Efficient Neutron Sources

2-5 September 2019

Cold Neutron Moderators and Reflectors
Some Recent Problems and Results

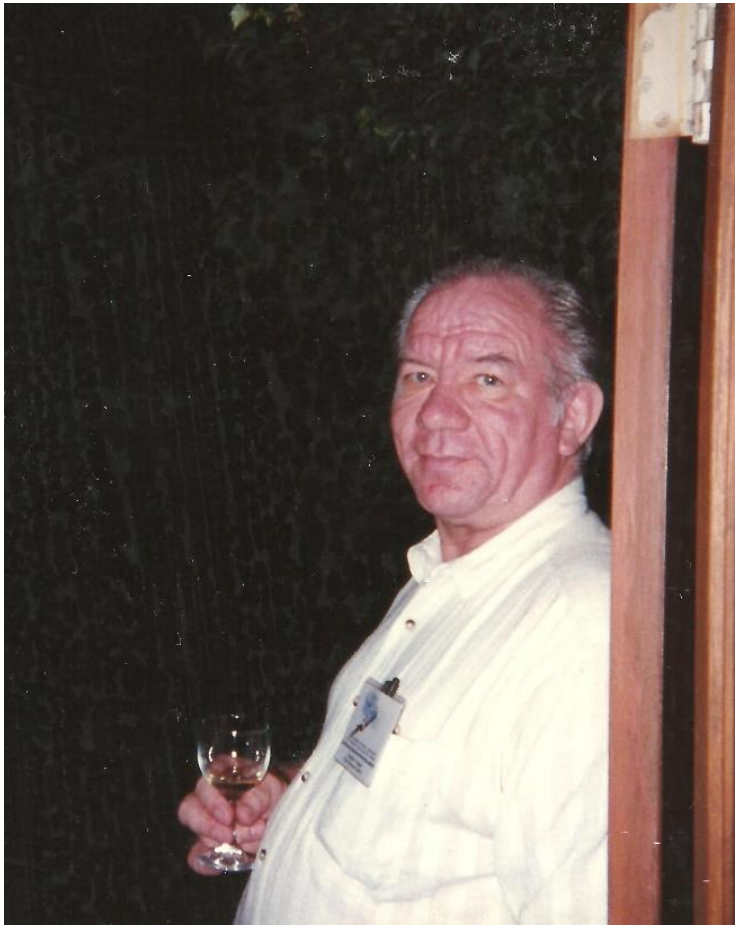
Rolando Granada

Neutron Physics Department and Instituto Balseiro,
Centro Atomico Bariloche, CNEA, Argentina

Dedicated to an unforgettable person and great scientist

GÜNTER BAUER

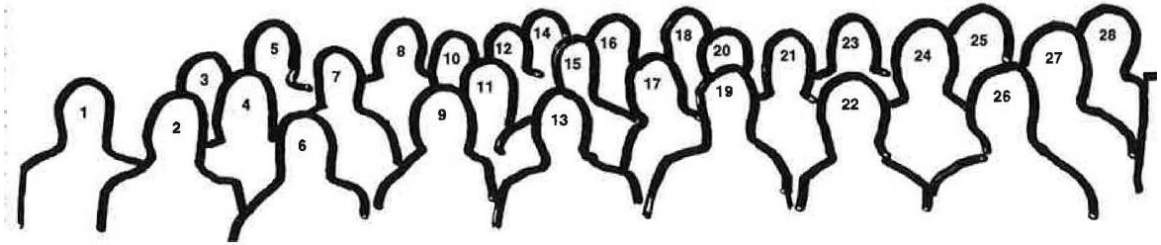
(1941 – 2013)



E. Shabalin's archive

ARGONNE 1997….

INTERNATIONAL WORKSHOP ON COLD MODERATORS FOR PULSED NEUTRONS SOURCES



1. Stendal, Karsten
2. Granada, J. Rolando
3. Ferguson, Phillip
4. Scott, Terry L.
5. Iverson, Erik B.
6. Watanabe, Noboru
7. MacFarlane, Robert E.
8. Lucas, Trevor
9. Dorning, John J.
10. Ludewig, Hans
11. Crawford, R. Kent
12. Russell, Gary J.
13. Shabalin, Eugene P.
14. Williams, Robert E.
15. Zemlyanov, Mikhail
16. Cser, Laszlo
17. Bauer, Gunter S.
18. Brun, Torben 0.
19. Jones, Henry J.
20. Broome, Timothy A.
21. Charlton, Lowell A.
22. Furusaka, Michihiro
23. Carpenter, John M.
24. Lanza, Richard C.
25. Picton, David
26. Kiyanagi, Y oshiaki
27. Gabriel, Tony A.
28. Spitzer, Harald

(Carpenter, private communication)

ACoM

An international collaboration on
Advanced **Co**ld **M**oderators

... an effort to develop more efficient cryogenic moderators for pulsed spallation sources.

Motivation

Both the **ESS** and the **SNS** (USA) study established the overwhelming **need for cryogenic moderators**, i.e. for the ESS, 36 of 45 proposed instruments and for the SNS, 33 of 37 proposed instruments **requested cold moderators**.
Calculations and experience have shown that the **best cryogenic moderator** material is **methane**.
Methane has so far been successfully operated in very low power (several kW) spallation sources only.
Unfortunately, in medium and high power sources **methane suffers from severe radiolysis problems** in both the solid (T < 90 K) and the liquid phase (90 K < T < 109 K) and from **heat removal problems** in the solid phase.

Investigating and developing **alternative routes for employing methane** and **searching for** similarily adequate **alternative moderator materials** are the **main goals of** the **ACoM** collaboration.

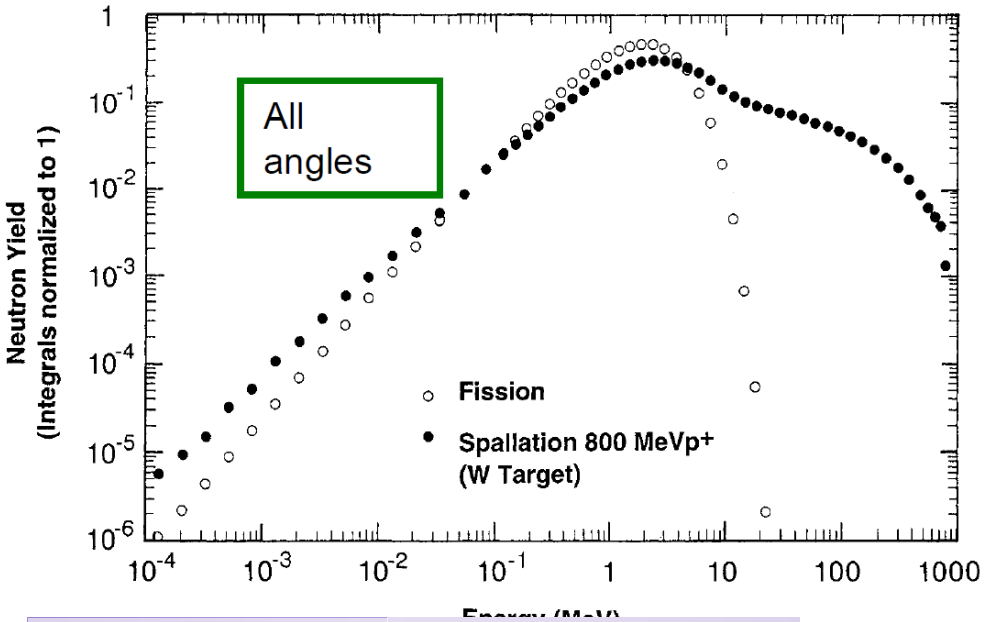
Participation

To date quite a number of labs from countries all over the world have informally expressed their intent to participate, such as from

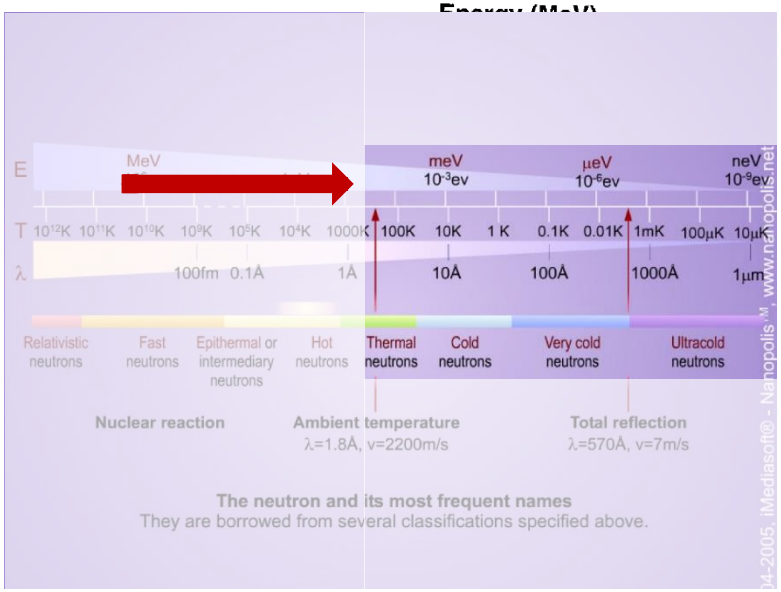
Argentina	Centro Atomico Bariloche	**Russia**	Joint Institute for Nuclear Research, Dubna
Denmark	Risø National Laboratory	**Switzerland**	Paul-Scherrer-Institut
Germany	Forschungszentrum Jülich GmbH	**United Kingdom**	Rutherford Appleton Laboratory
Japan	University of Hokkaido	**USA**	Argonne National Laboratory
	Japan Atomic Energy Research Institute (JAERI)		Brookhaven National Laboratory
	High energy accelerator research organisation (KEK)		Oak Ridge National Laboratory

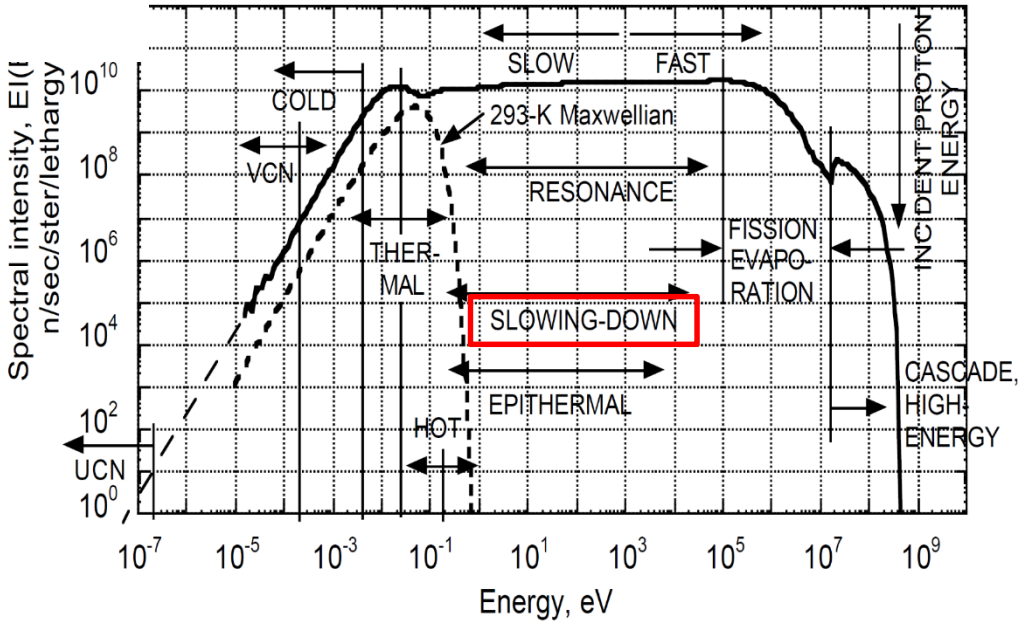
For more information about joining the collaboration, please contact **Dr. Günter S. Bauer**, Paul-Scherrer-Institut, Switzerland: guenter.bauer@psi.ch

NEUTRON
MODERATION AND THERMALIZATION



Calculated neutron spectra for fission and spallation.
(G.J. Russell, *ICANS-XI*, Tsukuba 1990)





Spectrum of neutrons from the 100 K liquid methane moderator of IPNS.
(Carpenter & Loong, *Elements of Neutron Scattering,* Cambridge 2015)

✓ **Moderation** occurs by collision processes within the material present in the system.

Energy range: Much larger than those associated to chemical binding and thermal motion of the atoms of the scatterer

$\alpha = [(A-1)/(A+1)]^2$

The average logarithmic energy decrement per collision ξ :

$\xi = [E(1-\alpha)]^{-1} \int_{\alpha E}^{E} \ln (E/E') \, dE' \longrightarrow \xi = 1 + \alpha \ln\alpha / (1-\alpha)$

The mean-squared logarithmic energy change per collision is $2\xi\gamma$

$\gamma = 1 - \alpha \ln^2 \alpha / [2\xi (1-\alpha)]$

The **slowing-down power** is $\xi\Sigma_{free}$; For H: $\xi = 1$, $\gamma = 1$

Slowing-Down Properties of some Moderators

Parameter	H_2O 293 K	H_2O 323 K	$(CH_2)_n$ 293 K	C_2H_6 180 K	C_2H_6 100 K	CH_4 100 K	CH_4 20 K	CH_4 4 K	C_9H_{12} 20 K	H_2 16K
σ_{free} (barn)	44.749	44.749	45.73	132.46	132.46	86.73	86.73	86.73	288.69	20.505
ρ (g/cm^3)	1	0.988	0.94	0.550	0.641	0.4392	0.510	0.510	0.91	0.0751
N^{molec} ($10^{24}/cm^3$)	0.0335	0.03305	0.0404	0.0110	0.0129	0.0165	0.0192	0.0192	0.0046	0.0226
N^H ($10^{22}/cm^3$)	6.69	6.611	8.09	6.63	7.72	6.61	7.68	7.68	5.48	4.52
Σ_{free} (cm^{-1})	1.5	1.48	1.849	1.463	1.705	1.431	1.665	1.665	1.318	0.927
ξ	0.926	0.926	0.913	0.940	0.940	0.954	0.954	0.954	0.876	1
γ	0.924	0.924	0.908	0.936	0.936	0.951	0.951	0.951	0.976	1
$\xi \Sigma_{free}$ (cm^{-1})	1.389	1.367	1.688	1.375	1.603	1.365	1.588	1.588	1.155	0.927

NEUTRON MODERATION

PULSED SOURCES

In the important cases where pulsed sources are employed, it is necessary to consider the time-dependent slowing-down processes that govern the evolution of the neutron field within a given medium.

The space-time-energy distribution of neutrons in such cases represents the complete information that we would like to know. This in turn allows the description of the behavior of the neutron fields in terms of slowing-down, diffusion, and time dependent characteristic parameters for the moderating media.

In the case of Hydrogen in an infinite medium, ignoring absorption, the time-dependent flux after the injection of a fast neutron pulse is:

$$\Phi(E, t) = S/2 \,.\, (\Sigma_s\, vt)^2 \,.\, \exp(-\Sigma_s\, vt) \,.\, 1/E)$$

for energies below those corresponding to the source distribution.

J.M. Carpenter & W.B. Yelon, in *Methods of Experimental Physics,* Vol.23 A, Ch.2 Neutron Sources, Academic Press (1986)

Slowing-Down Time Distribution

$$I(E,t) = (K/E)\,\frac{\xi\Sigma_s v}{2\Gamma(\frac{2}{\gamma})}\left(\frac{\xi\Sigma_s vt}{\gamma}\right)^{\frac{2}{\gamma}} \exp\left(-\frac{\xi\Sigma_s vt}{\gamma}\right)$$

$$t_{max} = \frac{2}{\xi\Sigma_s v}$$

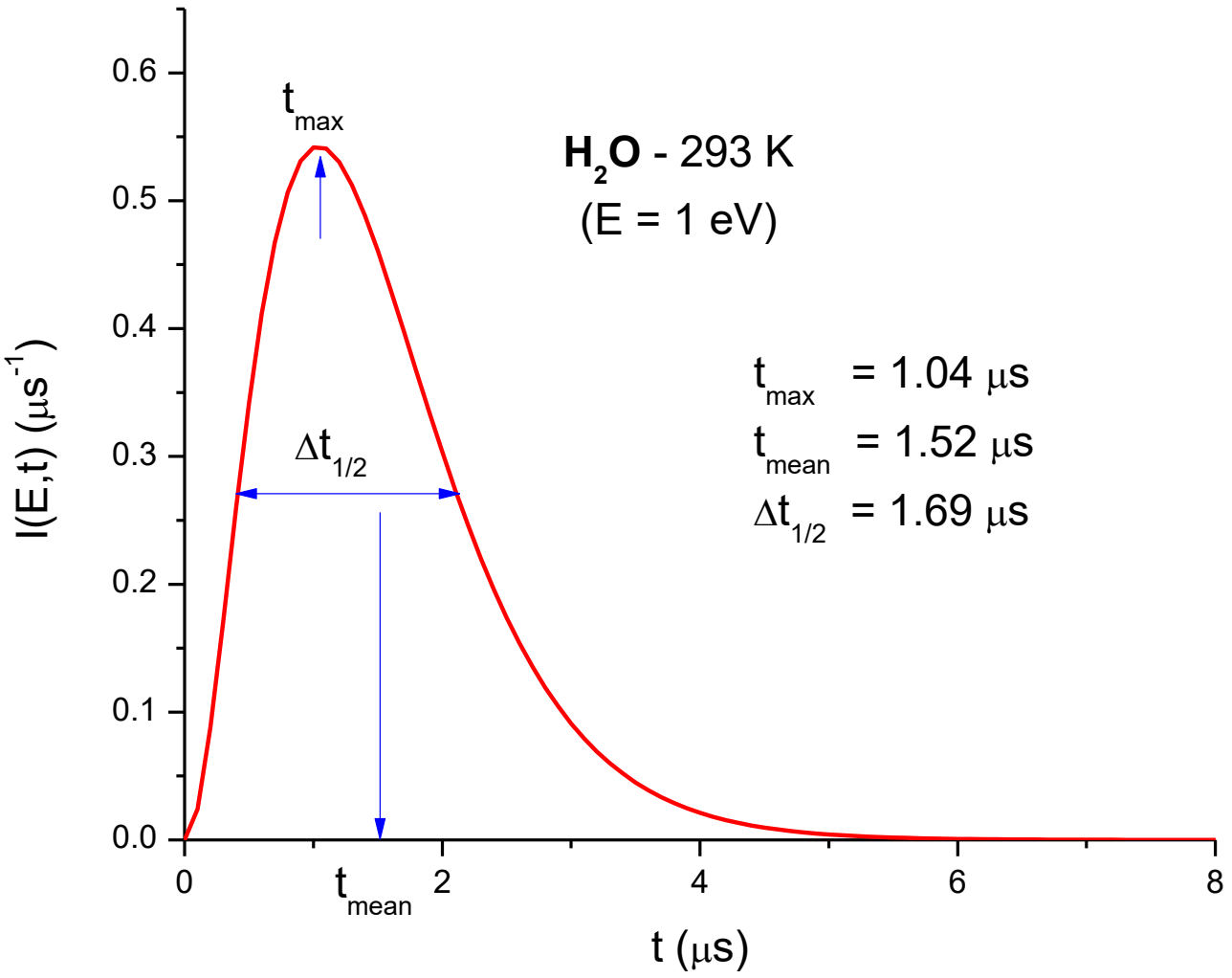
$$t_{mean} = \left(1+\frac{2}{\gamma}\right)\gamma\,/(\xi\Sigma_s v) \qquad \sigma_t = \sqrt{1+\frac{2}{\gamma}}\;\gamma\,/(\xi\Sigma_s v)$$

$$\Delta t_{1/2} = 3\pi^{-\frac{1}{2}}\,(1+\gamma)\,/\,(\xi\Sigma_s v) \qquad (f = ½)$$

Error ≤ 2 ‰
$0.9 \le \gamma \le 1$

(Granada, 2014)

Slowing-Down Time Distribution



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ρ (g/cm^3)	1	0.988	0.94	0.550	0.641	0.4392	0.510	0.510	0.91	0.0751
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ξ	0.926	0.926	0.913	0.940	0.940	0.954	0.954	0.954	0.876	1
γ	0.924	0.924	0.908	0.936	0.936	0.951	0.951	0.951	0.976	1
$\xi \Sigma_{free}$ (cm^{-1})	1.389	1.367	1.688	1.375	1.603	1.365	1.588	1.588	1.155	0.927
$v\ t_s$ (cm)	2.105	2.139	1.723	2.135	1.832	2.162	1.858	1.858	2.58	3.235
$v\ \Delta t_s$ (cm)	1.183	1.202	0.963	1.205	1.034	1.227	1.055	1.055	1.476	1.867
$v\ \Delta t_{1/2}$ (cm)	2.346	2.384	1.915	2.383	2.046	2.421	2.080	2.080	2.897	3.65

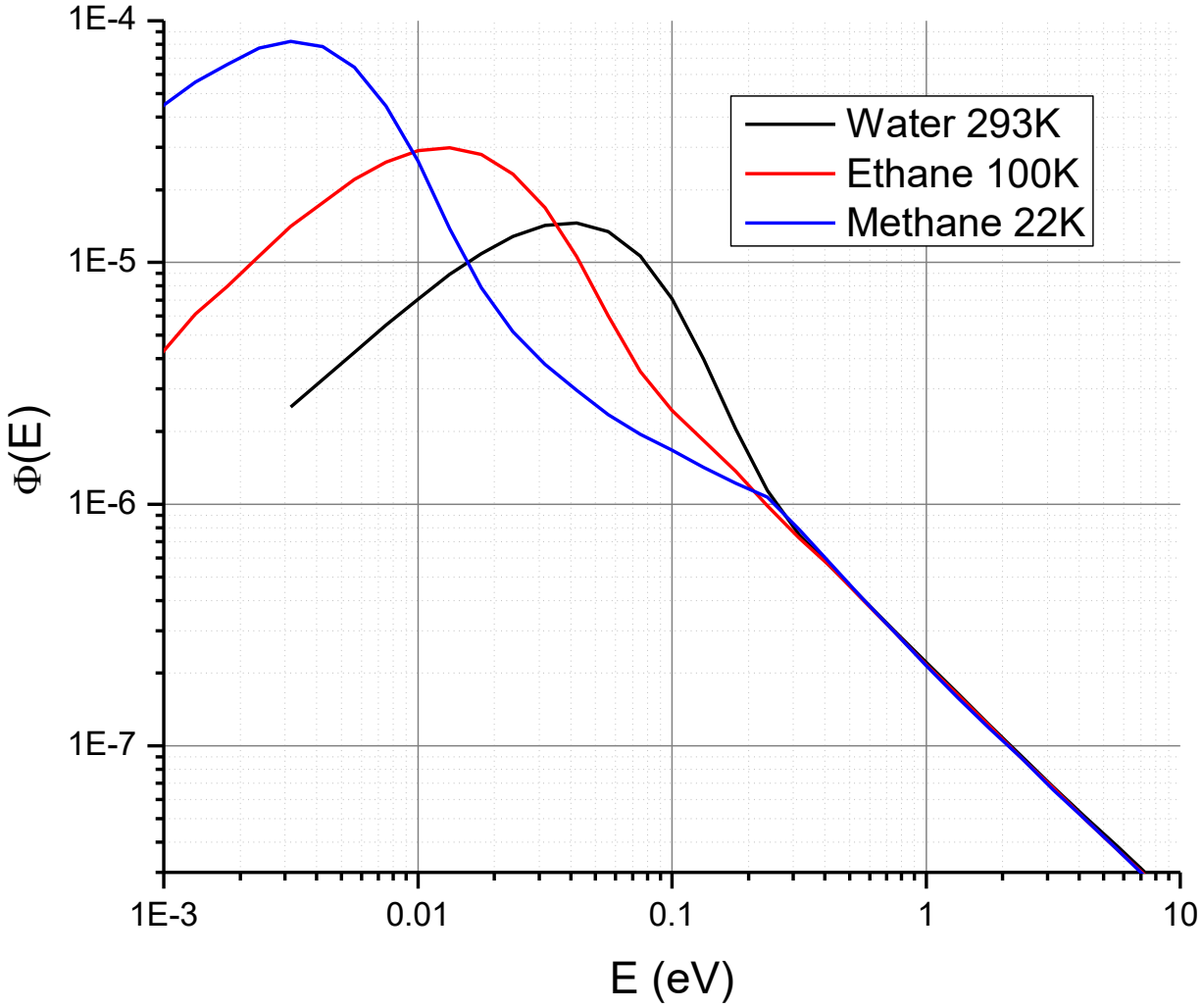
NEUTRON THERMALIZATION

When fast neutrons are introduced into an infinite, non-absorbing medium, they will remain there for a long time as they go through a moderation process, eventually reaching an equilibrium with the thermal motion of the scattering atoms.

Then, the neutron energies will have a *Maxwell distribution* with a characteristic temperature related to that of the medium.

$$\Phi_M(E) = \Phi_{th}(E) \cdot E/(k_B T_{eff})^2 \cdot \exp(-E/(k_B T_{eff}))$$

Detailed Balance applies (in general), establishing a symmetry condition on up-scattering and down-scattering inelastic processes.


1E-4
1E-5
1E-6
1E-7
Φ(E)
1E-3
0.01
0.1
1
10
E (eV)
Water 293K
Ethane 100K
Methane 22K

DECAY CONSTANT

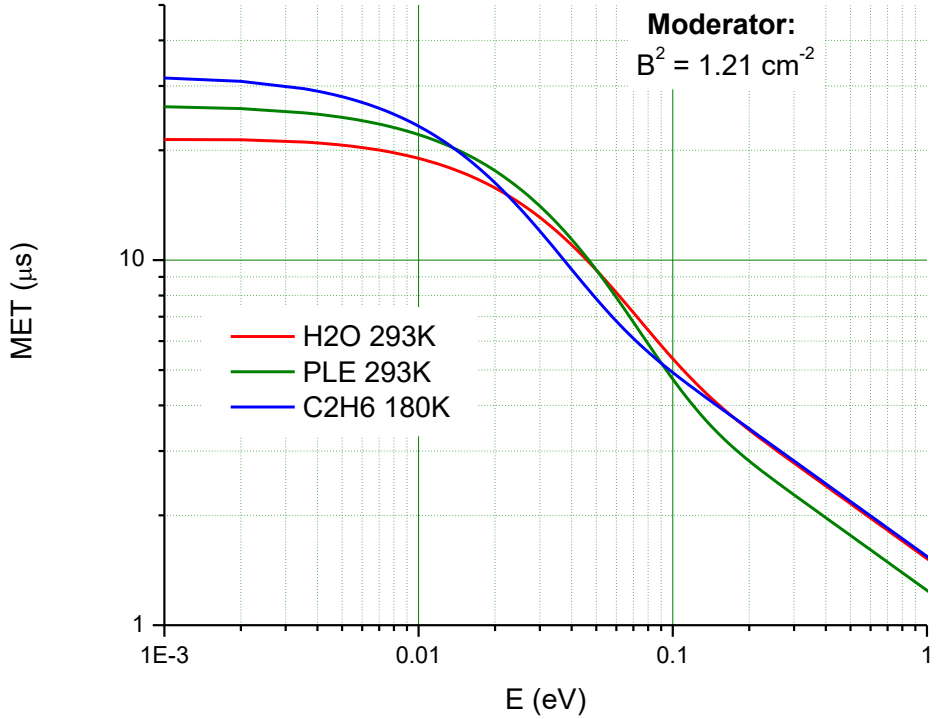
$$\propto = \bar{v}\,\Sigma_{abs} + \bar{v}\,D\,B^2 - \cdots \quad 1/s$$

$$\bar{v} = 14488.13\,\sqrt{T(K)} \qquad cm/s$$

$$D = \int dE\; D(E)\; M_T(E)$$

$$D(E) = \{3\,[\Sigma_s + \Sigma_{abs}\,]\}^{-1}$$

B^2 : Geometrical Buckling



$$\alpha = \alpha_0 + D_0\,B^2 - C\,B^4 \ldots \quad (1/s)$$

Parameter	H_2O 293 K	H_2O 323 K	$(CH_2)_n$ 293 K	C_2H_6 180 K	C_2H_6 100 K	CH_4 100 K	CH_4 22 K [40]	CH_4 4 K [20]	C_9H_{12} 20 K [40]
α_0 (s^{-1})	4885	4838	5821	4836	5672	4855	4198	2514	2858
D_0 ($cm^2\,s^{-1}$)	36310	40338	27133	23182	12082	16600	5678	1913	5763
L (cm)	2.73	2.89	2.16	2.19	1.46	1.85	1.16	0.87	1.42

PROPERTIES OF CURRENT THERMAL AND COLD MODERATORS

THERMAL SCATTERING LIBRARIES
RECENTLY GENERATED BY THE BARILOCHE GROUP

ENDF/B-VIII.0: H(H_2O), D(D_2O), O(D_2O).

JEFF-3.3: **H** (H_2-*para*), **H** (H_2-*ortho*), D (D_2-*para*), D (D_2-*ortho*),
H (Ice), D (D_2O), O (D_2O), H (Mesitylene), H (Toluene),
Al (Al_2O_3), O (Al_2O_3), Si (Silicon).

