NEUTRONS MATTER

VII International Workshop on Electron-volt Neutron Spectroscopy

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Neutron Moderation: Some Recent Problems and Results

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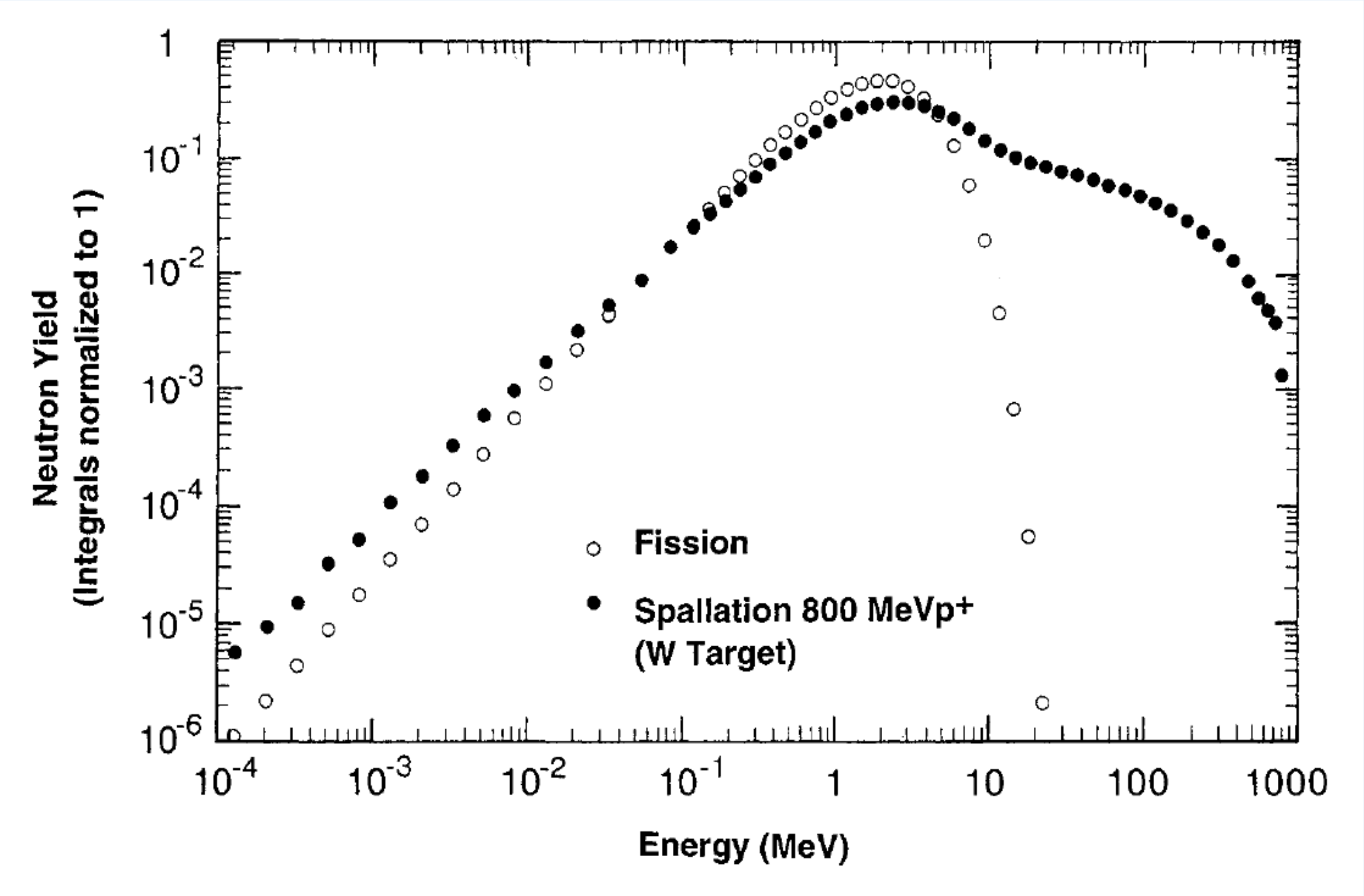
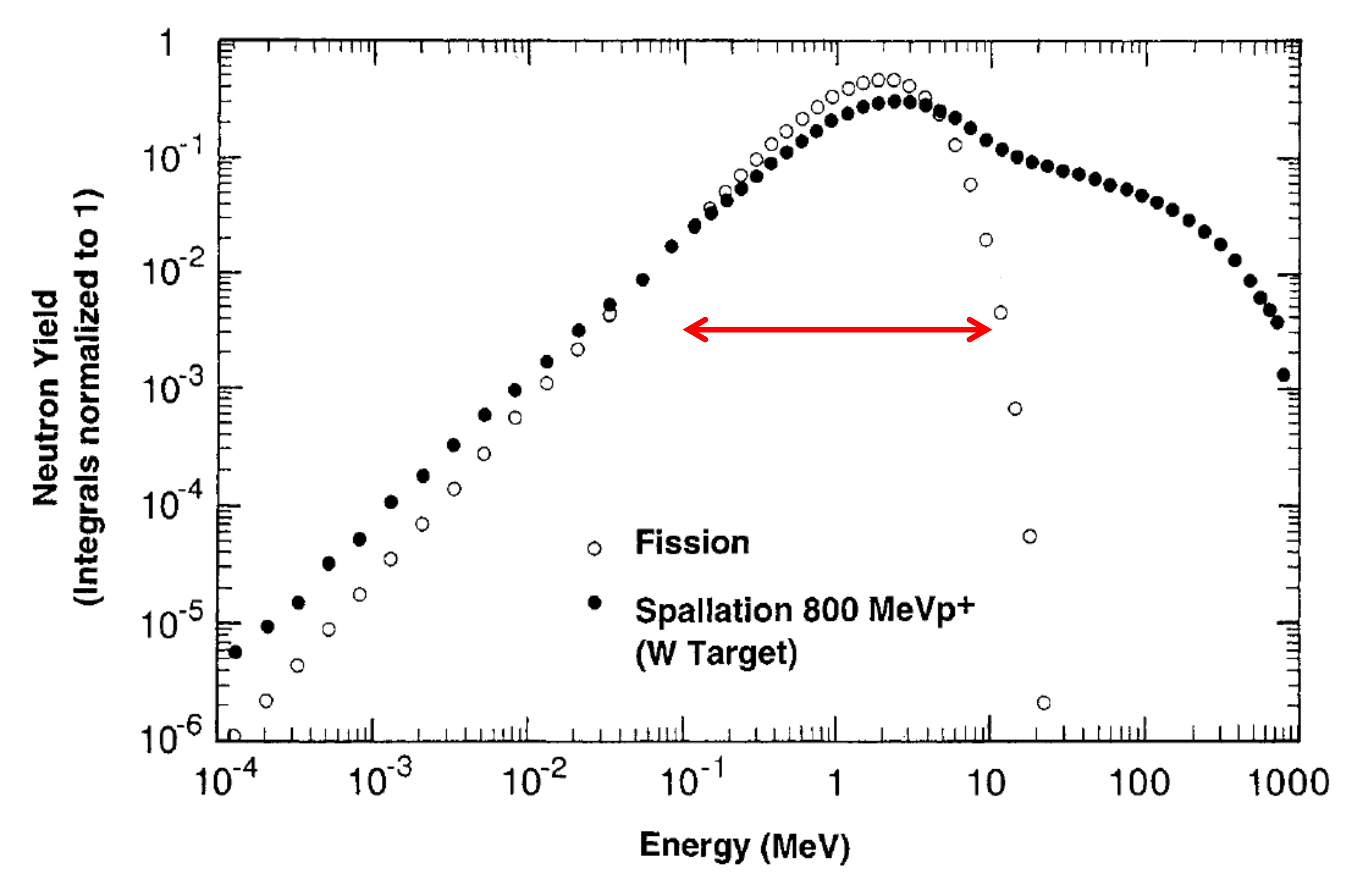
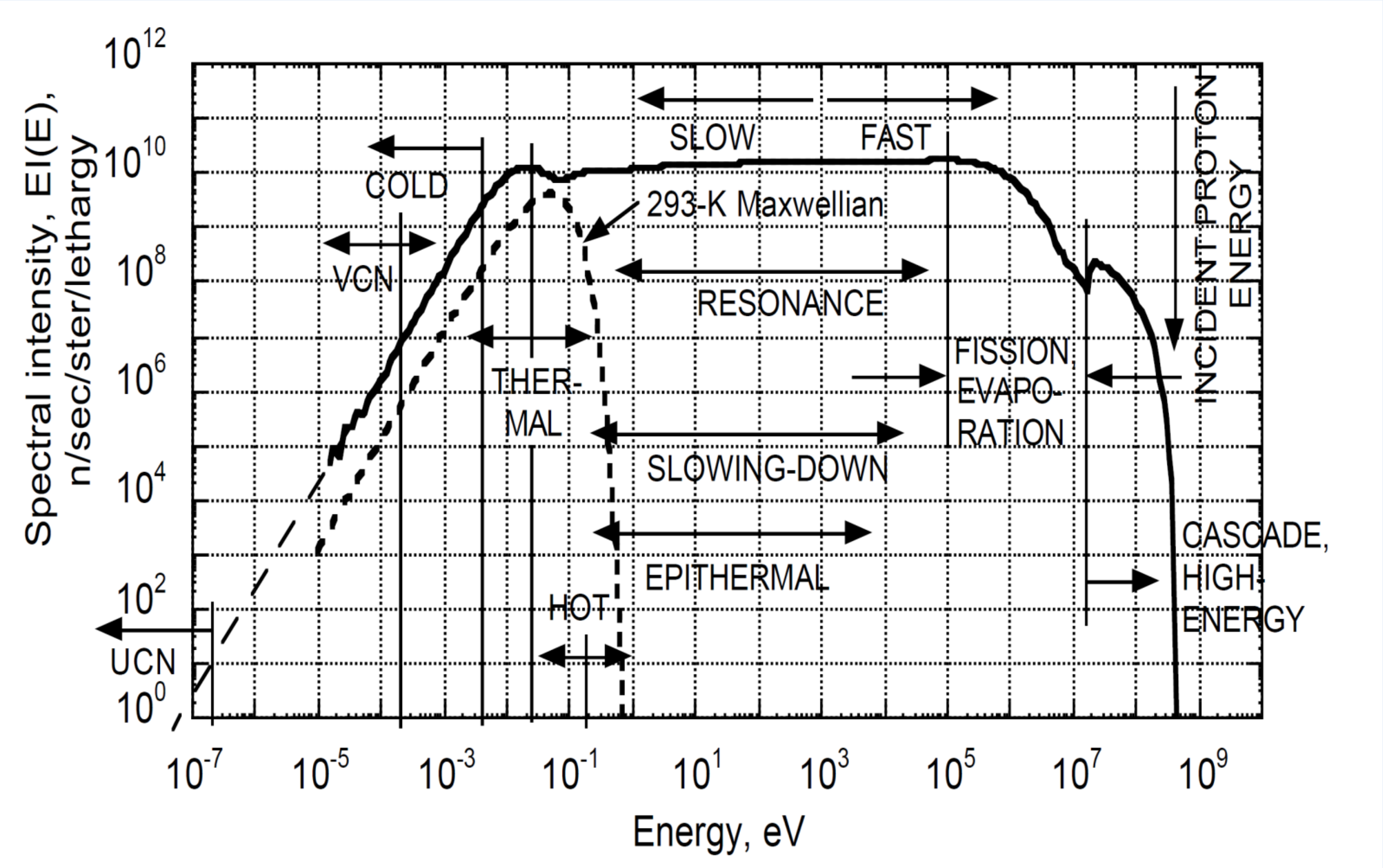
"Everything in moderation, including moderation."
Oscar Wilde



