Neutron lifetime measurements in material traps: history and prospects

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Wall meterial, reference	**n-lifetime**
Al (1980, Kosvintsev et al [1])	875±95
D_2O ice (1982, Kosvintsev et al [2])	950±60
D_2O ice (1986, Kosvintsev et al [3])	903±13
Be, 10 K (1989, Kharitonov et al [4])	870±8
Fomblin oil (1989, Mampe et al [5])	887.6±3
Be, O_2, 10 K (1992, Nesvizhevski et al [6])	888.4±3.3
Fomblin oil (1993, Mampe et al [7])	882.6±2.7
Fomblin grease (2000, Arzumanov et al [8])	885.4±1
Fomblin oil (2000, Pichlmaier et al [9])	881±3
PFPE, 120 K (2005, Serebrov et al [10])	878.5±0.8

[1] Yu. Yu. Kosvintsev et al, Pis'ma v ZhETF, 31 (1980) 257

[2] Yu. Yu. Kosvintsev et al, Pis'ma v ZhETF, 36 (1982) 346

[3] Yu. Yu. Kosvintsev et al, Pis'ma v ZhETF, 44 (1986) 444

[4] A. G. Kharitonov et al, Nucl. Instr. Meth., A284 (1989) 98

[5] W. Mampe et al, Phys. Rev. Lett., 63 (1989) 593; NIM A284 (1989) 111

[6] V. V. Nesvizhevsky et al, ZhETF, 102 (1992) 740; JETP, 75 (1992) 404

[7] W. Mampe et al, Pis'ma v ZhETF, 57 (1993) 77; JETP Lett, 57 (1993) 82

[8] S. S. Arzumanov et al, Phys. Lett., B 483 (2000) 15

[9] A. Pichlmaier et al, Nucl. Instr. Meth., A440 (2000) 517

[10] A. P. Serebrov et al, Phys. Lett., B 605 (2005) 72

UCN loss coefficient $\eta_{storage}$ from UCN storage experiments and $\eta_{theor,trans}$ from cold neutron transmission and dynamic model calculations.

Substance	$\eta_{storage}$	$\eta_{theor,trans}$
Be(6.5 K)	$3.\times10^{-5}$[1]	3×10^{-7} (Debye model calc.)
Be(300 K)	4×10^{-5}[2]	5×10^{-6} (cold neutron cross sections[9])
Be(10 K)	3.2×10^{-5}[2]	3×10^{-7} (Debye model calc.)
O_2 (10 K)	6×10^{-6}[2]	6×10^{-7} (magnon spectrum calc.[3, 4])
C (100 K)	5×10^{-5}[6]	2×10^{-6} (cold neutron cross sections[9])
D_2O(80 K)	9.4×10^{-6}[6]	$\leq 2\times10^{-6}$ (cold neutron cross sections[7, 8]
D_2O(90 K)	$\sim 6\times10^{-5}$[5]	$\leq 2\times10^{-6}$ (cold neutron cross sections[7, 8]
D_2O(7 K)	$\sim 6\times10^{-5}$[5]	$\leq 2\times10^{-6}$ (cold neutron cross sections[7, 8]

References

[1] P. Ageron. W. Mampe and K. I. Kilvington, Z. Phys., B59 (1985) 261.

[2] V. P. Alfimenkov, V. V. Nesvizhevski, A. P. Serebrov, A. V. Strelkov, R. R. Tal'daev, A. G. Kharitonov and V. N. Shvetsov , JETP Lett., 55 (1992) 84.

[3] P. W. Stephens ad C. F. Majkrzak, Phys. Rev. B 33 (1986) 1.

[4] Chen-Yu Liu, Proc. of the 3rd UCN Workshop, Pushkin, 2001; Dissertation, Princeton Univ., 2002.

[5] A. Serebrov, R. Tal'daev, V. Varlamov, A. Kharitonov, G. Shmelev, I. Krasnochtchekova, P. Geltenbort, K. Schrekenbach, J. M. Pendlebury, A. Pichlmaier, M. Daum, P. Hautle, T. Konter, ILL Reports 3-14-98 and 3-14-112, Grenoble, 2000.

[6] S. S. Arzumanov, L. N. Bondarenko, V. I. Morozov, Yu. N. Panin, P. Geltenbort, Yad. Fiz., 66 (2003) 1868.

[7] W. von Gissler, Z.Kristall. 118 (1963) 149.

[8] M. Utsuro and N. Morishima, J. Nucl. Sci. Engn. 18 (1981) 739.

[9] S. F. Mughabghab, M. Divadeenam, N. F. Nolte, Cross Sections Vol. 1, Part A, Academic Prees INC (1981); S. F. Mughabghab, Cross Section Vol. 1, Part B, Academic Press INC (1984).

"Fomblin Y"

CF_3-(O-CF-CF_2)$_n$-(O-CF_2)$_m$-O-CF_3
I
CF_3

n/m=20-40, ($\approx C_3OF_6$), molecular weight $\sim$3000

Perfluoropolyethers (or fluoropolyoximethilenes)

$CF_3O(CF_2O)_{m_1}(CF_2CF_2O)_n(CF_2O)_{m_2}\ CF_3$

with $m_1 + m_2$ $\approx$60.5, n$\approx$3.14 and molecular weight 4500.

These substances have much lower pour point ($\sim$ -90 ^{o}C) in comparison to Fomblin, that permitted to use in the UCN storage experiments much lower wall temperatures - down to -160 ^{o}

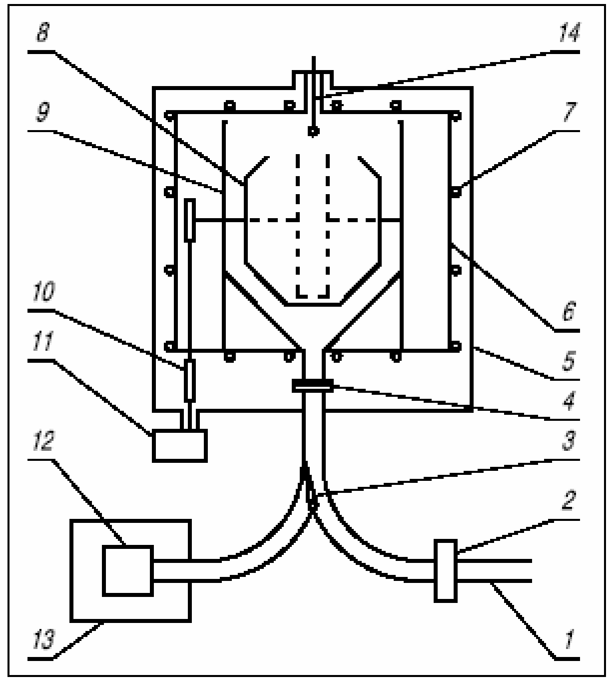


Figure 1. Schematic of the gravitational UCN storage system: 1, input neutron guide for UCNs; 2, inlet valve; 3, selector valve (shown in the position in which the trap is being filled with neutrons); 4, foil unit; 5, vacuum volume; 6, separate vacuum volume of the cryostat; 7, cooling system for the thermal shields; 8, UCN storage trap (the dashed lines depict a narrow cylindrical trap); 9, cryostat; 10, trap rotation drive; 11, step motor; 12, UCN detector; 13, detector shield, and 14, vaporizer.

