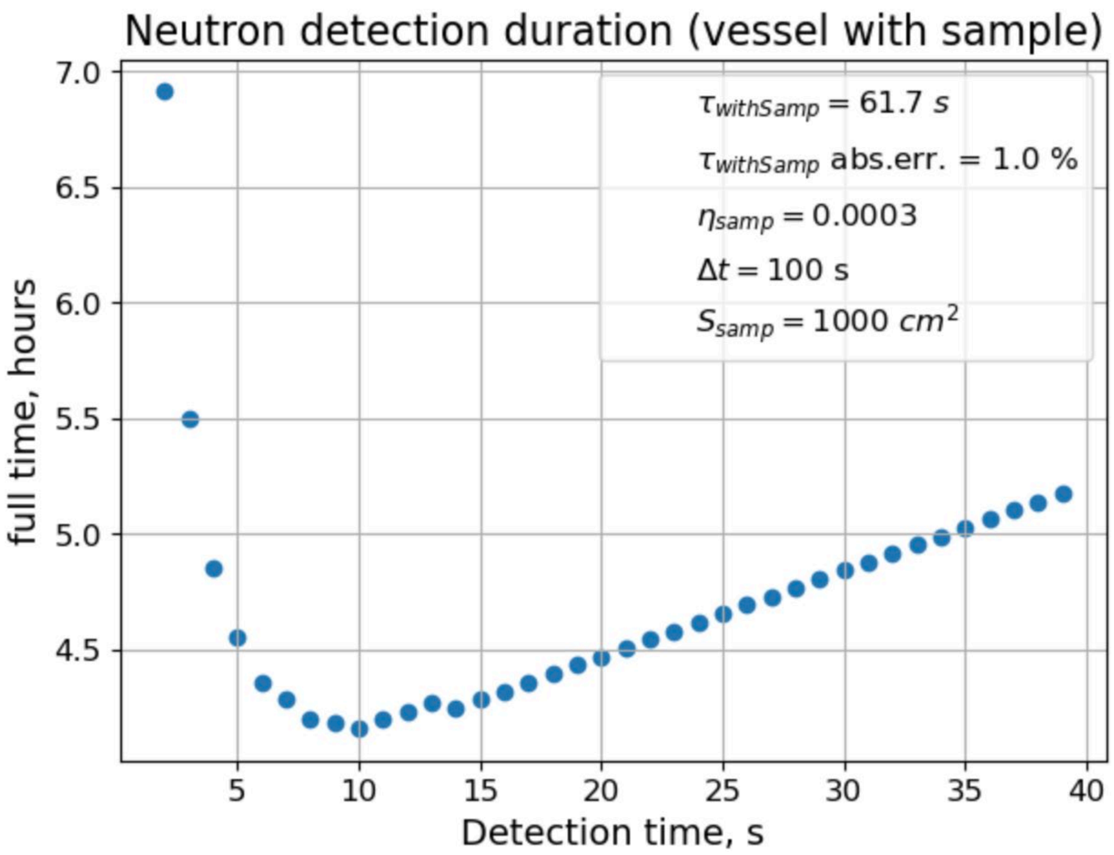
Empty ves.: 120 s < Δt < 170 s

Ves. With sample: 100 s < Δt < 130 s

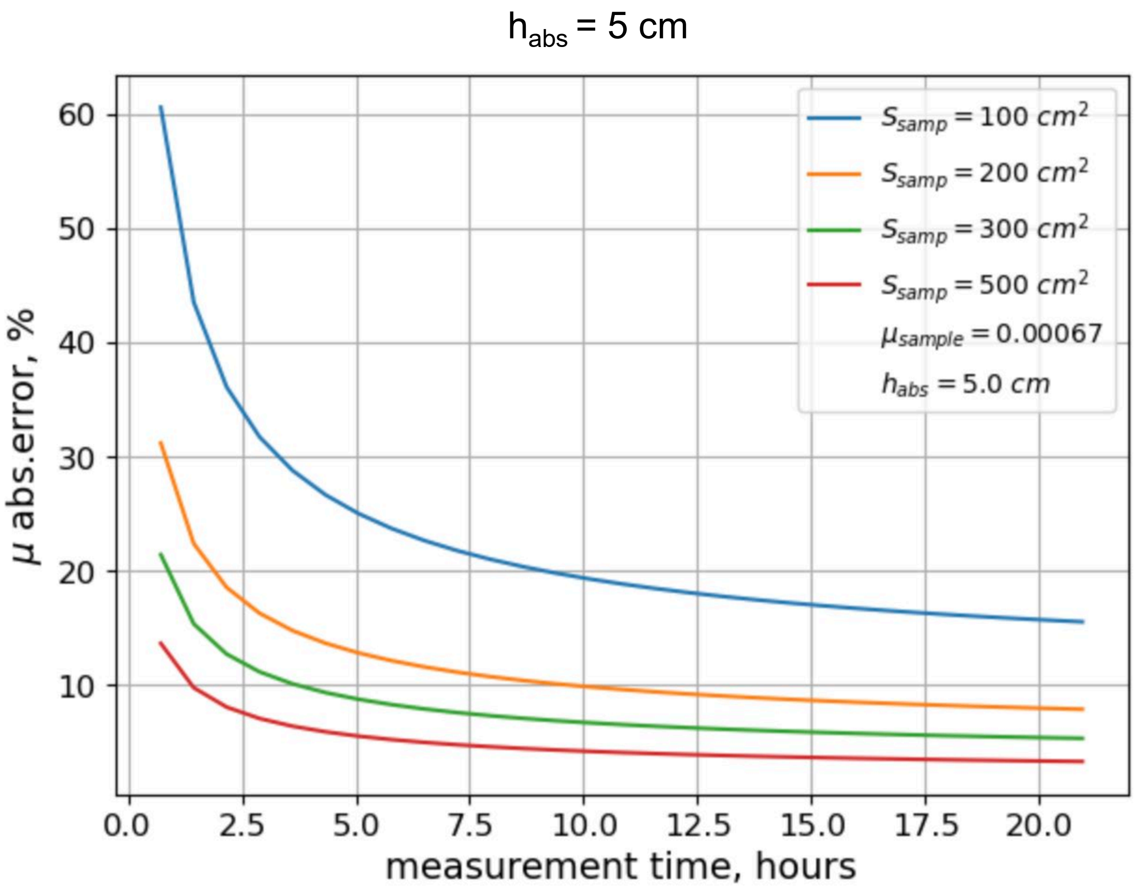


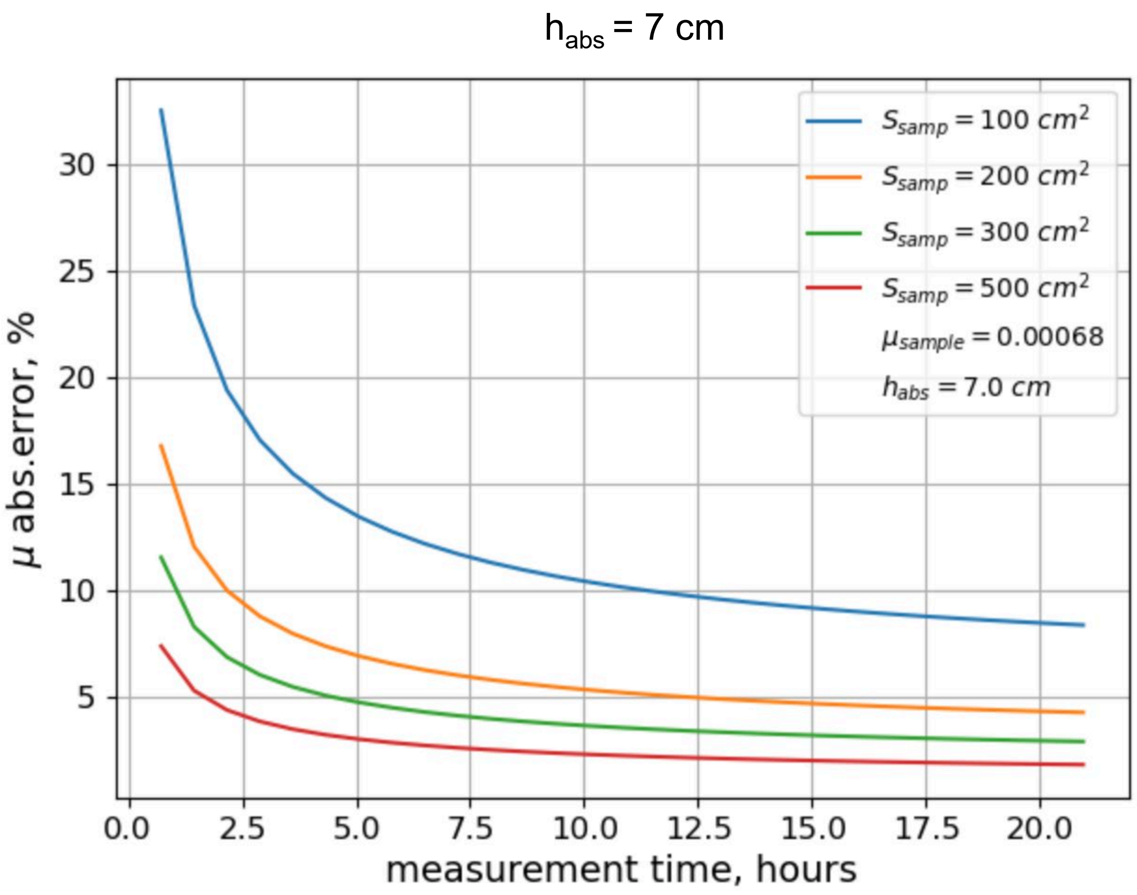



Neutron detection duration (empty vessel)
$\tau_{noSamp} = 96.1\ s$
τ_{noSamp} abs.err. = 1.00 %
$\Delta t = 140$ s
full time, hours
Detection time, s
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
5
10
15
20
25
30
35
40


Neutron detection duration (vessel with sample)
$\tau_{withSamp} = 61.7\ s$
$\tau_{withSamp}$ abs.err. = 1.0 %
$\eta_{samp} = 0.0003$
$\Delta t = 100$ s
$S_{samp} = 1000\ cm^2$
full time, hours
Detection time, s
7.0
6.5
6.0
5.5
5.0
4.5
5
10
15
20
25
30
35
40

Improving statistics by increasing the absorber's height.