ALSO: C (CH_4 – Phase II), D (Solid D_2), H (PLE), H (TPM)
H (C_2H_6), C (Graphite), **C** (n-Diamond), **H** (MgH_2)

International Collaboration on Advanced Neutron Sources (ICANS XXII)

27–31 March 2017, Saïd Business School, University of Oxford, UK

Preliminary Thermal Neutron Scattering Kernel for Liquid Ethane

J.R. Granada[1], F. Cantargi[1] and J.I. Márquez Damián [1,2]

[1]Neutron Physics Department and Instituto Balseiro, Centro Atomico Bariloche, CNEA, Argentina and [2]CONICET, Argentina

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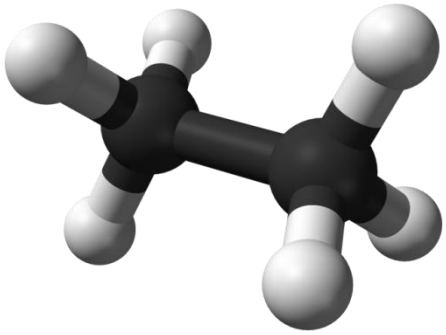
CENTRO ATÓMICO BARILOCHE

AN INTERESTING "COOL" (and COLD?) MODERATOR:

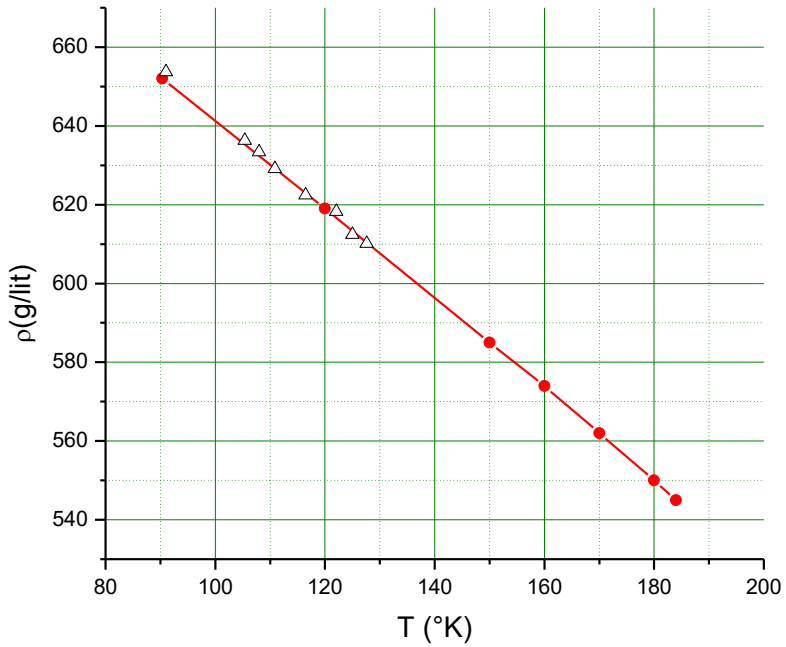


ETHANE

C_2H_6

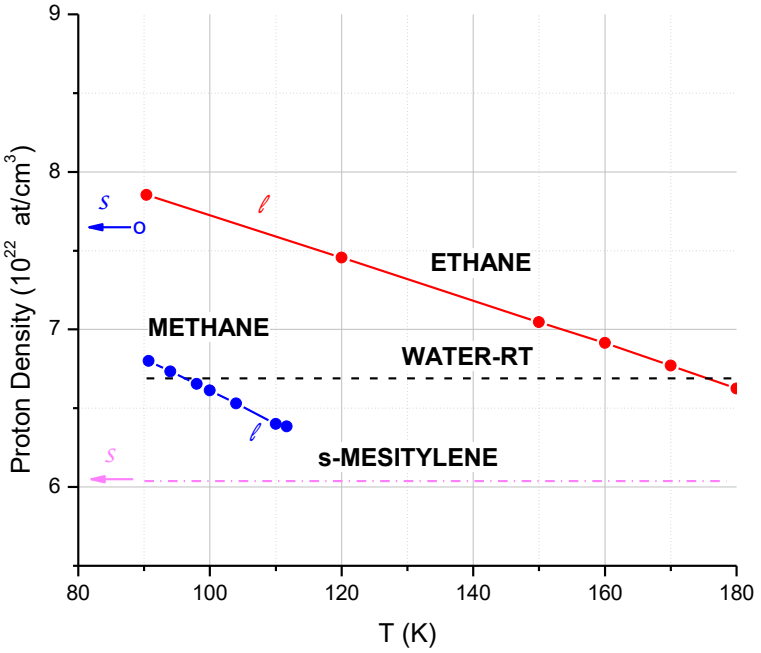
http://en.wikipedia.org/wiki/Ethane

Properties	
Molecular formula	C_2H_6
Molar mass	30.07 g·mol^{-1}
Density	•1.3562 mg cm^{-3} (at 0 °C)[1] •0.5446 g cm^{-3} (at 184 K)[2]
Melting point	−182.8 °C; −296.9 °F; 90.4 K
Boiling point	−88.5 °C; −127.4 °F; 184.6 K



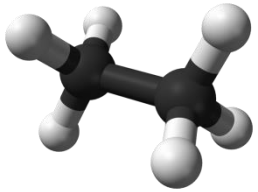
http://www.engineeringtoolbox.com/ethane-thermal-properties-d_1761.html

Liquid Ethane exists over a large temperature range



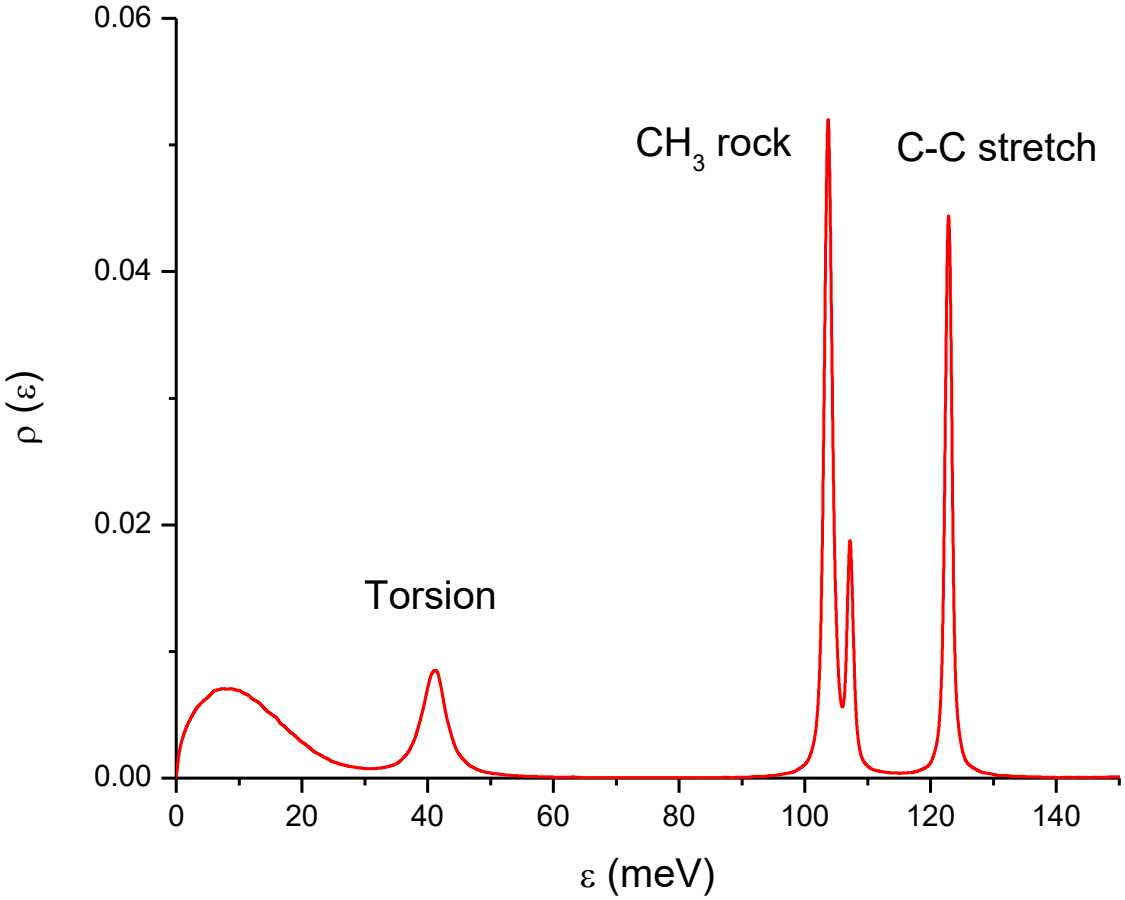
http://www.engineeringtoolbox.com/ethane-thermal-properties-d_1761.html

OUR MODEL FOR LIQUID ETHANE

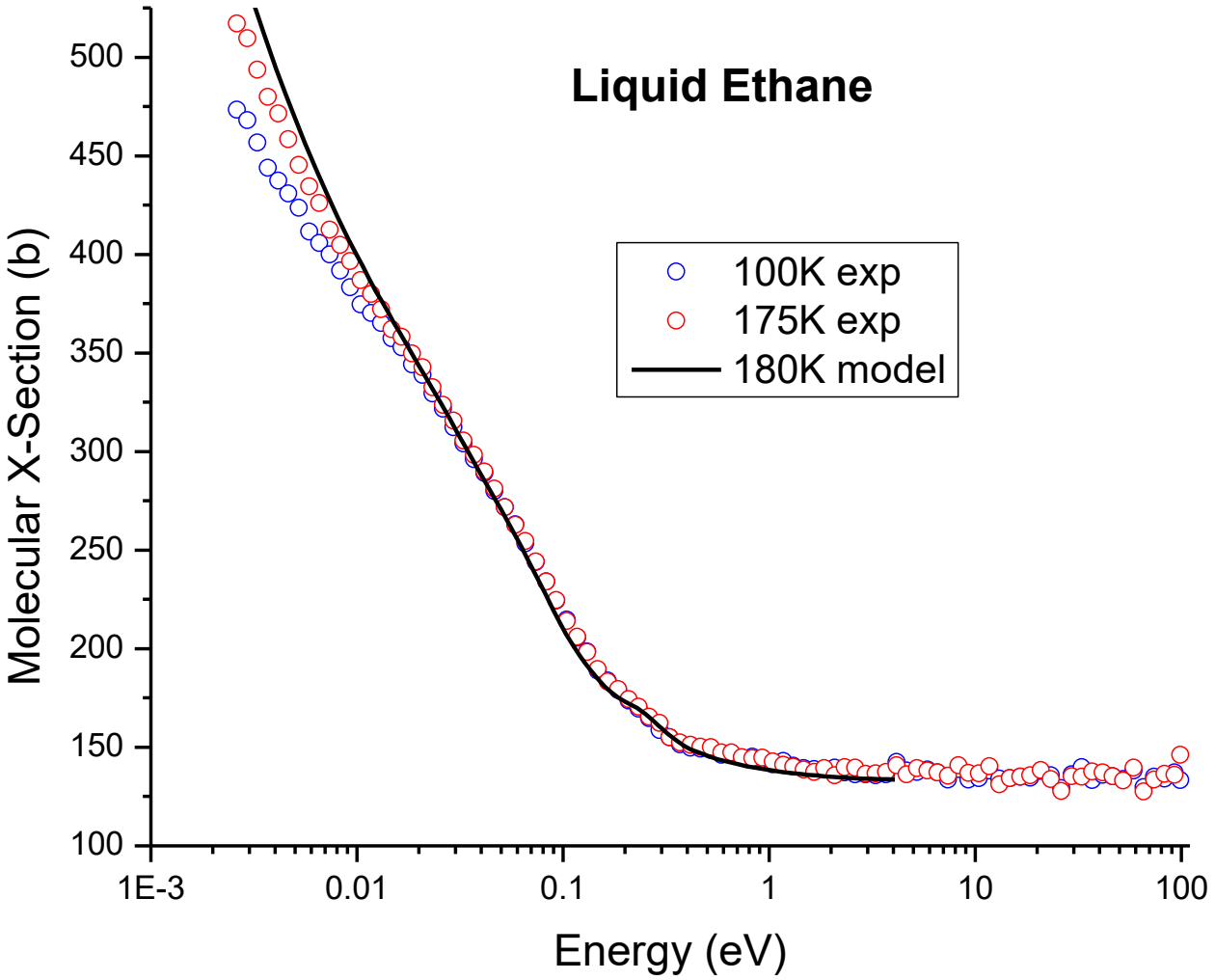


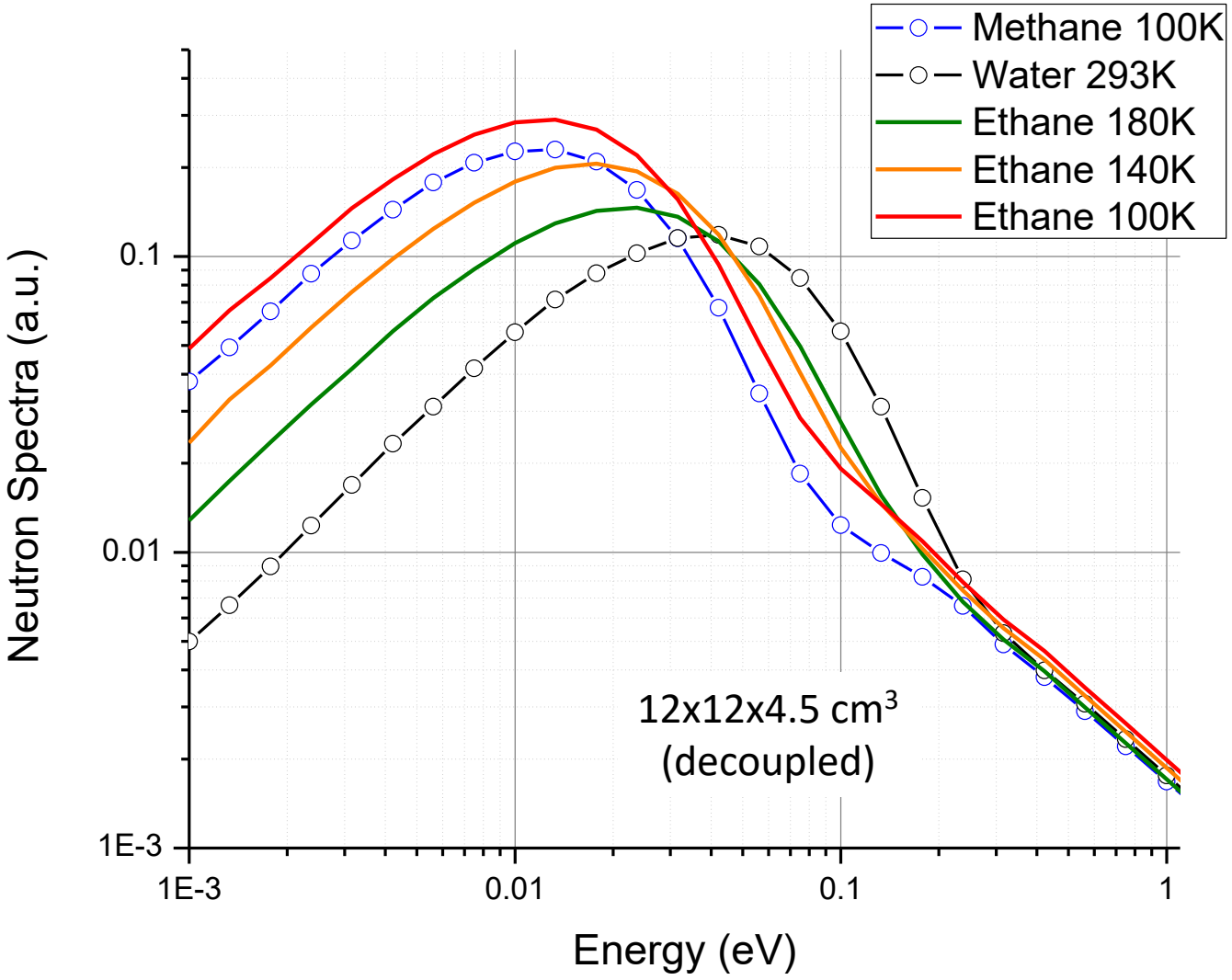
ETHANE (100K)

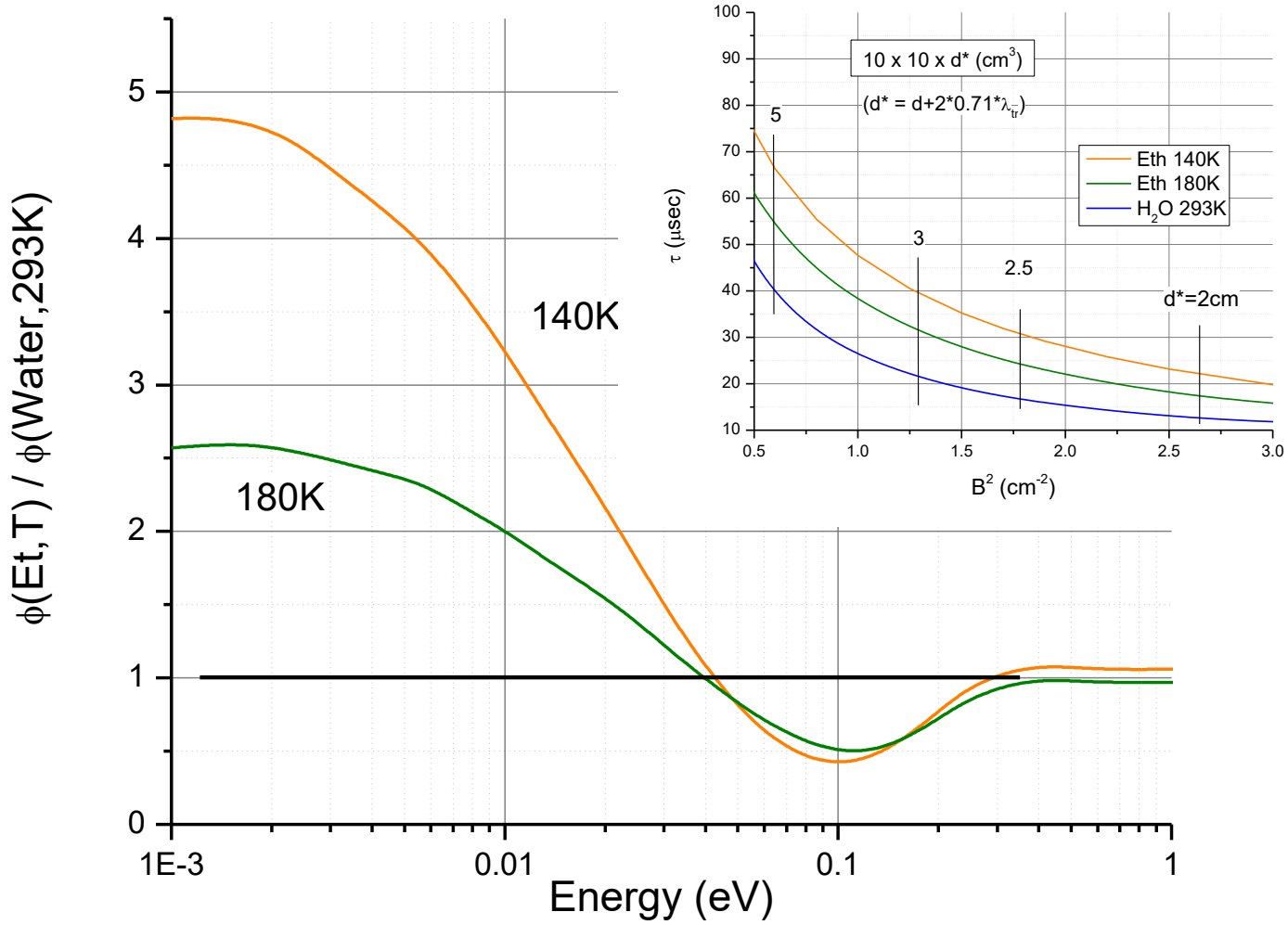
Frequency Spectrum from MD (continuous part)

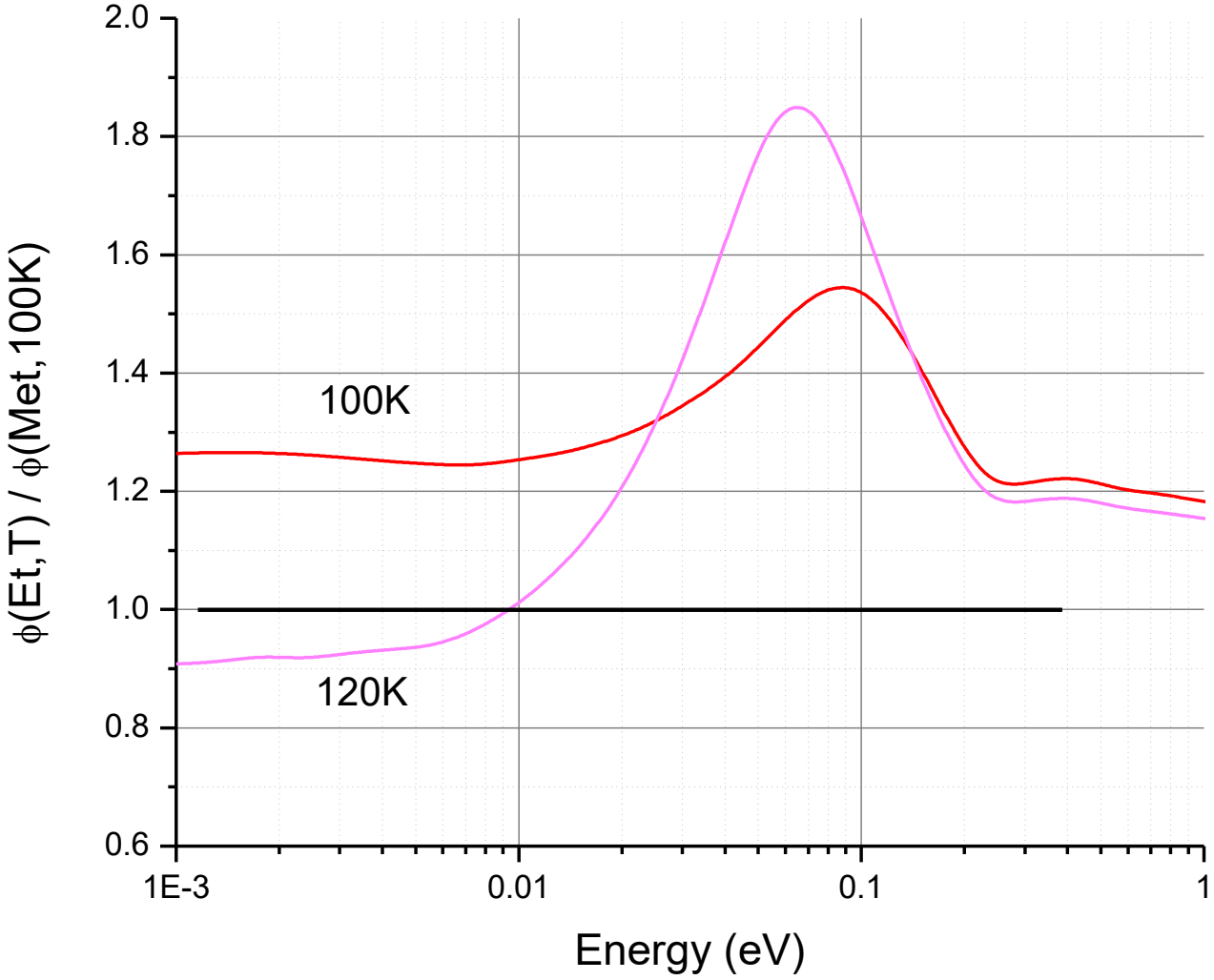


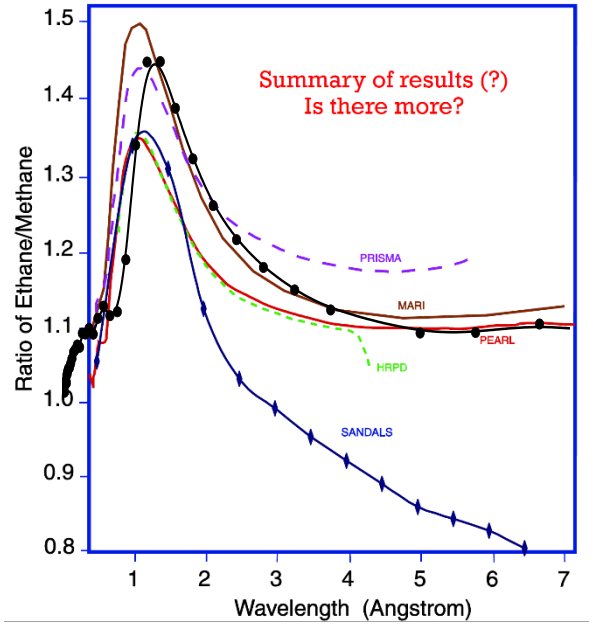
Transmission Experiments performed at VESUVIO (2017)




Methane 100K
Water 293K
Ethane 180K
Ethane 140K
Ethane 100K
Neutron Spectra (a.u.)
0.1
0.01
1E-3
1E-3
0.01
0.1
1
Energy (eV)
12x12x4.5 cm3
(decoupled)


ϕ(Et,T) / ϕ(Water,293K)
Energy (eV)
1E-3
0.01
0.1
1
0
1
2
3
4
5
140K
180K
τ (μsec)
B² (cm⁻²)
10 x 10 x d* (cm³)
(d* = d+2*0.71*λtr)
Eth 140K
Eth 180K
H₂O 293K
5
3
2.5
d*=2cm


2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1E-3
0.01
0.1
1
ϕ(Et,T) / ϕ(Met,100K)
Energy (eV)
100K
120K

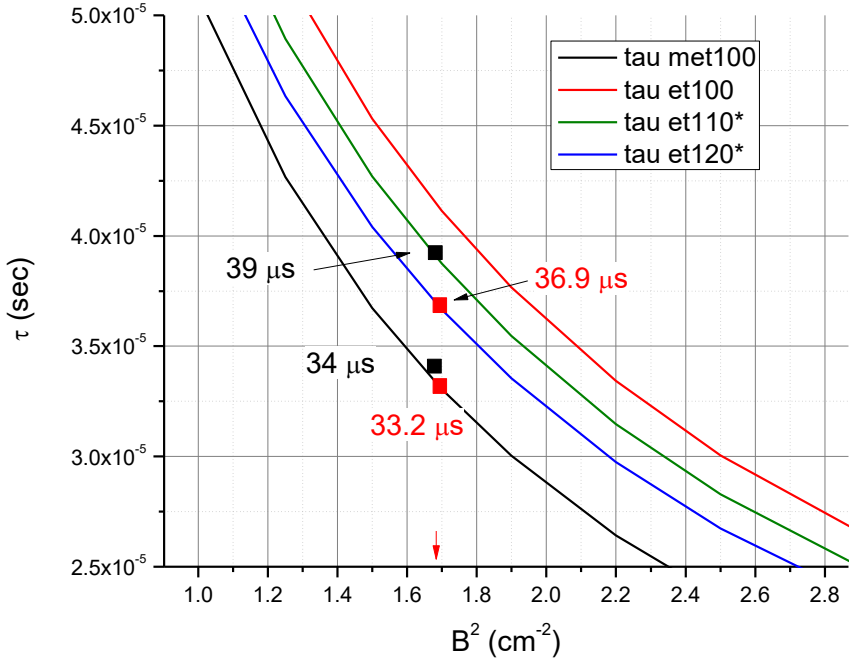


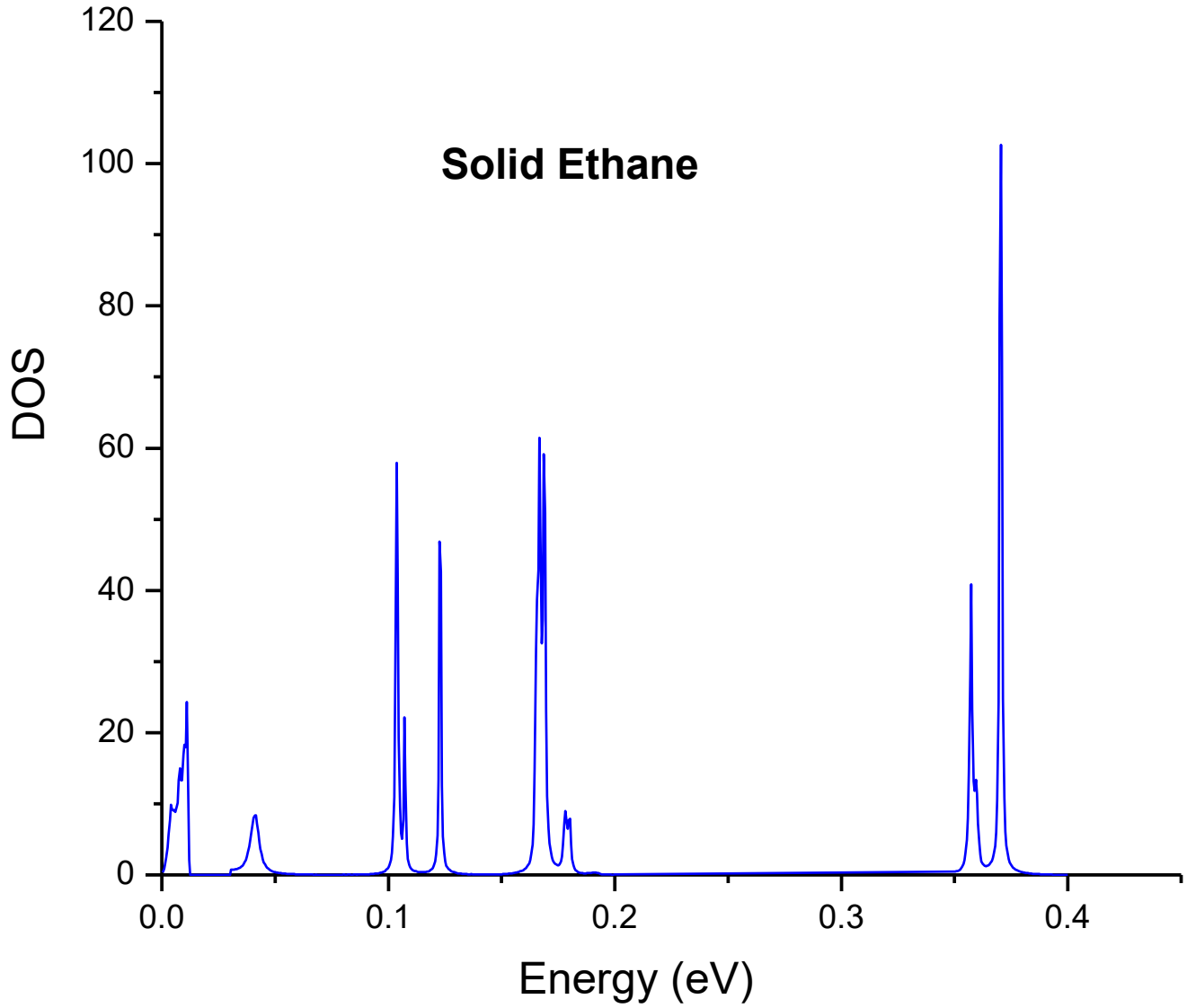
ISIS TS1 – Liquid Methane (dec.)

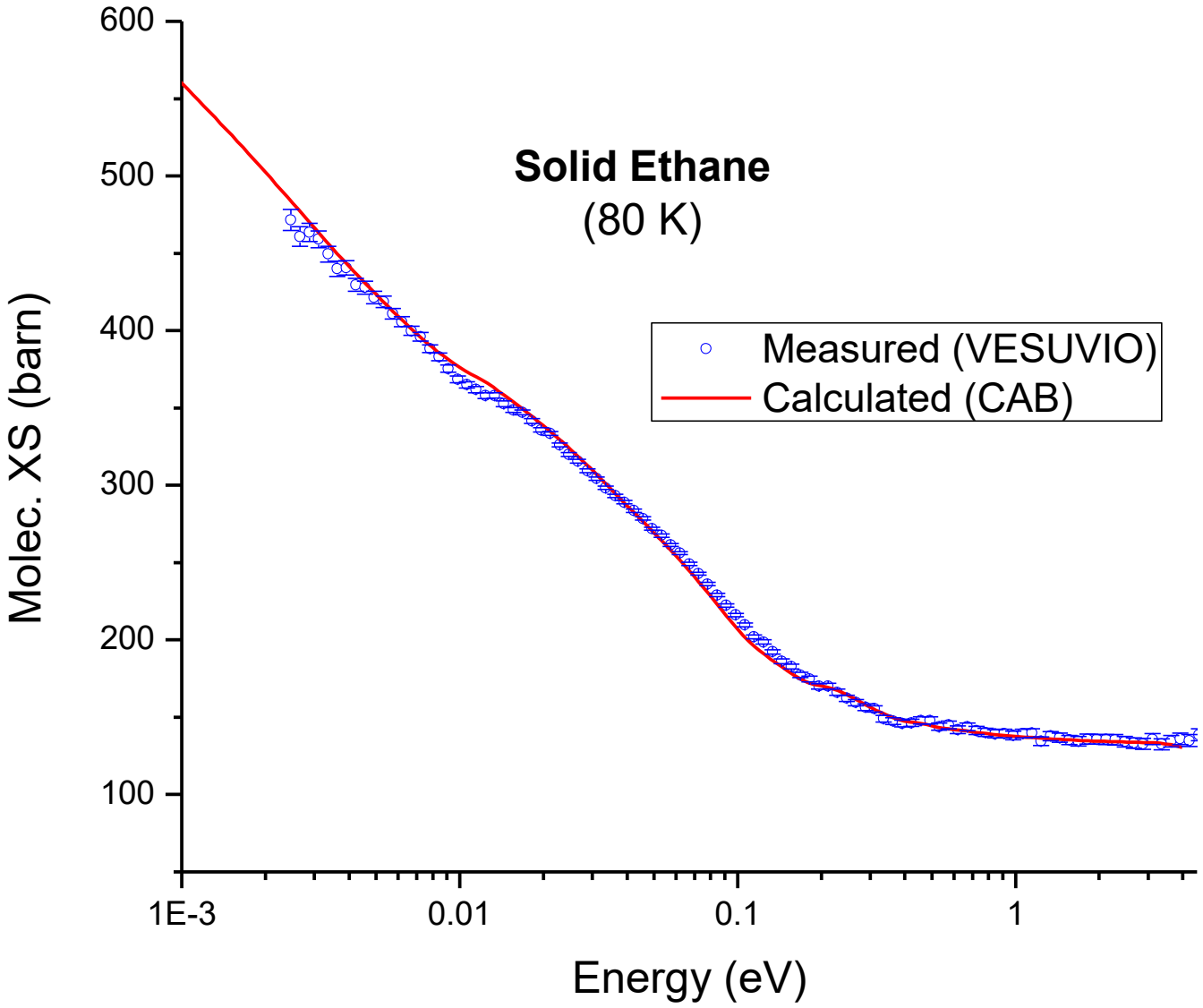
$B^2 = 1.69$ $10x10xd^*$ cm^3 , $d^* = 2.5$ cm = $d+2*0.71*\lambda_{tr}$