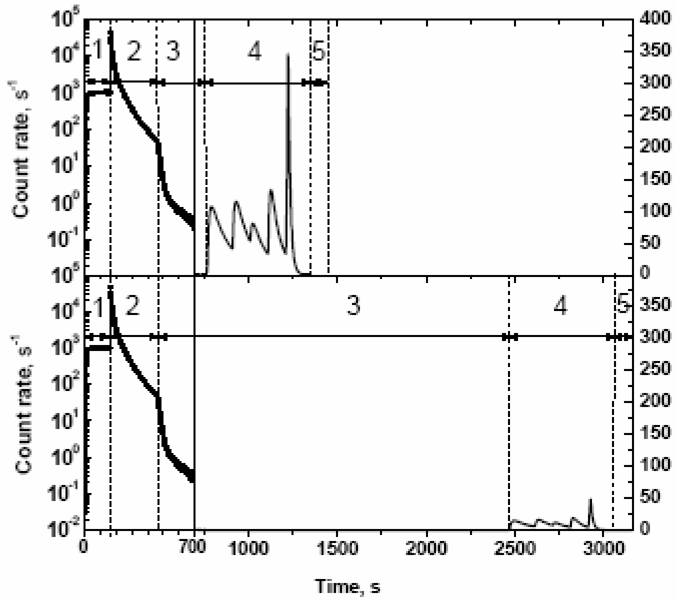
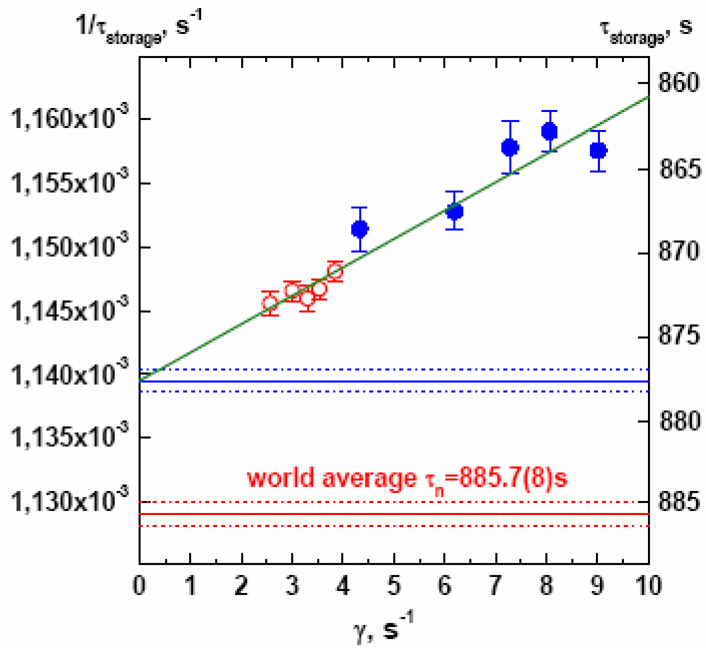
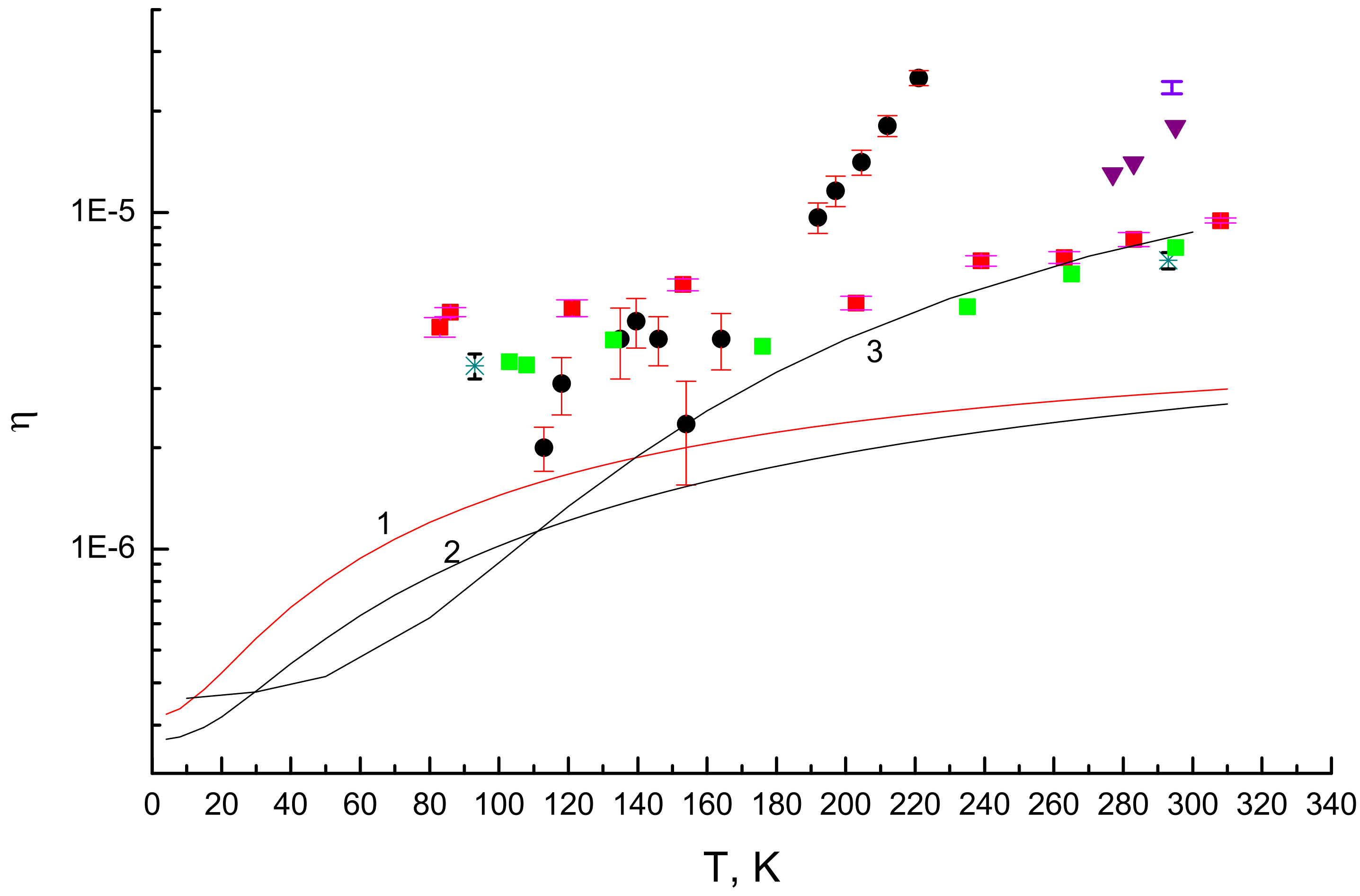


Figure 3. Time diagrams of the storage cycle for two different holding times in a quasispherical trap. 1: filling 160 s (time of trap rotation (35 s) to monitoring position is included); 2: monitoring 300 s; 3: holding 300 s or 2000 s (time of trap rotation (7 s) to holding position is included); 4: emptying has 5 periods 150 s, 100 s, 100 s, 100 s, 150 s (time of trap rotation (2.3 s, 2.3 s, 2.3 s, 3.5 s, 24.5 s) to each position is included); 5: measurement of background 100 s.