NiP: U = ~ 215 neV

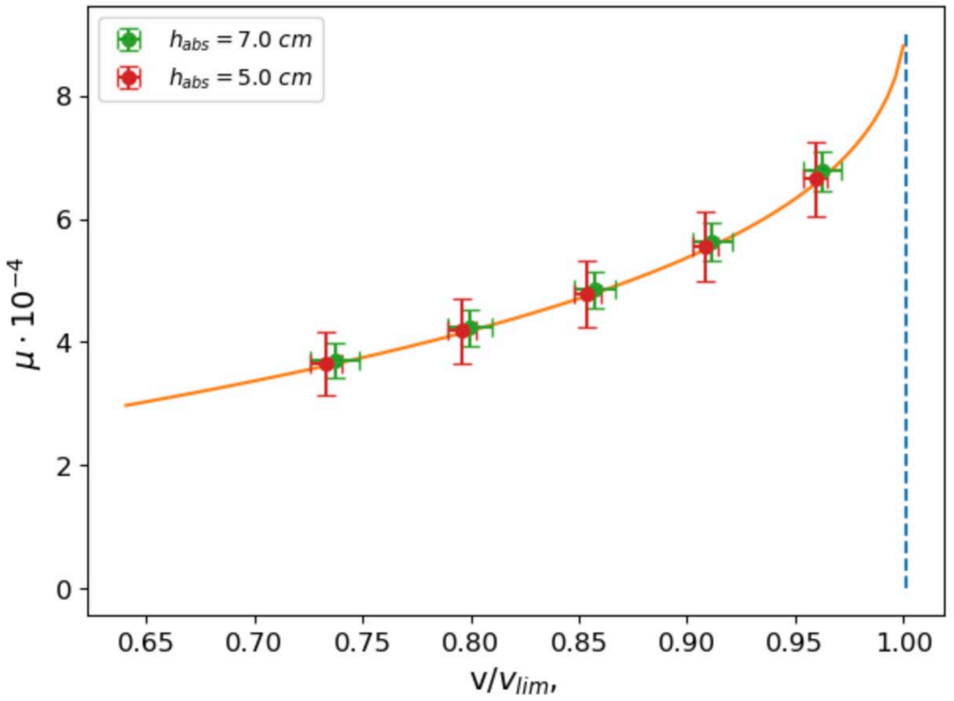
$\eta = 3\cdot10^{-4}$

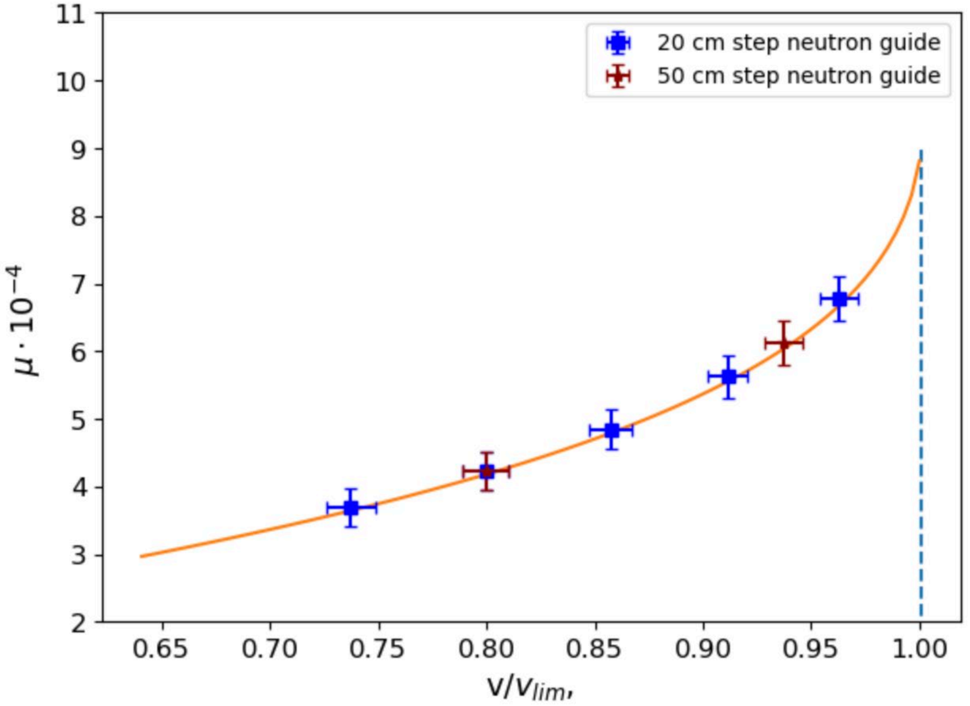
h_{12} = 1.6 m.

h_2 = 0.3 m.

Absorber height and neutron guide length

7 hours per velocity point.