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

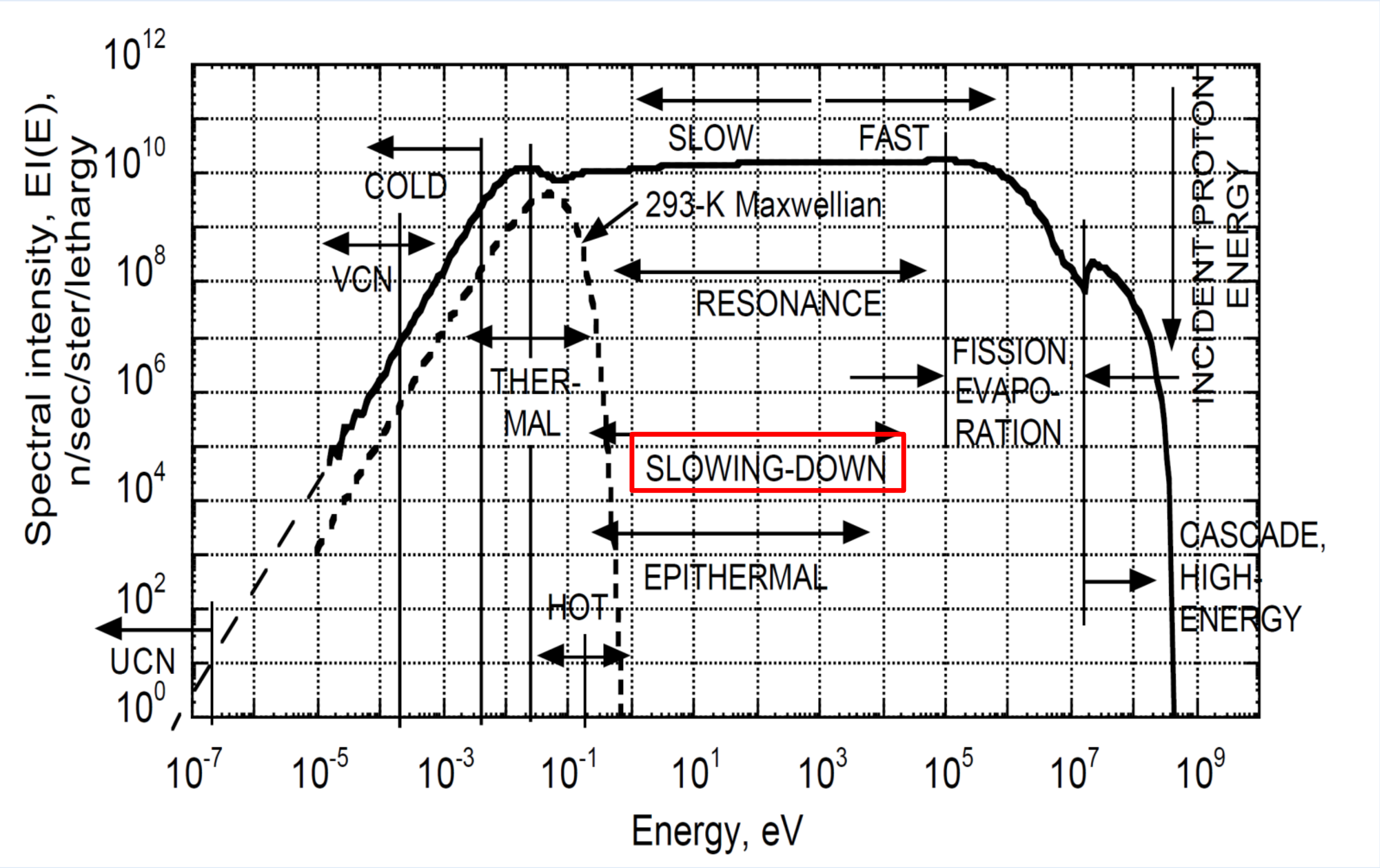


The neutrons produced in nuclear reactions have energies in the MeV range.



(Carpenter & Loong, *Elements of Neutron Scattering,* Cambridge 2015)

To be useful for neutron scattering research, they must have their energies reduced by many orders of magnitude.



The process by which the energy of a neutron is slowed down is called **MODERATION**.

✓ **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 :

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

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	$(CH_2)_n$ 293 K	C_2H_6 180 K	C_2H_6 100 K	CH_4 100 K	CH_4 20 K	C_9H_{12} 20 K	$C_{19}H_{16}$ 20K	H_2 16K
σ_{free} (barn)	44.749	45.73	132.46	132.46	86.73	86.73	288.69	417.95	20.505
ρ (g/cm^3)	1	0.94	0.550	0.641	0.4392	0.510	0.91	1.148	0.0751
N^{molec} ($10^{24}/cm^3$)	0.0335	0.0404	0.0110	0.0129	0.0165	0.0192	0.0046	0.0028	0.0226
N^H ($10^{22}/cm^3$)	6.69	8.09	6.63	7.72	6.61	7.68	5.48	4.53	4.52
Σ_{free} (cm^{-1})	1.5	1.849	1.463	1.705	1.431	1.665	1.318	1.183	0.927
ξ	0.926	0.913	0.940	0.940	0.954	0.954	0.876	0.819	1
γ	0.924	0.908	0.936	0.936	0.951	0.951	0.976	0.960	1
$\xi \Sigma_{free}$ (cm^{-1})	1.389	1.688	1.375	1.603	1.365	1.588	1.155	0.969	0.927

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SLOWING-DOWN FUNDAMENTALS

STATIONARY SOURCES

When fast neutrons collide with the atoms of a scattering medium, loss of energy occurs simultaneously with the diffusion process. Slowing-down theory aims at determining the space and energy distributions of the neutron flux arising from a fast neutron source.

Transport equation (infinite medium, uniformly distributed sources):

$$(\Sigma_a + \Sigma_s)\,\Phi(E) = \int \Sigma_s\,(E' \rightarrow E)\,\Phi(E')\,dE' + S(E)$$

Solution

$$\Phi(E) = q(E)\,/[(\Sigma_a + \Sigma_s)\,E] \;+\; S(E)\,/\,(\Sigma_a + \Sigma_s)$$

$q(E)$: slowing-down density ; $S(E)$: source distribution

a) A=1

i) Non-absorbing media ($E < \{E_s\}$, source S neutron energies)

$$\Phi(E) = (S / \Sigma_s) \,.\, 1/E \quad + \quad S\, D(E) / \Sigma_s$$

ii) Absorbing or finite media

$$\Phi(E) = [S / (\Sigma_s + \Lambda)] \,.\, (E/E_Q)^{\alpha} \,.\, 1/E$$

$\alpha = \Lambda / (\Sigma_s + \Lambda)$; $\Lambda = \Sigma_a$ (absorbing media)

$= DB^2$, D: diffusion coeff.

B^2: geom. Buckling

b) A≠1

$$\Phi(E) = q(E) / (\xi\, \Sigma_s) \,.\, 1/ E$$

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)

"MODERATION RANGE"

In the Grueling–Goertzel approximation,

$$I(E,t) = \left(\frac{K}{E}\right)\frac{\xi\Sigma_s v}{2\Gamma(2/\gamma)}\left(\frac{\xi\Sigma_s vt}{\gamma}\right)^{2/\gamma}\exp\left(-\frac{\xi\Sigma_s vt}{\gamma}\right). \quad (2.56)$$

This is a differential χ^2 distribution with $2 + 4/\gamma$ degrees of freedom (which is useful to know for purposes of calculations), and is called the "slowing-down time" distribution. Γ is the gamma function. In monatomic materials, ξ is the mean logarithmic energy change per collision,

The average slowing-down time and the standard deviation of the slowing-down time distribution at energy E (speed v) are

$$\bar{t} = (1 + 2/\gamma)\gamma/(\xi\Sigma_s v), \qquad \sigma_t = \sqrt{1 + 2/\gamma}\,\gamma/(\xi\Sigma_s v). \quad (2.60)$$

When the cross sections and slowing-down parameters are independent of energy, $v\bar{t}$ and $v\sigma_t$ are independent of energy. Indeed, the distribution $EI(E,t)$ is a function of the variable vt only, and invariant with E, a fact that is sometimes useful in connection with numerical calculations and the presentation of data.

The time widths are

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

(Granada, 2014)

Error ≤ 2 ‰

$0.9 \le \gamma \le 1$

Neutronic Properties of some Moderators

Parameter	H_2O 293 K	$(CH_2)_n$ 293 K	C_2H_6 180 K	C_2H_6 100 K	CH_4 100 K	CH_4 20 K	C_9H_{12} 20 K	$C_{19}H_{16}$ 20K	H_2 16K
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$v\ t_s$ (cm)	2.105	1.723	2.135	1.832	2.162	1.858	2.58	3.06	3.235
$v\ \Delta t_s$ (cm)	1.183	0.963	1.205	1.034	1.227	1.055	1.476	1.74	1.867
$v\ \Delta t_{1/2}$ (cm)	2.346	1.915	2.383	2.046	2.421	2.080	2.897	3.42	3.65

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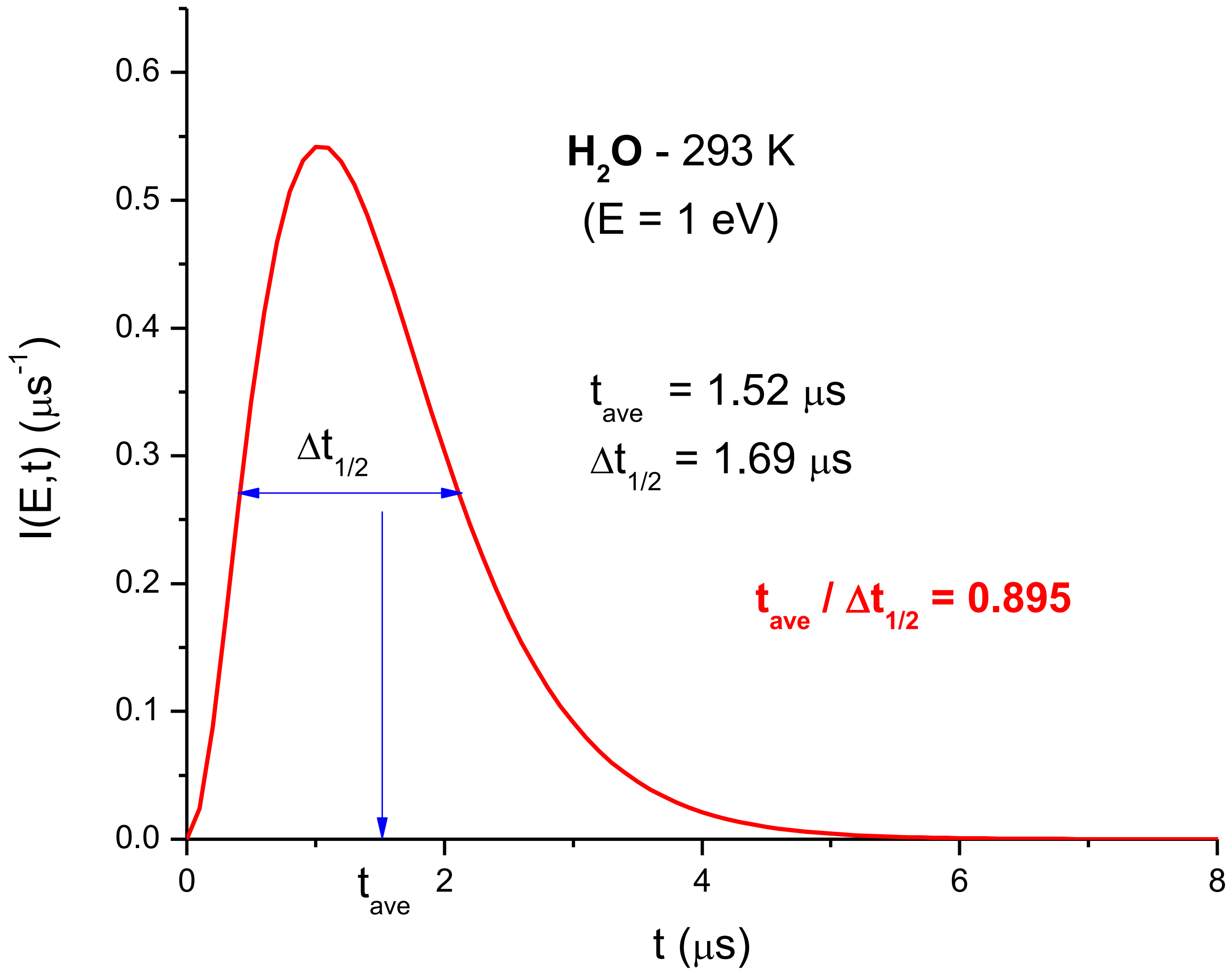
Slowing-Down Time Distribution