1/τstorage, s-1
τstorage, s
1,160x10-3
1,155x10-3
1,150x10-3
1,145x10-3
1,140x10-3
1,135x10-3
1,130x10-3
860
865
870
875
880
885
world average τn=885.7(8)s
0 1 2 3 4 5 6 7 8 9 10
γ, s-1



1E-5
1E-6
η
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
T, K
1
2
3

The experimental and calculated density of vibrational states of perfluoropolyethers at low temperatures and UCN loss coefficient

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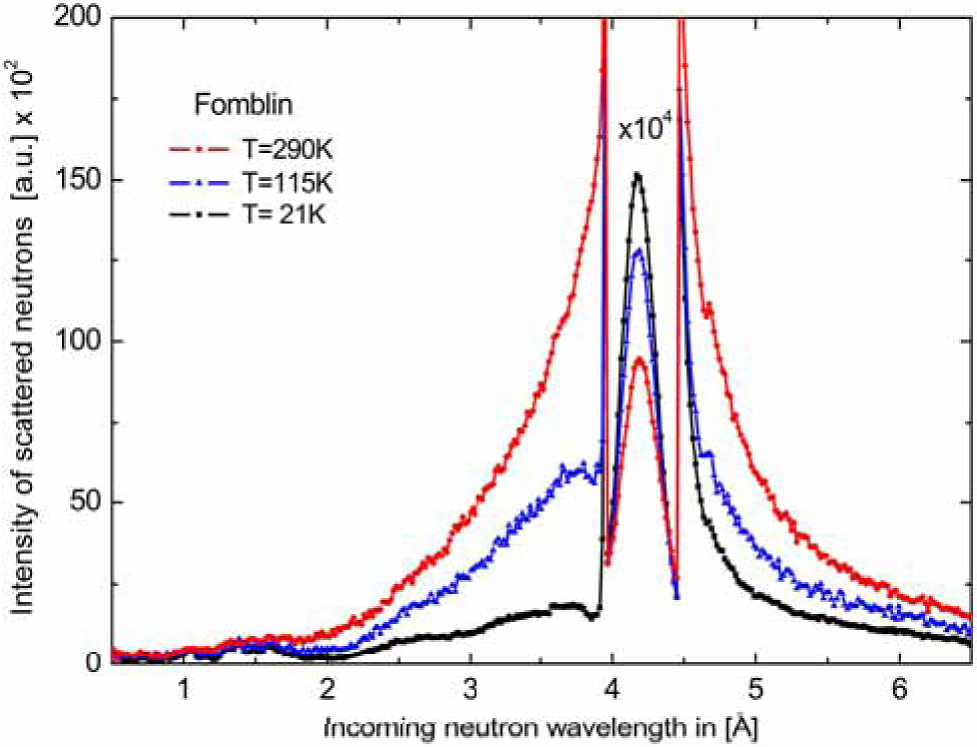
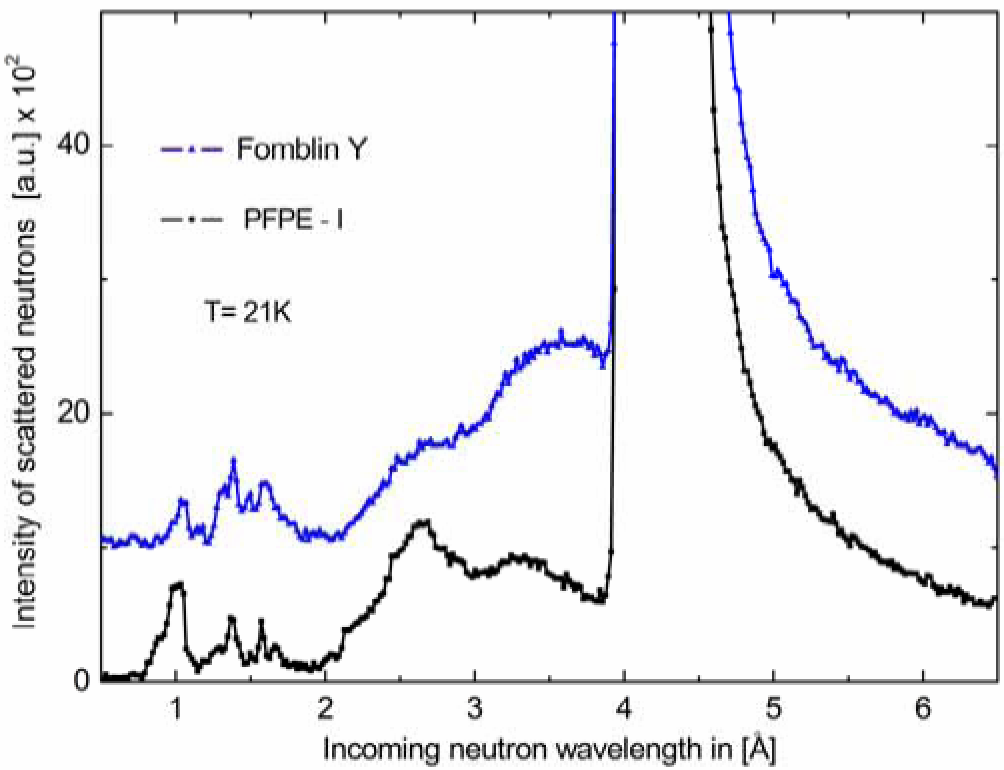


Fomblin
T=290K
T=115K
T= 21K
x10^4
Intensity of scattered neutrons [a.u.] x 10^2
Incoming neutron wavelength in [Å]
0
50
100
150
200
1
2
3
4
5
6



Intensity of scattered neutrons [a.u.] x 10^2
Incoming neutron wavelength in [Å]
Fomblin Y
PFPE - I
T= 21K
0
20
40
1
2
3
4
5
6

$$I(t,\theta,T)\Delta t = \Delta t\iiint \sigma(E_i,E_f,\theta,T)\otimes\Phi(E_i)\otimes R(E_i,E_f,t_0,t)dE_i dE_f dt_0 \qquad (3)$$

where: t - is time of neutron registration, θ - scattering angle, T – sample temperature, Δt is the time interval corresponding to the channel width of the TOF analyzer, E_i and E_f are incoming and scattered neutron energies, respectively. The apparatus resolution function in the case of the NERA spectrometer, can be written as

$$R(E_i,E_f,t_0,t) = \rho(E_i,t_0)n(E_f)\delta(t-t_0-t_1-t_2) \qquad (4)$$

where: $\rho(E_i,t_0)$ is the time distribution of incoming neutrons with the energy E_i leaving the source at time t_0, $n(E_f)$ is the energy distribution of scattered neutrons, $\delta(t-t_0-t_1-t_2)$ gives the condition for registration of neutrons at time t which left the source at time t_0 and scattered to energy E_f. The time $t_1 = \alpha L_1/\sqrt{E_i}$ is the time-of-flight of the neutron with energy E_i for the flight path L_1 = 109.05 m, and $t_2 = \alpha L_2/\sqrt{E_f}$ is the flight time of the scattered neutron with energy E_f from the sample to detector distance L_2 = 1.015 m, α is a conversion coefficient of neutron energy to velocity. The time distribution $\rho(E_i,t_0)$ of incoming neutrons leaving the IBR-2 moderator is well approximated by a Gaussian with the FWHM of (250 - 350) μsec for E_i in the range of (1000 - 5) meV. The energy distribution $\Phi(E_i)$ of incoming neutrons transported by the evacuated nickel-coated mirror guide is measured by elastic scattering of a vanadium sample. The energy distribution $n(E_f)$ of scattered neutrons measured after the beryllium filter and pyrolitic graphite monochromator is well approximated by a Gaussian centered on E_0 = 4.5 meV and the FWHM of 0.6 meV.