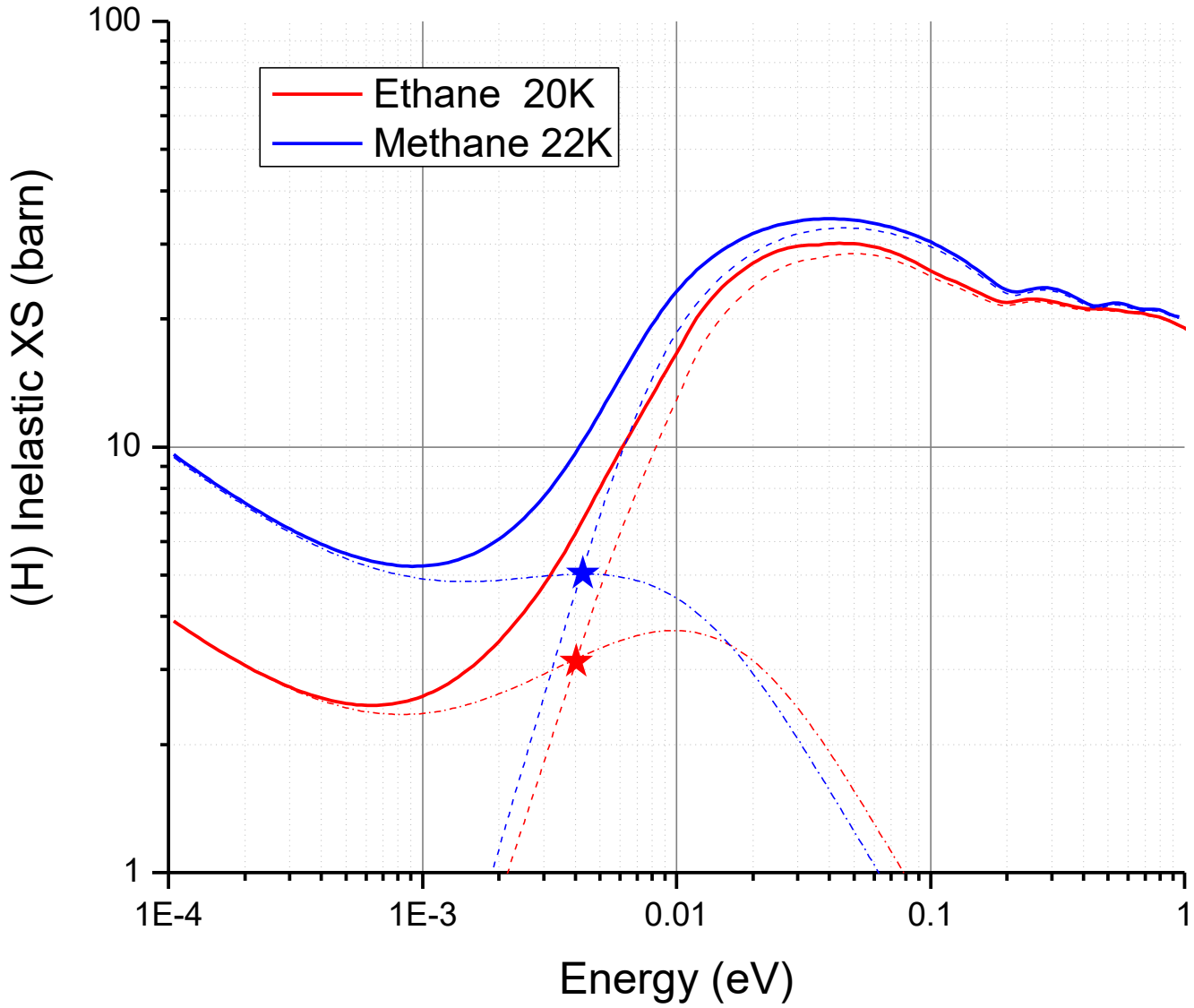
Goran Skoro, private communication

■ 1998 data
■ 1999 data




Solid Ethane
DOS
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
Energy (eV)


Solid Ethane
(80 K)
Measured (VESUVIO)
Calculated (CAB)
Molec. XS (barn)
600
500
400
300
200
100
1E-3
0.01
0.1
1
Energy (eV)


Ethane 20K
Methane 22K
(H) Inelastic XS (barn)
100
10
1
1E-4
1E-3
0.01
0.1
1
Energy (eV)

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New Neutron Scattering Kernels for Liquid Hydrogen and Deuterium

J.R. Granada[1], J.I. Márquez Damián [1,2] and F. Cantargi[1]

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CENTRO ATÓMICO BARILOCHE

Sköld approximation ($S^{cm}(Q)$ is the structure factor of molecular centres of mass):

$$I^{cm}(Q,t) \simeq S^{cm}(Q)\, I_s^{cm}\left(Q/[S^{cm}(Q)]^{½}, t\right)$$

$$S^{in}(Q,\omega) = \left\{S_{JJ'}(Q,\omega) \otimes S_s^{cm}(Q,\omega)\right\} e^{-\gamma Q^2}$$

$$S^{out}(Q,\omega) = 4\, b_c^2\, j_0^2(Qb)\left\{S^{cm}(Q)\, S_s^{cm}(Q',\omega) - S_s^{cm}(Q,\omega)\right\} e^{-\gamma Q^2}$$

$$Q' = Q/[S^{cm}(Q)]^{½},$$

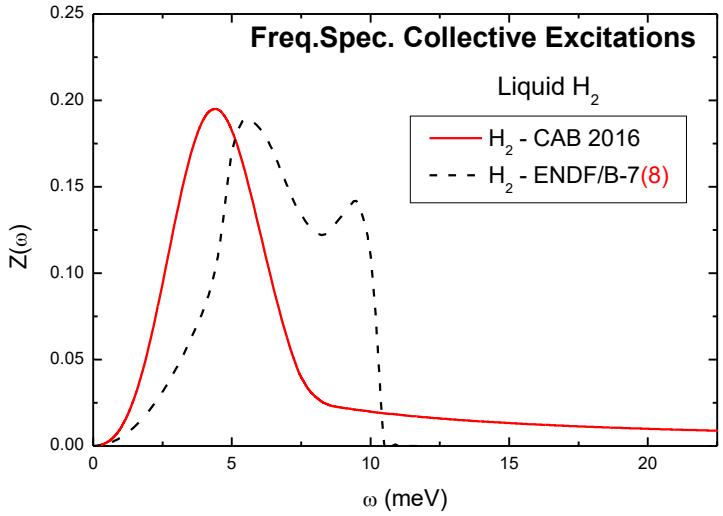
$S^{cm}(Q)$: Centers of mass Structure Factor

$S_s^{cm}(Q,\omega)$: Centers of mass Self Scattering Law

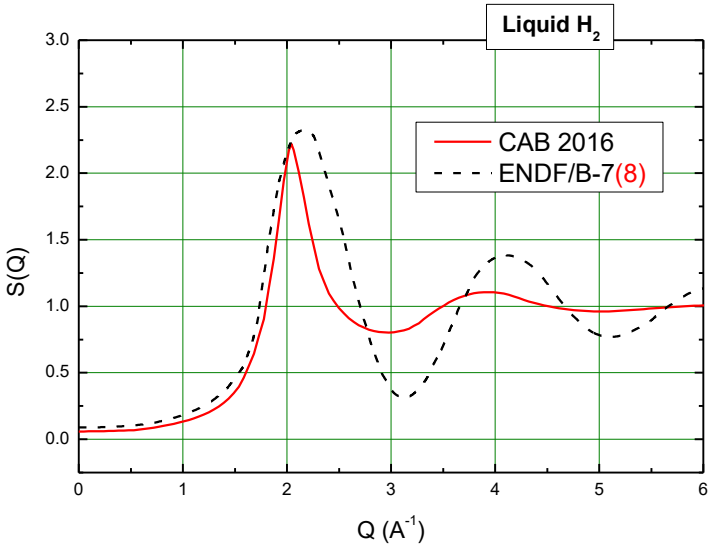
$S_{JJ'}(Q,\omega)$: Molecular Rotational Scattering Law (Young-Koppel)

LIQUID HYDROGEN

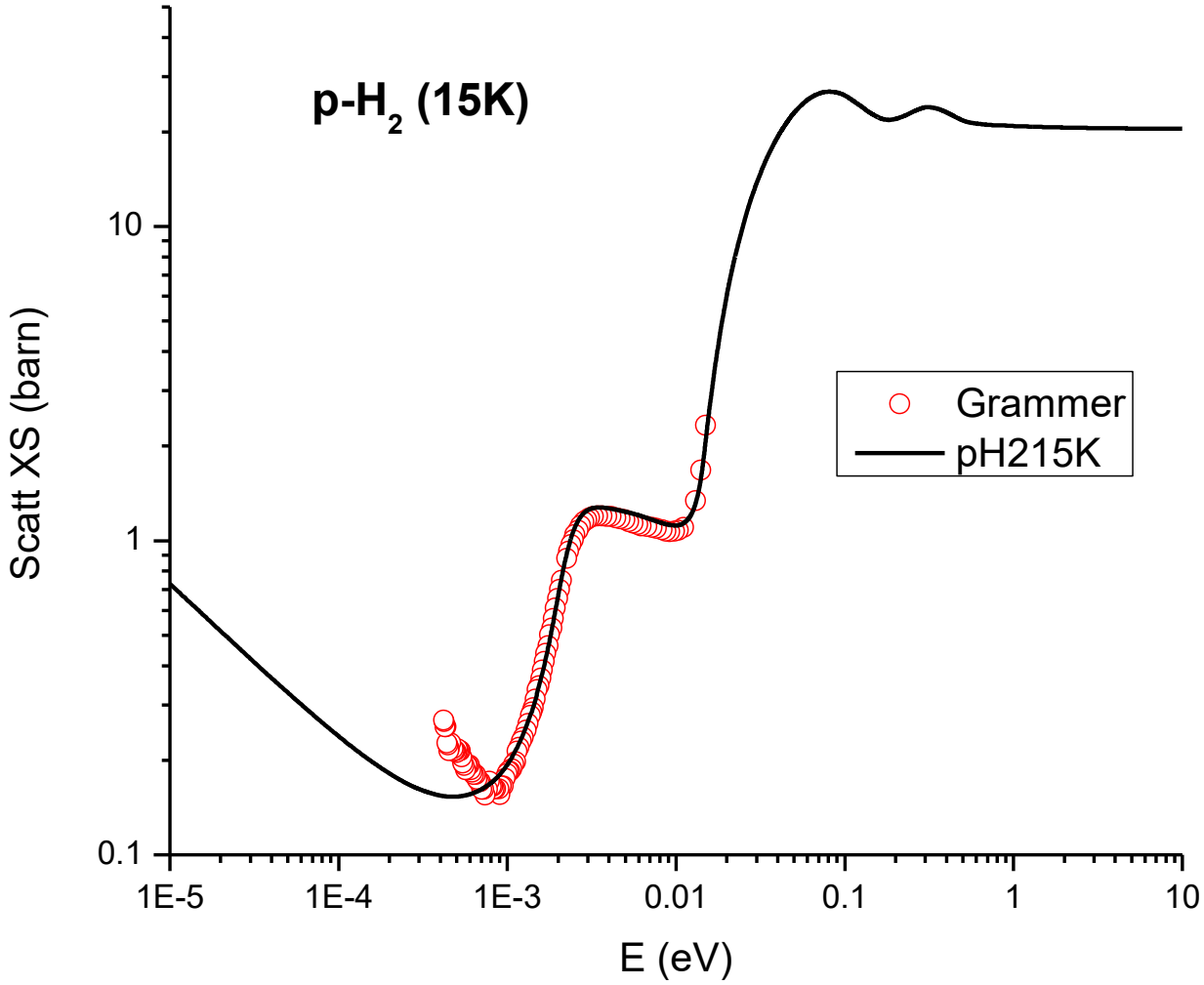
Dynamics



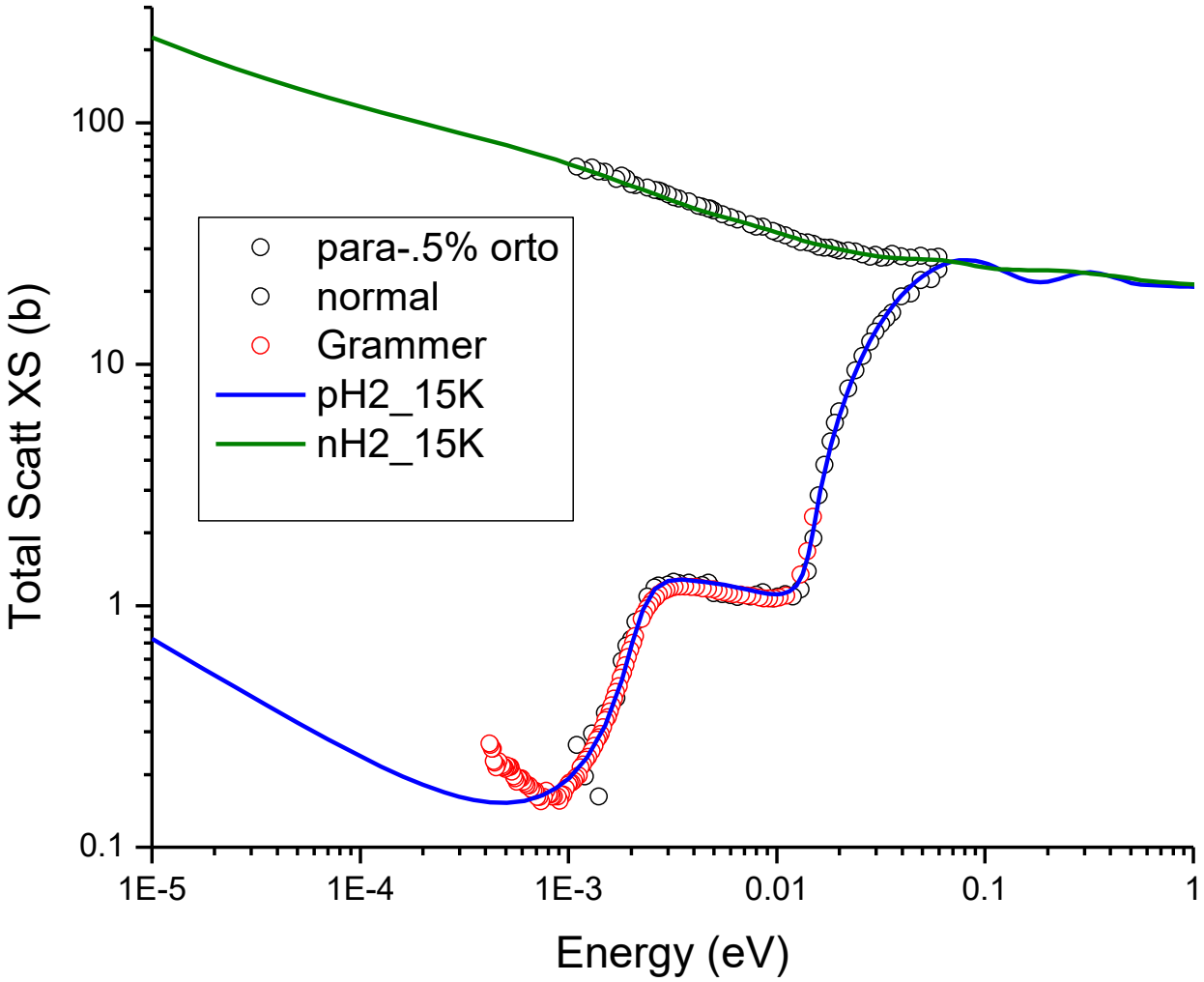
Structure



(H in) LIQUID HYDROGEN



(H in) LIQUID HYDROGEN



J. Phys.: Condens. Matter **11** (1999) 10229–10242. Printed in the UK PII: S0953-8984(99)05575-7

The total neutron cross section of liquid para-hydrogen

M Celli†, N Rhodes‡, A K Soper‡ and M Zoppi†

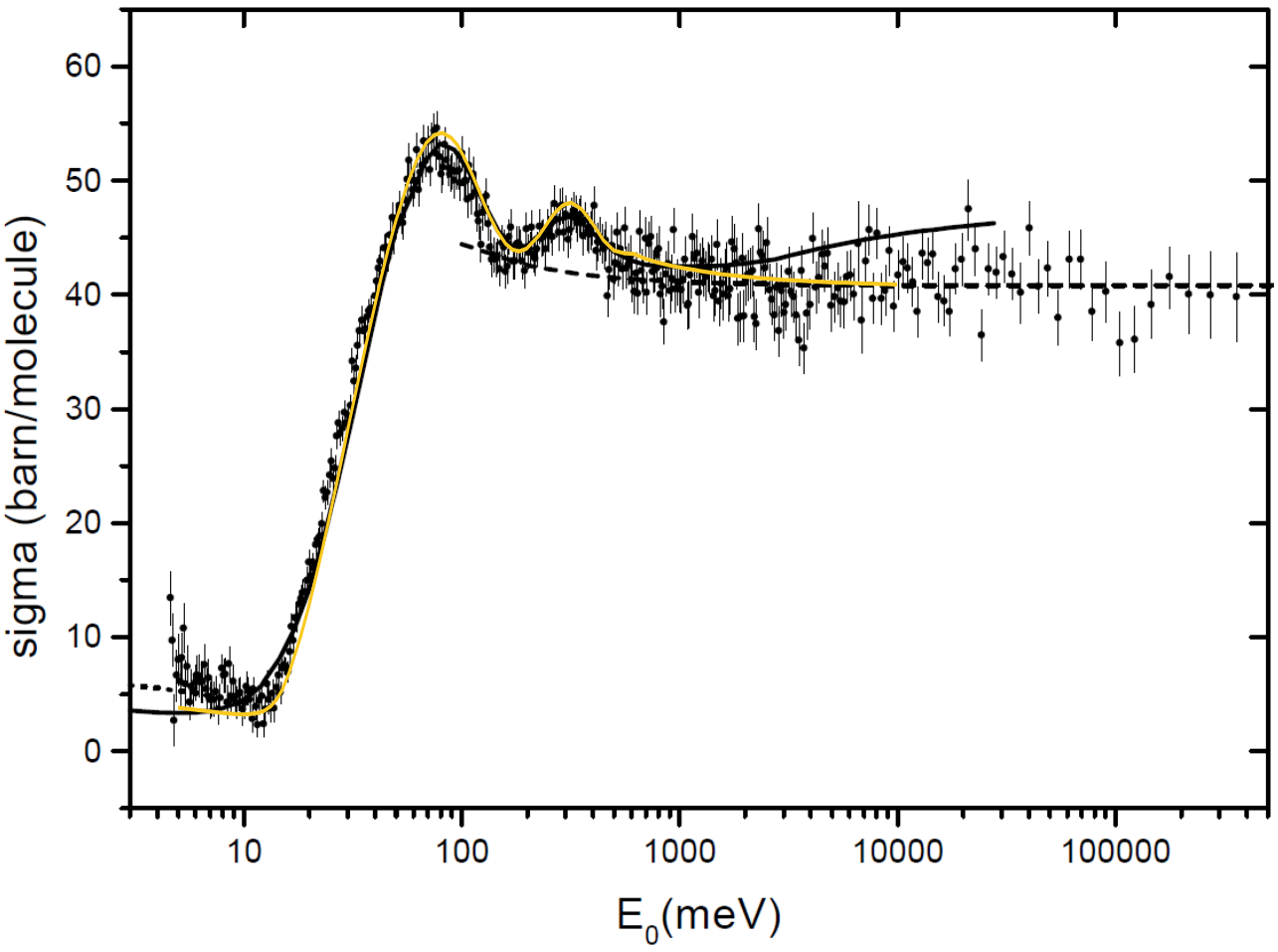
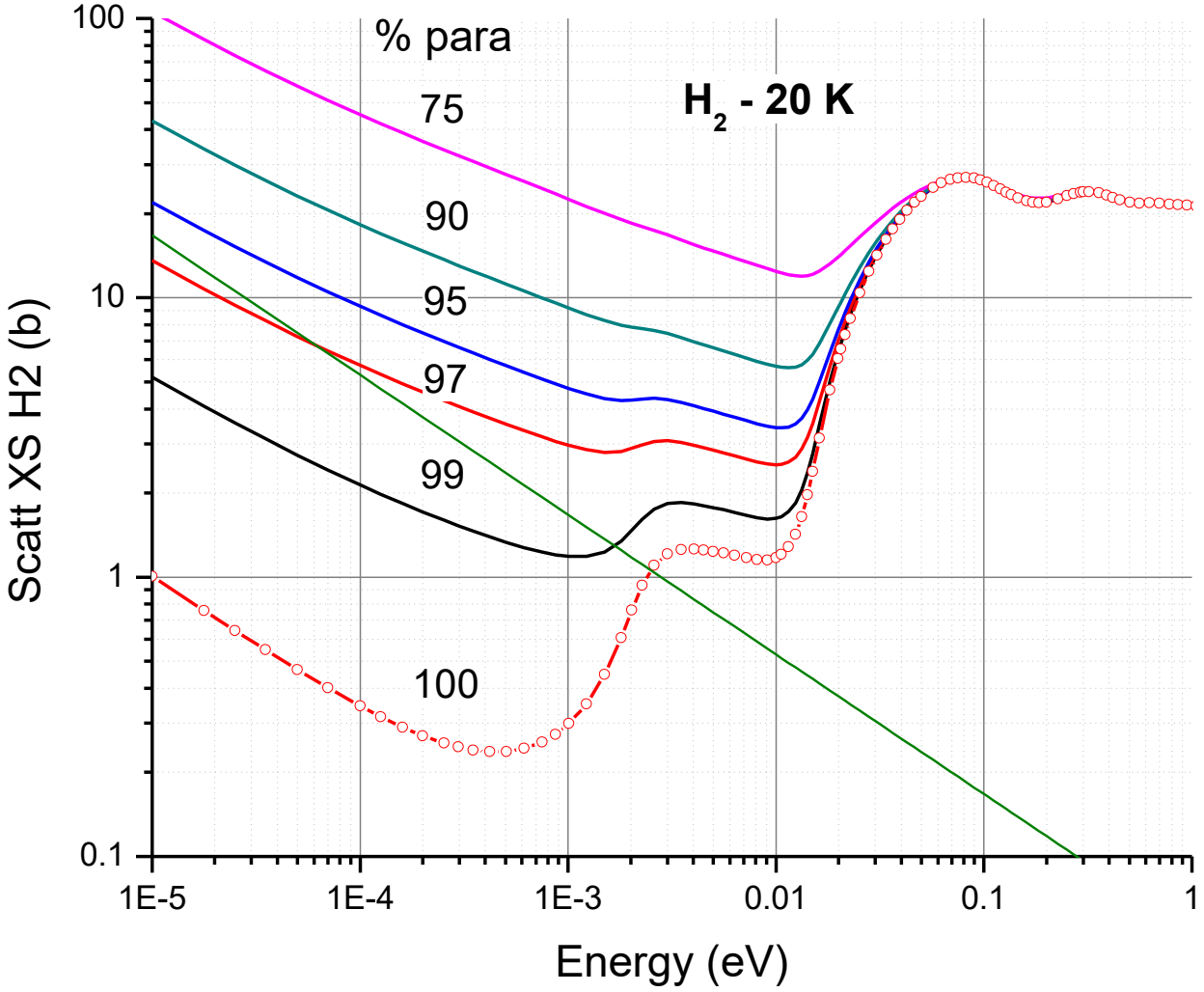
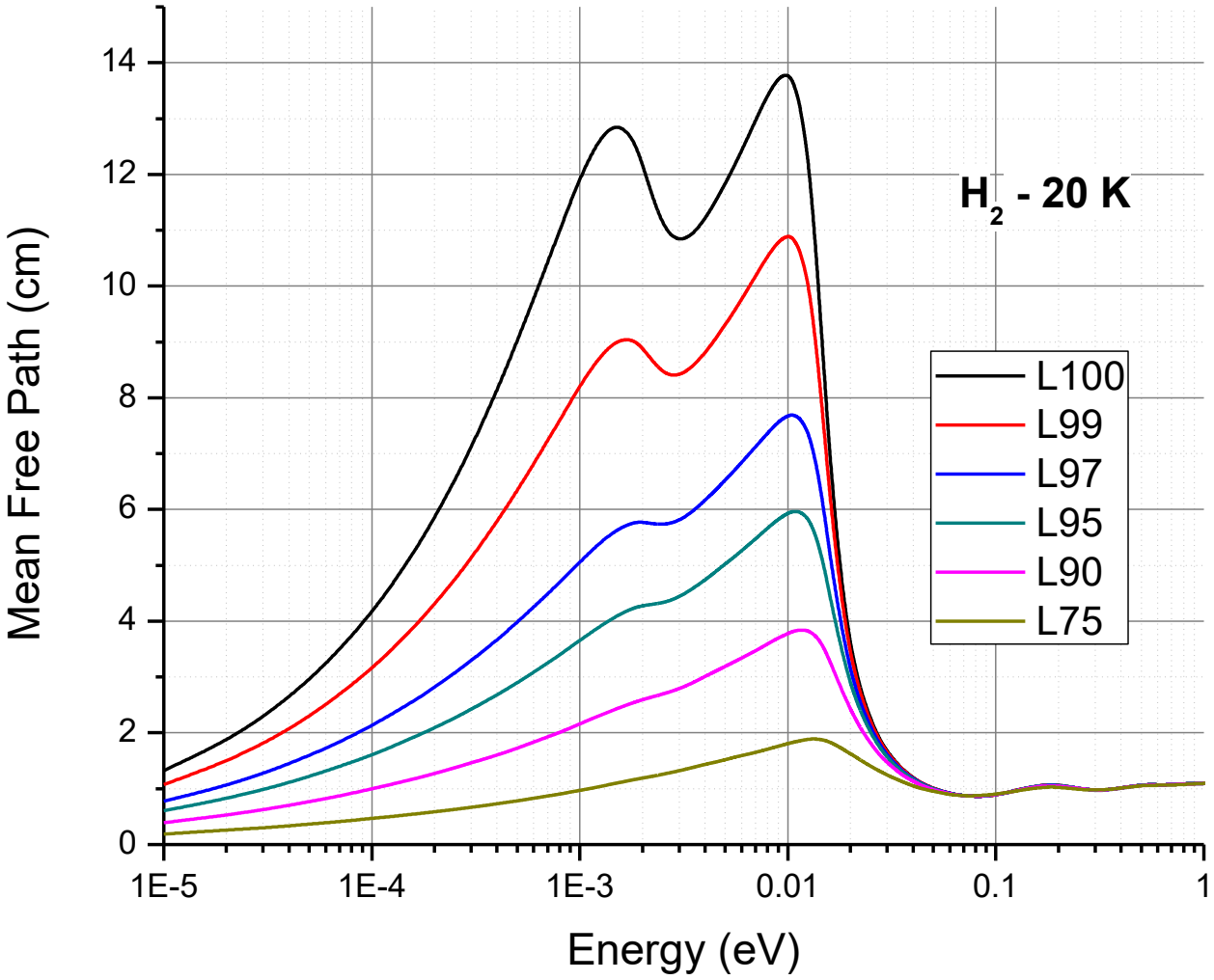
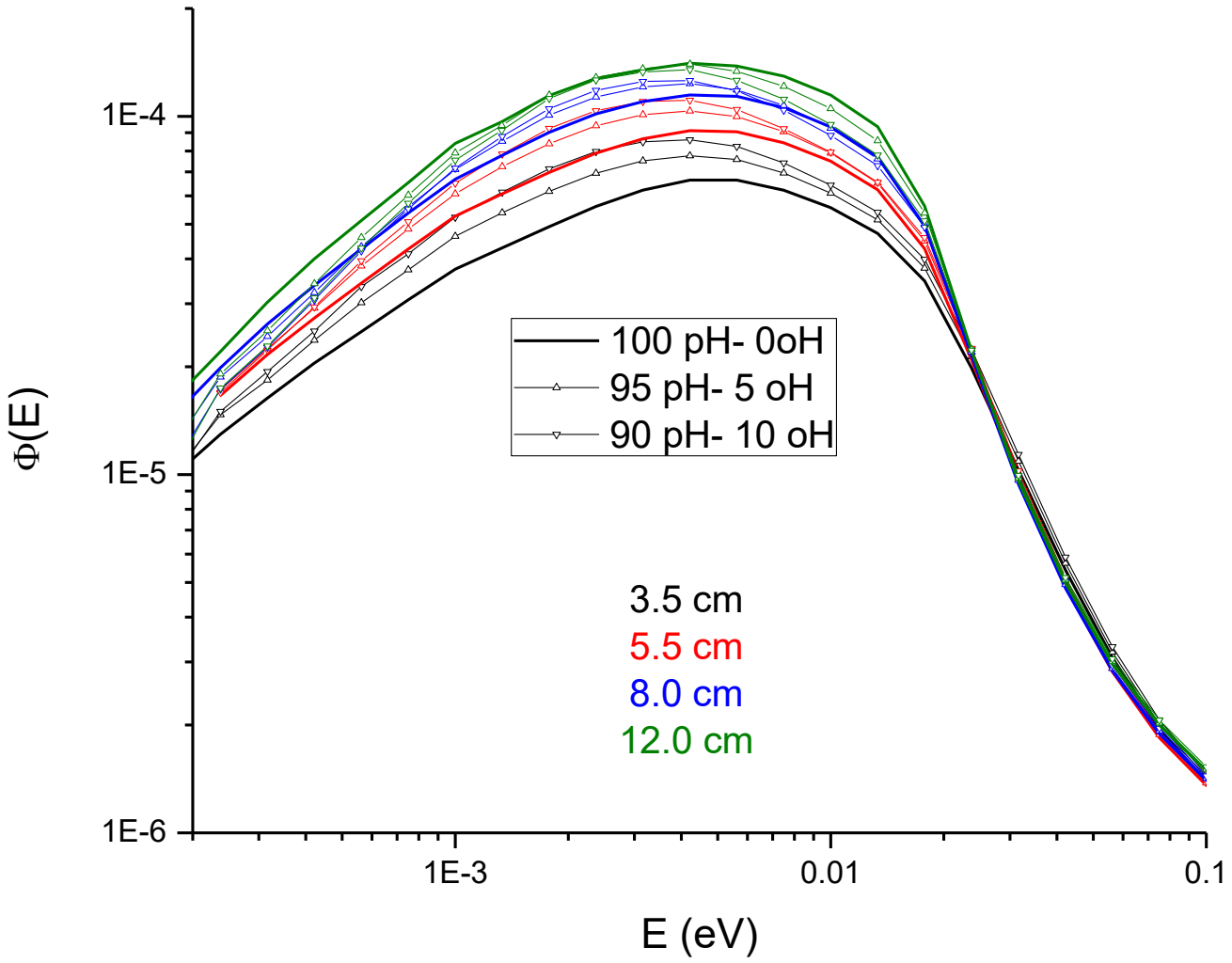
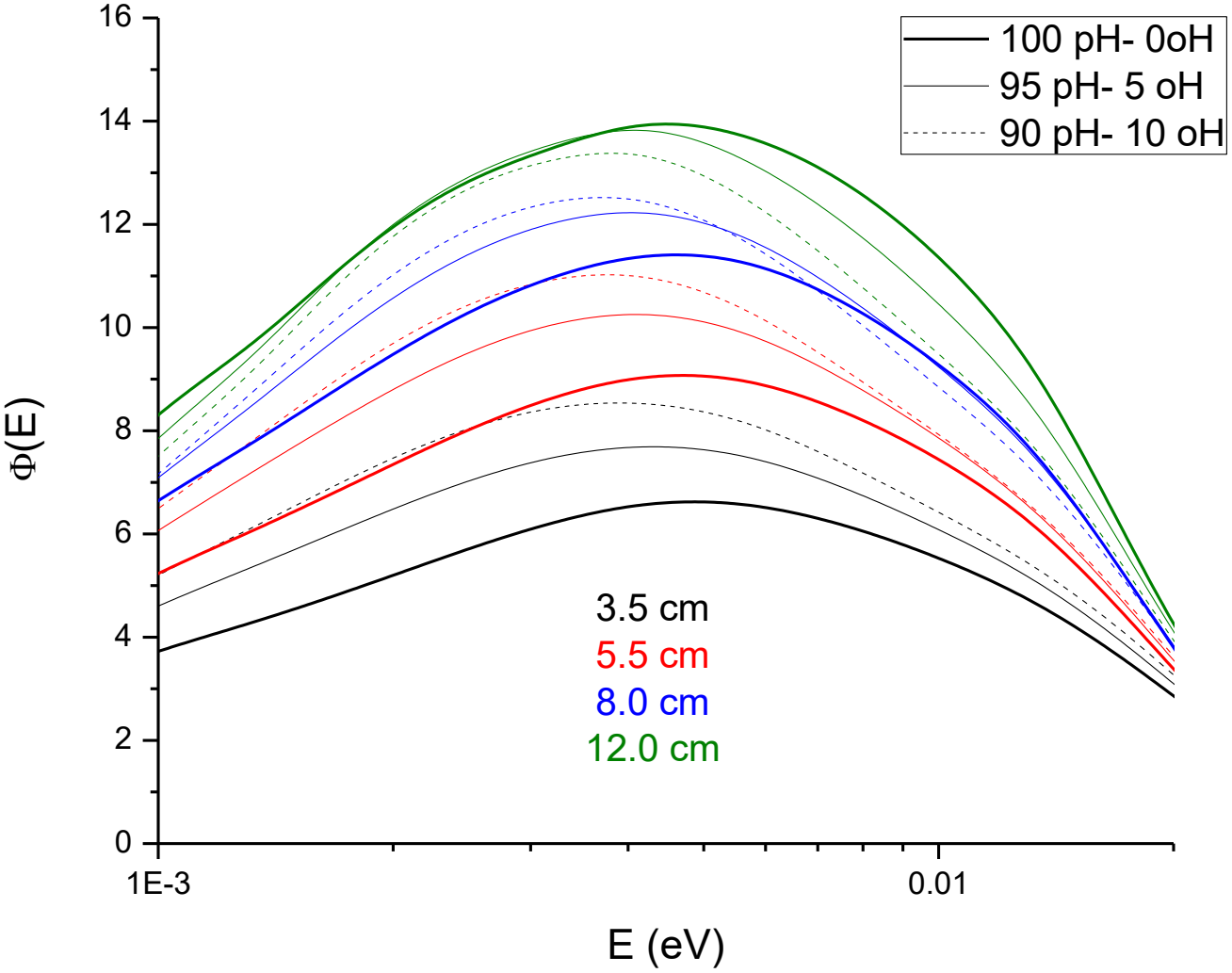


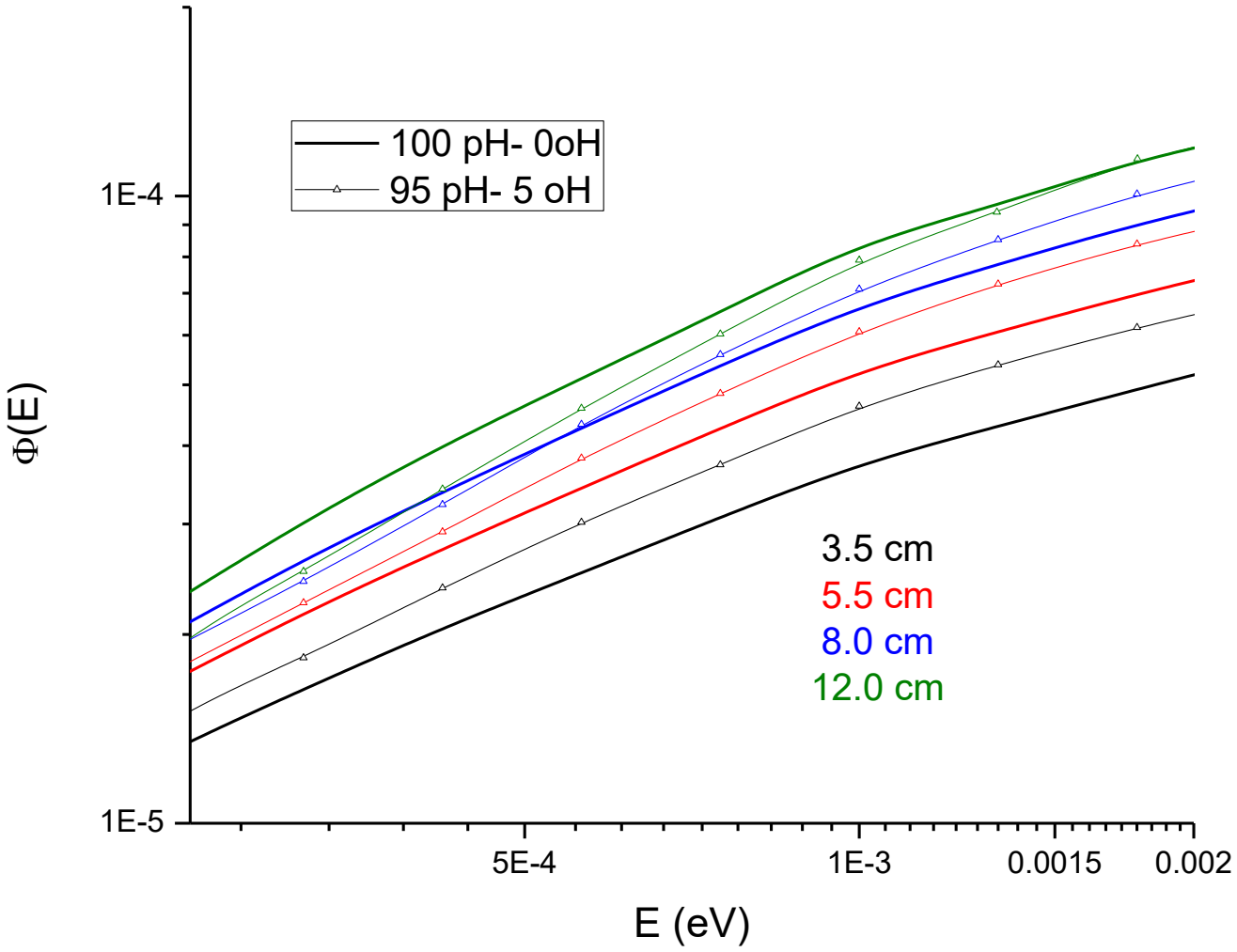
Figure 6. The total neutron cross section of liquid para-hydrogen ($T = 16$ K) as a function of the incident energy. Comparison between the experimental results and the various models. The MYK model is represented by the full line. In the low-energy region we use a heuristic effective mass of 26 amu (dotted line).The dashed line represents the high-energy limit of the YK theory that has been solved analytically. The overall agreement is very good and covers the whole energy range.