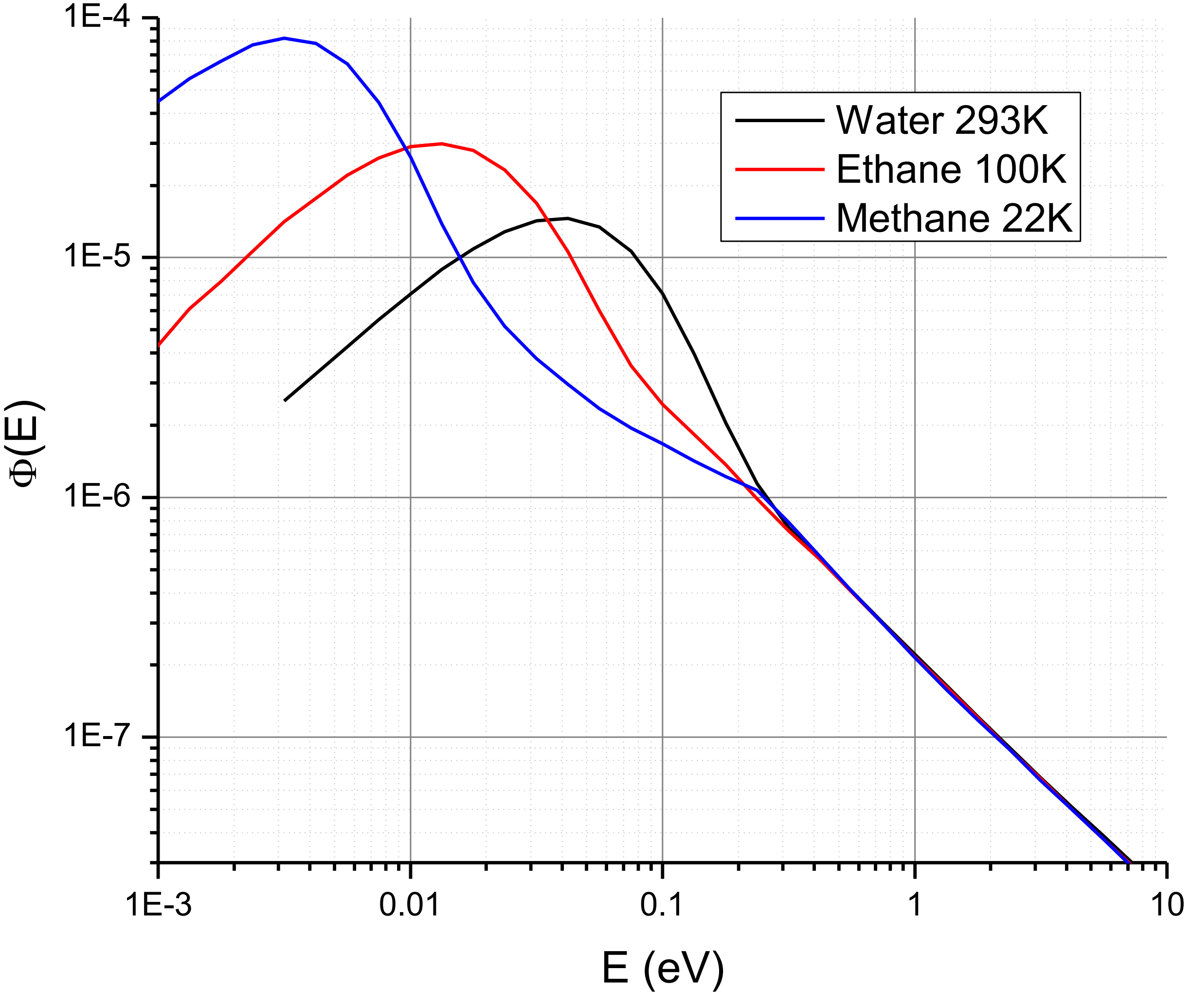
NEUTRON THERMALIZATION

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.

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

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



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

DECAY CONSTANT

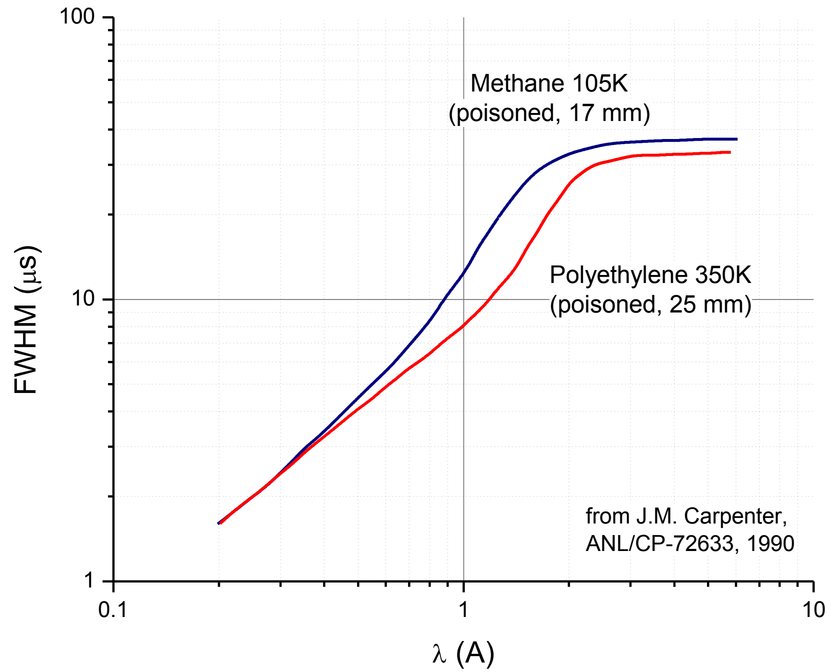
$$\propto = \bar{v}\,\Sigma_{abs} + \bar{v}\,D\,B^2 - \cdots \quad 1/s$$

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

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

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

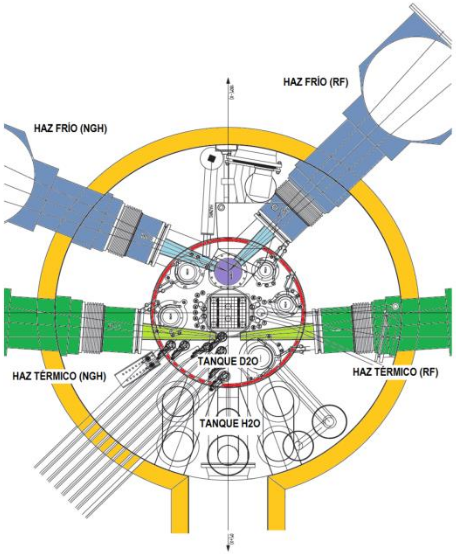
B^2 : Geometrical Buckling

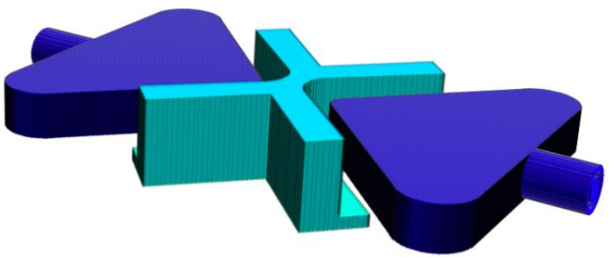


	Methane 100K	Ethane 100K	Ethane 120K	Ethane 140K	Ethane 180K	Water 293K
$\bar{v}$	144881	144881	158710	171426	194379	247996
Σ_{abs}	0.03102	0.03626	0.03626	0.03626	0.03626	0.04885
D	0.1046	0.07488	0.08021	0.08614	0.09897	0.03631

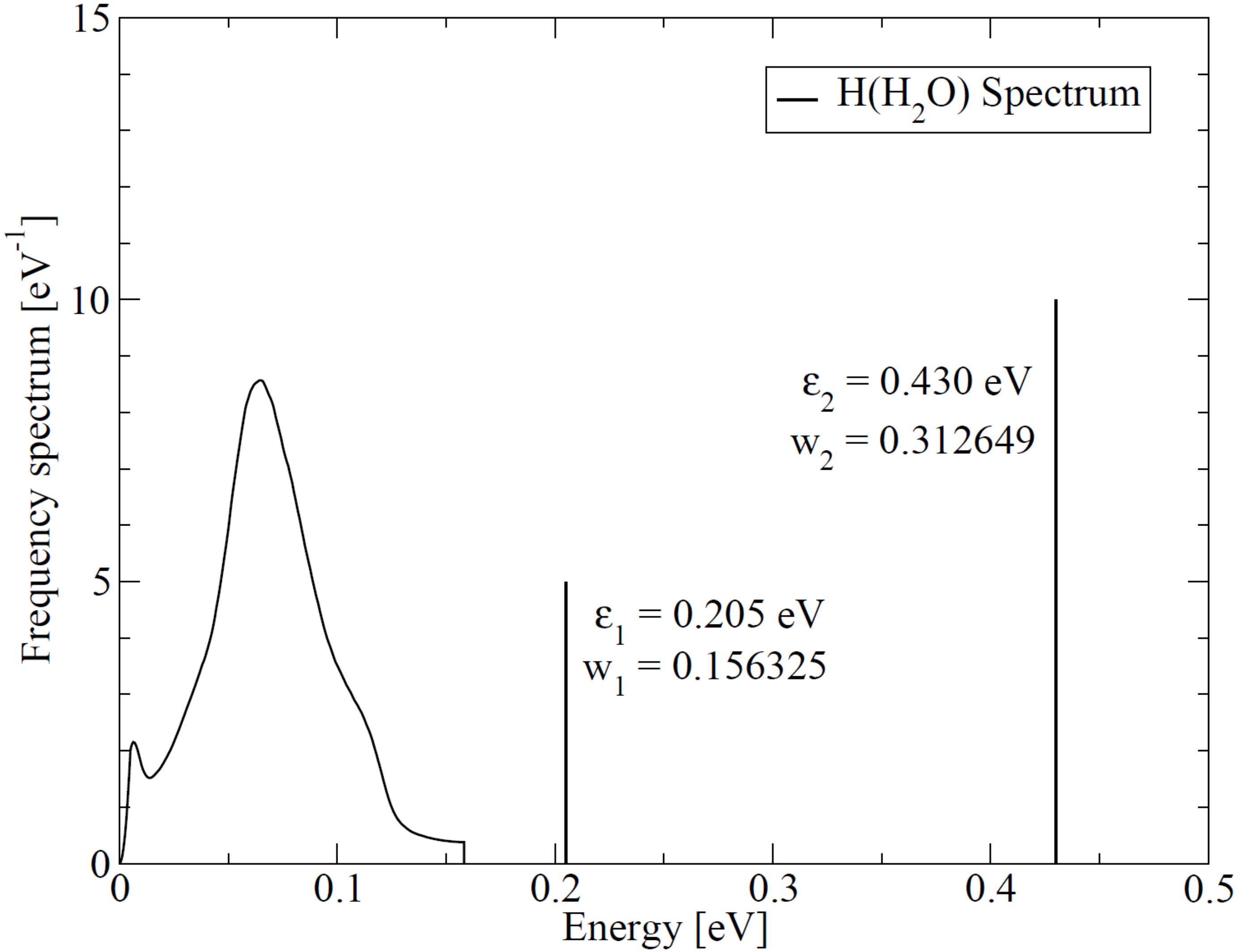
RECENT RESULTS ON SOME COMMON MODERATORS

(Scattering Kernels)