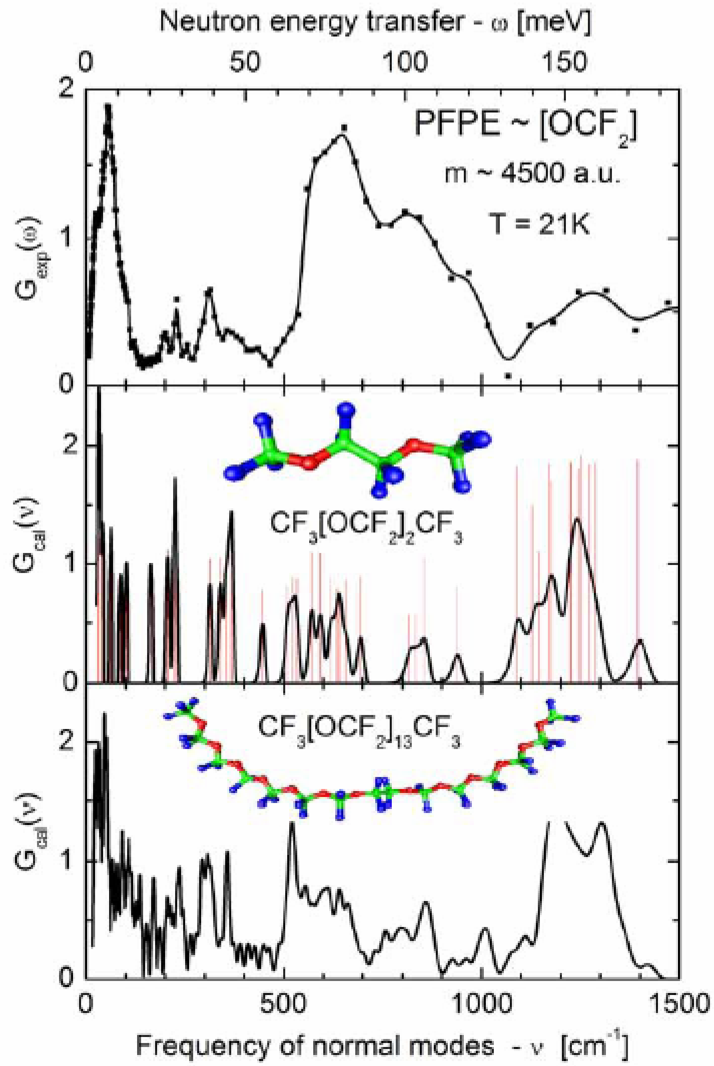
The scattering cross section for the phonon creation process at low temperatures can be written in the incoherent one-phonon scattering approximation as [12,13]:

$$\sigma_1^{inc}(E_i, E_f, \theta, T) \approx \sqrt{\frac{E_f}{E_i}} \frac{\hbar\left|Q(E_i, E_f, \theta)\right|^2}{\omega} \sum_n \frac{(b_n^{inc})^2}{M_n} \frac{\exp(-2W_n)}{1-\exp(-\hbar\omega/k_B T)} G(\omega) \qquad (5)$$

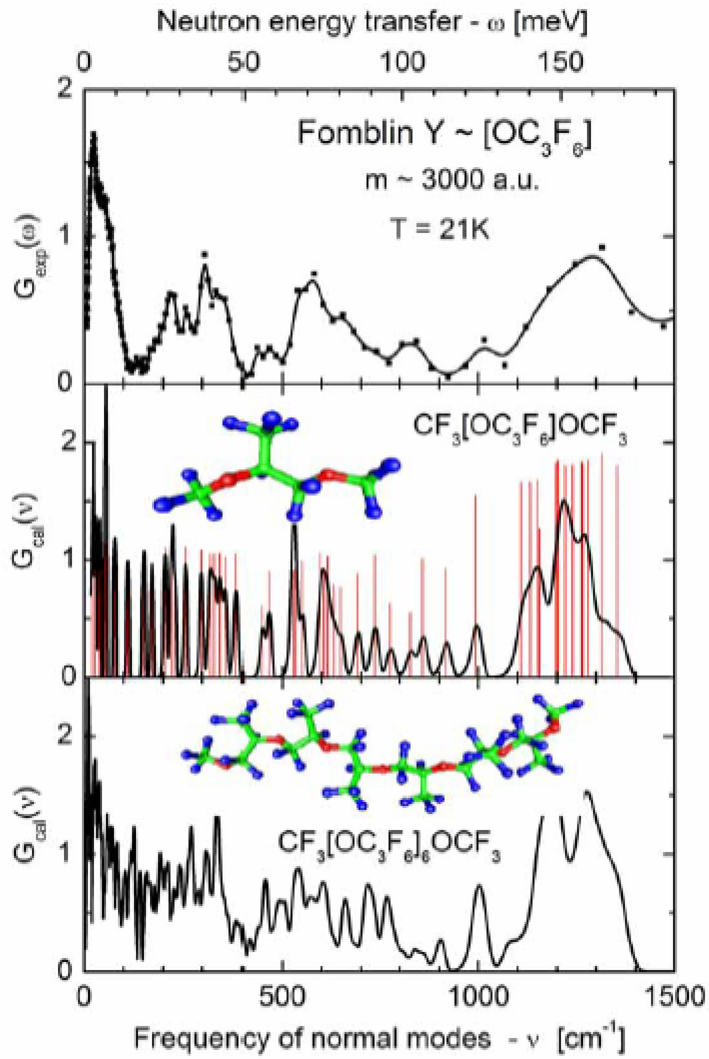
where: $Q(E_i, E_f, \theta)$ is the neutron momentum transfer, $\omega = (E_i - E_f)$ is the neutron energy transfer, b_n^{inc} is the value of the incoherent scattering length, M_n is the mass of *n-th* atom, $\exp(-2W_n)$ is the Debye-Waller factor. The $G(\omega)$ is the so-called generalized or amplitude weighed density of vibrational states:

$$G(\omega) = \sum_n \sum_j \int d^3q \left[A_j^n(q)\right]^2 \delta\left[\omega - \omega_j(q)\right] \qquad (6)$$

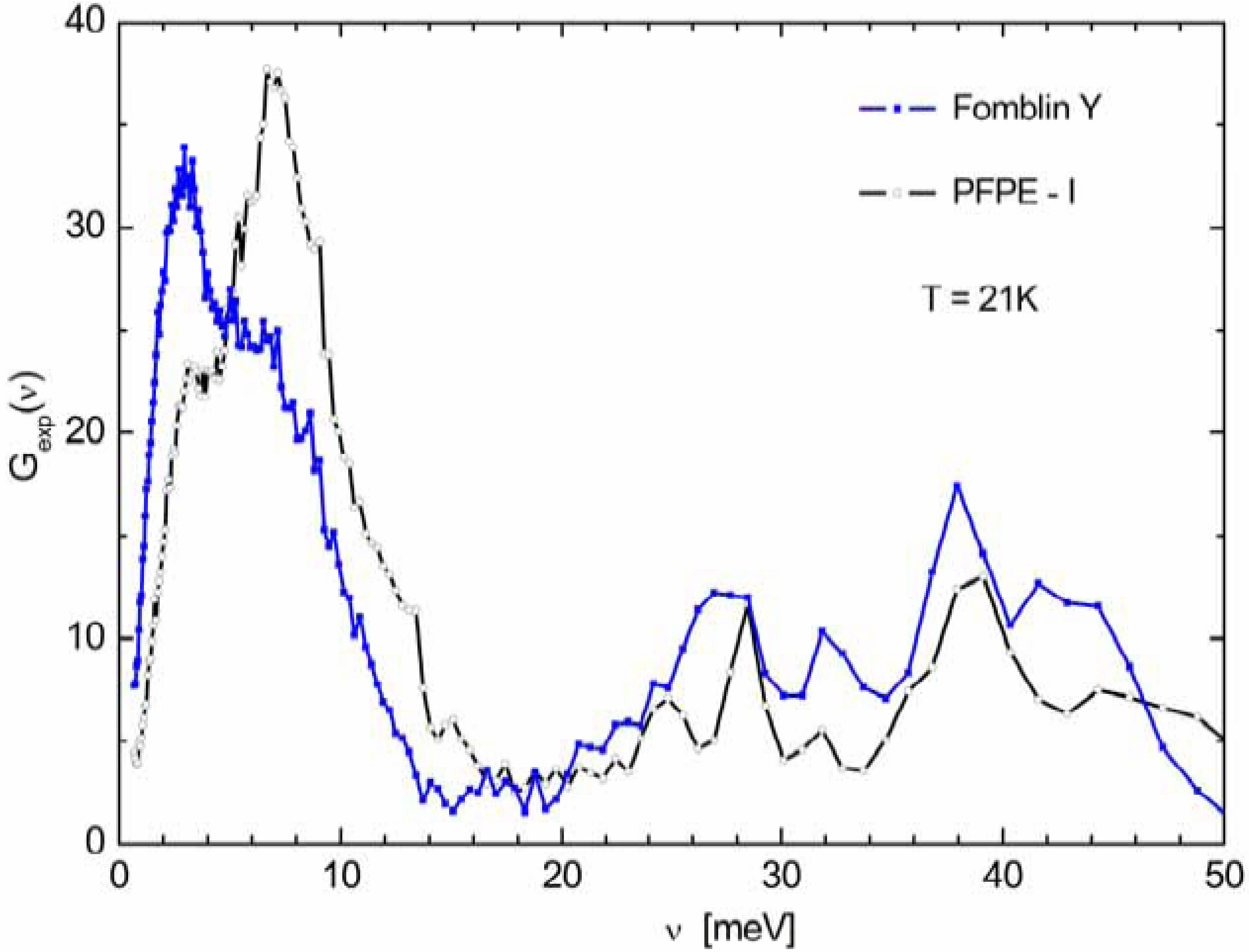
$A_j^n(q)$ is the amplitude of displacement of *n-th* atom in the unit cell for the vibrational mode $\omega_j(q)$, j is the numbering of the dispersion curves or internal normal modes, and q is a reciprocal lattice wave vector in the Brillouin zone.