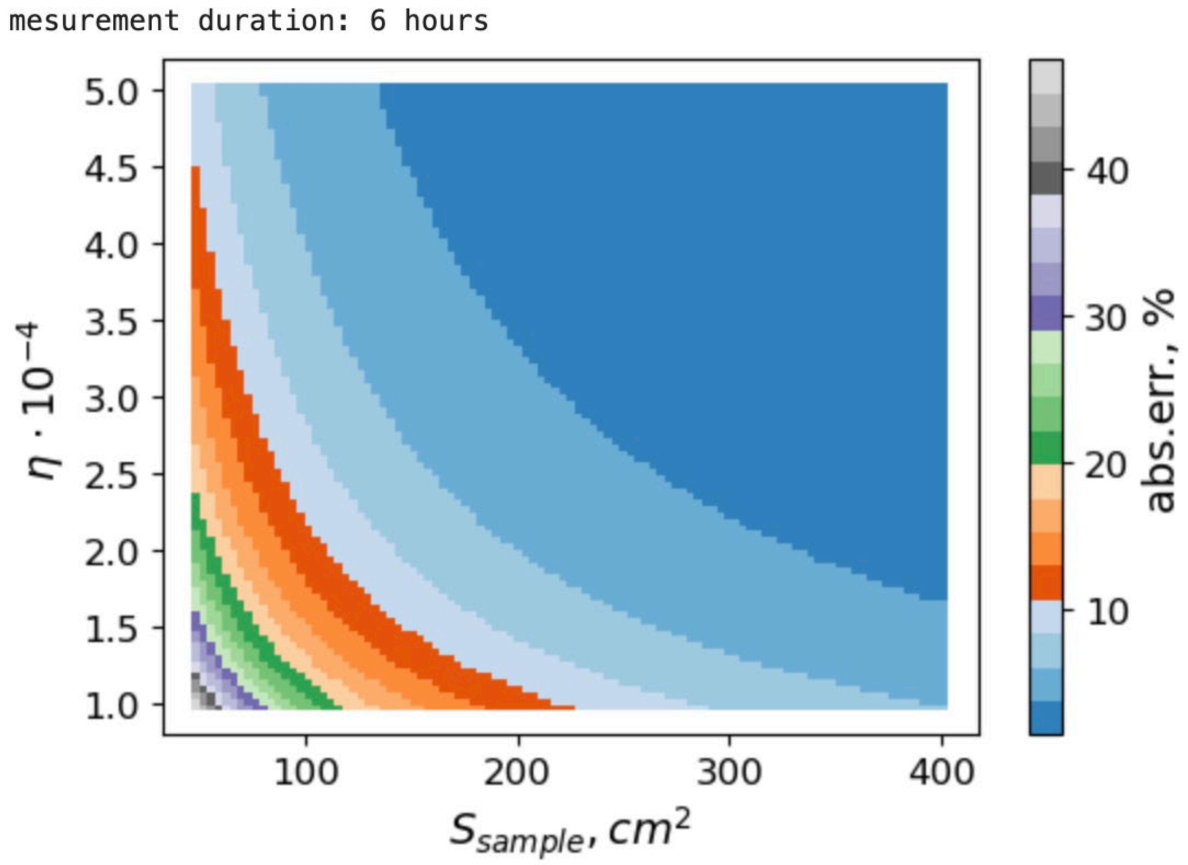
Ni-P:
Ssamp = 250 cm2

7 cm. abs. err. < 7.6 %
5 cm. abs. err. < 14.2 %

By choosing a height of 7 cm, we do not significantly degrade the quality of the obtained dependence. Distinguishing points during sharp changes in the dependence remains possible.

Adjusting the distance between the upper and lower volumes to control the UCN (ultracold neutron) velocity is easier when assembled from 20 cm elements. However, the connection points may potentially increase transmission losses. It should be noted that this only worsens the statistics and nothing more.

Loss probability abs. error distribution in (S,eta) parametric space



Coatings	U, nEV	v_{lim}, m/s	$\eta \cdot 10^{-4}$	Recomended sample area, cm^2
BeO	~261	7.1	~ 1.35	>200
Be	~252	6.9	~ 0.35	>800
Diamond	~305	7.6	~ 3.5	>100
Ni-P	~215	6.4	~ 3.0	>150
Wall Ni58	~335	8.0	~ 3.0	>150

SUMMARY

- The geometry and dimensions of the experimental setup for measuring the loss factor at different energies have been determined.
- Optimal timing parameters for the experiment have been identified.
- Dimensions for various studied materials in the planned experiment have been established.
- Possible ways to improve the statistical accuracy of the experiment have been explored.

Thank You for Your Attention!