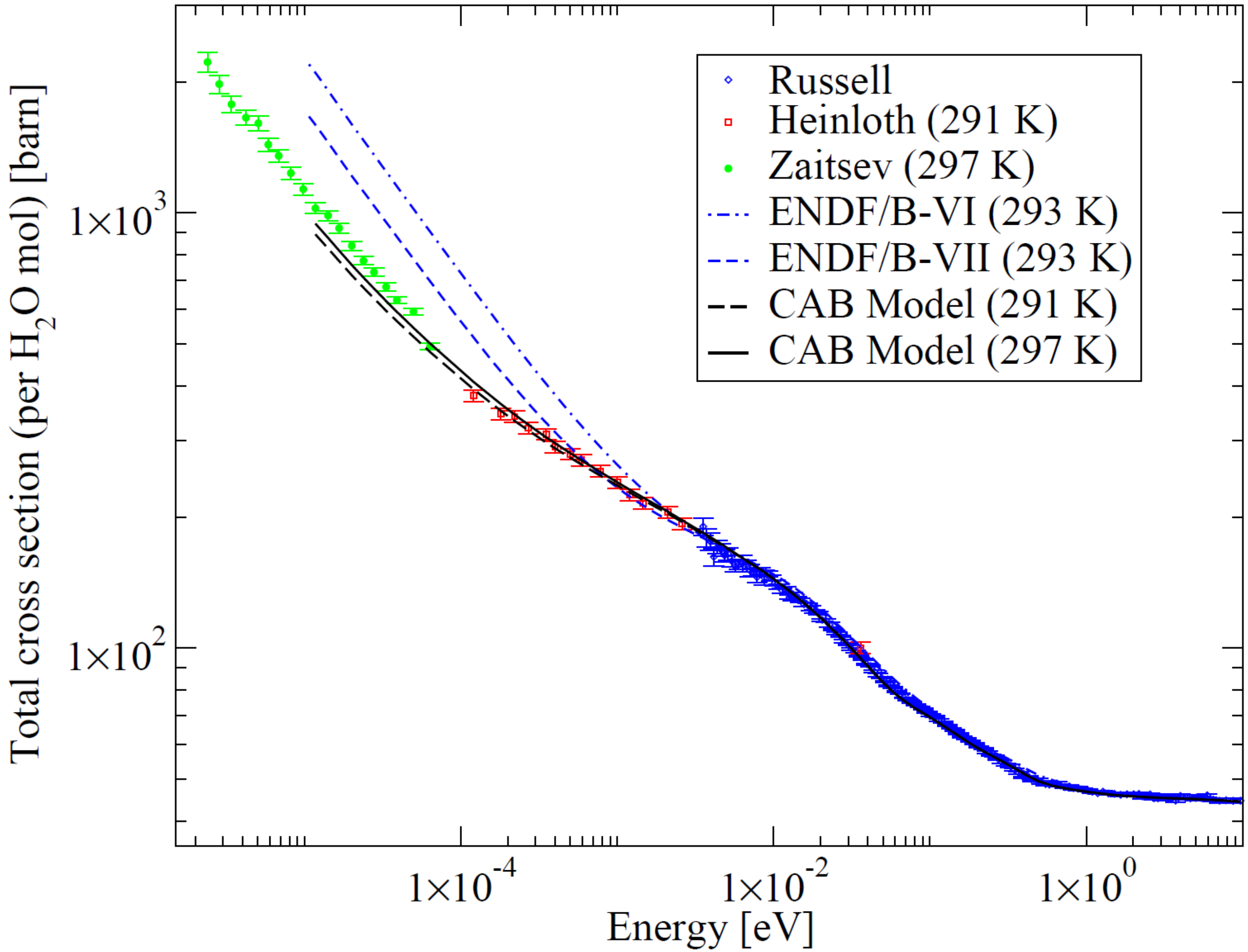


WATER



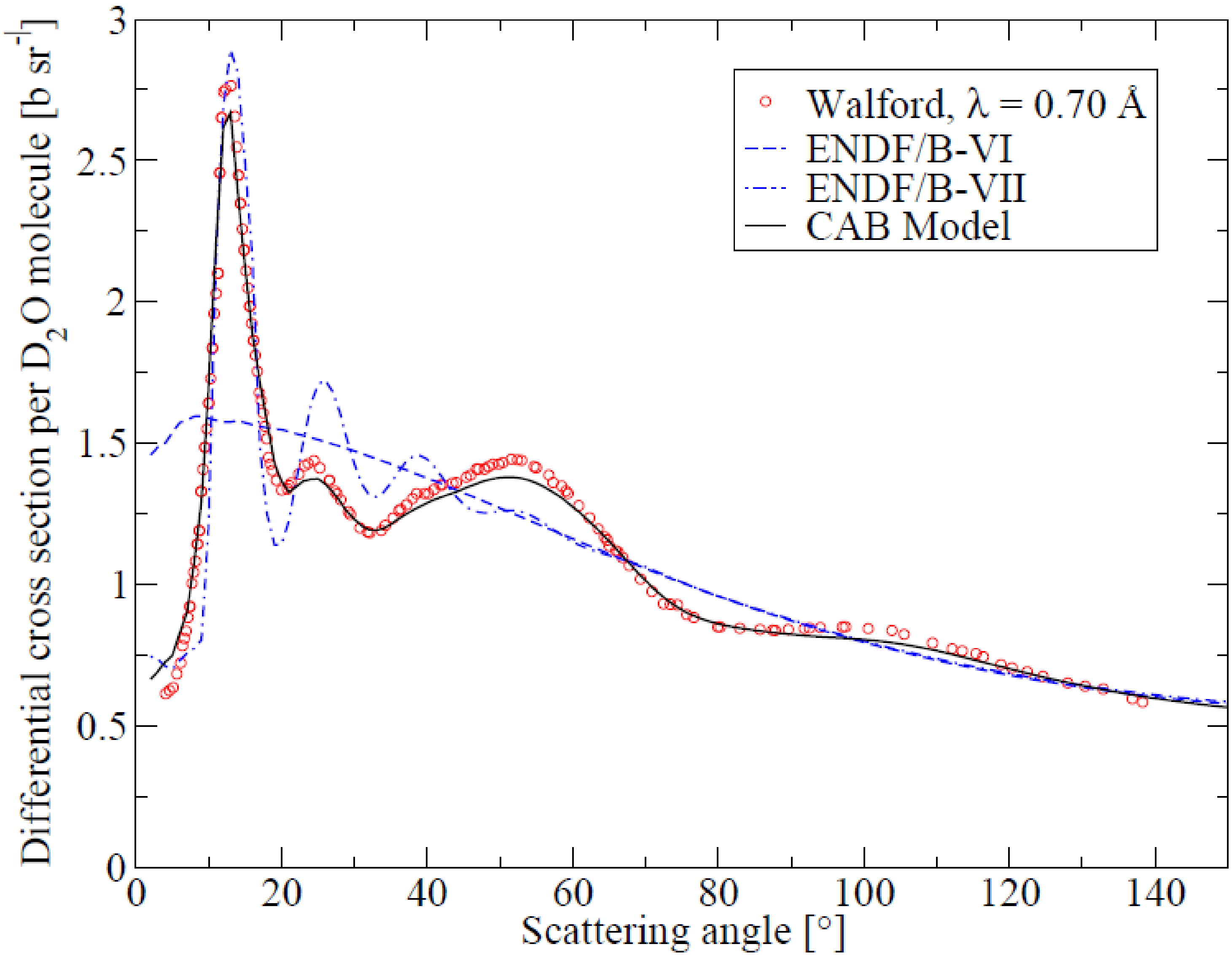
Continuous spectrum and discrete vibrations.

LIGHT WATER



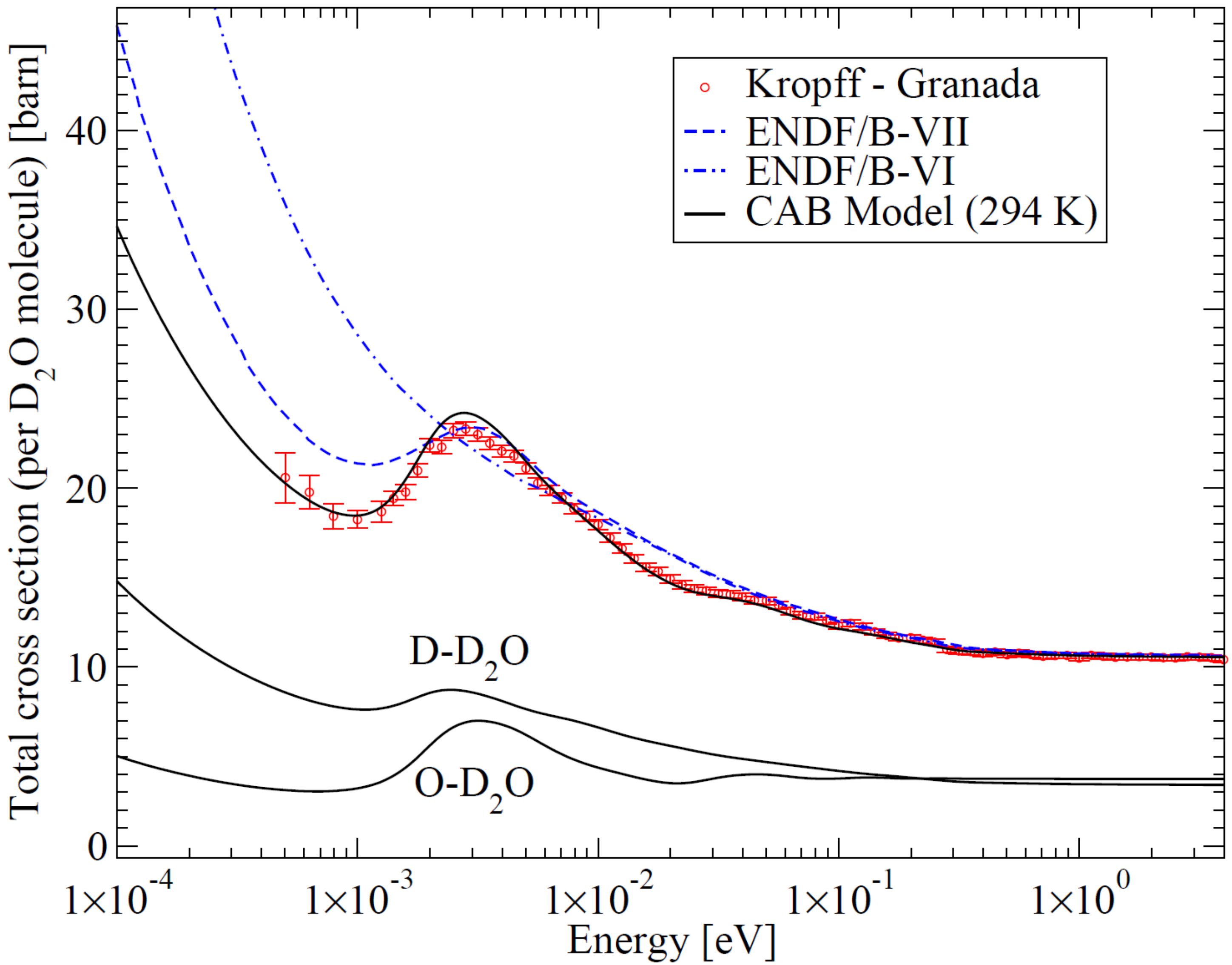
Russell
Heinloth (291 K)
Zaitsev (297 K)
ENDF/B-VI (293 K)
ENDF/B-VII (293 K)
CAB Model (291 K)
CAB Model (297 K)
Total cross section (per H_2O mol) [barn]
1×10^3
1×10^2
1×10^{-4}
1×10^{-2}
1×10^0
Energy [eV]