Neutron energy transfer - ω [meV]
0
50
100
150
2
1
0
PFPE ~ [OCF2]
m ~ 4500 a.u.
T = 21K
G exp(ω)
2
1
0
CF3[OCF2]2CF3
G cal(ν)
2
1
0
CF3[OCF2]13CF3
G cal(ν)
0
500
1000
1500
Frequency of normal modes - ν [cm-1]



Neutron energy transfer - ω [meV]
0
50
100
150
2
1
0
Fomblin Y ~ [OC3F6]
m ~ 3000 a.u.
T = 21K
Gexp(ω)
CF3[OC3F6]OCF3
Gcal(ν)
CF3[OC3F6]6OCF3
Gcal(ν)
0
500
1000
1500
Frequency of normal modes - ν [cm-1]



Fomblin Y
PFPE - I
T = 21K
$G_{exp}(\nu)$
ν [meV]
0
10
20
30
40
50

The UCN upscattering cross sections were calculated in the one-phonon incoherent approximation:

$$\frac{d\sigma}{d\epsilon} = \sigma_0 \frac{k_1}{k_0}(1 - e^{-\epsilon/kT})^{-1} \frac{g(\epsilon)}{\mu} e^{-\gamma\epsilon},$$

where $\sigma_0 = 4\pi|b|^2$; b is the scattering amplitude for bound nucles, k_1 and k_0 are the final and incident neutron wave vectors, ω is the energy transfer, $g(\omega)$ – the phonon density of states, μ is the relative atomic mass, γ is the Debye-Waller factor:

$$\gamma = \frac{1}{\mu} \int_0^{\epsilon_D} \frac{g(t)}{t} coth(\frac{t}{2kT}) dt.$$

When $k_1 >> k_0$, the up-scattering cross section is:

$$\sigma_{ups} = 4\pi \int \sum \frac{b_i^2}{\mu_i} \frac{\epsilon^{1/2} e^{-\gamma\epsilon} g_i(\epsilon)}{(e^{\epsilon/kT} - 1)} d\epsilon$$

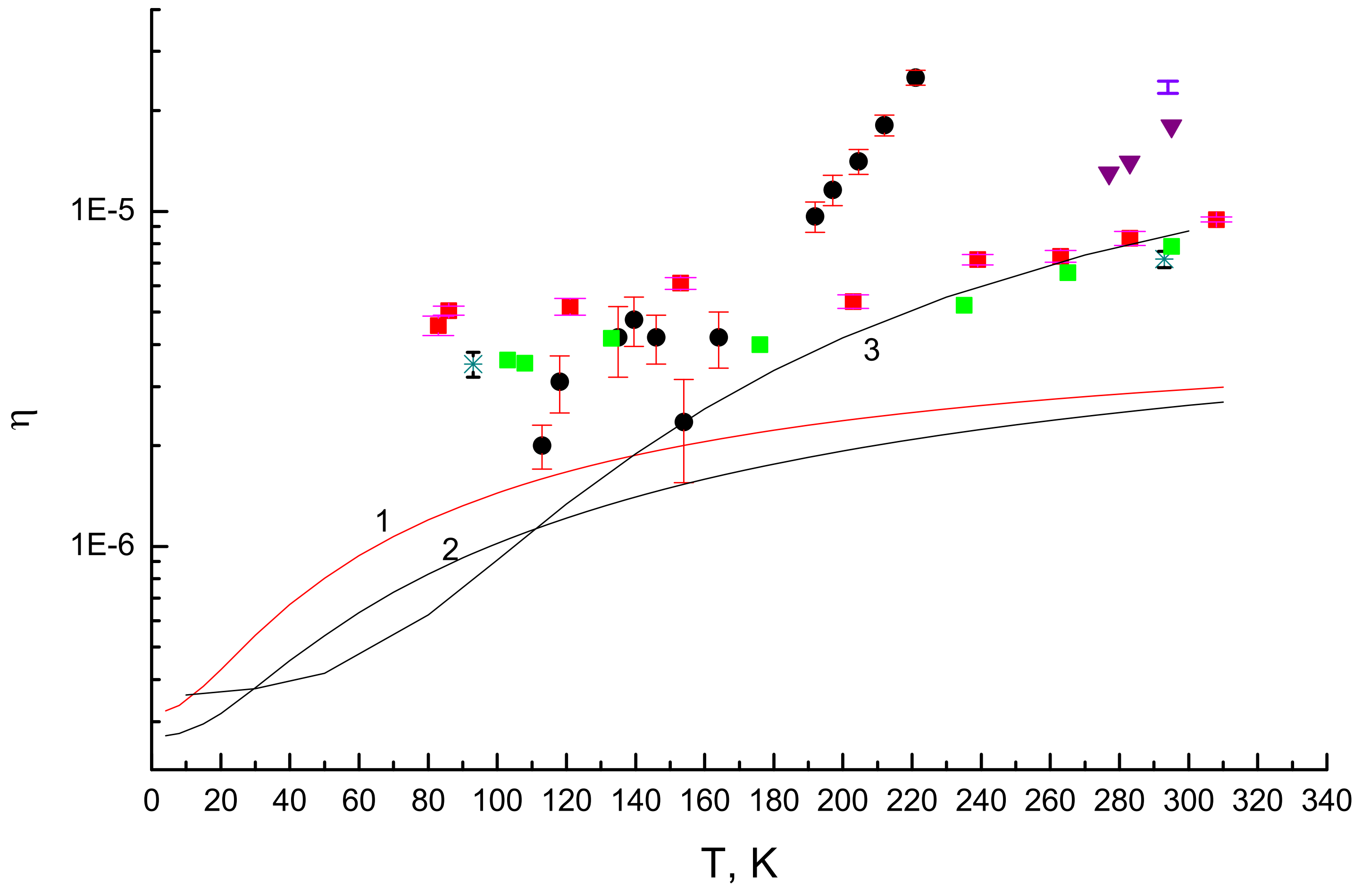
The loss probability (averaged over isotropic angular distribution) of neutrons with energy E in a trap with boundary energy U is:

$$\bar{\mu}(E) = 2\eta\Big[\frac{V}{E}\ \arcsin\Big(\sqrt{\frac{E}{V}}\Big) - \sqrt{\frac{V-E}{E}}\Big].$$