% para
75
90
95
97
99
100
H2 - 20 K
Scatt XS H2 (b)
Energy (eV)
100
10
1
0.1
1E-5
1E-4
1E-3
0.01
0.1
1

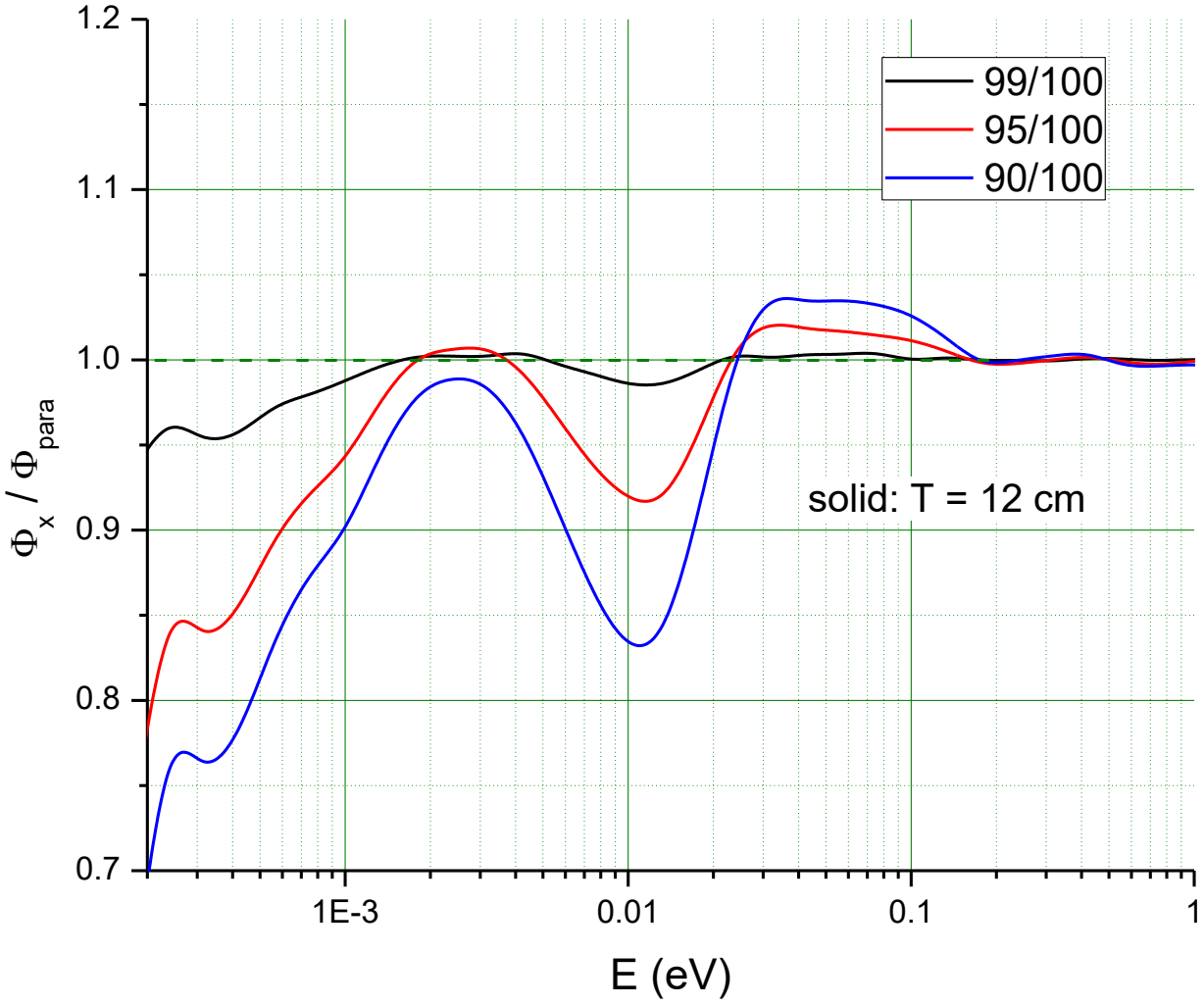

Mean Free Path (cm)
Energy (eV)
H2 - 20 K
L100
L99
L97
L95
L90
L75
0
2
4
6
8
10
12
14
1E-5
1E-4
1E-3
0.01
0.1
1


1E-4
1E-5
1E-6
Φ(E)
1E-3
0.01
0.1
E (eV)
100 pH- 0oH
95 pH- 5 oH
90 pH- 10 oH
3.5 cm
5.5 cm
8.0 cm
12.0 cm

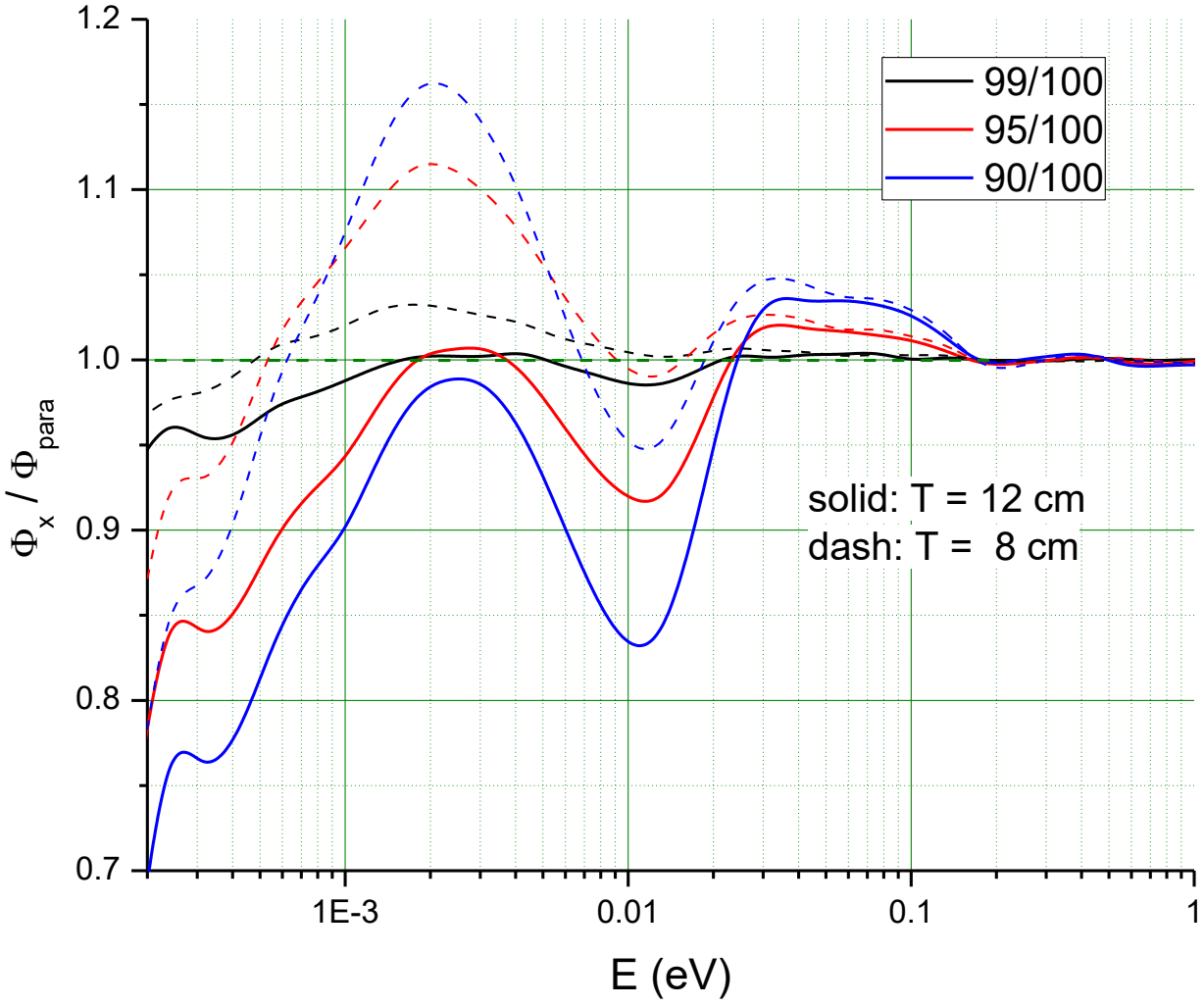

100 pH- 0oH
95 pH- 5 oH
90 pH- 10 oH
3.5 cm
5.5 cm
8.0 cm
12.0 cm
Φ(E)
E (eV)
16
14
12
10
8
6
4
2
0
1E-3
0.01

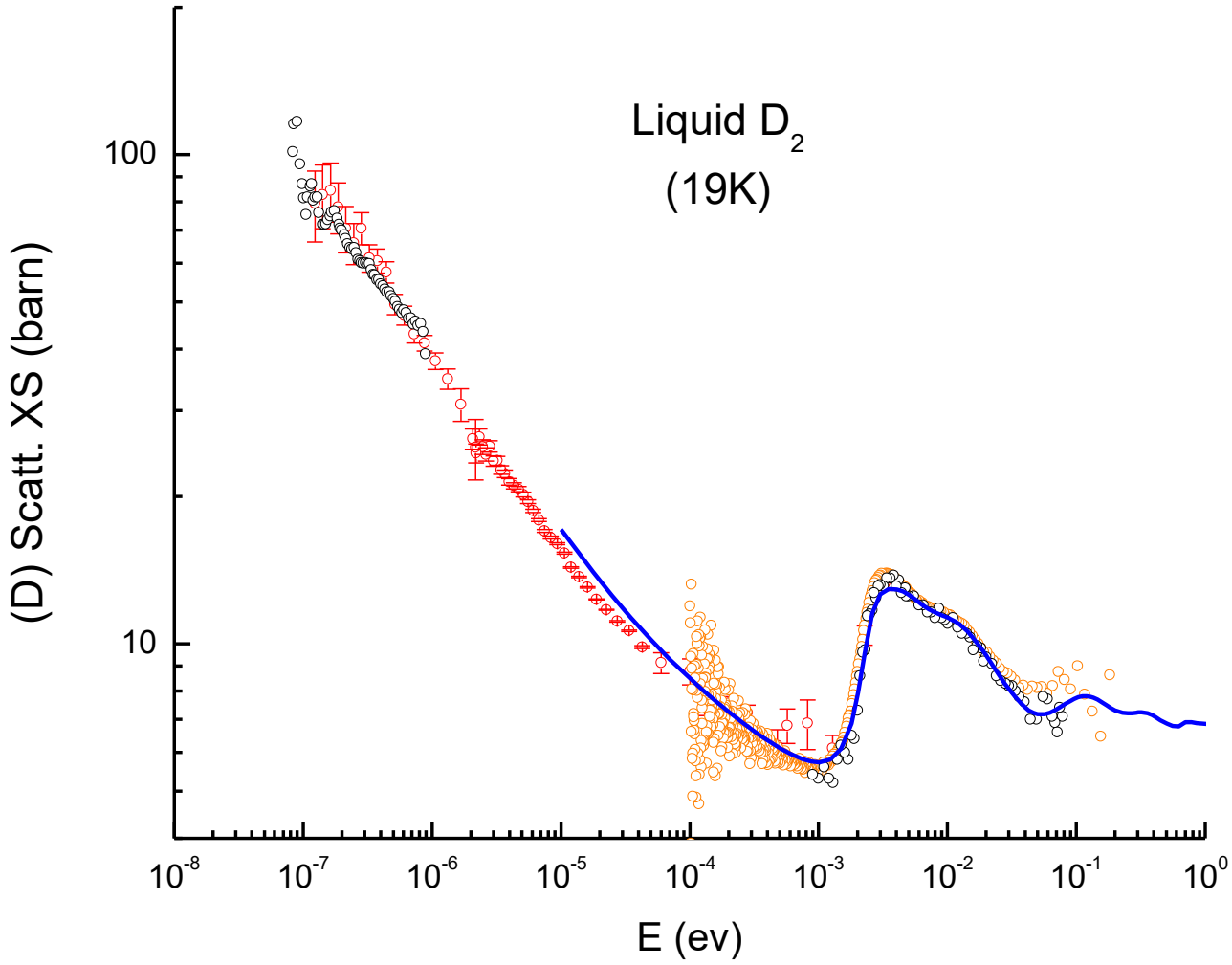

100 pH- 0oH
95 pH- 5 oH
3.5 cm
5.5 cm
8.0 cm
12.0 cm
1E-4
1E-5
Φ(E)
5E-4
1E-3
0.0015
0.002
E (eV)

THE *ORTHO – PARA* RATIO….

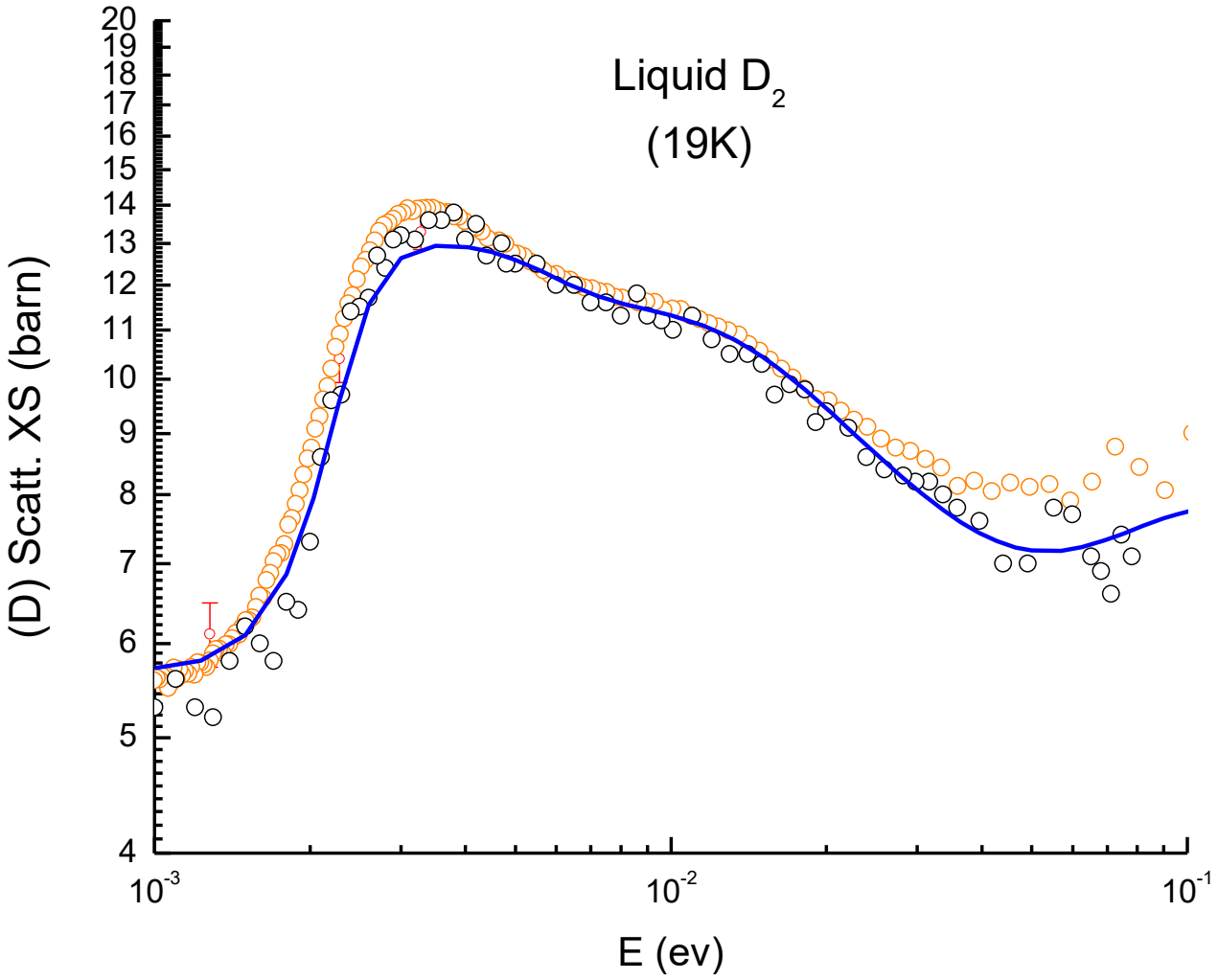


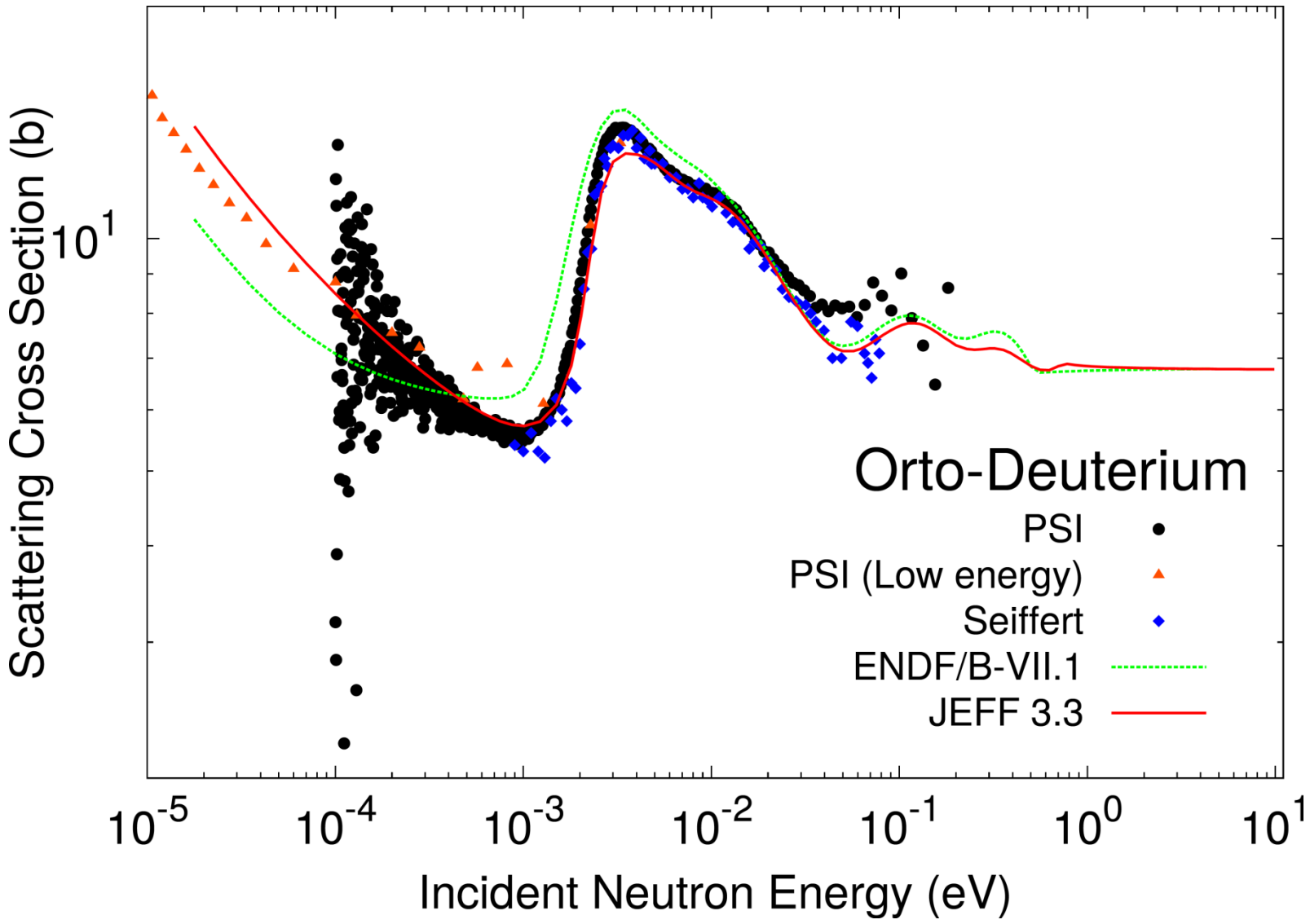
THE *ORTHO – PARA* RATIO….




Liquid D_2
(19K)
(D) Scatt. XS (barn)
100
10
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
E (ev)

LIQUID DEUTERIUM




Scattering Cross Section (b)
10^1
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
Incident Neutron Energy (eV)
Orto-Deuterium
PSI
PSI (Low energy)
Seiffert
ENDF/B-VII.1
JEFF 3.3

SLOW NEUTRON REFLECTORS

STUDIES ON REFLECTOR MATERIALS FOR COLD NEUTRONS

J.R. Granada[1], J.I. Márquez Damián[2] and Ch. Helman[1]

Centro Atómico Bariloche and Instituto Balseiro, 8400 S.C. de Bariloche (RN)

[1]CNEA, Argentina

[2]CONICET, Argentina

CENTRO ATÓMICO BARILOCHE

- ✓ The tremendous potential of slow neutrons as a probe of matter or as a research object by itself is limited by the relatively low flux intensity of the neutron sources.
- ✓ The different processes (production, slowing-down) and devices (moderators, transport systems, collimators, energy-selectors, detectors, etc.) reduce by several orders of magnitude the actual neutron intensity that eventually conveys the experimental information of interest.
- ✓ To minimize part of those loses much effort has been oriented to the search for efficient reflector materials, that may improve the efficiency of guiding surfaces or the actual reflection of neutrons on a containment walls to reduce their leakage.

STUDIES ON DIAMOND NANO-POWDERS

Valery Nesvizhevsky *et al.*, Carbon 130 (2018) 799e805

For the fabrication of efficient slow-neutron reflectors (SNRs), currently there is no alternative to the mimicking of conventional reflectors by means of replacing atoms/nuclei with nanoparticles of low-absorbing highly-scattering materials thus changing the characteristic length scale, and consequently the neutron wavelength corresponding to the efficient neutron reflection

Crystallography Reports, 2016, Vol. 61, No. 1, pp. 84–88.

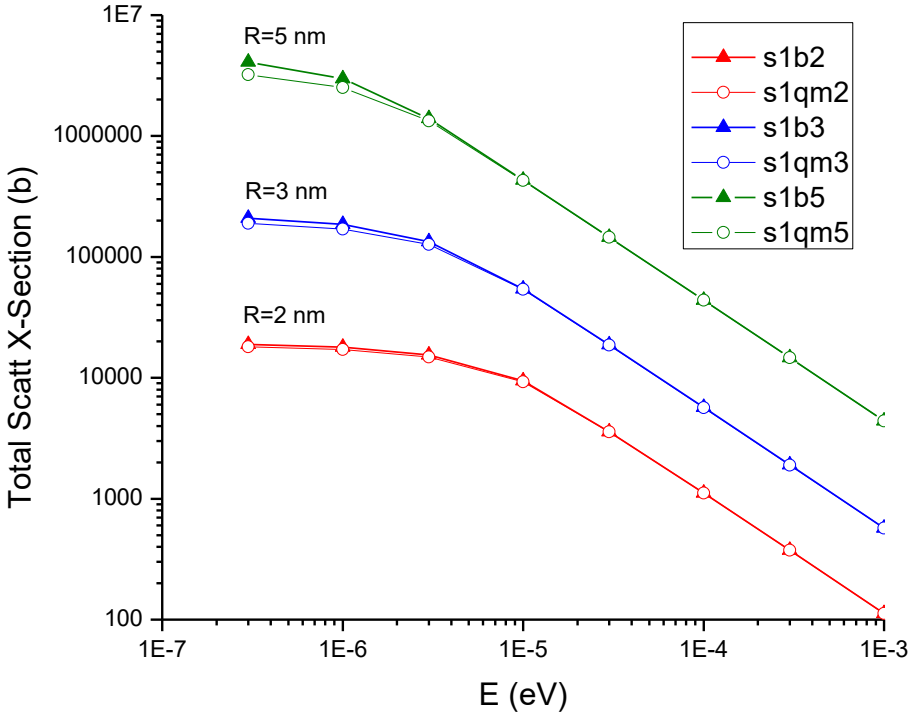
Precise Calculations in Simulations of the Interaction of Low Energy Neutrons with Nano-Dispersed Media[1]

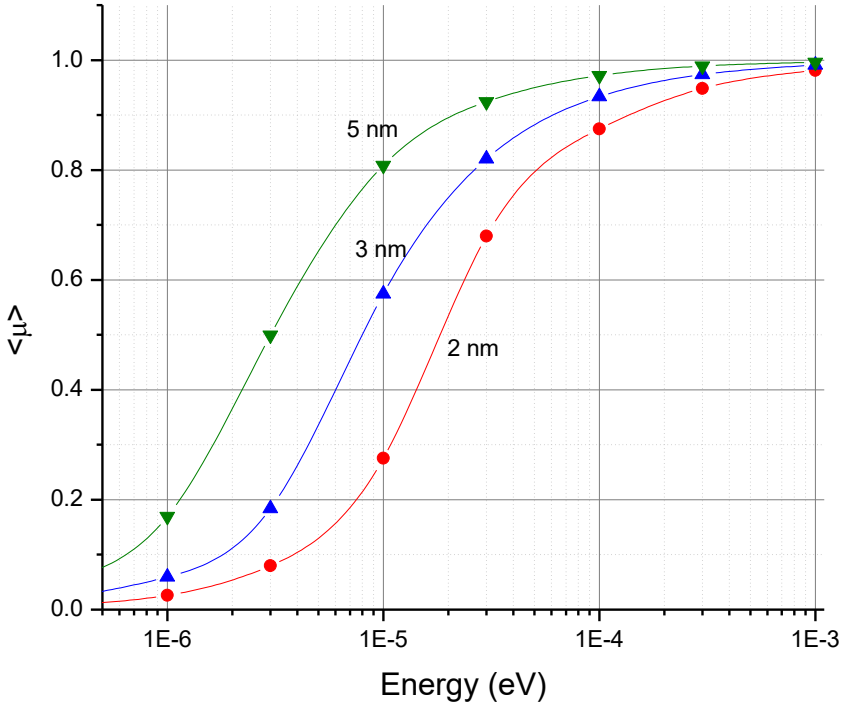
V. A. Artem'ev[a, b], A. Yu. Nezvanov[b], and V. V. Nesvizhevsky[c]

[a] *Research Institute of Materials Technology, Moscow, Russia*

[b] *Moscow State Industrial University, Russia*

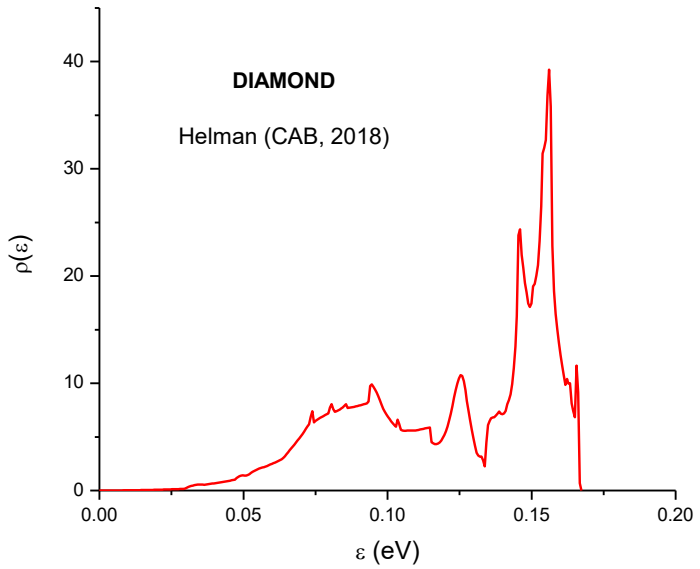
[c] *Institut Max von Laue—Paul Langevin, Grenoble, France*

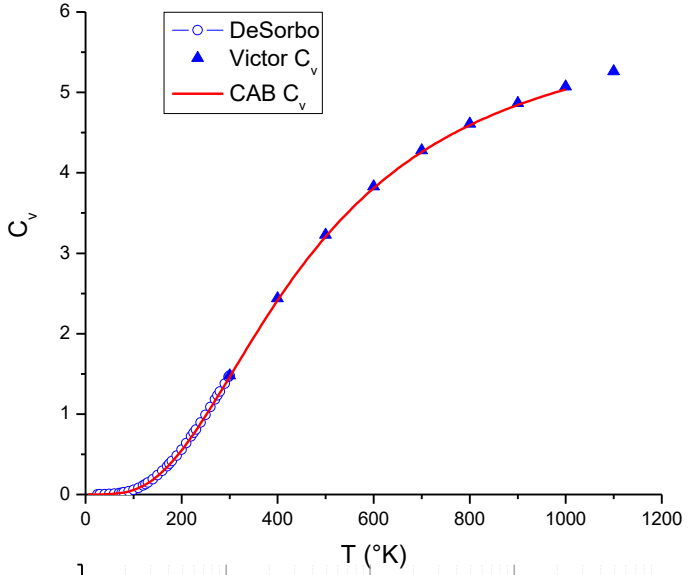


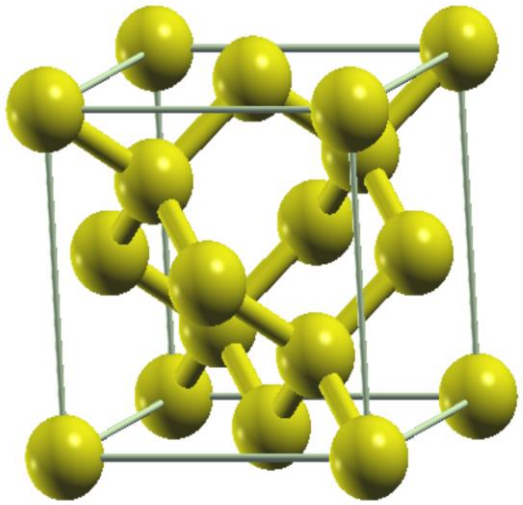


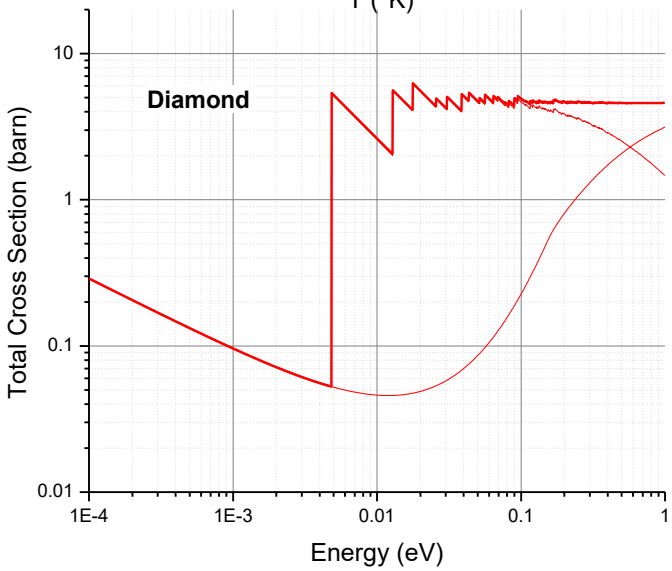
OUR SCATTERING MODEL FOR ND (2.5 nm radius)

The scattering model was developed using NJOY (for the inelastic component) + NCrystal (for the coherent elastic component) + an analytical model of SANS implemented in OpenMC.