HEAVY WATER

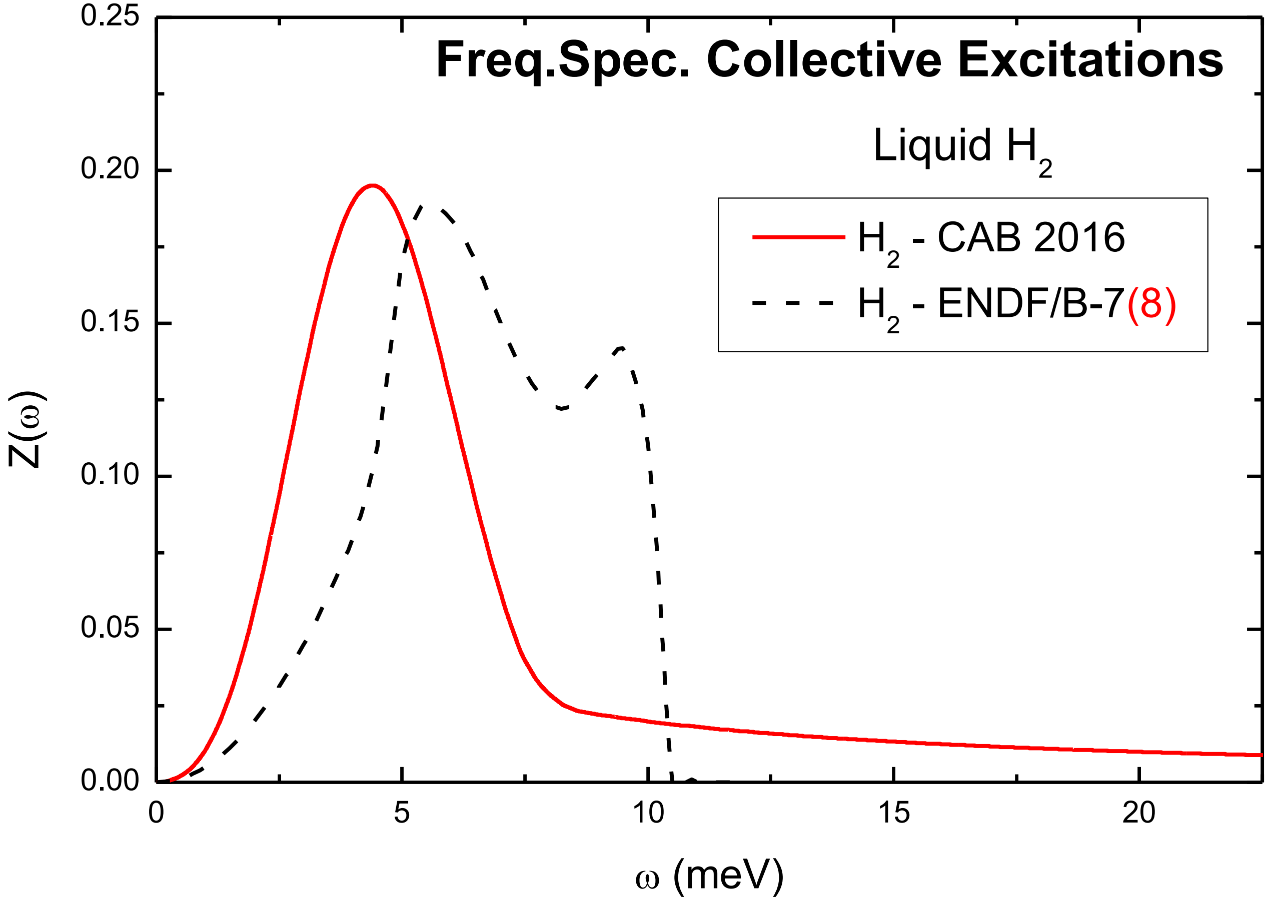


Walford, λ = 0.70 Å
ENDF/B-VI
ENDF/B-VII
CAB Model
Differential cross section per D2O molecule [b sr-1]
Scattering angle [°]
0
0.5
1
1.5
2
2.5
3
0
20
40
60
80
100
120
140

HEAVY WATER


Kropff - Granada
ENDF/B-VII
ENDF/B-VI
CAB Model (294 K)
D-D_2O
O-D_2O
Total cross section (per D_2O molecule) [barn]
0
10
20
30
40
1×10^{-4}
1×10^{-3}
1×10^{-2}
1×10^{-1}
1×10^{0}
Energy [eV]

LIQUID HYDROGEN



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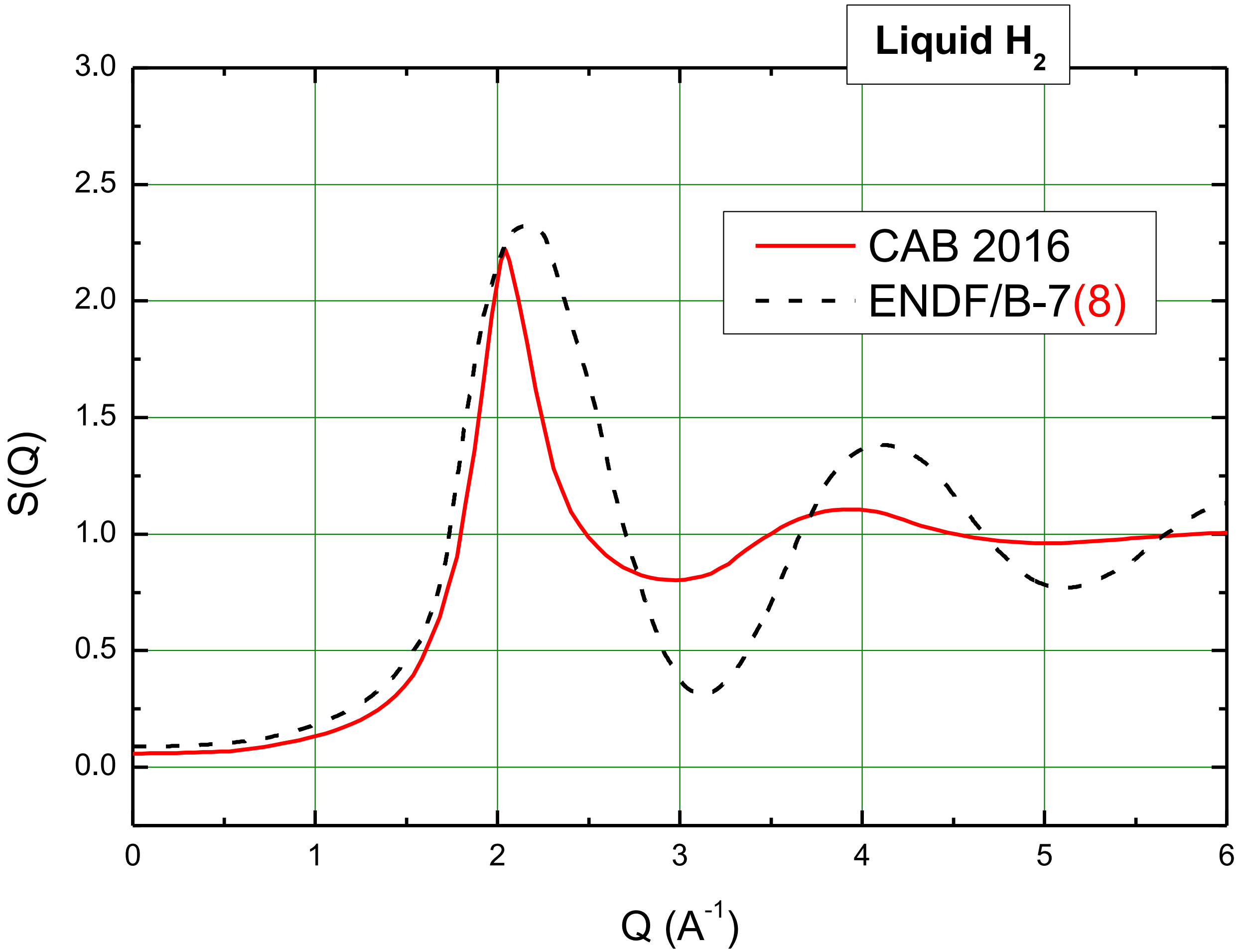
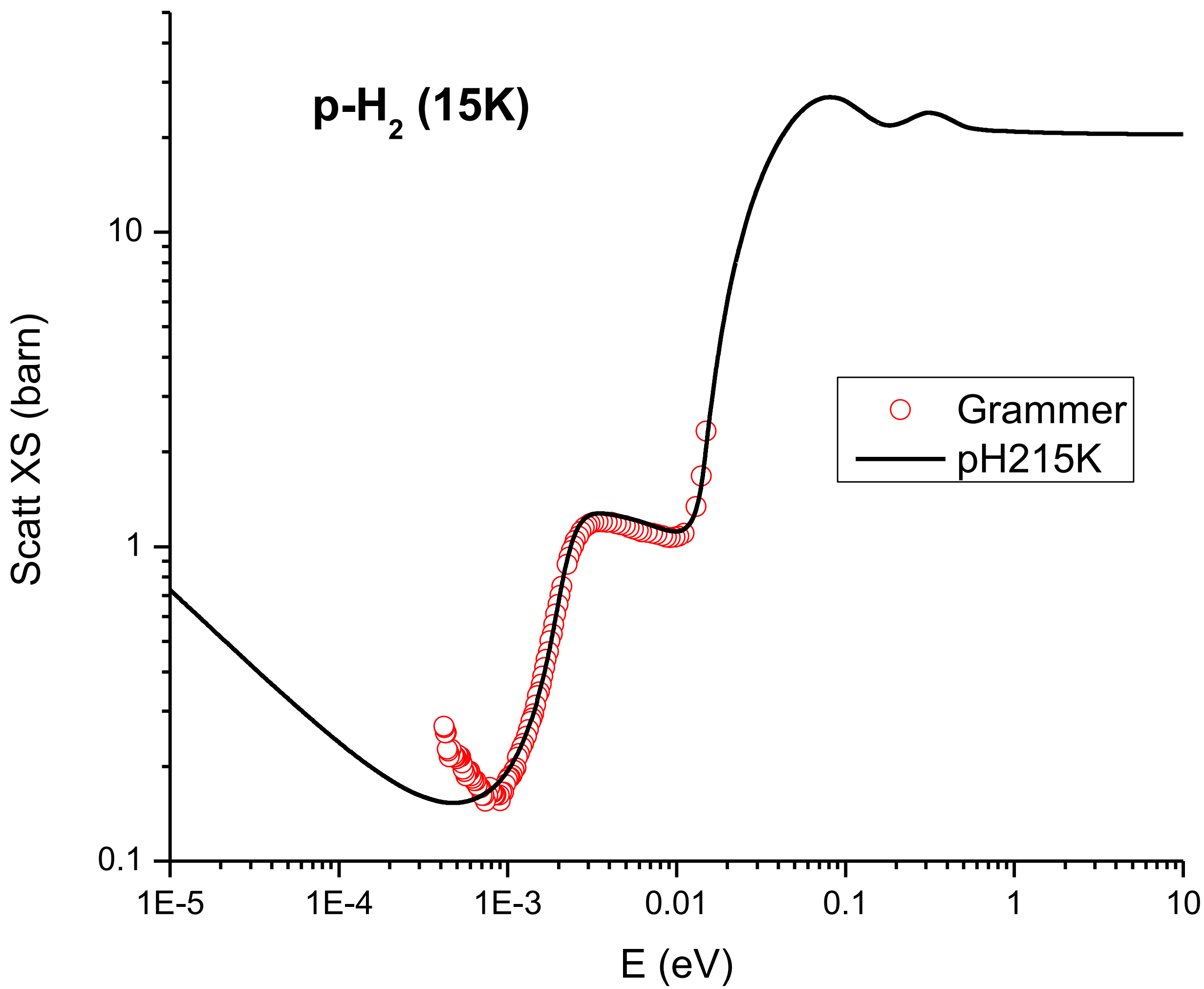