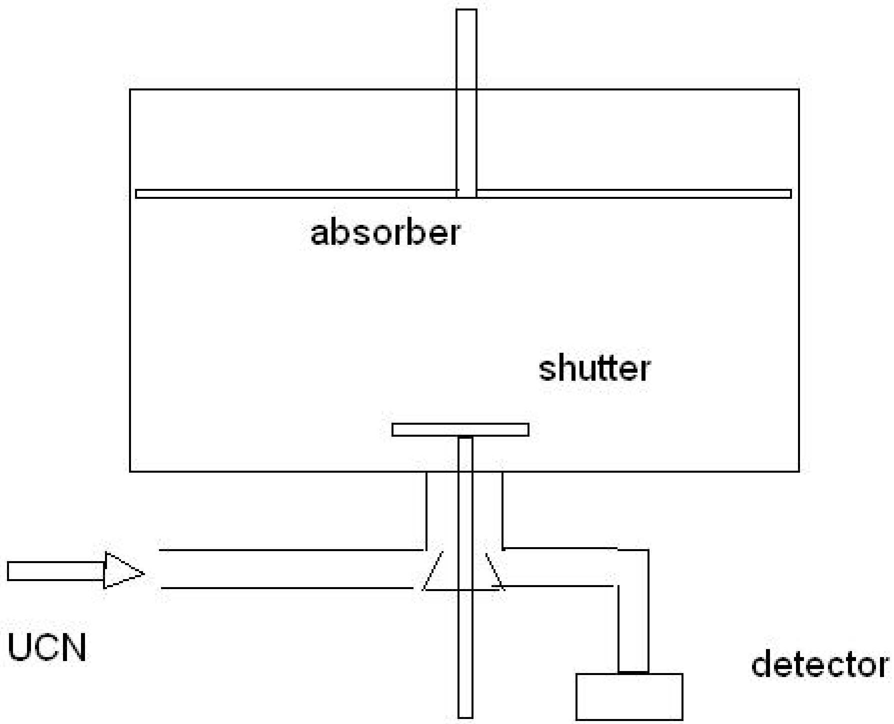
The loss coefficient is expressed through the complex potential U, describing UCN interaction with the walls

$$\eta = -\ \mathrm{Im}\ U /\ \mathrm{Re}\ U; \quad U = (\hbar^2/2m)4\pi \sum_i N_i b_i; \quad \mathrm{Im}\ b = -\sigma/2\lambda,$$

where m is the neutron mass, N_i is the number of nuclei in a unit volume of a wall material, b_i is the coherent scattering length on a bound nucleus of the wall, and σ is the cross-section of inelastic processes for neutrons with wavelength λ.



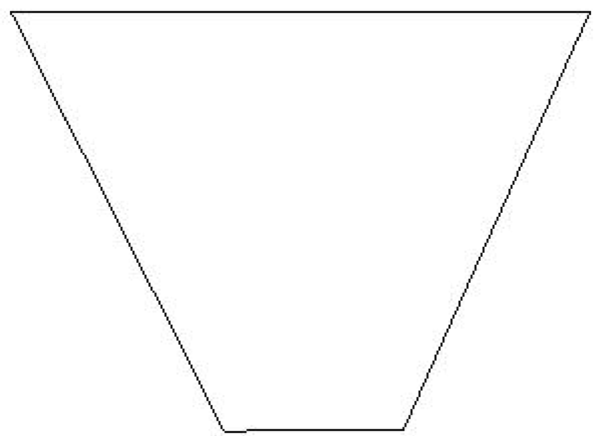
η
1E-5
1E-6
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
T, K
1
2
3