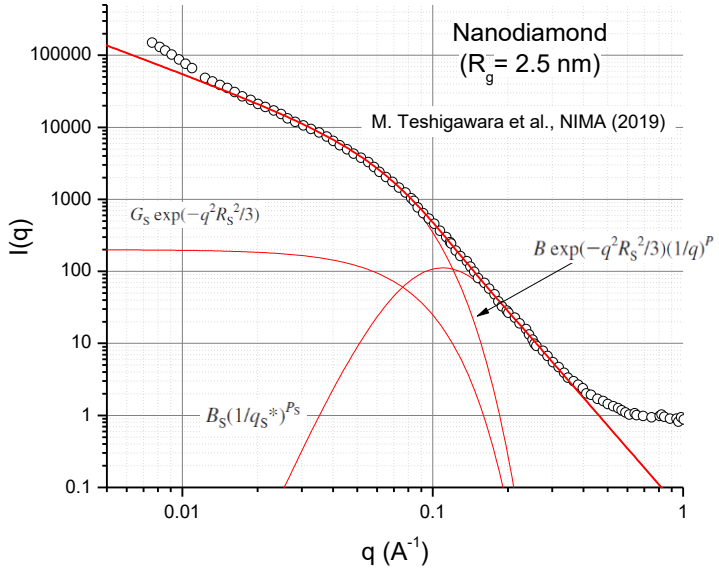
OUR SCATTERING MODEL FOR ND (2.5 nm radius)

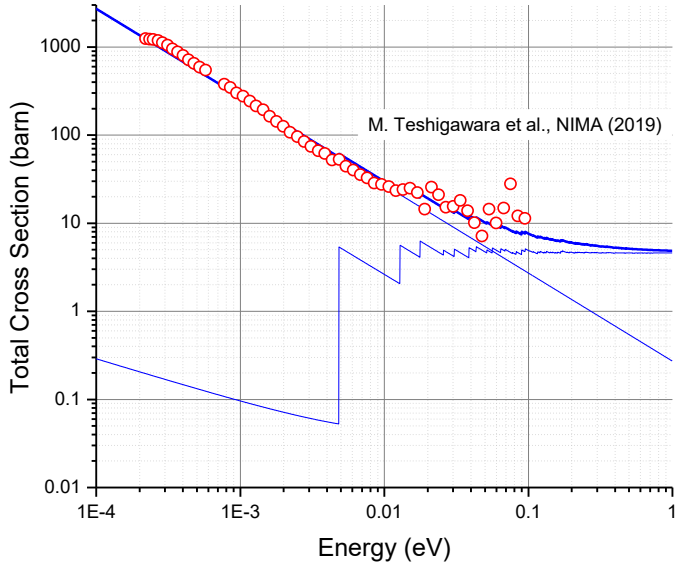
Nuclear Inst. and Methods in Physics Research, A 929 (2019) 113–120

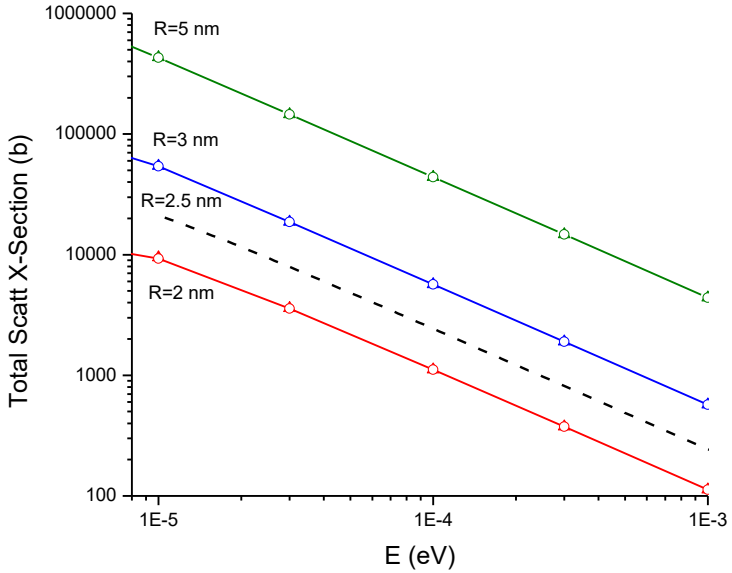
Measurement of neutron scattering cross section of nano-diamond with particle diameter of approximately 5 nm in energy range of 0.2 meV to 100 meV

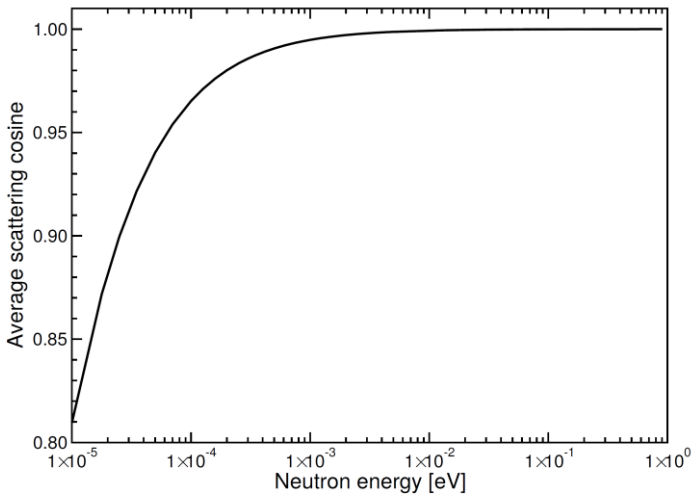
M. Teshigawara [a,*], Y. Tsuchikawa [b], G. Ichikawa [b], S. Takata [a], K. Mishima [c], M. Harada [a], M. Ooi [a], Y. Kawamura [a], T. Kai [a], S. Ohira-Kawamura [a], K. Nakajima [a], Y. Ikeda [a], Y. Kiyanagi [b]

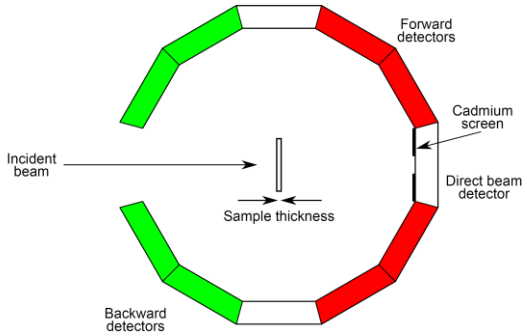
(R_g = 2.5 nm)



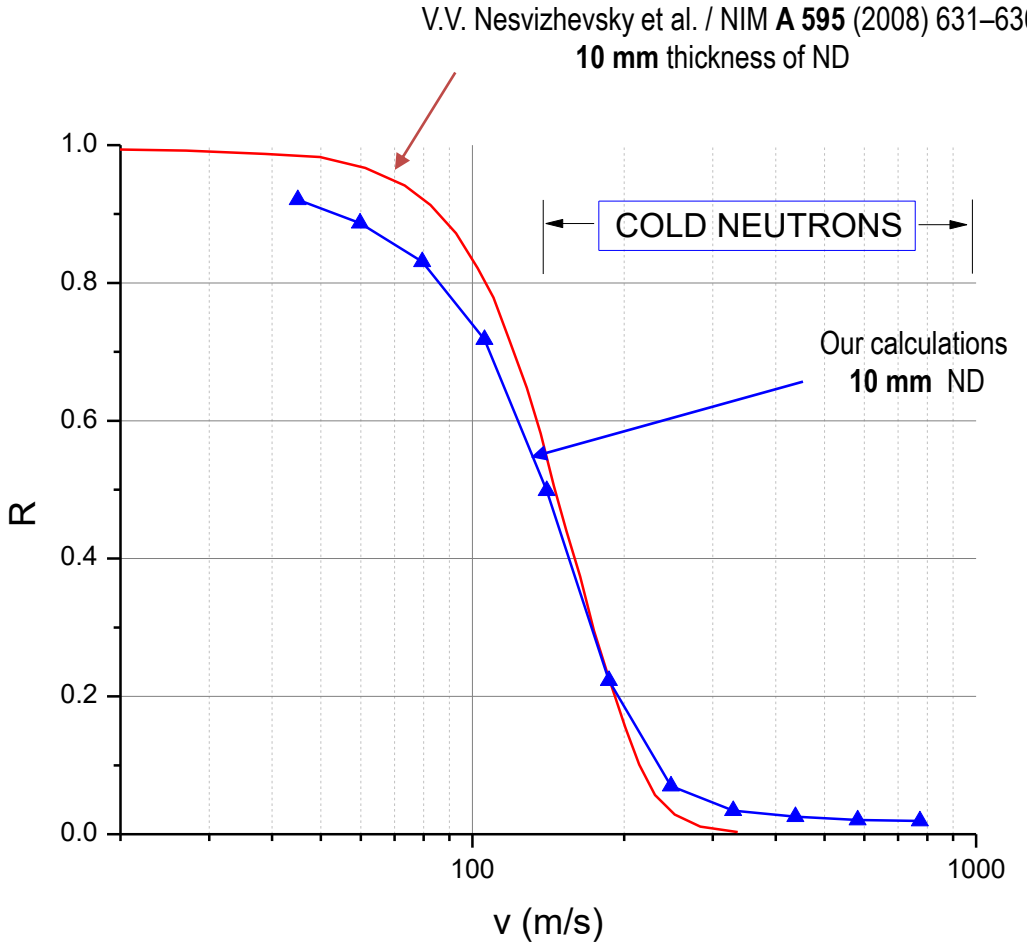








$\rho_{ND} = 0.6\ g/cm^3$



INGREDIENTS FOR A COLD NEUTRON REFLECTOR

LARGE SCATTERING CROSS SECTION (Coherent + Incoherent)

LARGE ELASTIC CROSS SECTIONS

HIGHLY ISOTROPIC ANGULAR CROSS SECTION

LARGE [ELASTIC/INELASTIC] CROSS SECTIONS RATIO

SMALL ABSORPTION CROSS SECTION

INGREDIENTS FOR A COLD NEUTRON REFLECTOR

LARGE SCATTERING CROSS SECTION	HYDROGEN (σ_s = 82.02 b)
LARGE ELASTIC CROSS SECTIONS	SOLID
HIGHLY ISOTROPIC ANGULAR CROSS SECTION	LARGE EFFECTIVE MASS
LARGE [ELASTIC/INELASTIC] CROSS SECTIONS RATIO	NO LOW-FREQUENCY MODES
SMALL ABSORPTION CROSS SECTION	

International Collaboration on Advanced Neutron Sources
March 4 – 9, 2012
Bariloche, Argentina

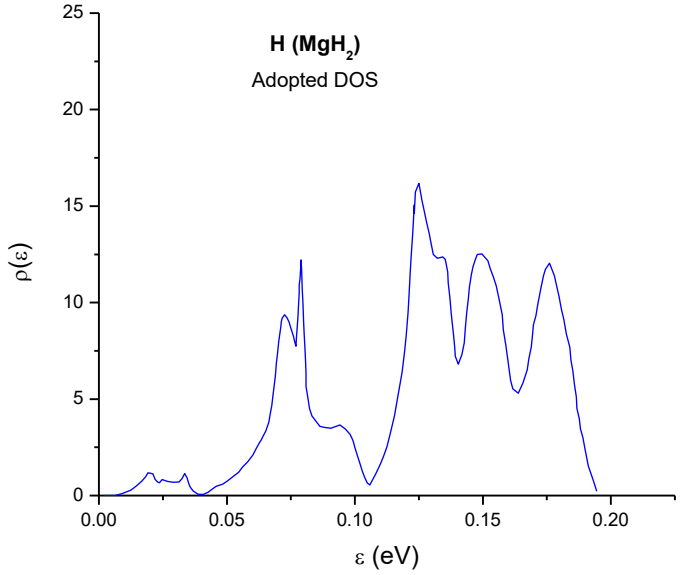
New Design of a Compact Cryogenic Neutron Moderator

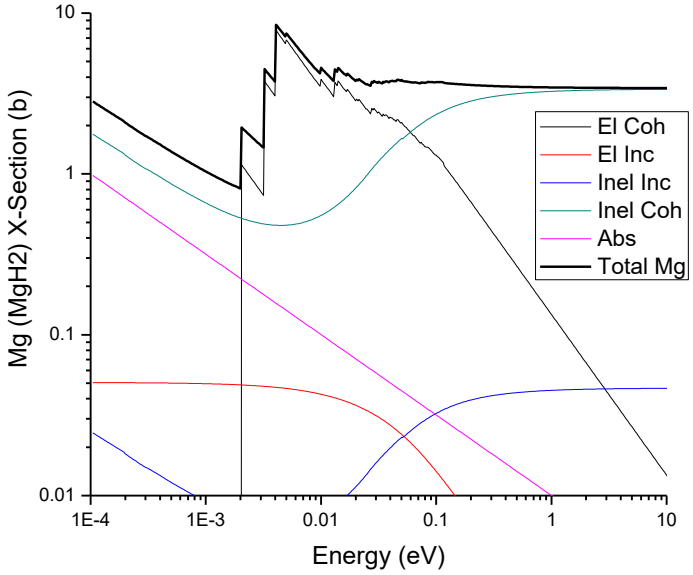
Rolando Granada et al.

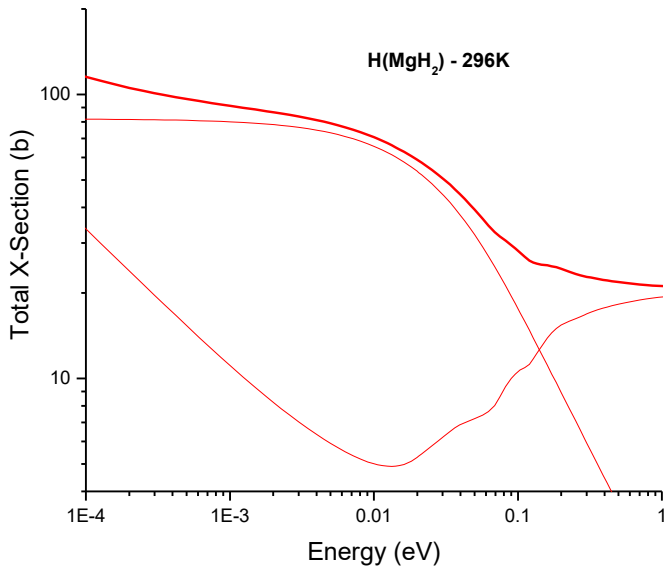
SOME PRELIMINARY CONCLUSIONS

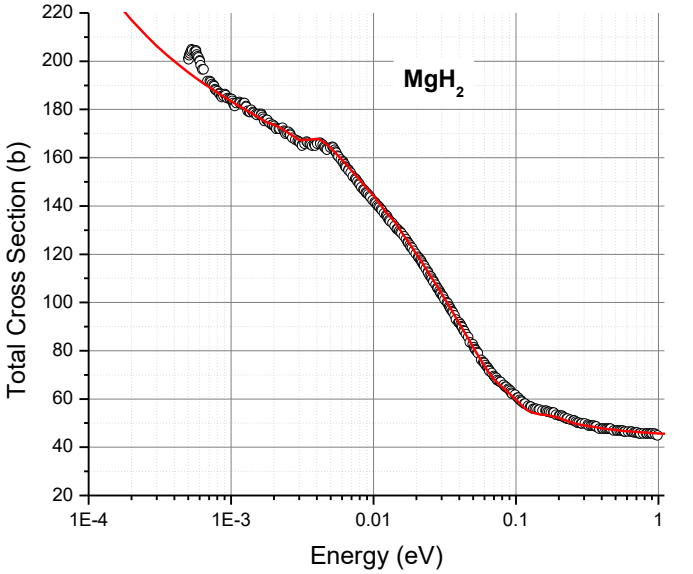
► Low temperature **Magnesium Hydride** is an excellent reflector

OUR SCATTERING MODEL FOR MgH_2

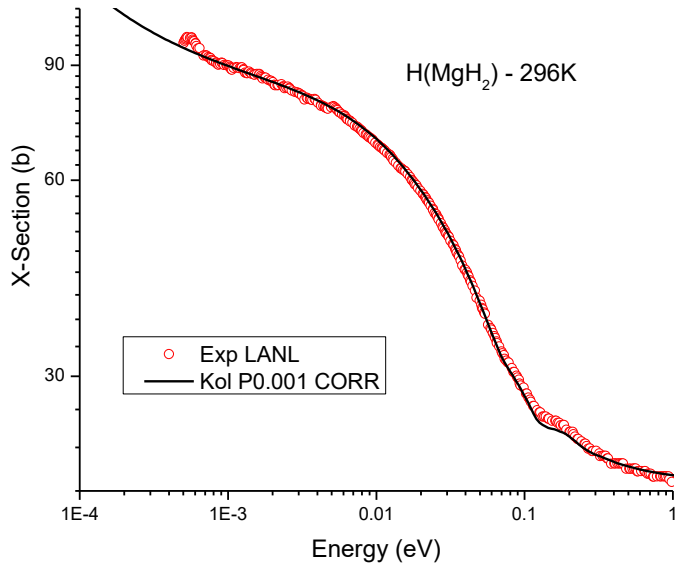


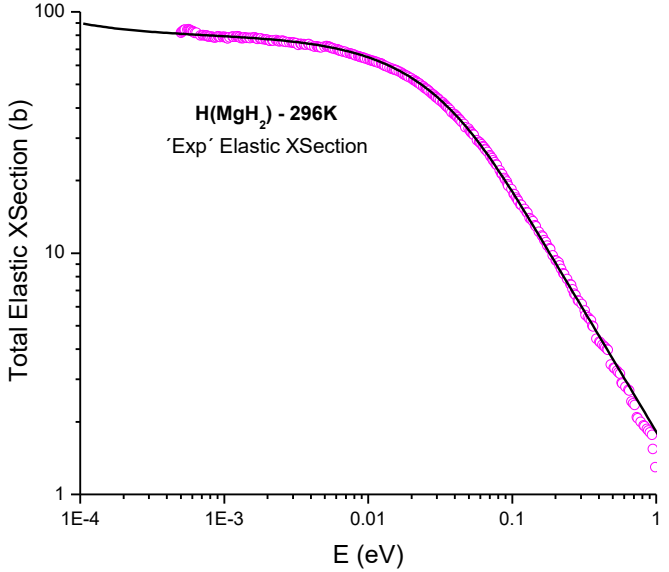


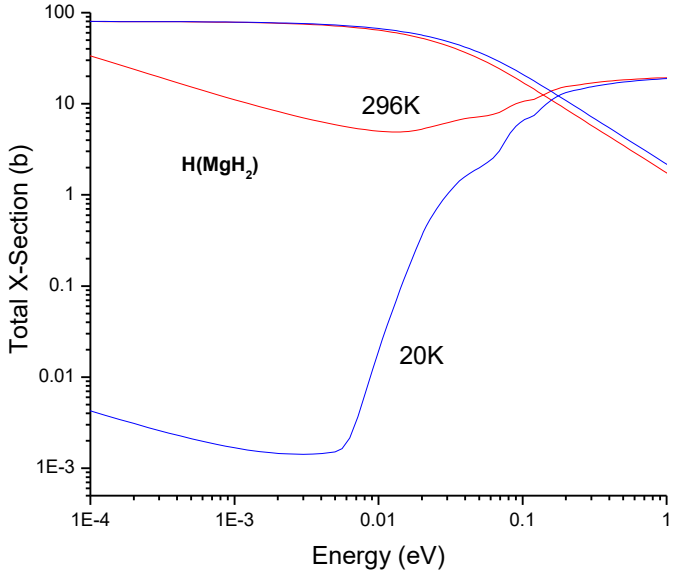


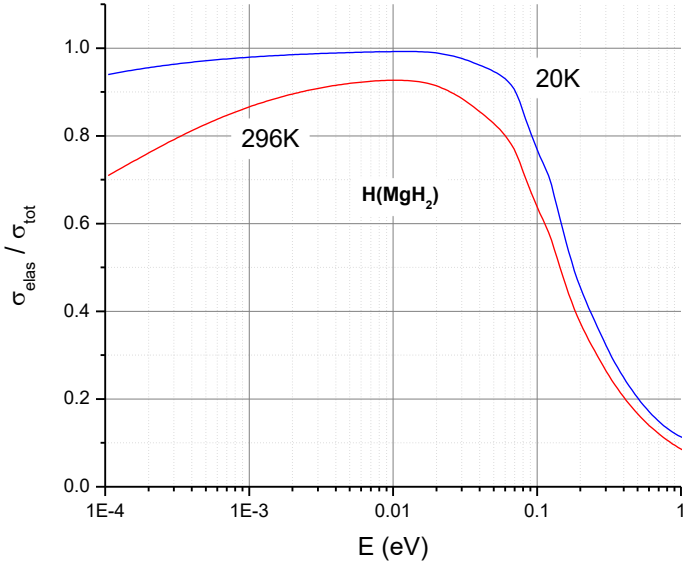


Nuclear Instruments and Methods in Physics Research A 629 (2011) 251–259

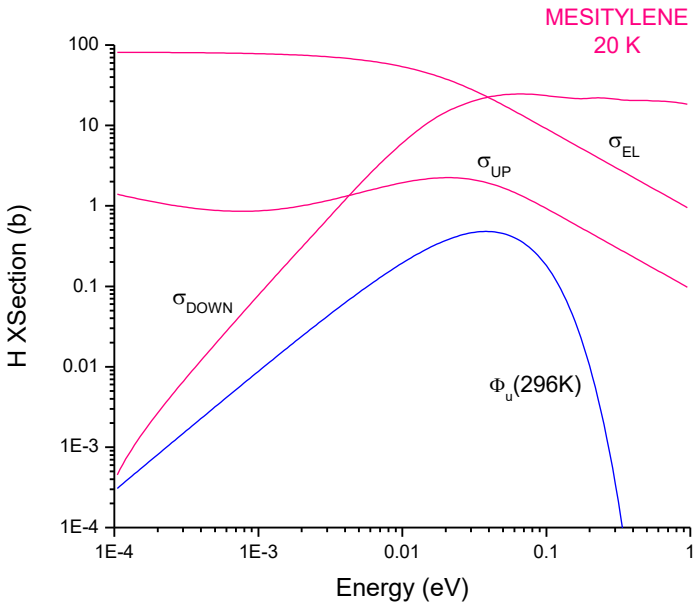

H(MgH2) - 296K
X-Section (b)
90
60
30
Exp LANL
Kol P0.001 CORR
1E-4
1E-3
0.01
0.1
1
Energy (eV)


100
10
1
H(MgH2) - 296K
´Exp´ Elastic XSection
Total Elastic XSection (b)
1E-4
1E-3
0.01
0.1
1
E (eV)

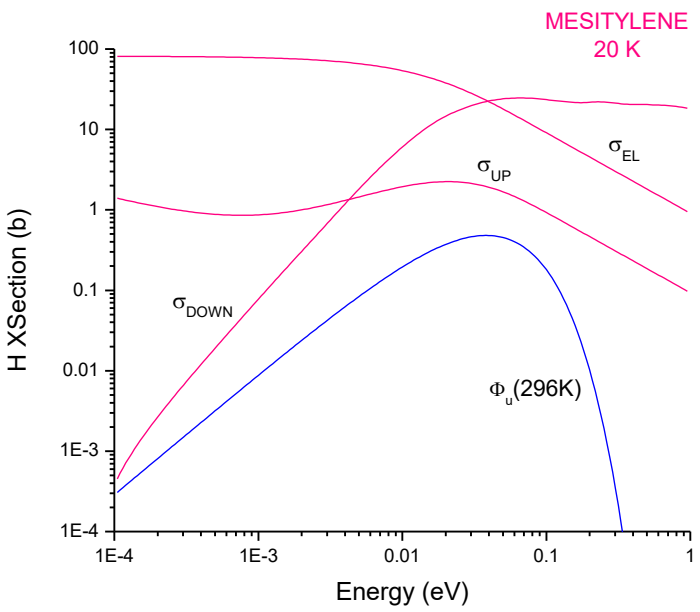

100
10
1
0.1
0.01
1E-3
296K
H(MgH2)
20K
Total X-Section (b)
1E-4
1E-3
0.01
0.1
1
Energy (eV)


1.0
0.8
0.6
0.4
0.2
0.0
20K
296K
H(MgH2)
σelas / σtot
1E-4
1E-3
0.01
0.1
1
E (eV)

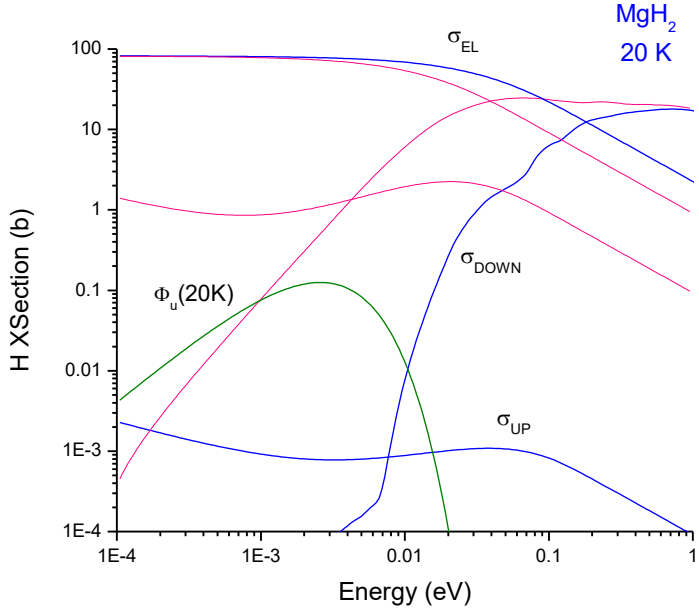
A GOOD COLD NEUTRON MODERATOR….



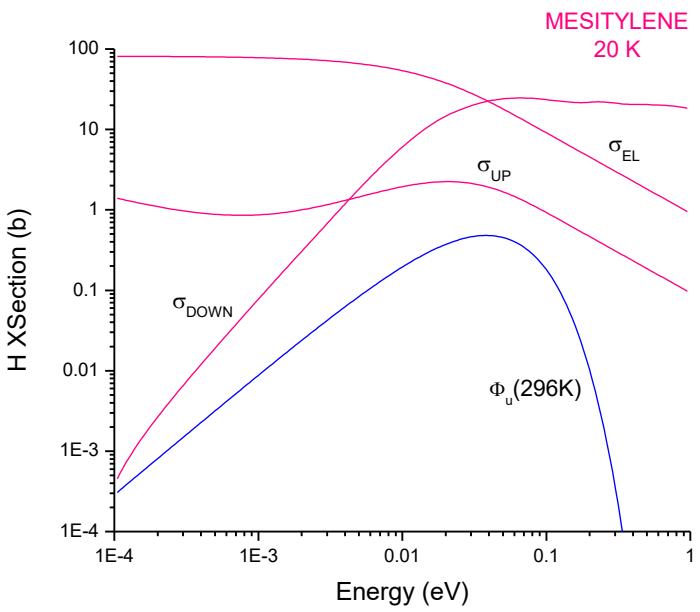
A GOOD COLD NEUTRON MODERATOR….

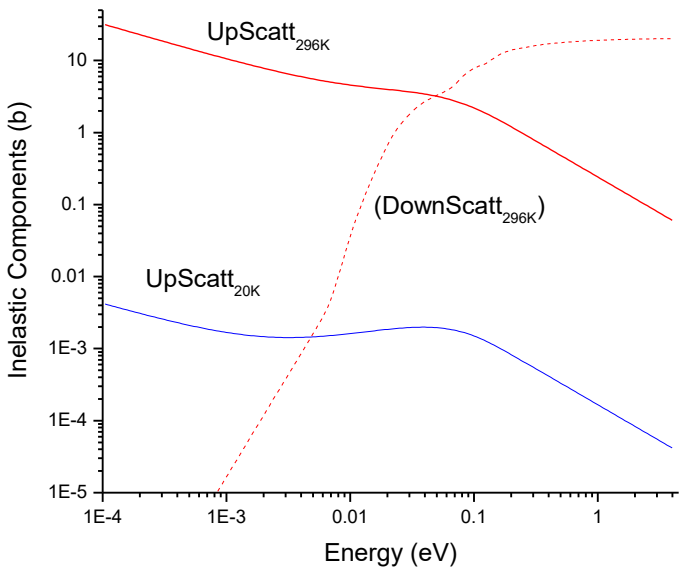


AND A GOOD COLD NEUTRON REFLECTOR…?

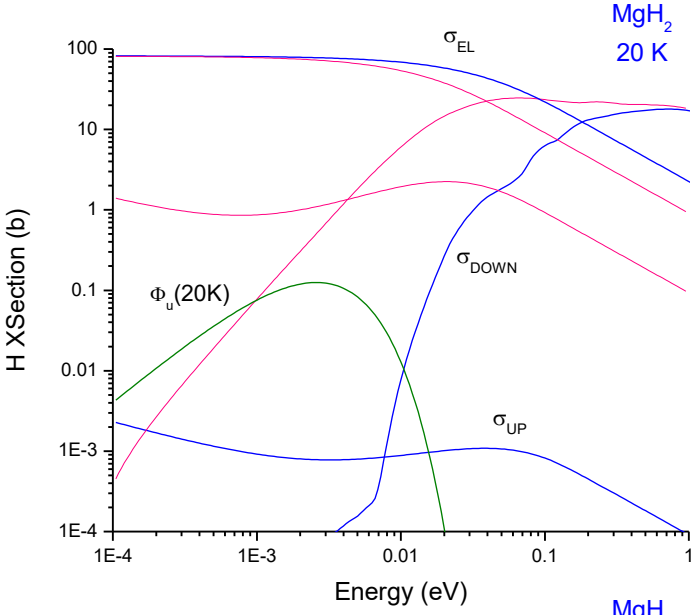


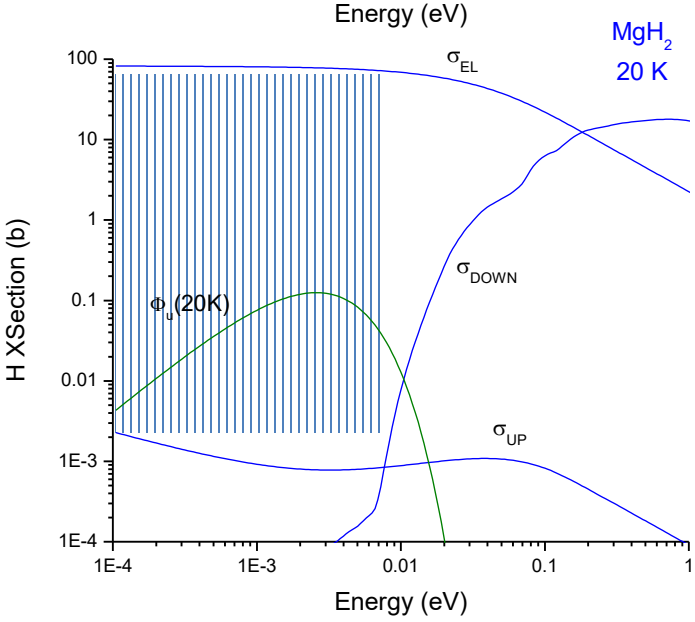
A GOOD COLD NEUTRON MODERATOR….