LIQUID HYDROGEN



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†

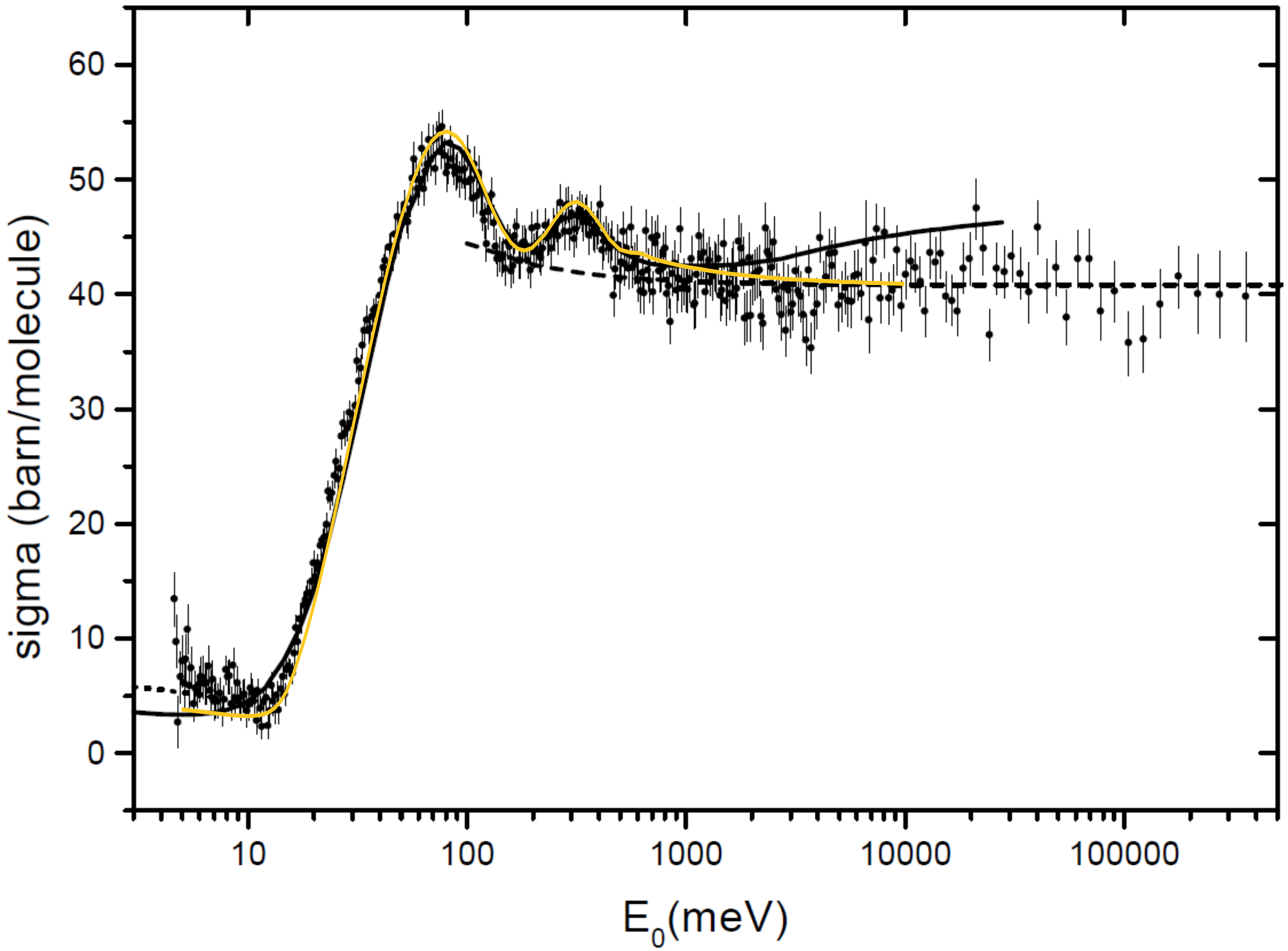
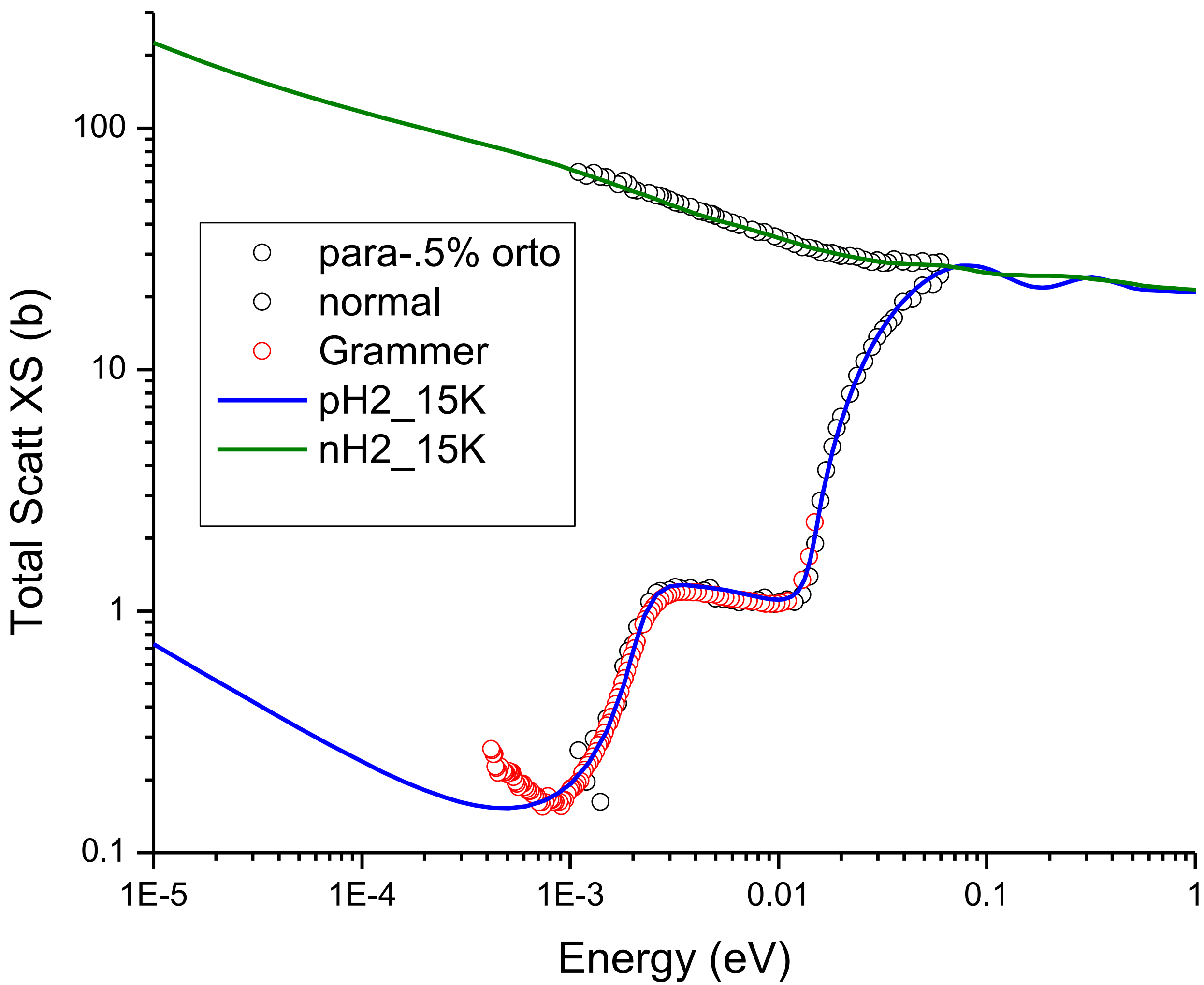
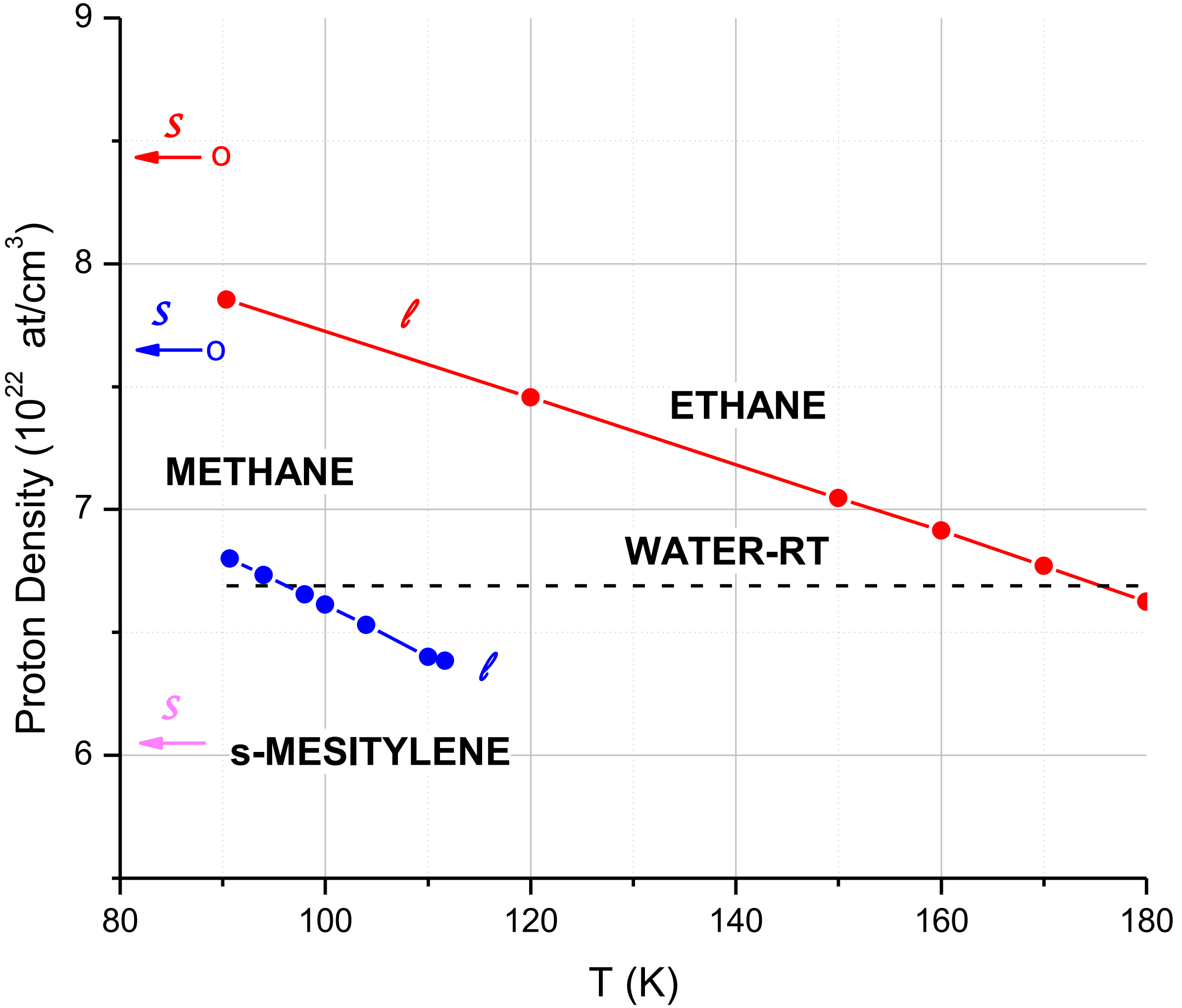


Figure 6. The total neutron cross section of liquid para-hydrogen ($T = 16$ K) as a function of the incident energy. Comparison between the experimental results and the various models. The MYK model is represented by the full line. In the low-energy region we use a heuristic effective mass of 26 amu (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.

LIQUID HYDROGEN

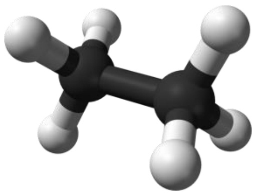


LIQUID ETHANE



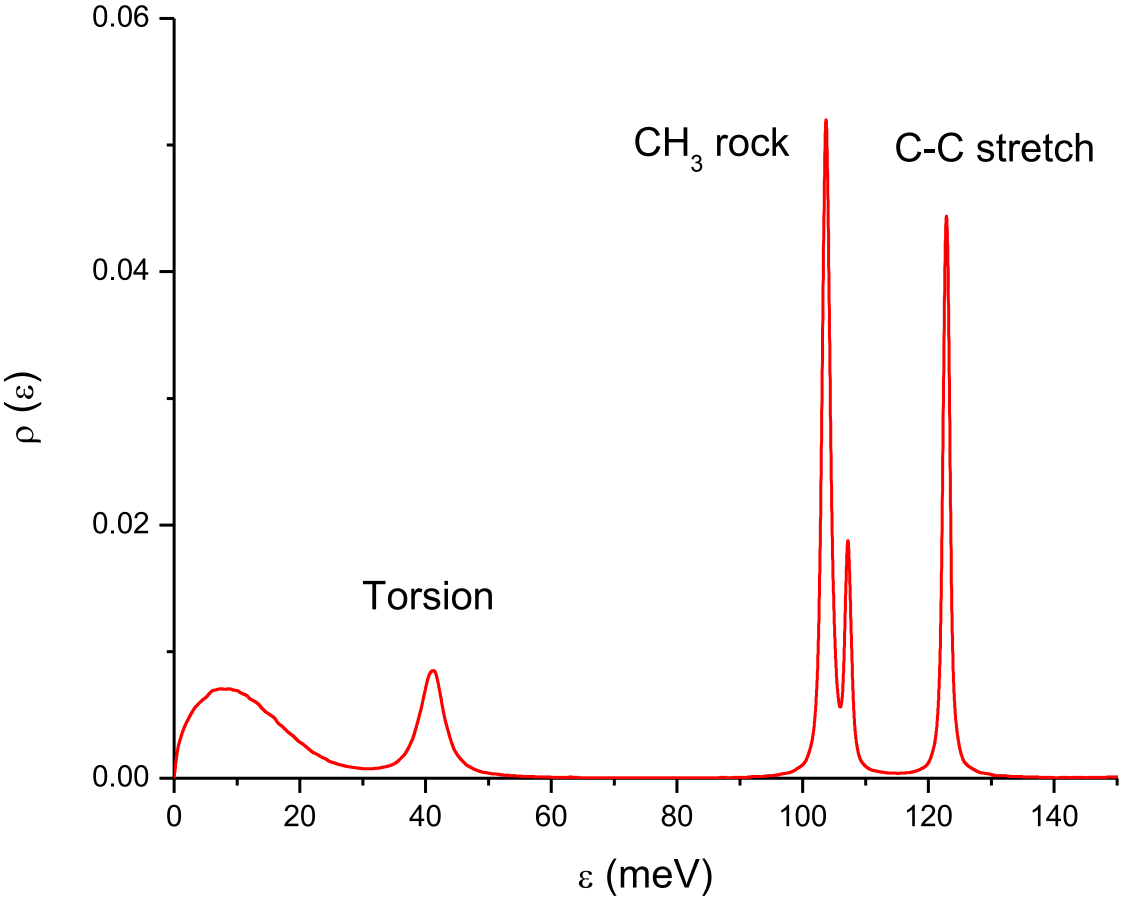
http://www.engineeringtoolbox.com/ethane-thermal-properties-d_1761.html