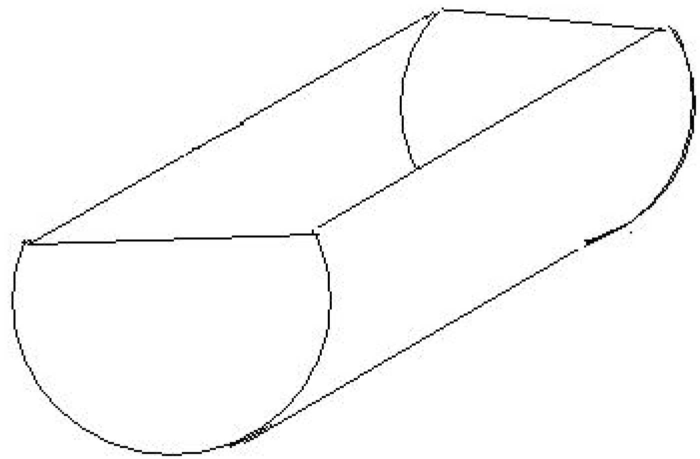

absorber
shutter
UCN
detector

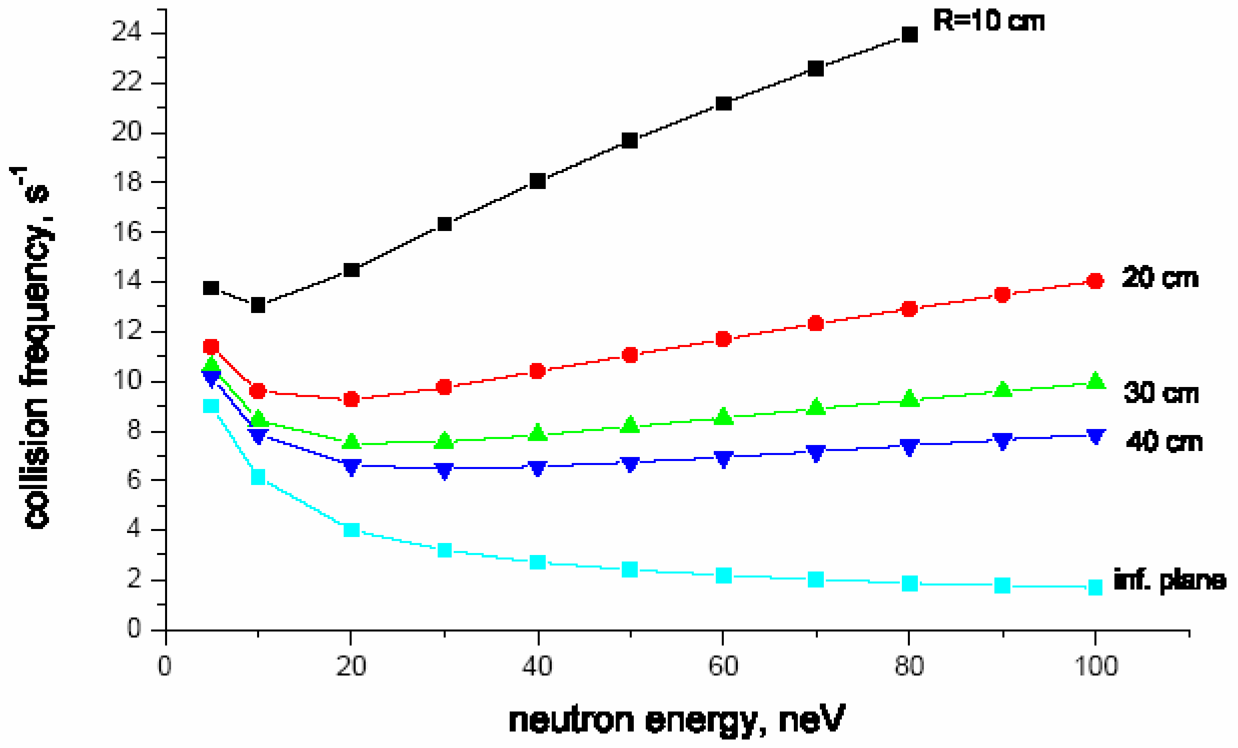
glycerid of melisinic acid

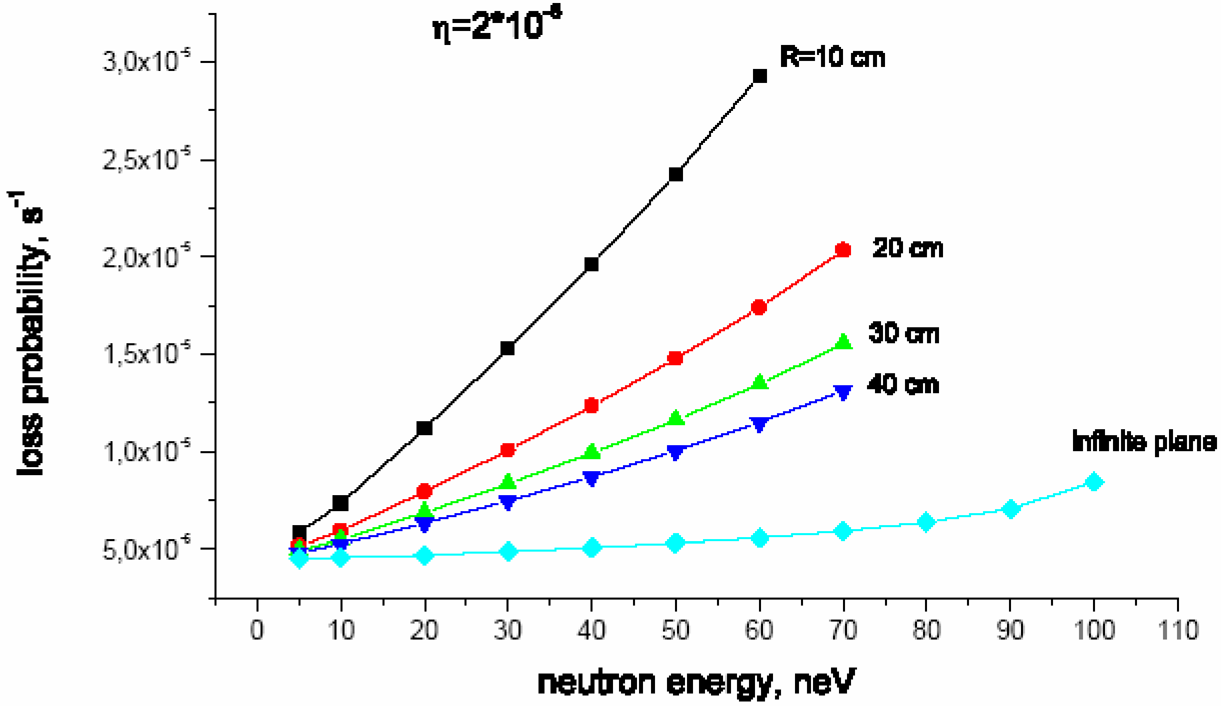
$C_{96}H_{188}O_6$

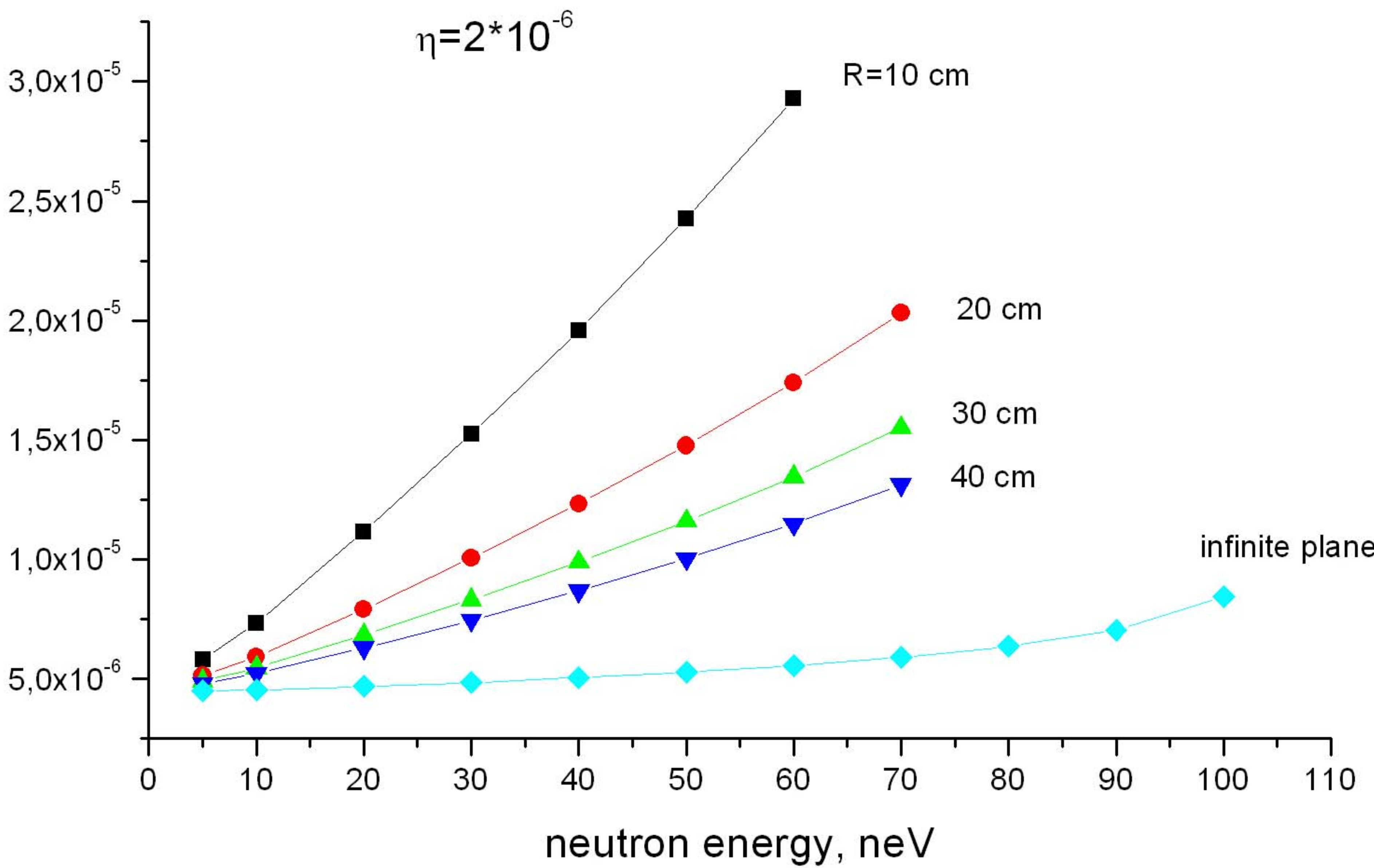
U=-3.3 neV
to compare with $U(CH_2)$=-9.3 neV