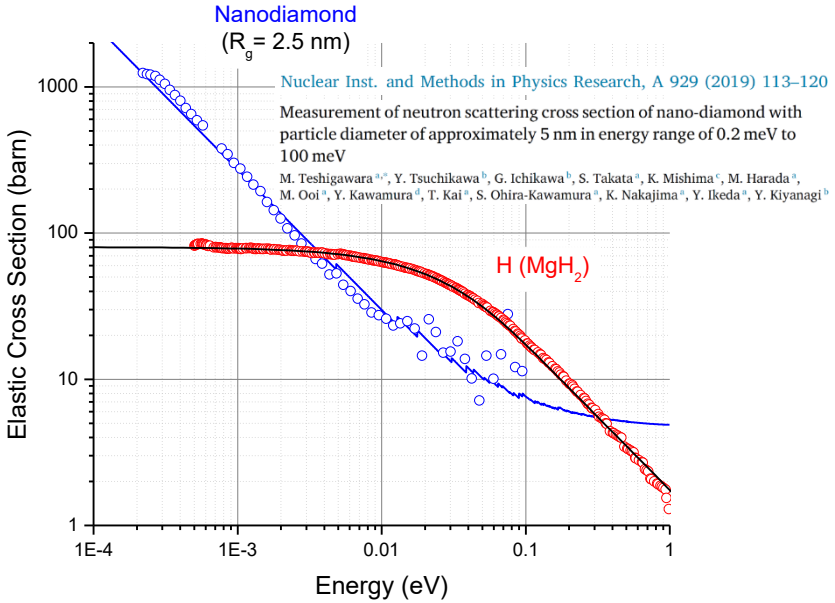


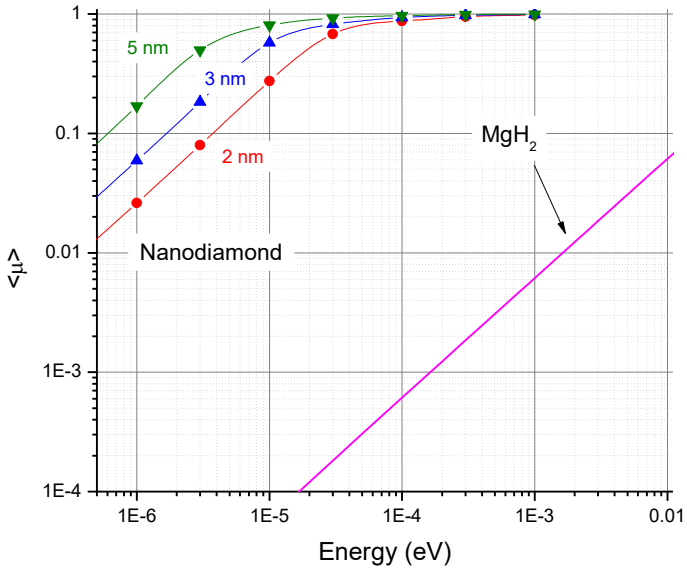
AND A GOOD COLD NEUTRON REFLECTOR…?

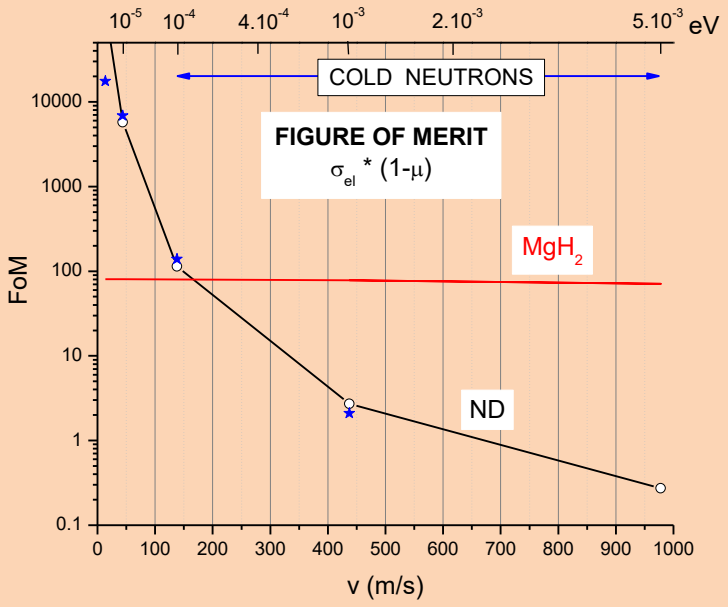


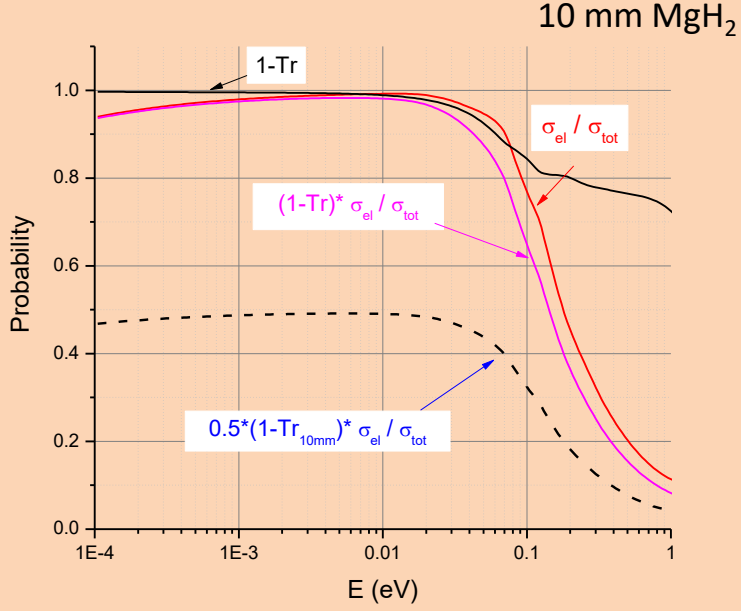


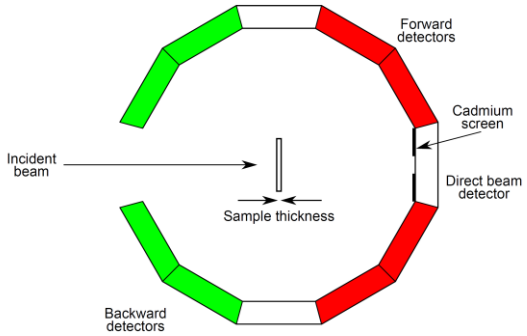
FACTS AND THOUGHTS…



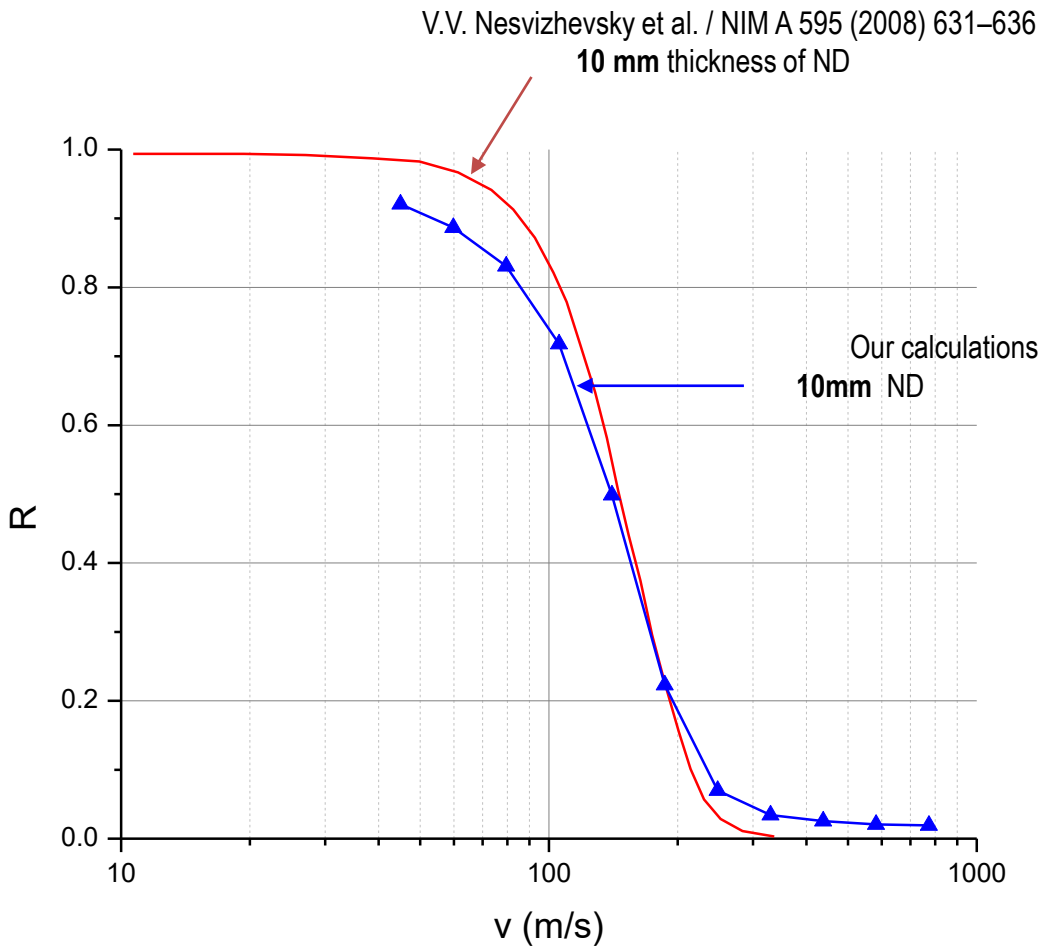


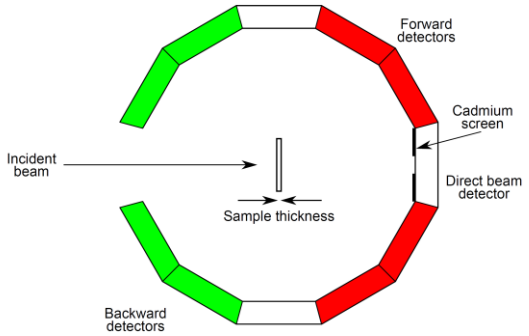






REFLECTIVITY CALCULATIONS



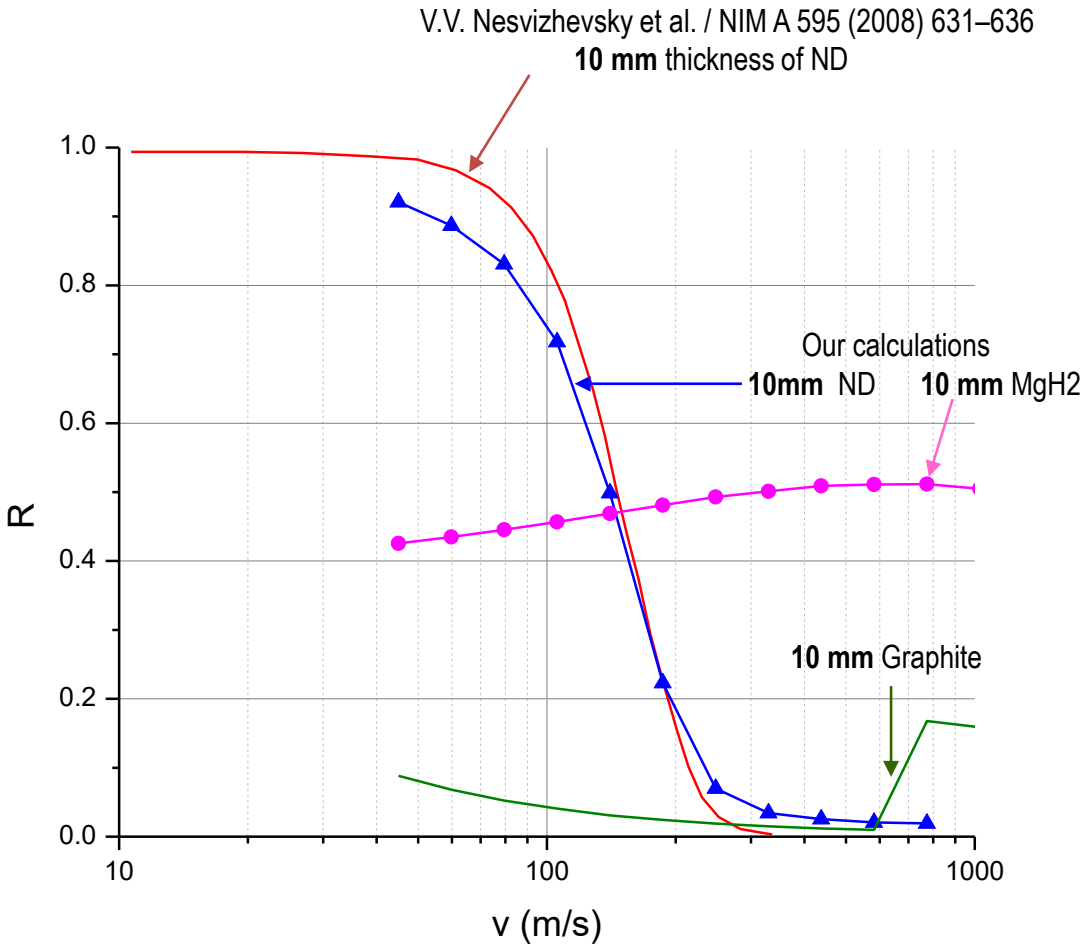


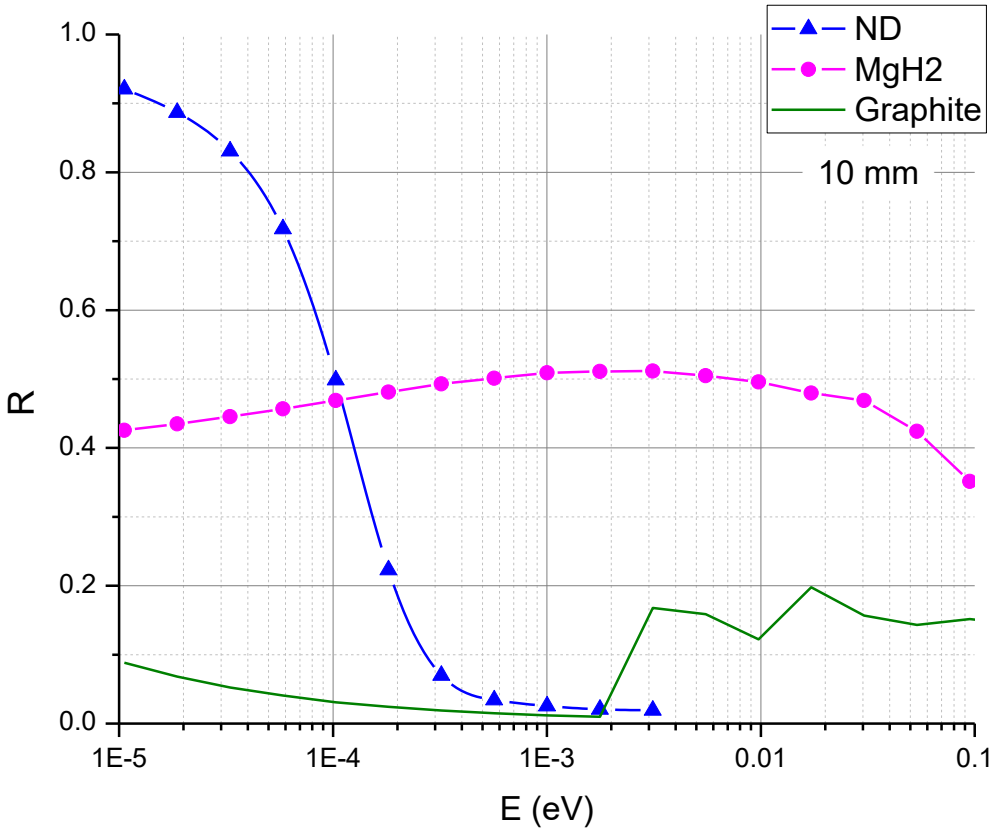
Comparison of backscattering neutron current with a 10 mm sample of nanodiamonds, MgH2 at 20 K, and graphite in the configuration used by Nesvizhevsky.

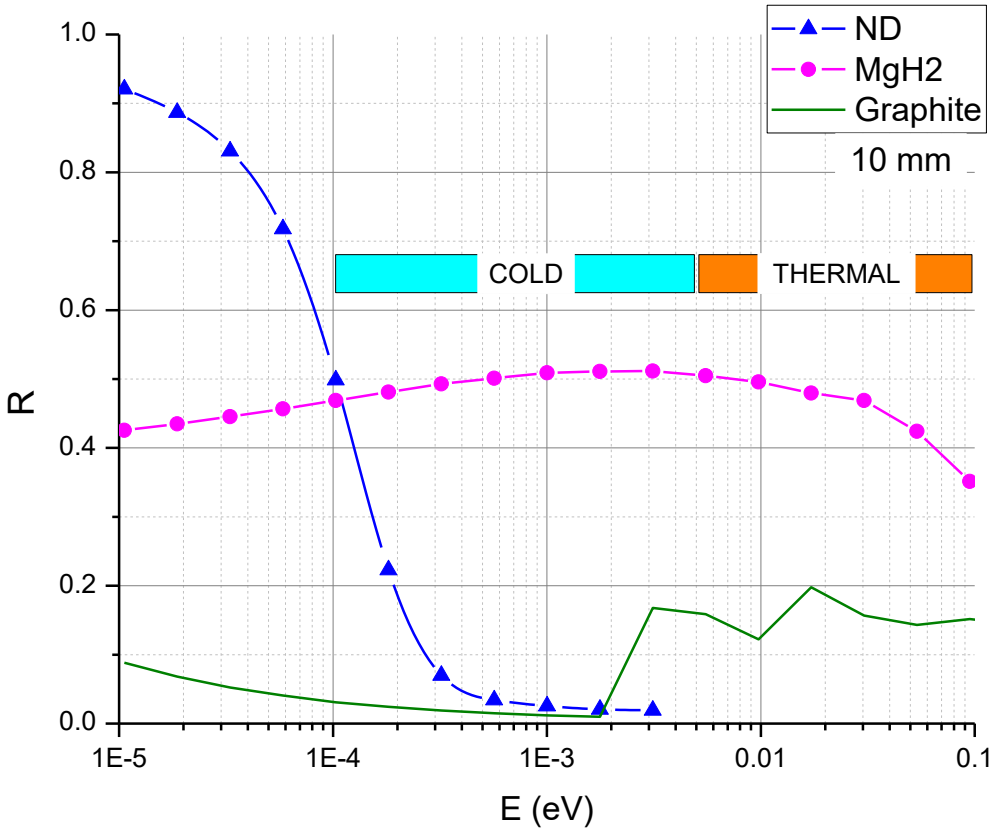
The calculations were performed using OpenMC and our kernels for those materials.

$\rho_{ND} = 0.6\ g/cm^3$

$\rho_{MgH2} = 1\ g/cm^3$

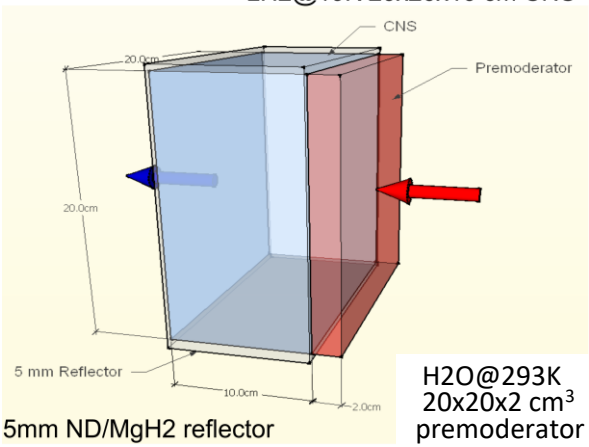



ND
MgH2
Graphite
10 mm
R
E (eV)
1.0
0.8
0.6
0.4
0.2
0.0
1E-5
1E-4
1E-3
0.01
0.1


ND
MgH2
Graphite
10 mm
COLD
THERMAL
R
E (eV)
1.0
0.8
0.6
0.4
0.2
0.0
1E-5
1E-4
1E-3
0.01
0.1

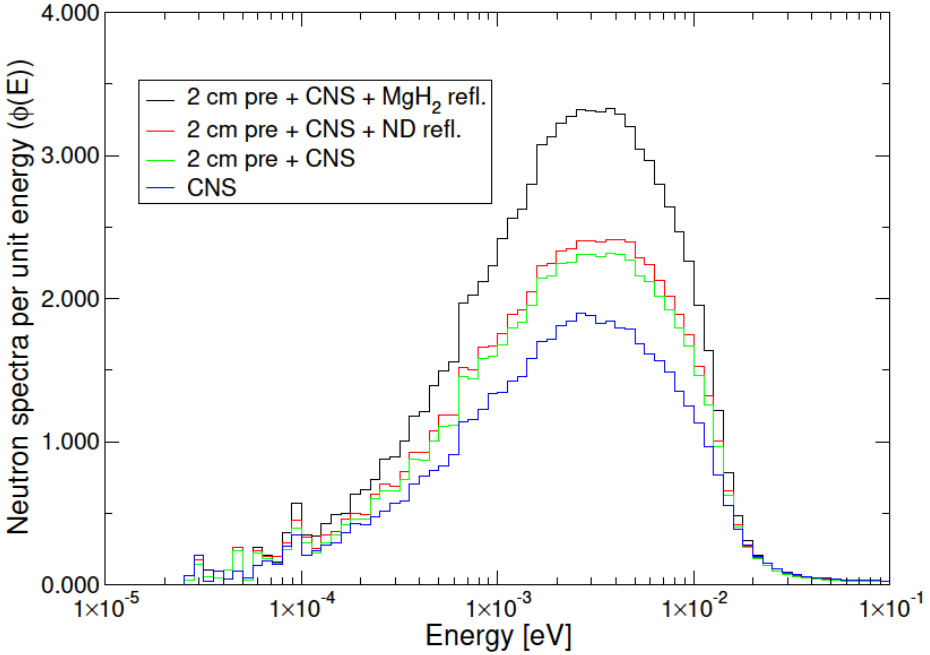
CNS CALCULATIONS

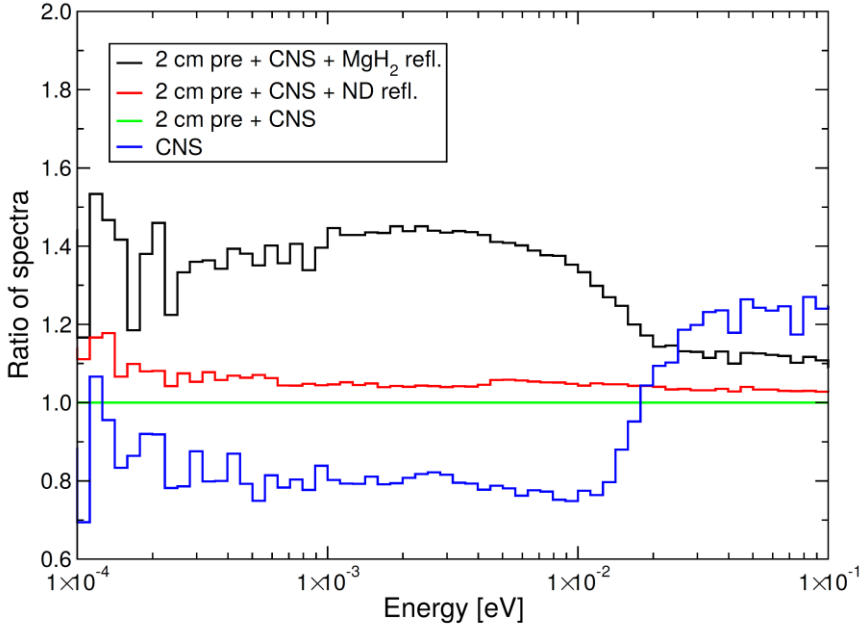
LH2@19K 20x20x10 cm CNS

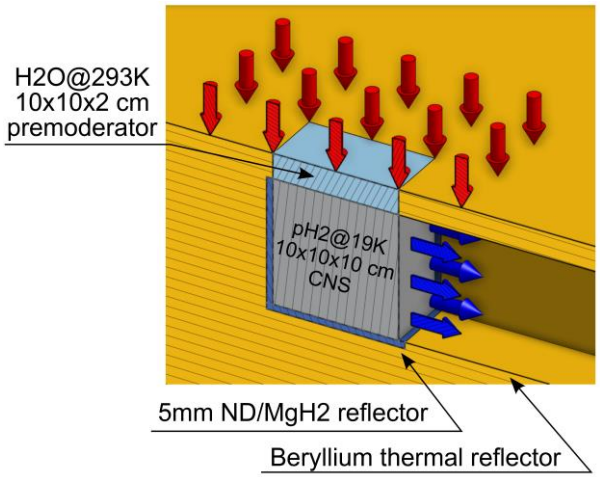


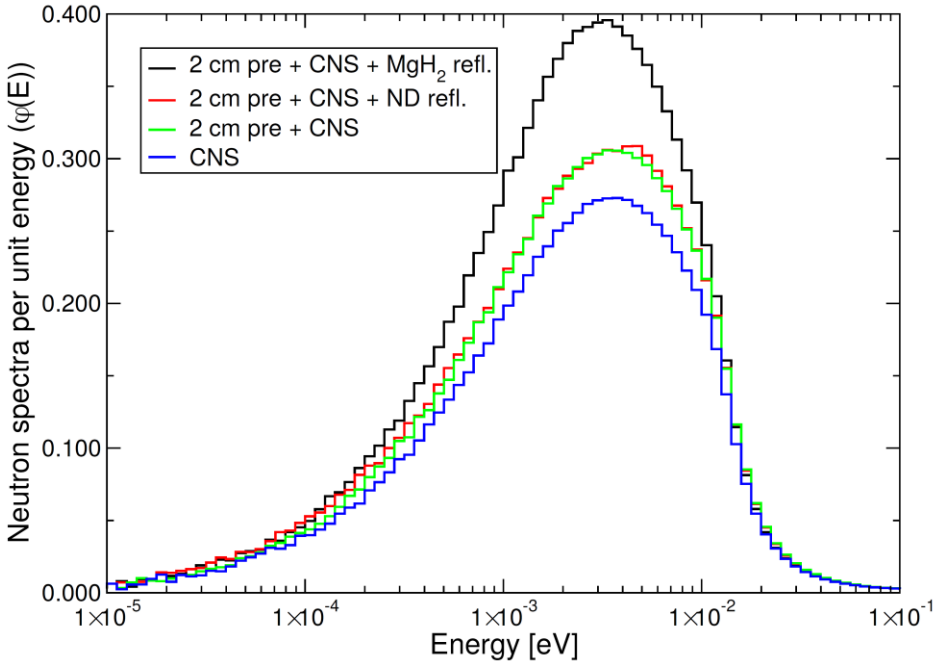
5mm ND/MgH2 reflector

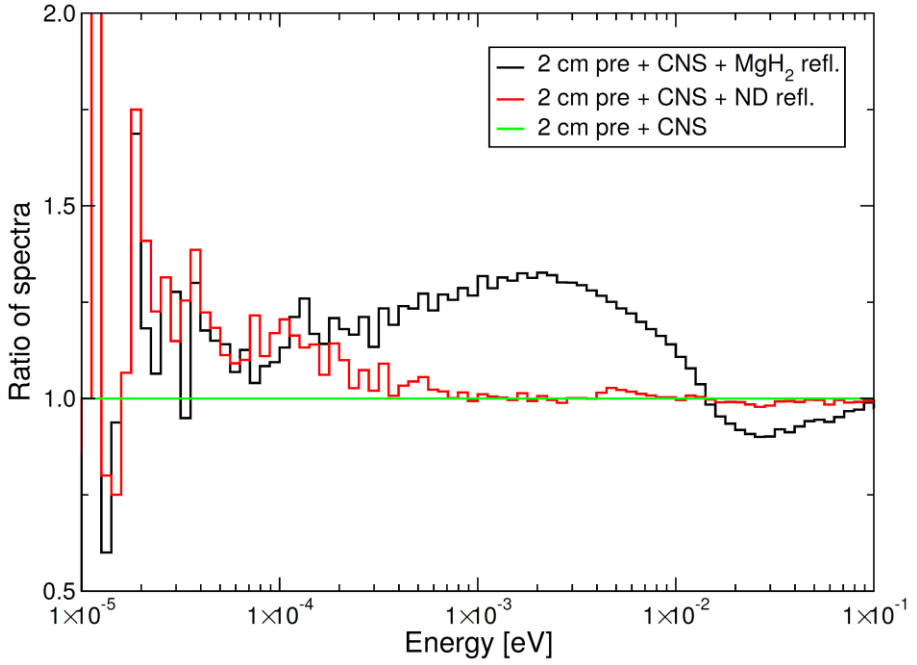
H2O@293K
20x20x2 cm^3
premoderator



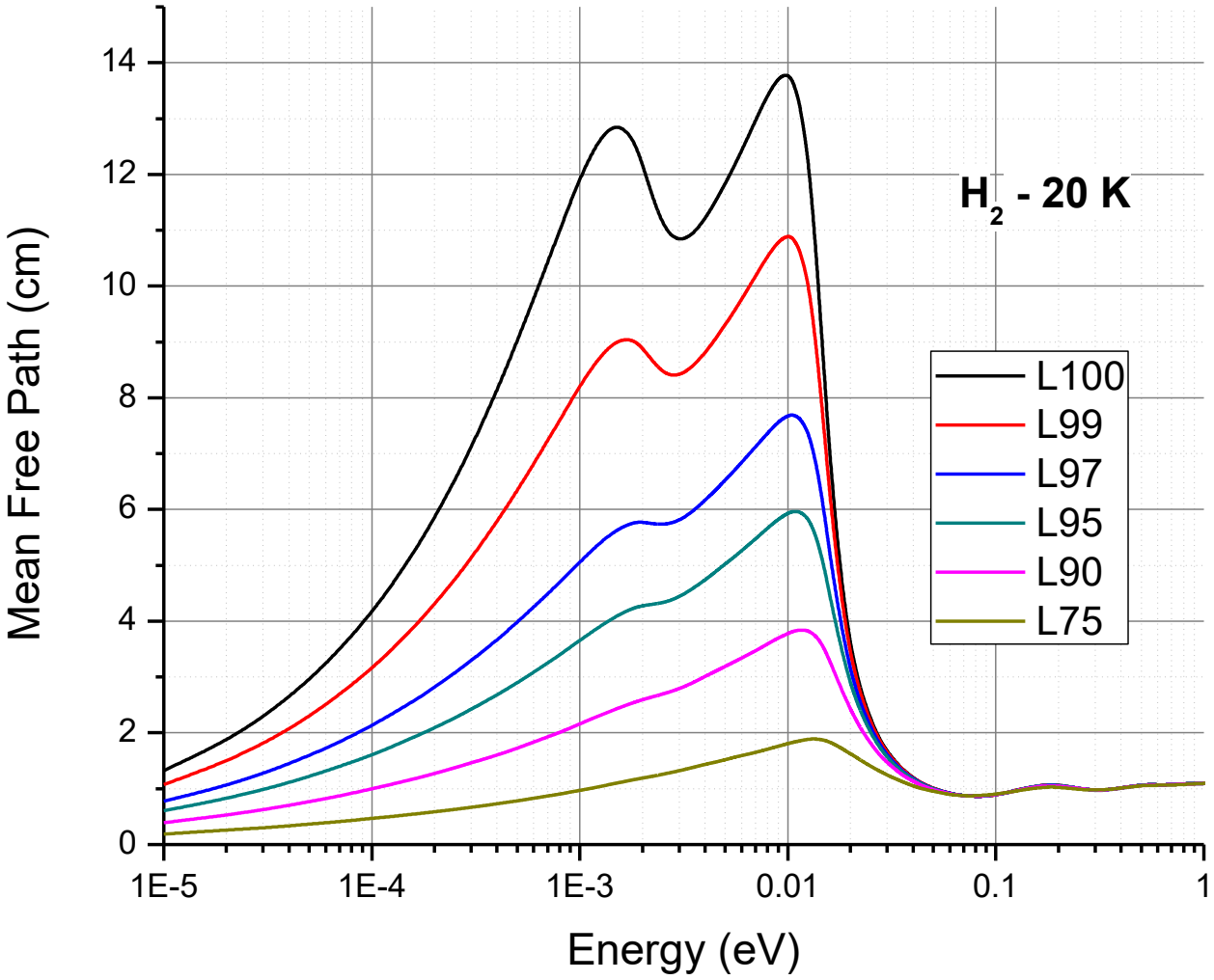


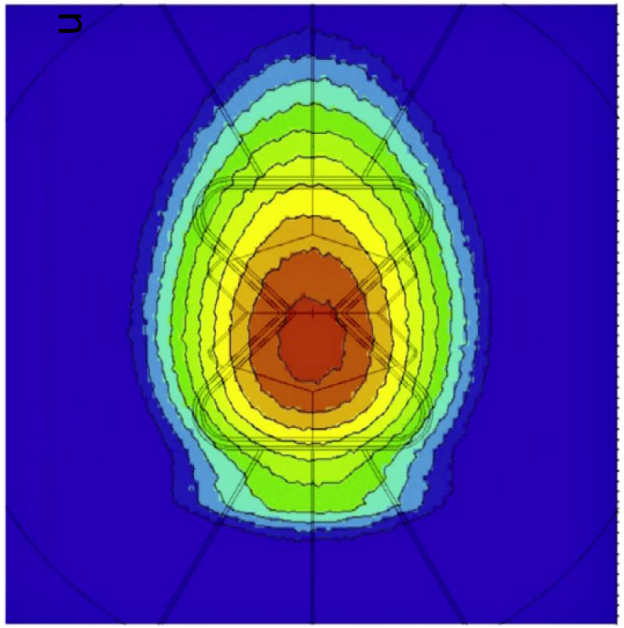

H2O@293K
10x10x2 cm
premoderator
pH2@19K
10x10x10 cm
CNS
5mm ND/MgH2 reflector
Beryllium thermal reflector