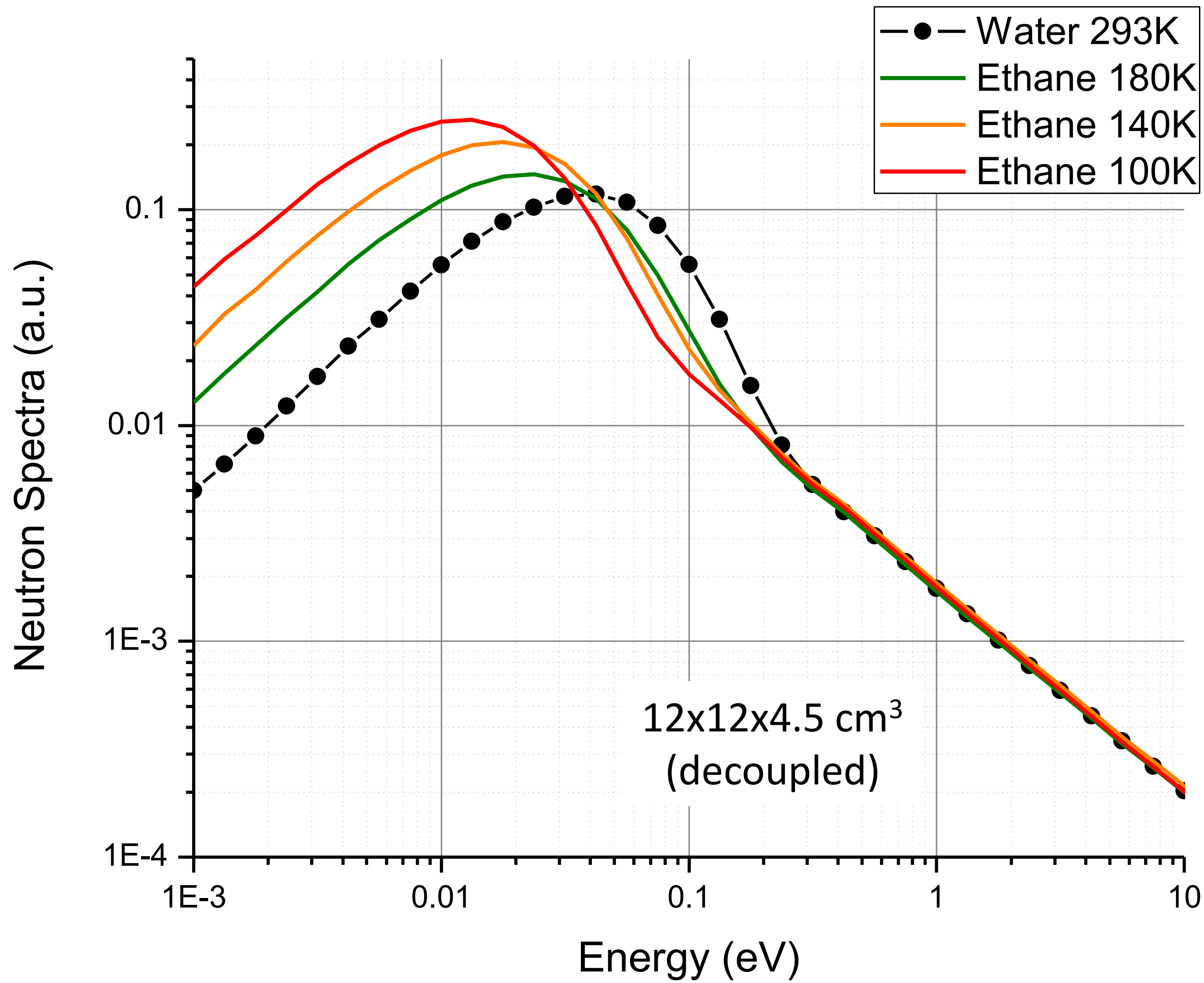
OUR MODEL FOR LIQUID ETHANE



ETHANE (100K)

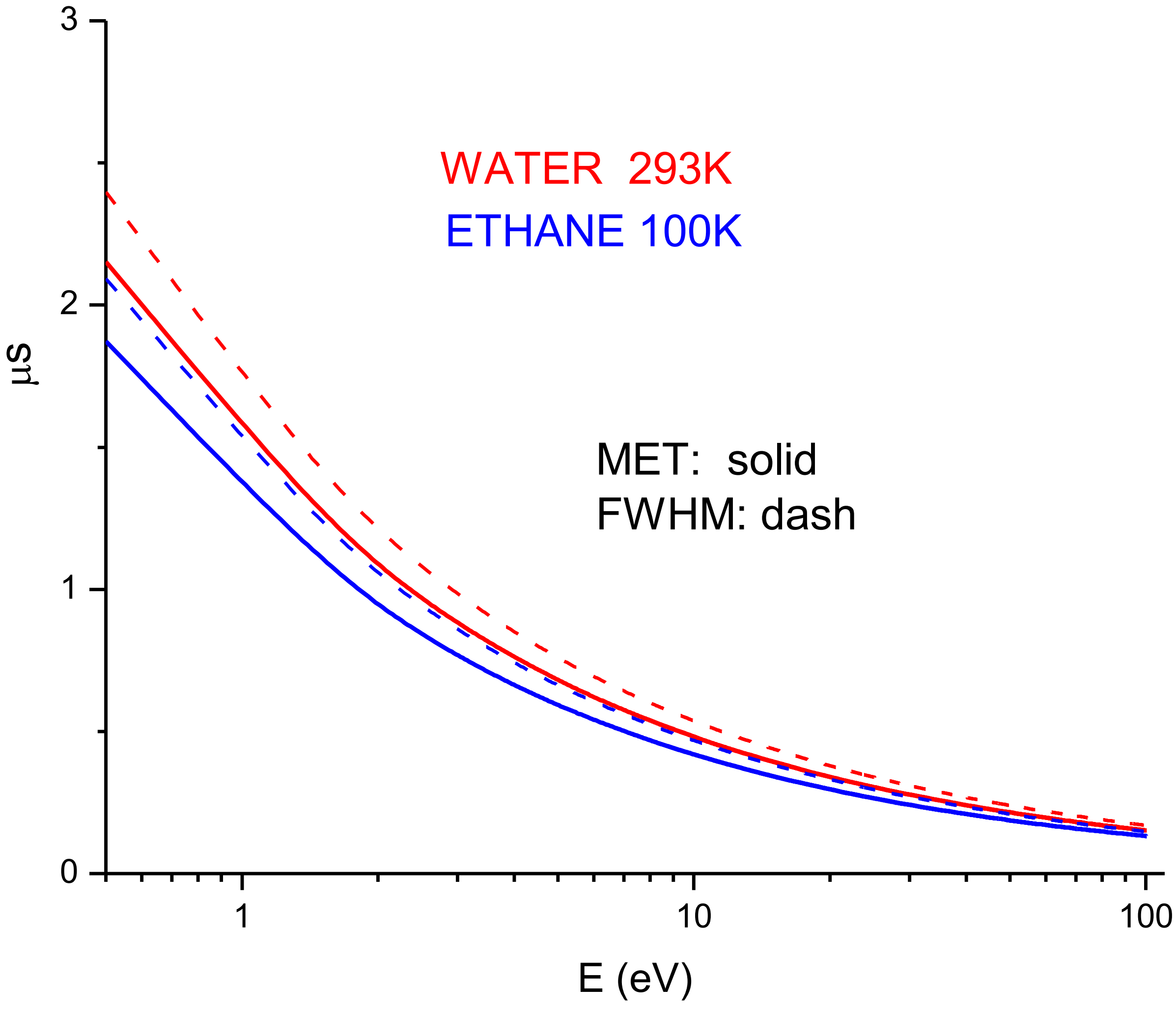
Frequency Spectrum from MD (continuous part)



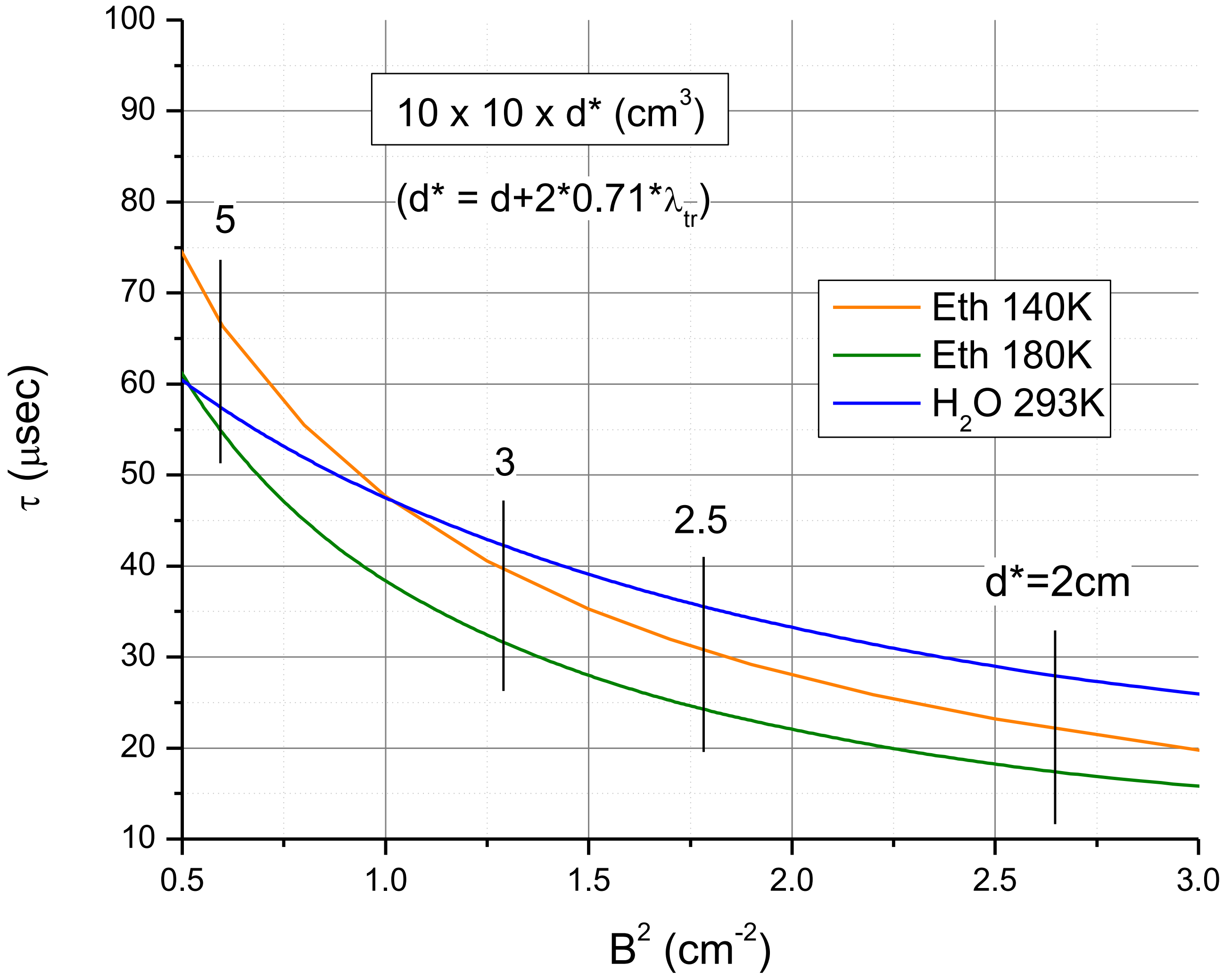


Water 293K
Ethane 180K
Ethane 140K
Ethane 100K
Neutron Spectra (a.u.)
0.1
0.01
1E-3
1E-4
1E-3
0.01
0.1
1
10
Energy (eV)
12x12x4.5 cm³
(decoupled)