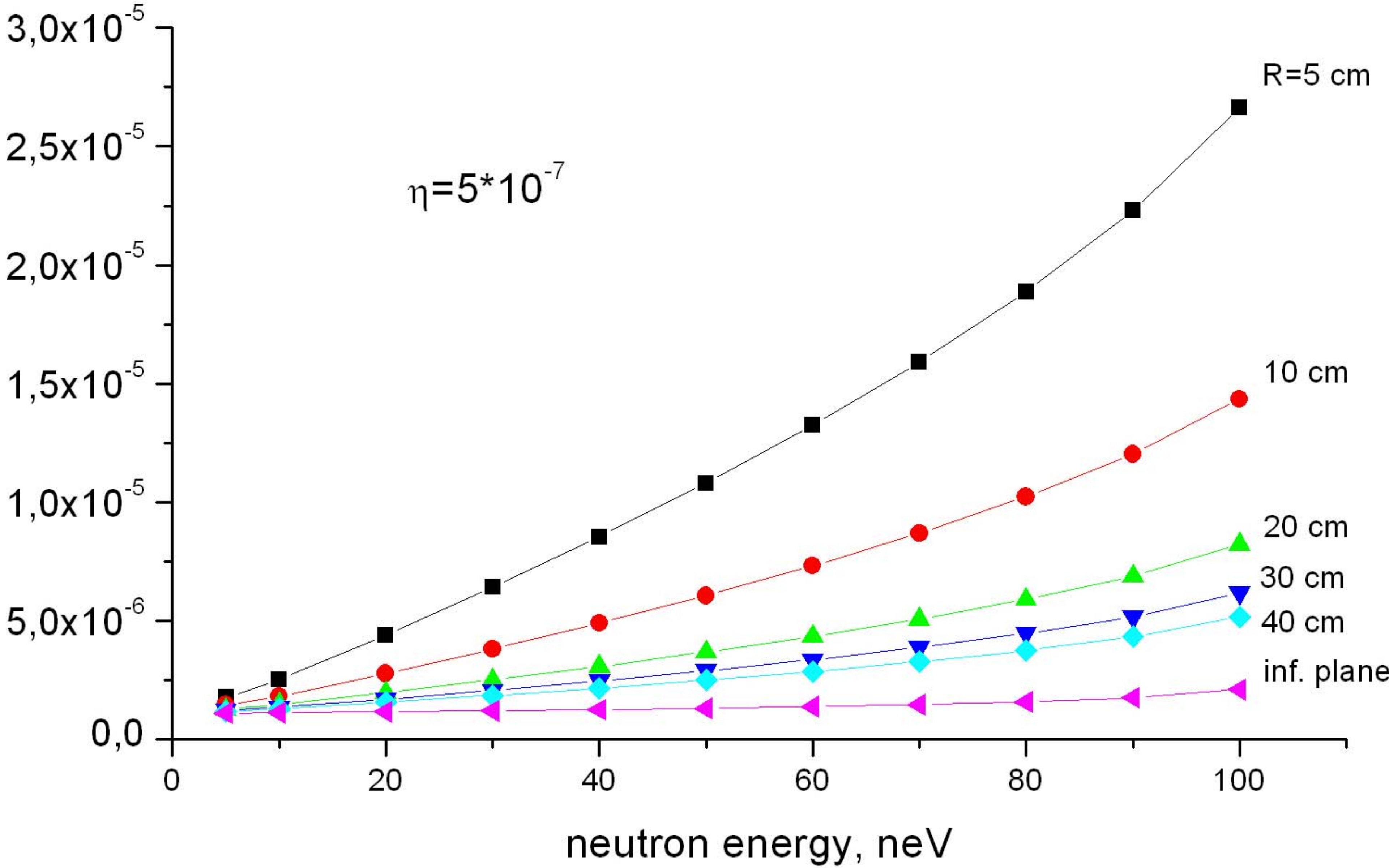


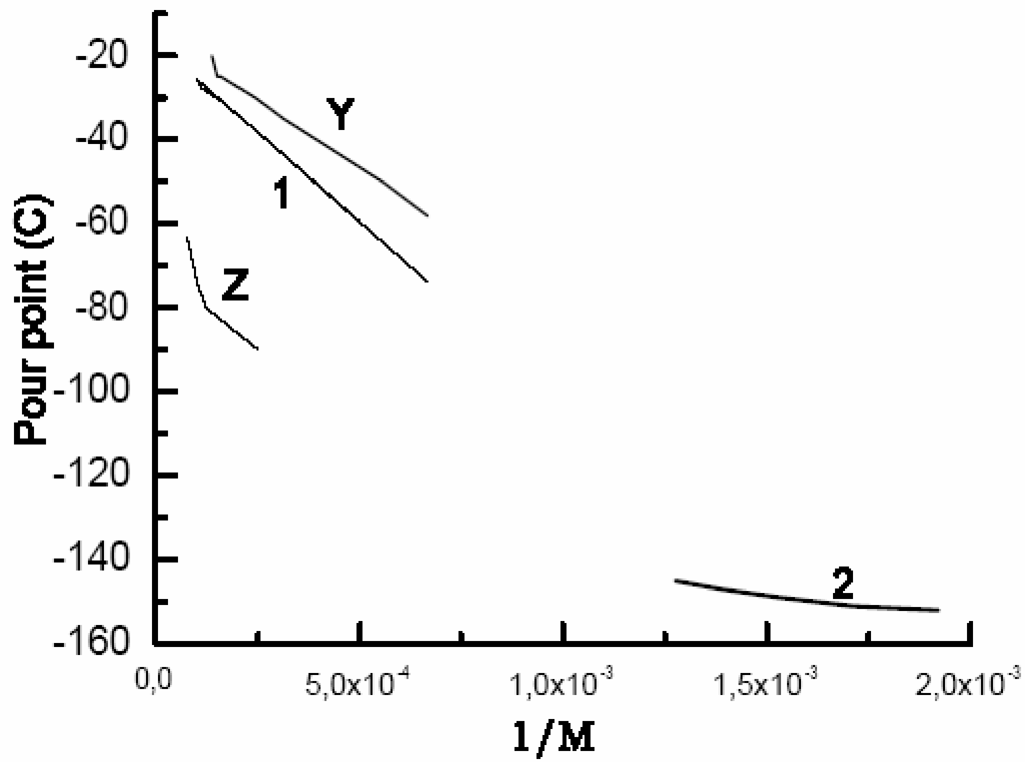



R=10 cm
20 cm
30 cm
40 cm
inf. plane
collision frequency, s^{-1}
neutron energy, neV
0
2
4
6
8
10
12
14
16
18
20
22
24
0
20
40
60
80
100


η=2*10^-6
R=10 cm
20 cm
30 cm
40 cm
infinite plane
loss probability, s^-1
3,0x10^-5
2,5x10^-5
2,0x10^-5
1,5x10^-5
1,0x10^-5
5,0x10^-6
0 10 20 30 40 50 60 70 80 90 100 110
neutron energy, neV


η=2*10^-6
R=10 cm
20 cm
30 cm
40 cm
infinite plane
3,0x10^-5
2,5x10^-5
2,0x10^-5
1,5x10^-5
1,0x10^-5
5,0x10^-6
0
10
20
30
40
50
60
70
80
90
100
110
neutron energy, neV


3,0x10^-5
2,5x10^-5
2,0x10^-5
1,5x10^-5
1,0x10^-5
5,0x10^-6
0,0
0
20
40
60
80
100
neutron energy, neV
η=5*10^-7
R=5 cm
10 cm
20 cm
30 cm
40 cm
inf. plane



Pour point (C)
-20
-40
-60
-80
-100
-120
-140
-160
Y
1
Z
2
0,0
5,0x10-4
1,0x10-3
1,5x10-3
2,0x10-3
1/M