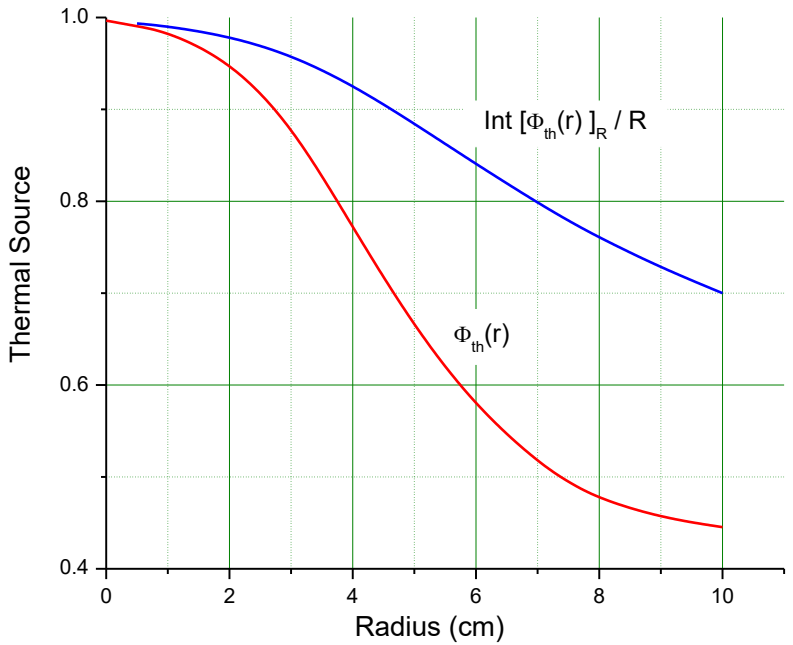

2 cm pre + CNS + MgH2 refl.
2 cm pre + CNS + ND refl.
2 cm pre + CNS
CNS
Neutron spectra per unit energy (φ(E))
Energy [eV]
0.400
0.300
0.200
0.100
0.000
1×10-5
1×10-4
1×10-3
1×10-2
1×10-1

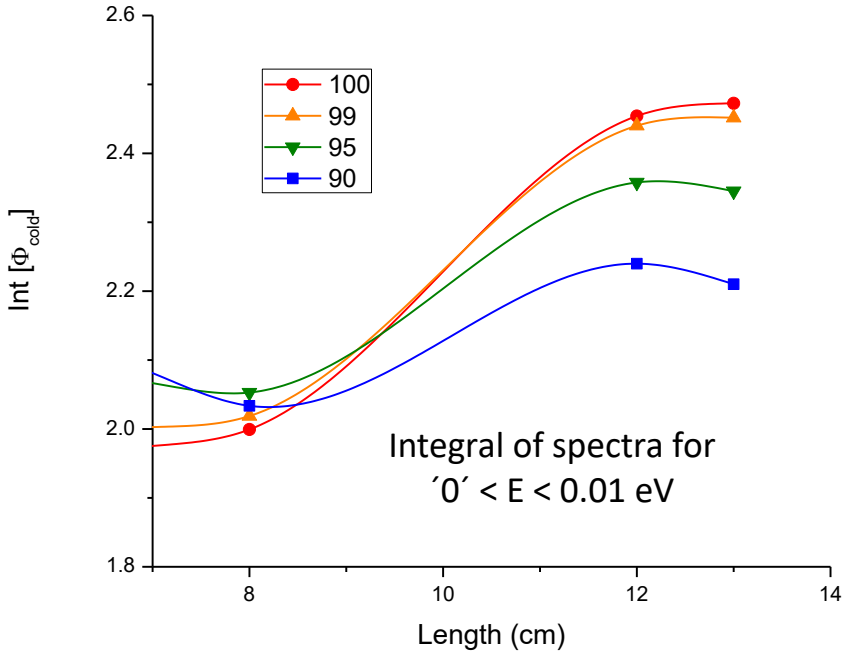

2 cm pre + CNS + MgH2 refl.
2 cm pre + CNS + ND refl.
2 cm pre + CNS
Ratio of spectra
Energy [eV]
2.0
1.5
1.0
0.5
1×10-5
1×10-4
1×10-3
1×10-2
1×10-1

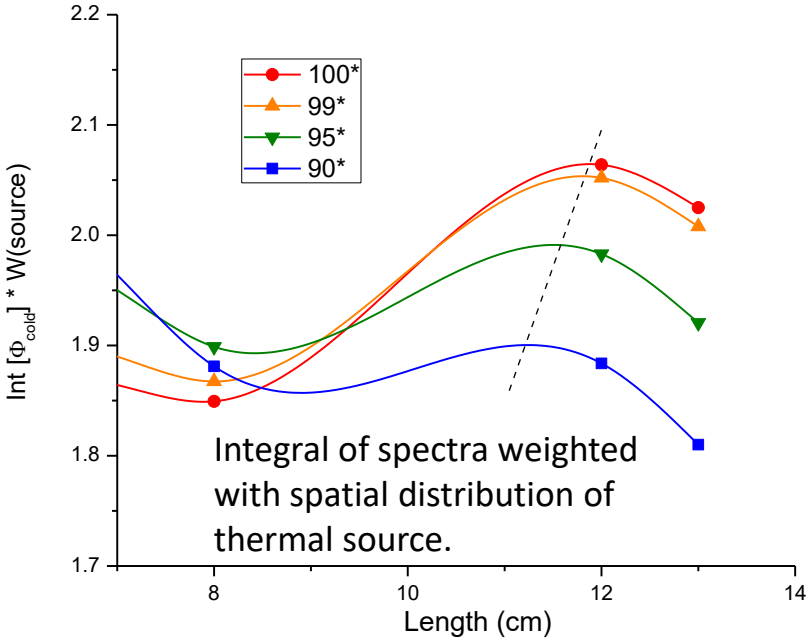
IDEAS FOR AN EFFICIENT COLD (& THERMAL) NEUTRON MODERATOR

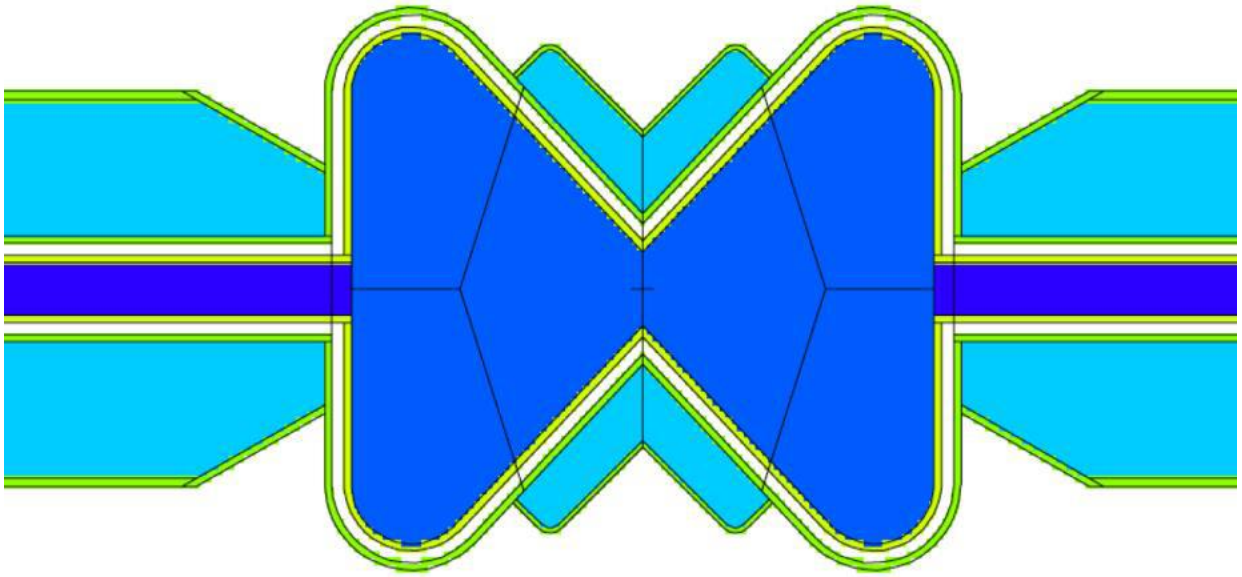

Mean Free Path (cm)
Energy (eV)
H2 - 20 K
L100
L99
L97
L95
L90
L75
0
2
4
6
8
10
12
14
1E-5
1E-4
1E-3
0.01
0.1
1


u

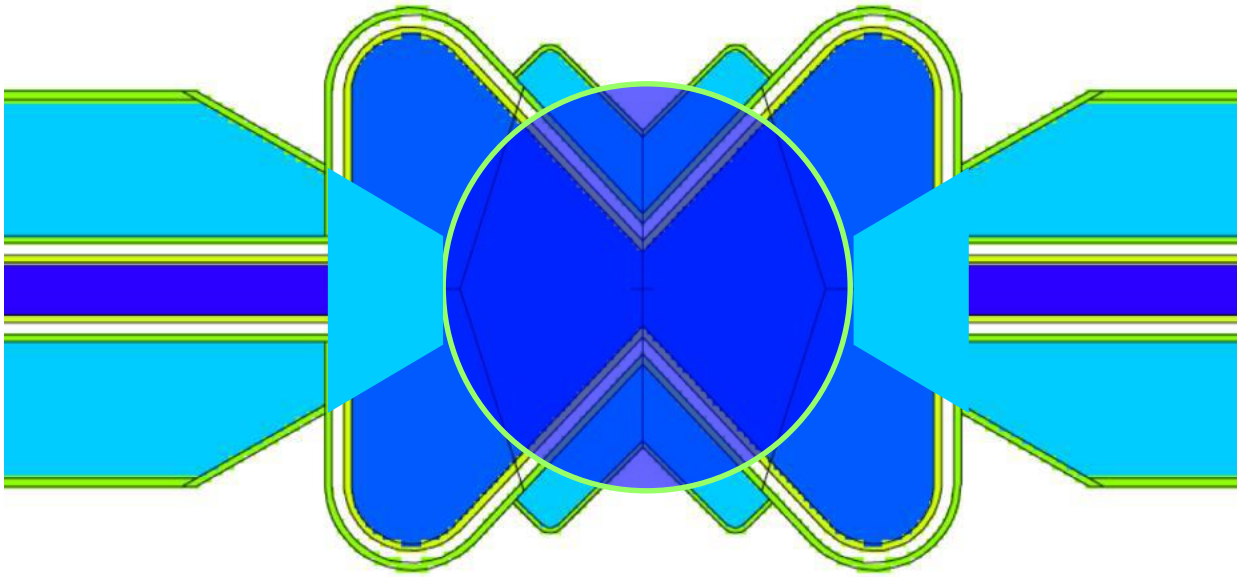

Thermal Source
Int [Φth(r)]R / R
Φth(r)
Radius (cm)


Int [Φcold]
100
99
95
90
Integral of spectra for
´0´ < E < 0.01 eV
Length (cm)

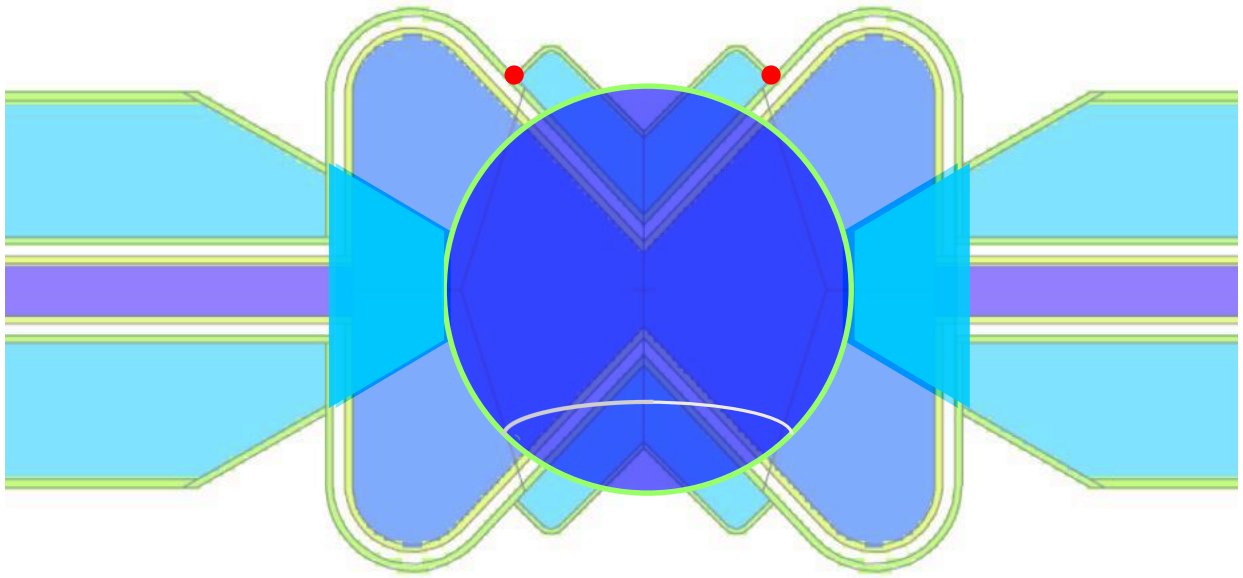

Int [Φcold] * W(source)
100*
99*
95*
90*
Integral of spectra weighted
with spatial distribution of
thermal source.
Length (cm)



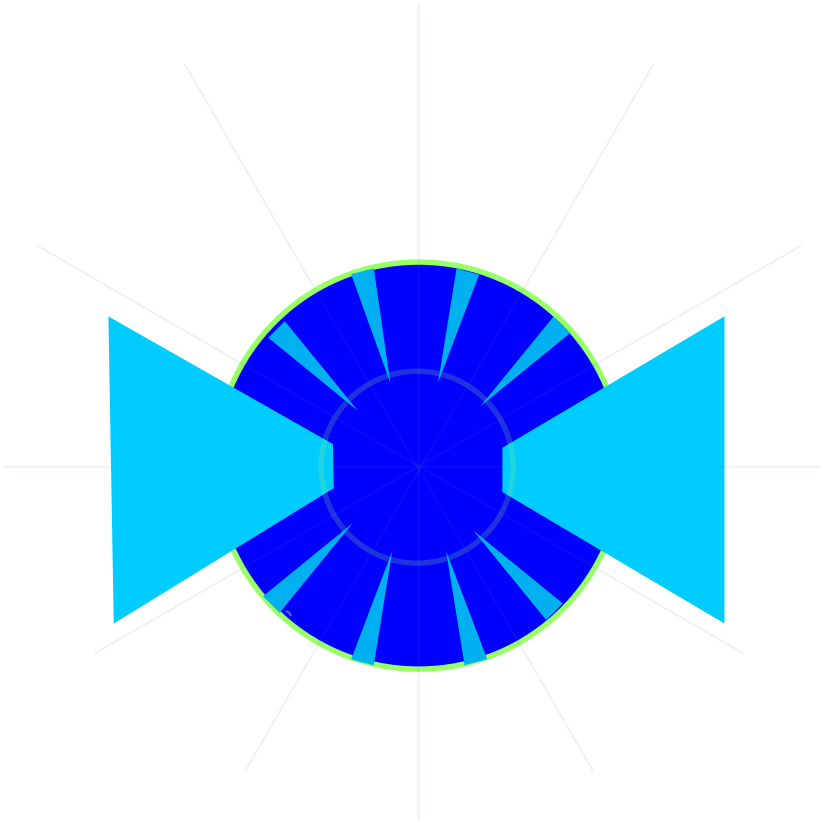
The ESS Butterfly 1 moderator



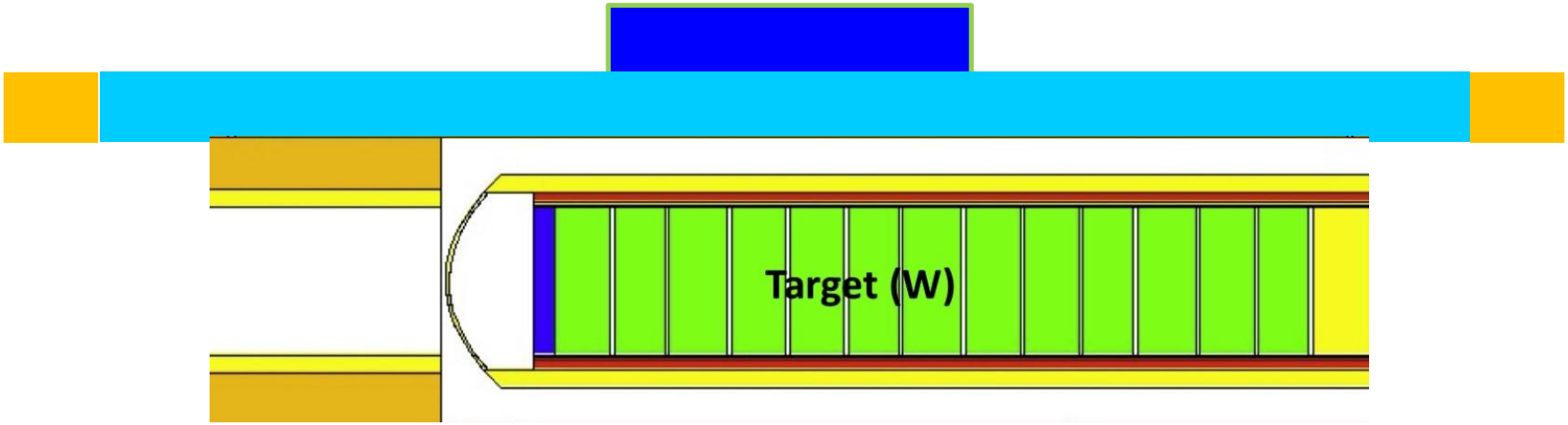
Φ = 16 cm

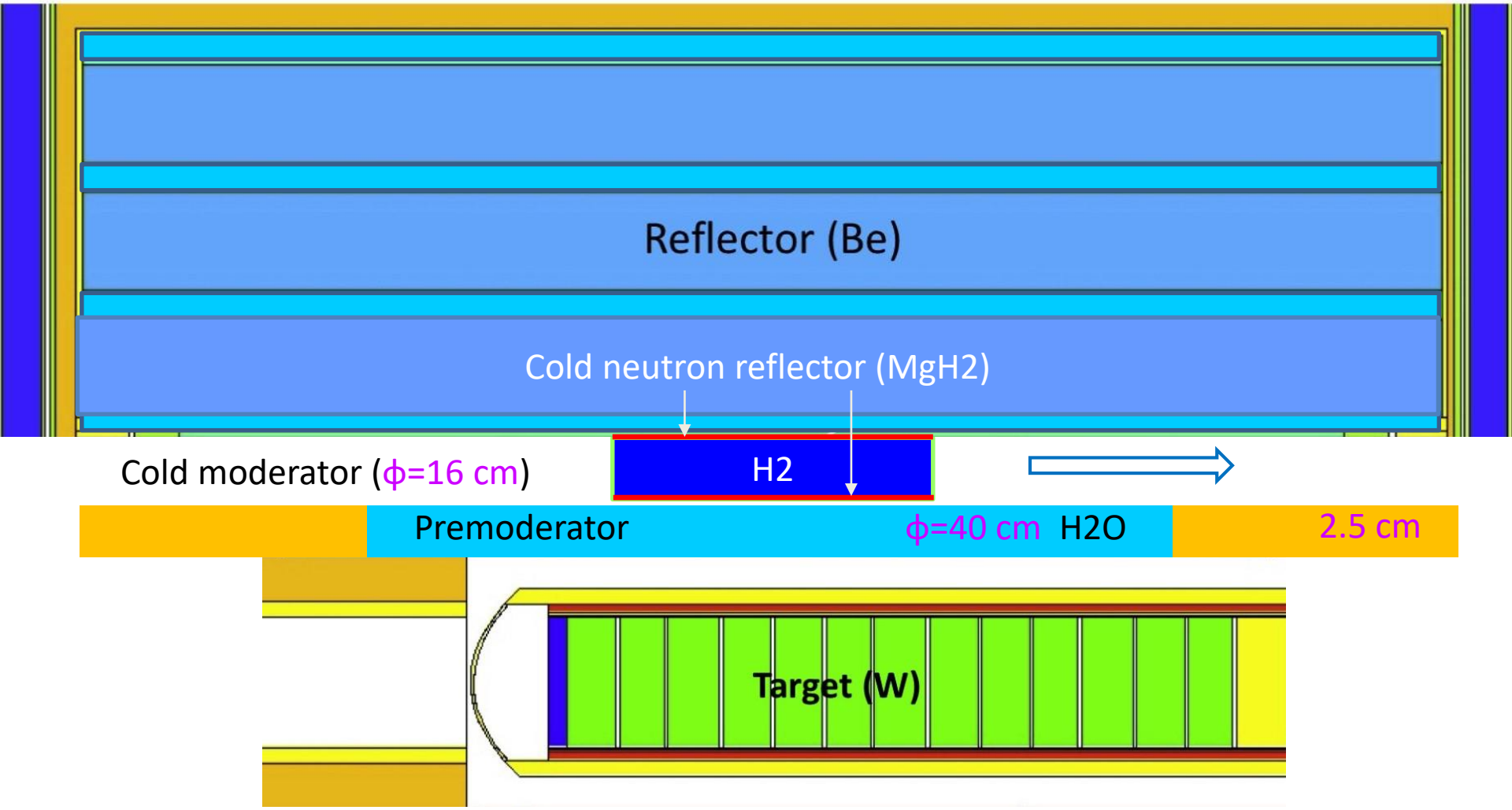


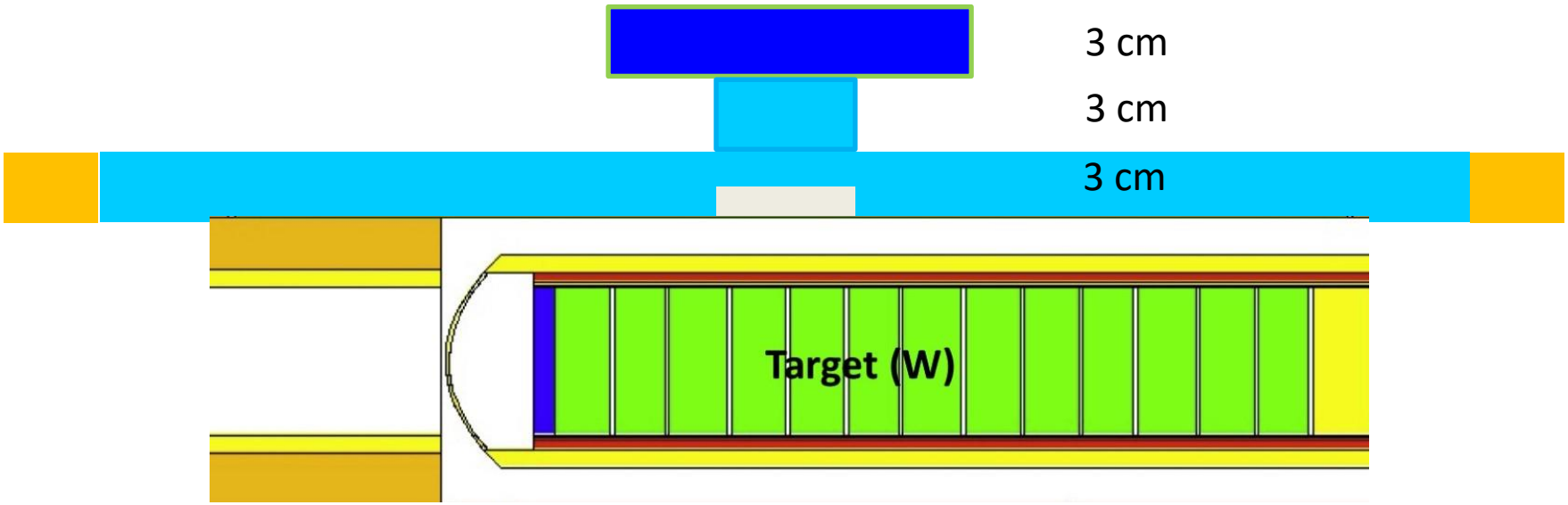
Φ = 16 cm

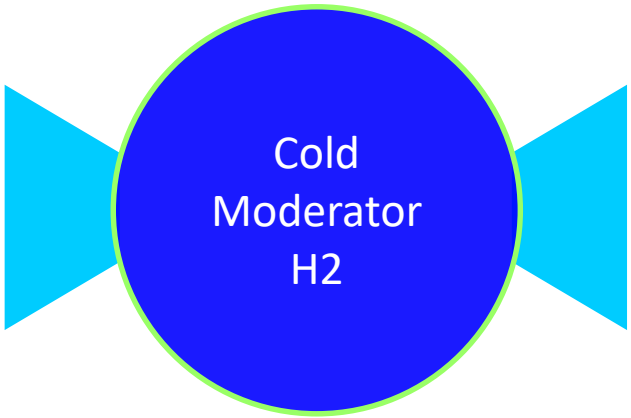


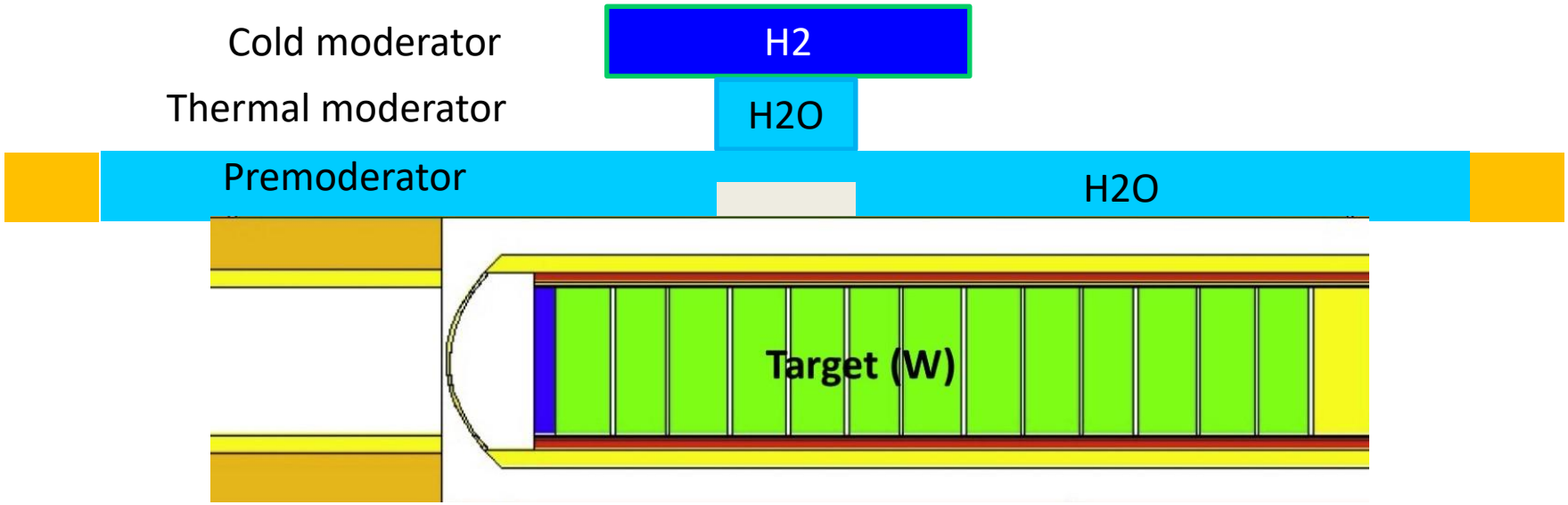
Φ = 16 cm

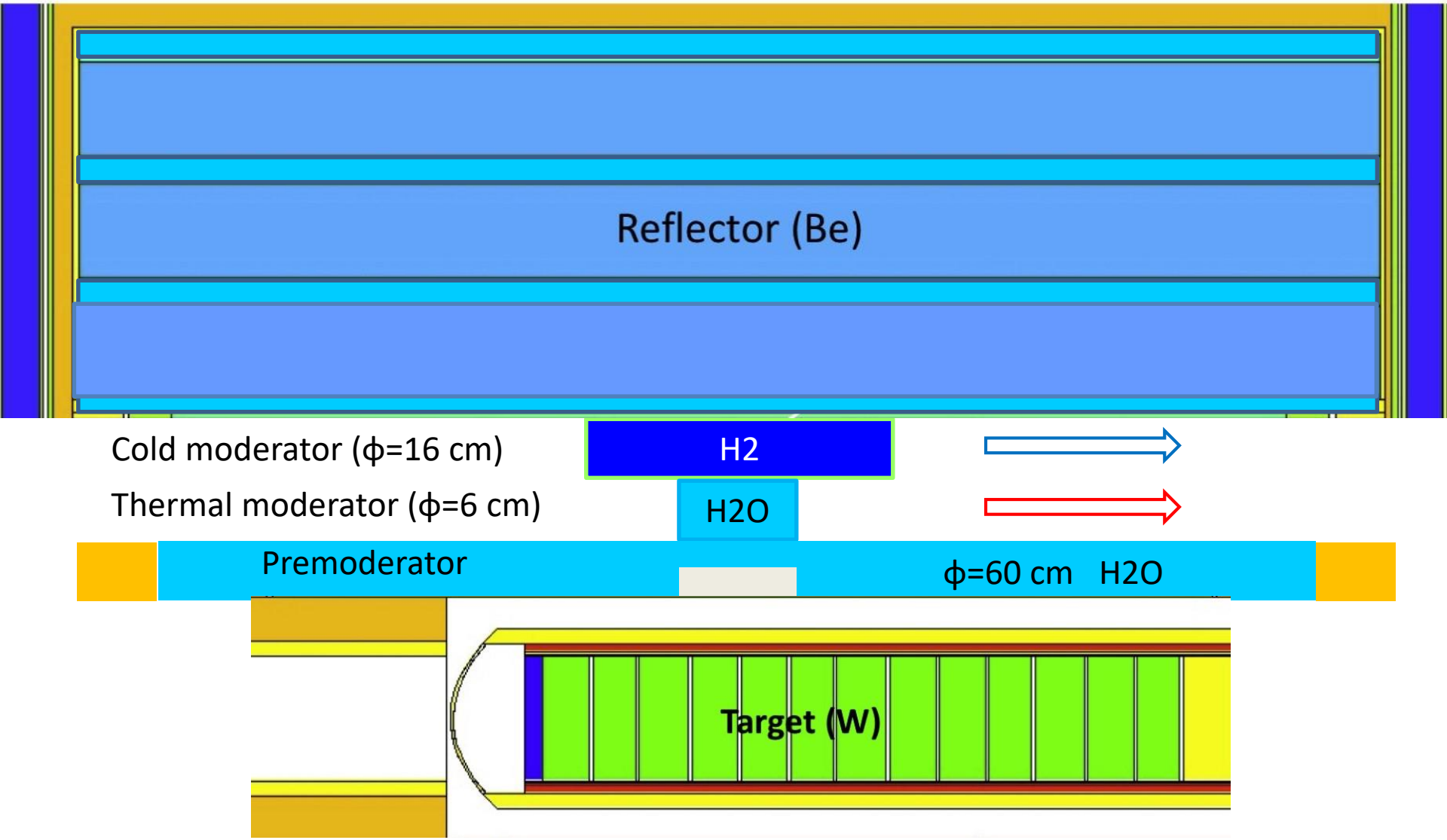

Target (W)