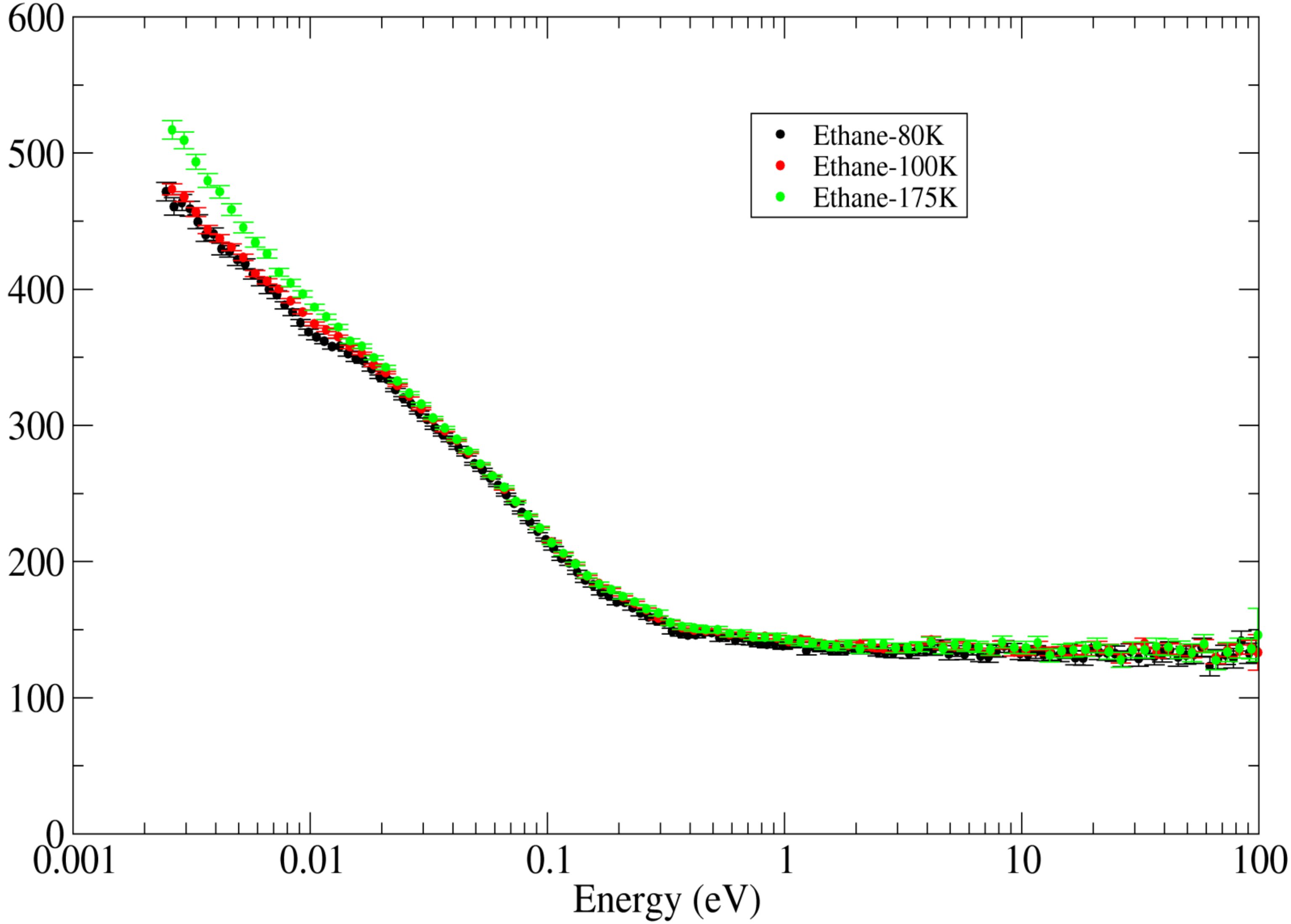
MODERATION ENERGY RANGE



THERMAL ENERGY RANGE



Transmission Experiments performed at VESUVIO (2017)



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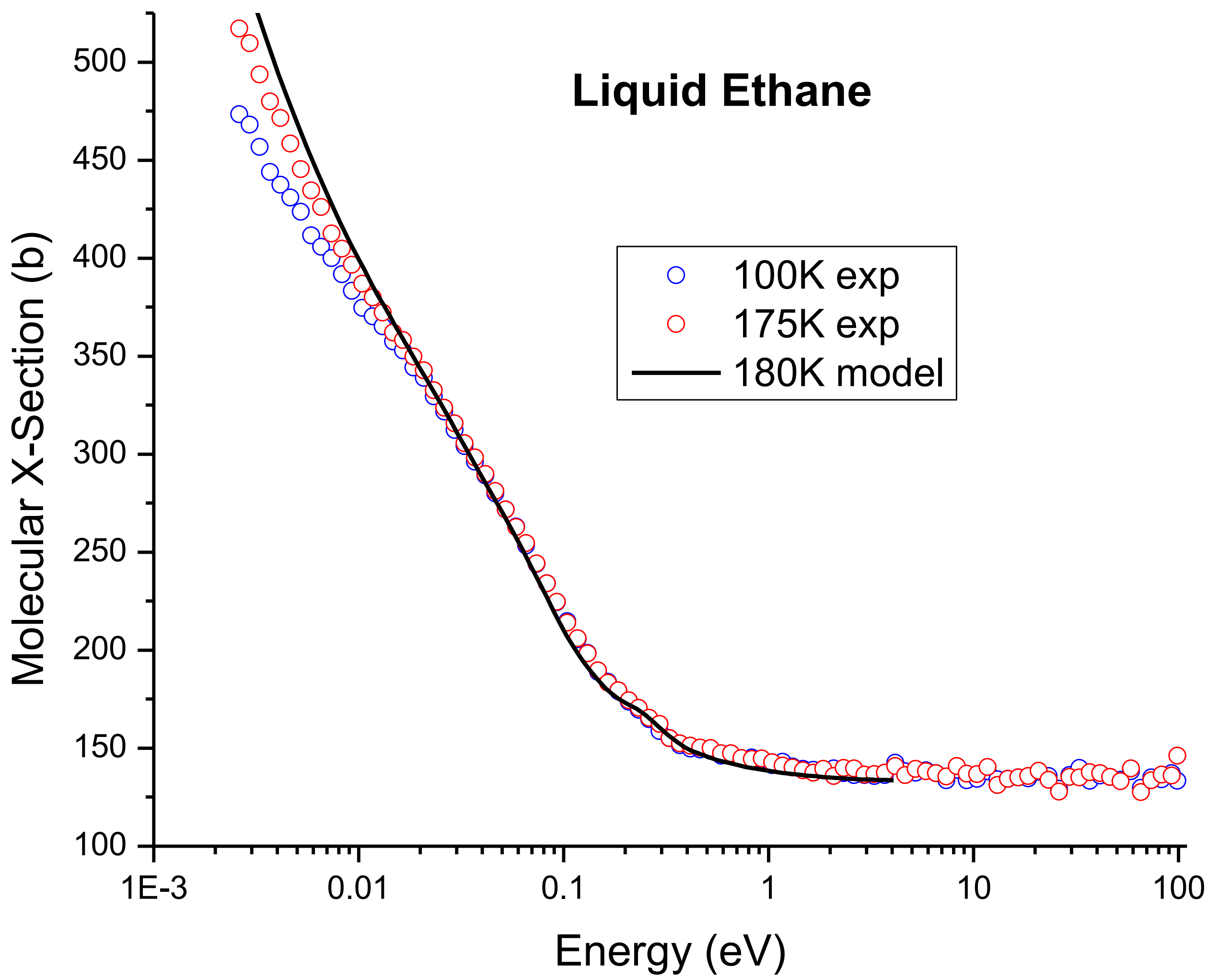

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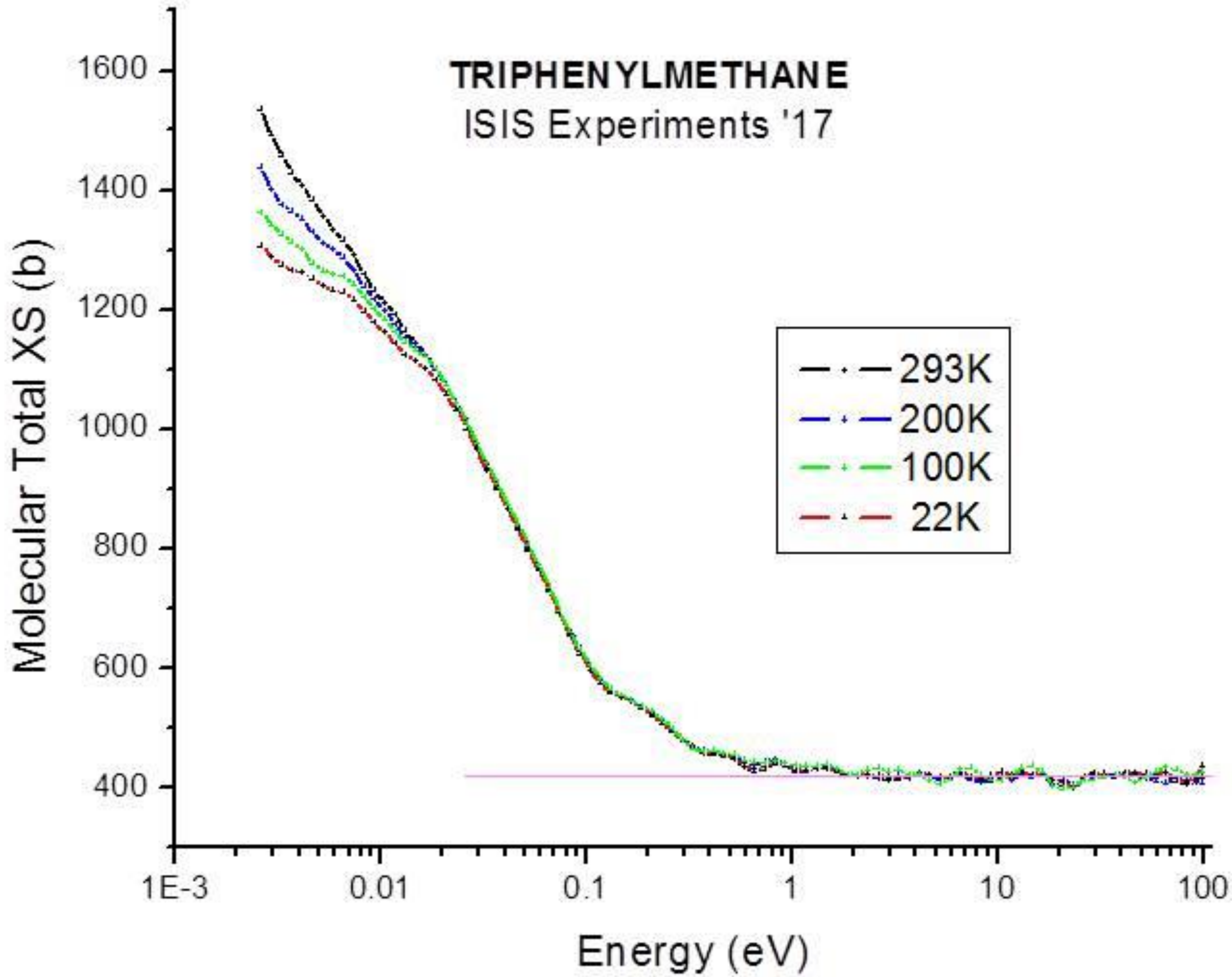

CONCLUSIONS

1. During the last few decades great advances were attained in the search for more efficient thermal and cold neutron moderators. Of particular importance is the body of work related to the design of premoderators to improve the overall performance.

CONCLUSIONS

2. Besides the recent development of high-accuracy cross section libraries for important moderators, liquid Ethane is an interesting material for an epithermal, thermal and subthermal moderator system, where by changing the temperature over its large liquid range an optimized performance can be achieved for a particular neutron energy range.

CONCLUSIONS

3. Because neutron techniques are intensity-limited, the field is open and the applications demand a continuous effort to keep improving the capacity to supply a copious flux of thermal and cold neutrons.

7th International Meeting of
Union for Compact Accelerator-driven Neutron Sources

March 11 – 15, 2018
Bariloche, ARGENTINA

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Florencia Cantargi (Co-Chair) cantargi@cab.cnea.gov.ar
Javier Dawidowski (Co-Chair) javier@cab.cnea.gov.ar


THANK YOU FOR YOUR ATTENTION