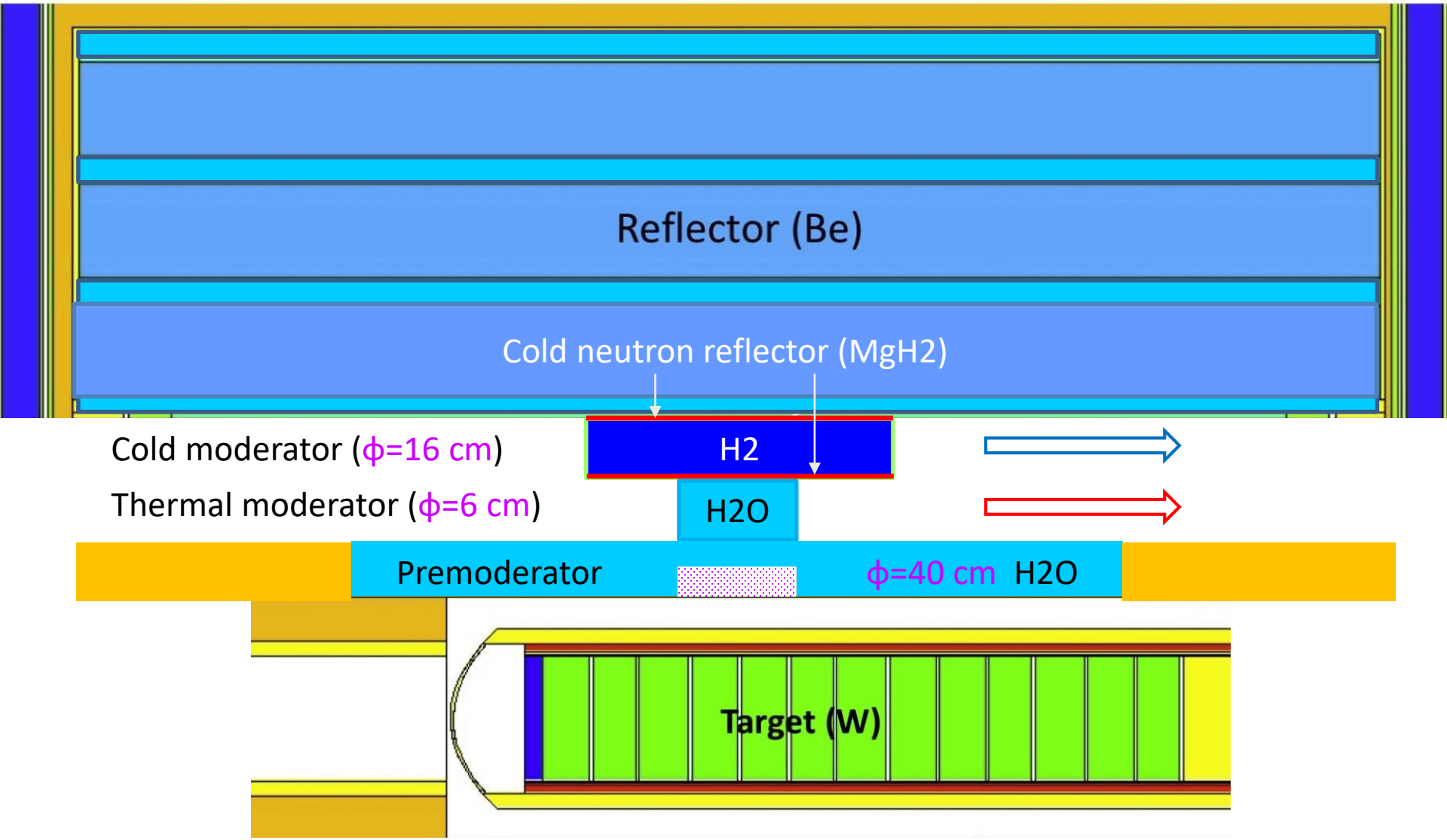

Reflector (Be)
Cold neutron reflector (MgH2)
Cold moderator (ϕ=16 cm)
H2
Premoderator
ϕ=40 cm H2O
2.5 cm
Target (W)

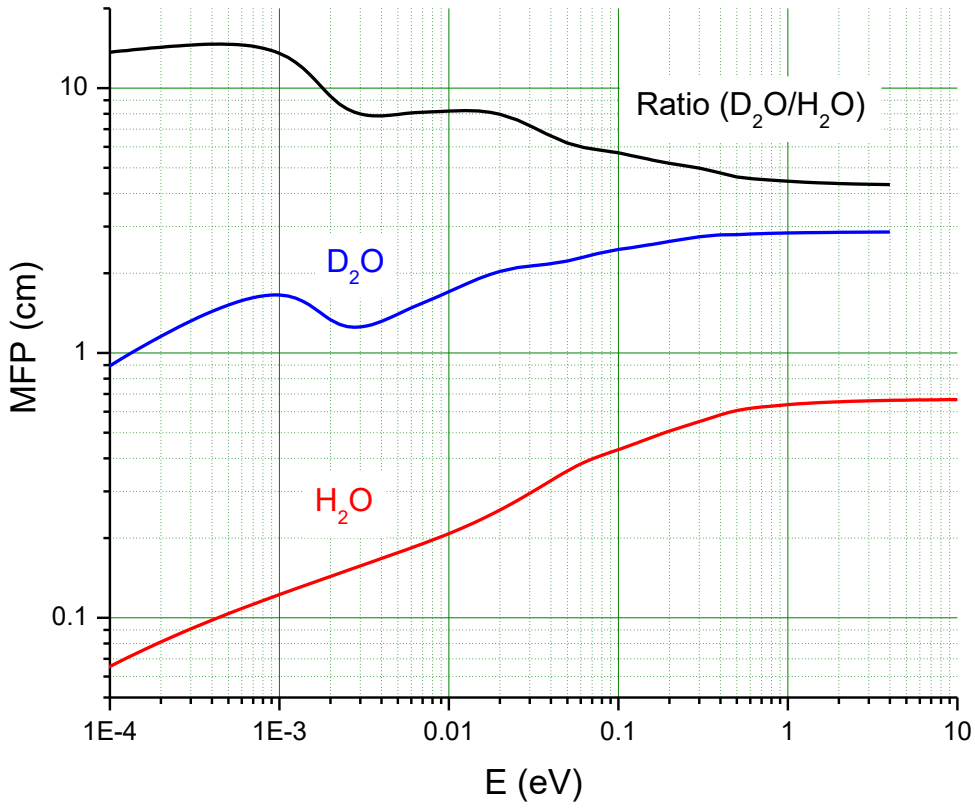

3 cm
3 cm
3 cm
Target (W)

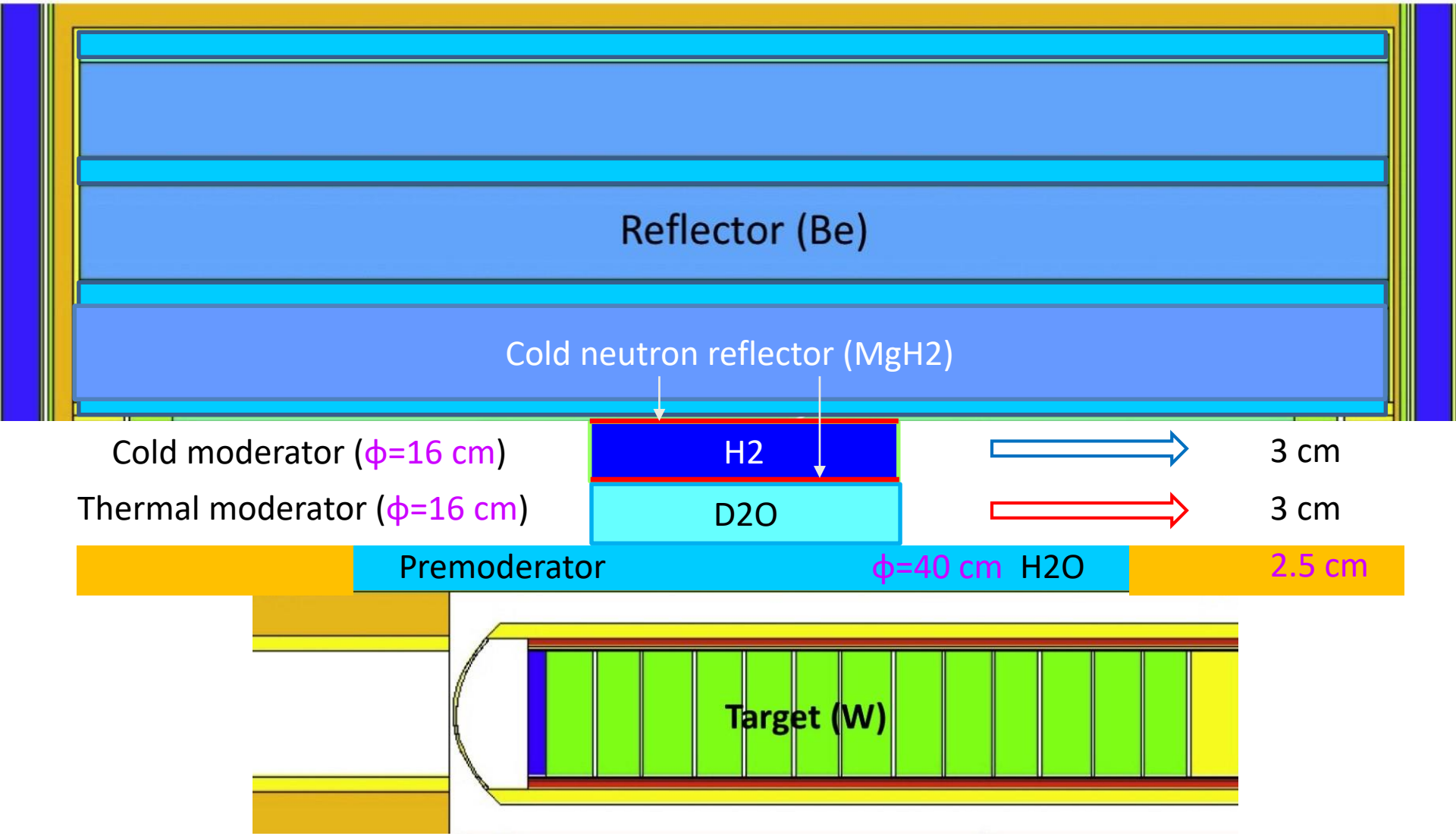

Cold
Moderator
H2


Cold moderator
H2
Thermal moderator
H2O
Premoderator
H2O
Target (W)

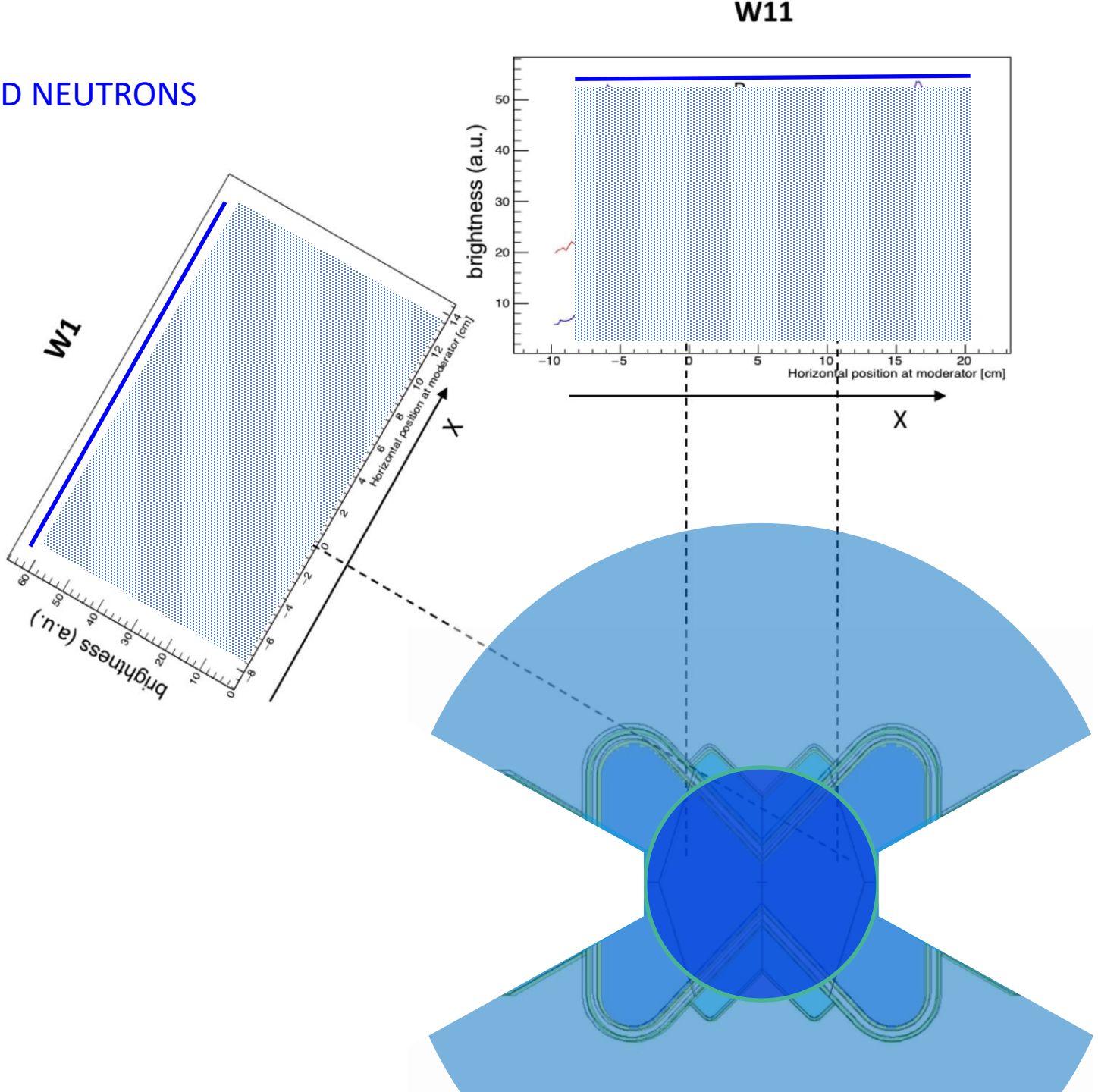

Reflector (Be)
Cold moderator (ϕ=16 cm)
H2
Thermal moderator (ϕ=6 cm)
H2O
Premoderator
ϕ=60 cm H2O
Target (W)


Reflector (Be)
Cold neutron reflector (MgH2)
Cold moderator (ϕ=16 cm)
H2
Thermal moderator (ϕ=6 cm)
H2O
Premoderator
ϕ=40 cm H2O
Target (W)

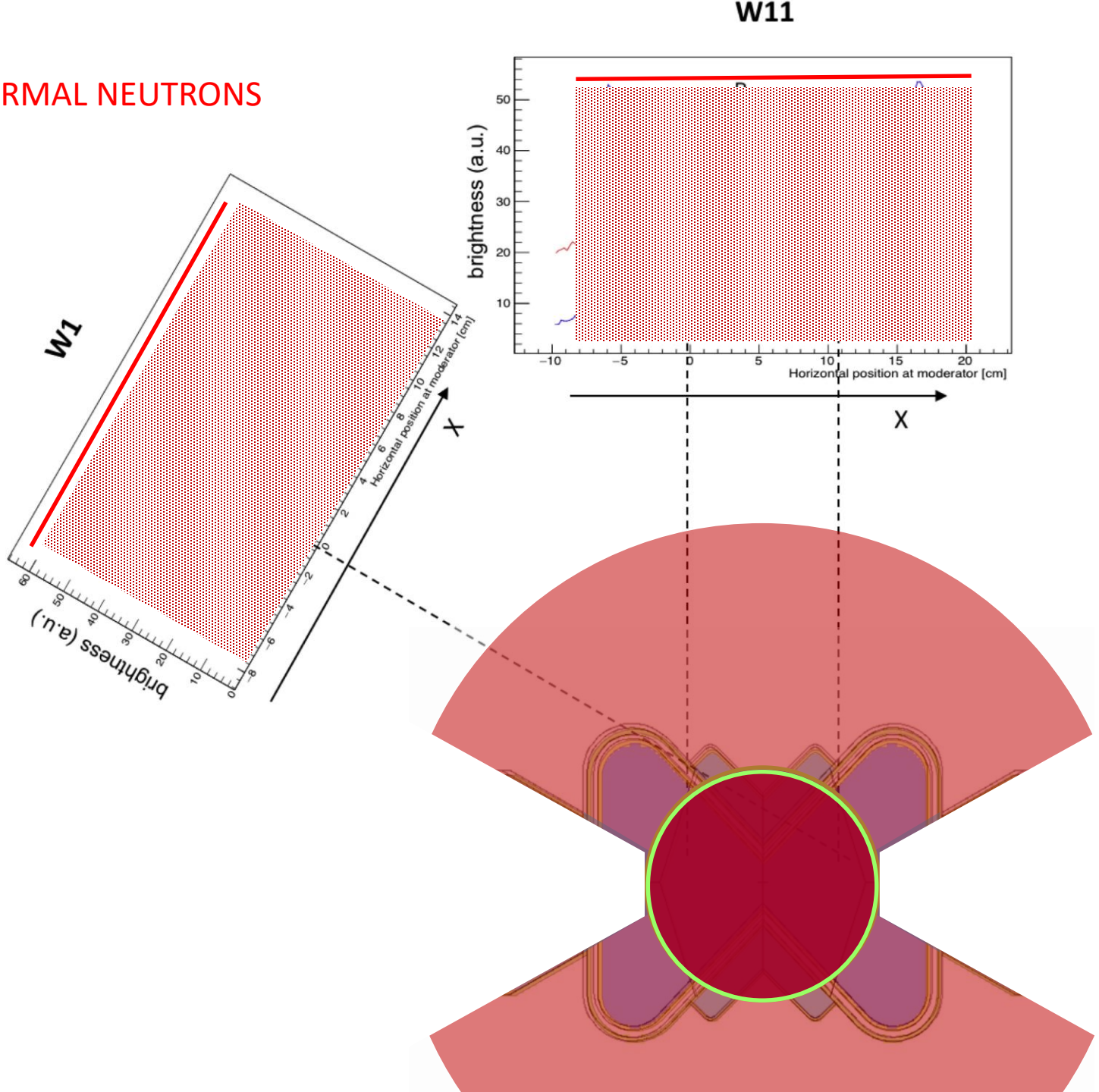

Ratio (D_2O/H_2O)
D_2O
H_2O
MFP (cm)
10
1
0.1
1E-4
1E-3
0.01
0.1
1
10
E (eV)


Reflector (Be)
Cold neutron reflector (MgH2)
Cold moderator (ϕ=16 cm)
H2
3 cm
Thermal moderator (ϕ=16 cm)
D2O
3 cm
Premoderator
ϕ=40 cm H2O
2.5 cm
Target (W)

COLD NEUTRONS

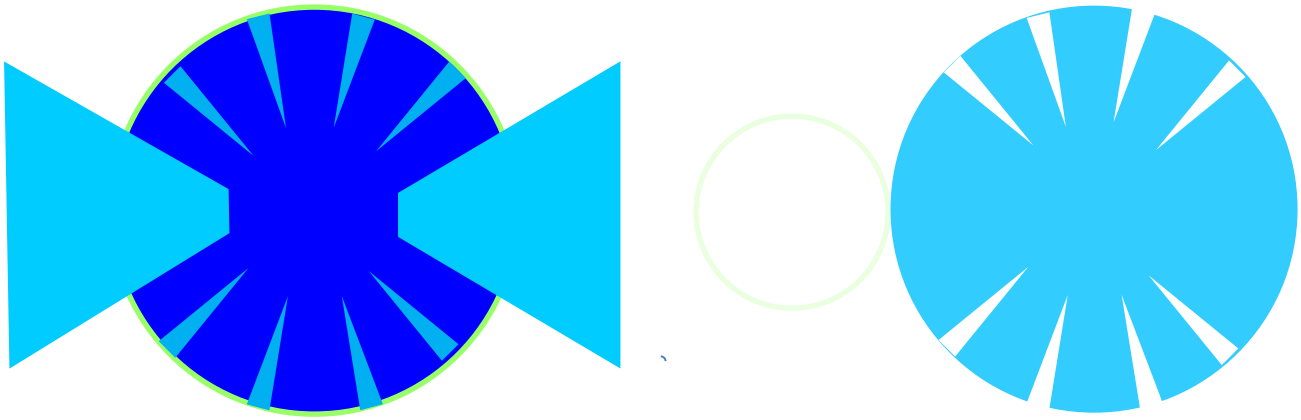


THERMAL NEUTRONS

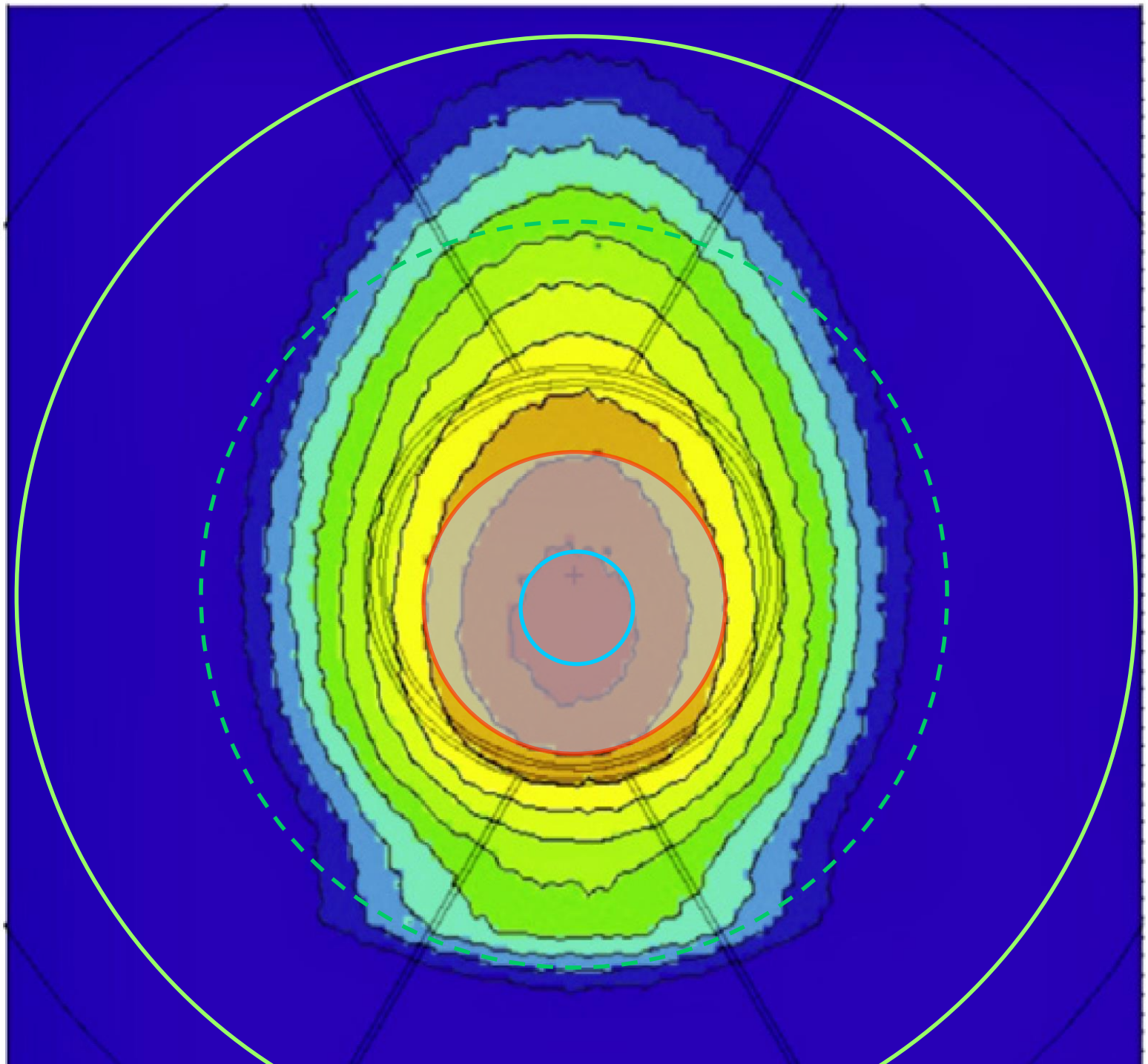


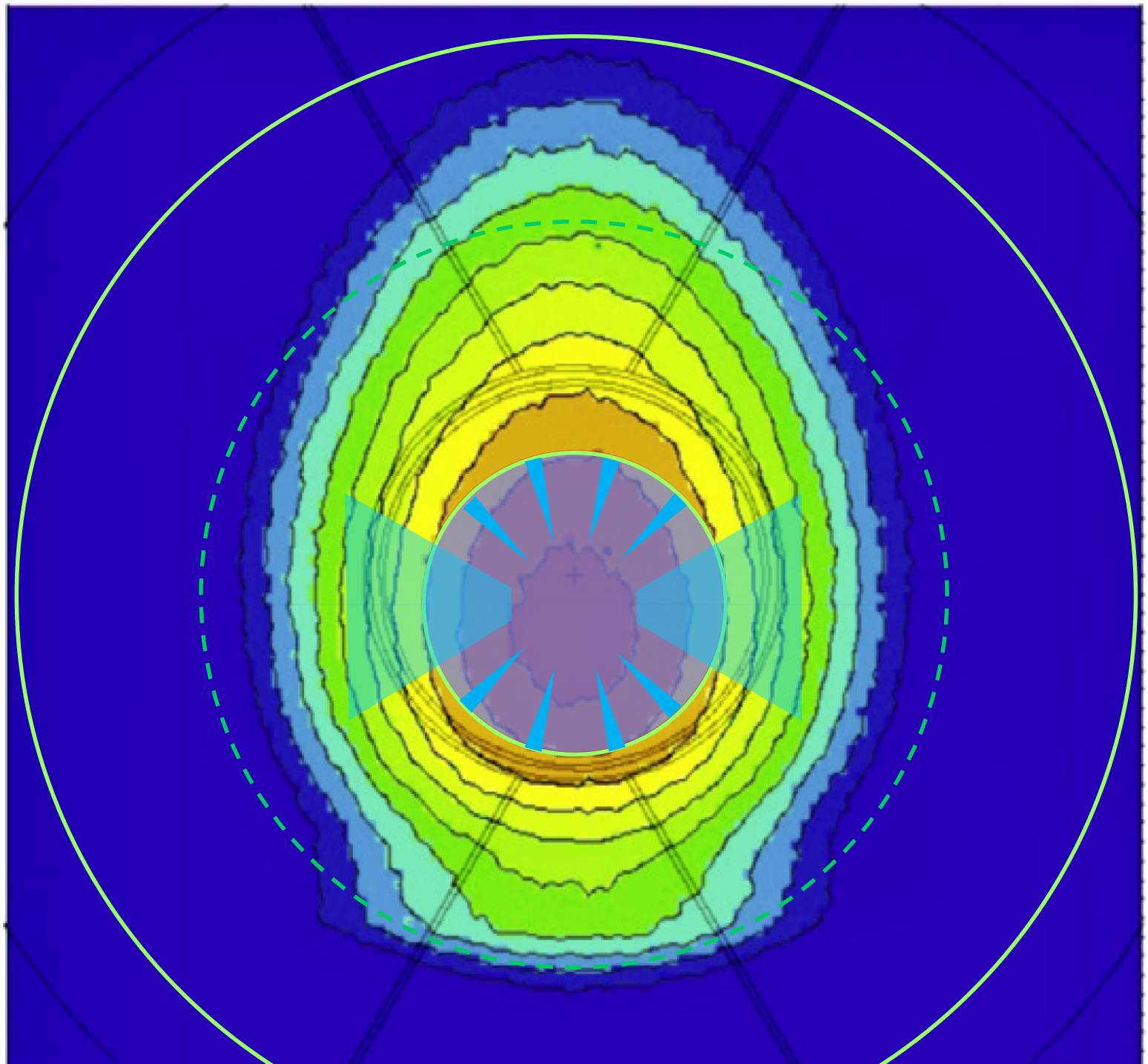
A cold neutron moderator
as a set of efficient tubes.

A thermal neutron moderator
as a set of efficient reentrant holes.



Φ = 16 cm

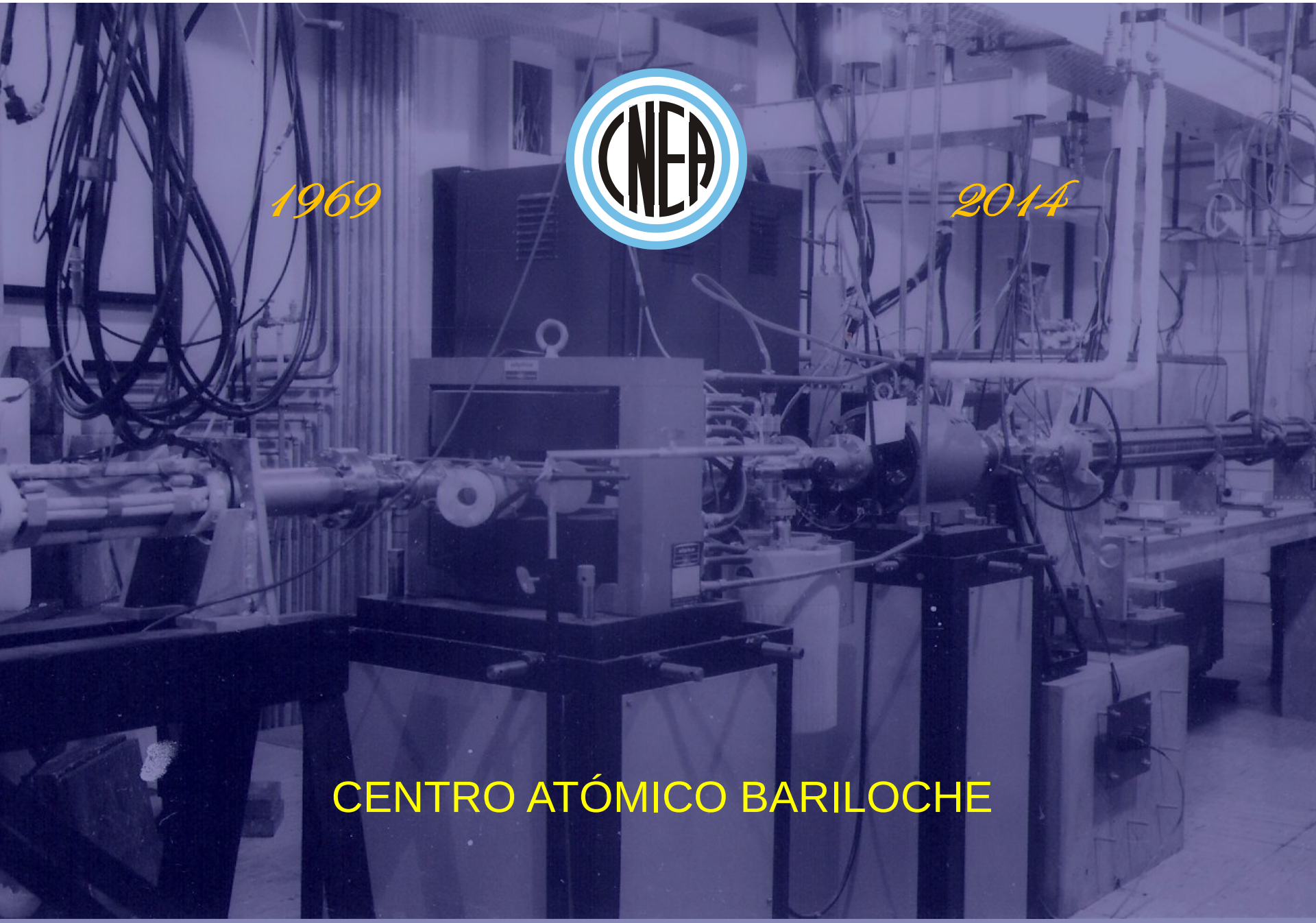




ACKNOWLEDGMENTS

MEMBERS OF THE NEUTRON PHYSICS DEPARTMENT:

J.I. Márquez Damián, F. Cantargi, Ch. Helman, R. E. Mayer, J. Dawidowski



CENTRO ATÓMICO BARILOCHE

1969
CNEA
2014
THANK YOU!!
CENTRO ATÓMICO BARILOCHE