Cold & Ultra-cold Neutron Sources R&D

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Cold Neutron Source Development

- Goal: cool the neutron MB spectrum towards 5K

- Moderator Material
  - Large inelastic scattering (H, D, O)
  - Small neutron absorption (D, O)

  } This talk.

- Geometry
  - Enhance efficiency of thermal neutron flux trap (C, D_2O, nano-particles)
  - Enhance efficiency of extraction of moderated cold neutrons (grooved moderator, hybrid moderators)

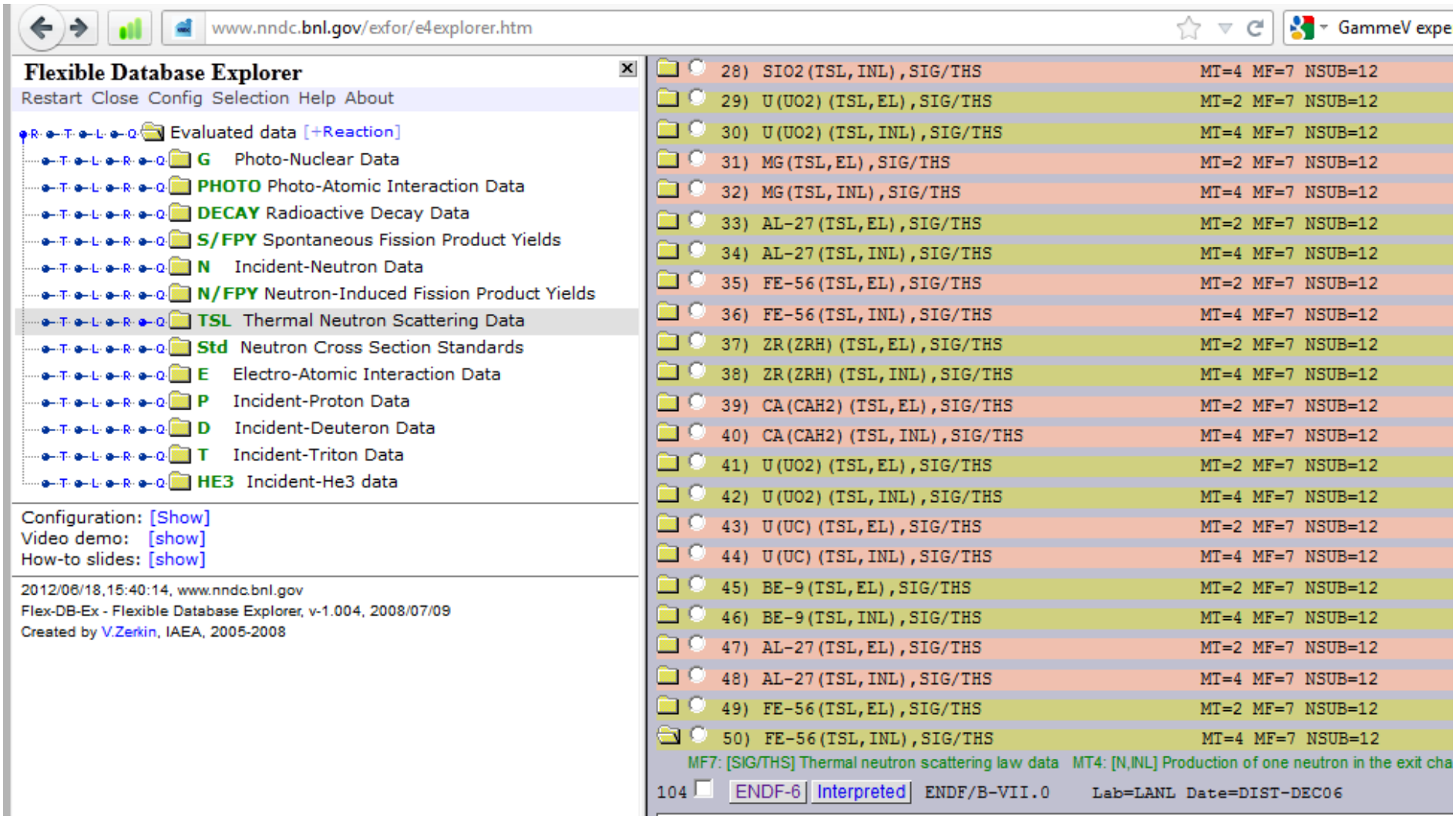
- High power requirement
  - Cooling 1MW target (sub-cooled He)

Existing Cold Neutron Scattering Kernels

www.nndc.bnl.gov/exfor/4web/lists/tsl-ENDF-VII0.list

#	Material	Lab.	Date	Authors	MAT
1)	H(H2O)	IKE,LANL	EVAL-MAR06	MacFarlane,Keinert,Mattes	1
2)	para-H	LANL	EVAL-APR93	MacFarlane	2
3)	ortho-H	LANL	EVAL-APR93	MacFarlane	3
4)	H(ZrH)	LANL	EVAL-APR93	MacFarlane	7
5)	D(D2O)	LANL	EVAL-MAR06	MacFarlane,Mattes,Keinert	11
6)	para-d	LANL	EVAL-APR93	MacFarlane	12
7)	ortho-d	LANL	EVAL-APR93	MacFarlane	13
8)	Be metal	LANL	EVAL-APR93	MacFarlane	26
9)	Be(BeO)	LANL	EVAL-JUL05	MacFarlane	27
10)	O(BeO)	LANL	EVAL-JUL05	MacFarlane	28
11)	graphite	LANL	EVAL-APR93	MacFarlane	31
12)	l-ch4	LANL	EVAL-APR93	MacFarlane	33
13)	s-ch4	LANL	EVAL-APR93	MacFarlane	34
14)	H(CH2)	GA	EVAL-DEC69	Koppel,Houston,Sprevak	37
15)	BENZINE	GA	EVAL-DEC69	Koppel,Houston,Borgonovi	40
16)	13-Al- 27	LANL	EVAL-OCT05	MacFarlane	45
17)	26-Fe- 56	LANL	EVAL-OCT05	MacFarlane	56
18)	Zr(ZrH)	LANL	EVAL-APR93	MacFarlane	58
19)	O(UO2)	LANL	EVAL-FEB05	MacFarlane	75
20)	U(UO2)	LANL	EVAL-FEB05	MacFarlane	76

Existing Cold Neutron Scattering Kernels



NEW THERMAL NEUTRON SCATTERING FILES FOR ENDF/B-VI RELEASE 2

R. E. MacFarlane

August 24, 1994

- Incoherent Elastic (easy)
- Coherent Elastic (OK)
- Incoherent Inelastic (easy)
- Coherent Inelastic (hard!)

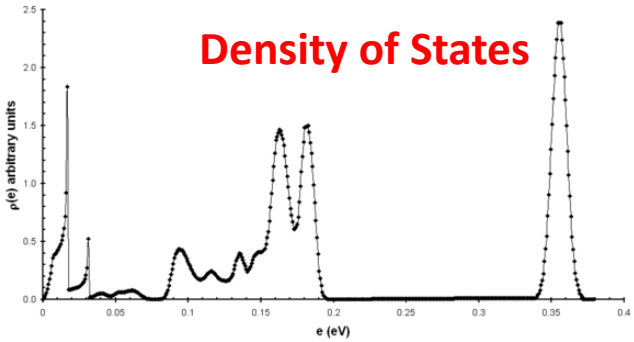
CONTENTS

hcp lattice

fcc →

spin

Cold Neutron Scattering Kernel (using NJOY)



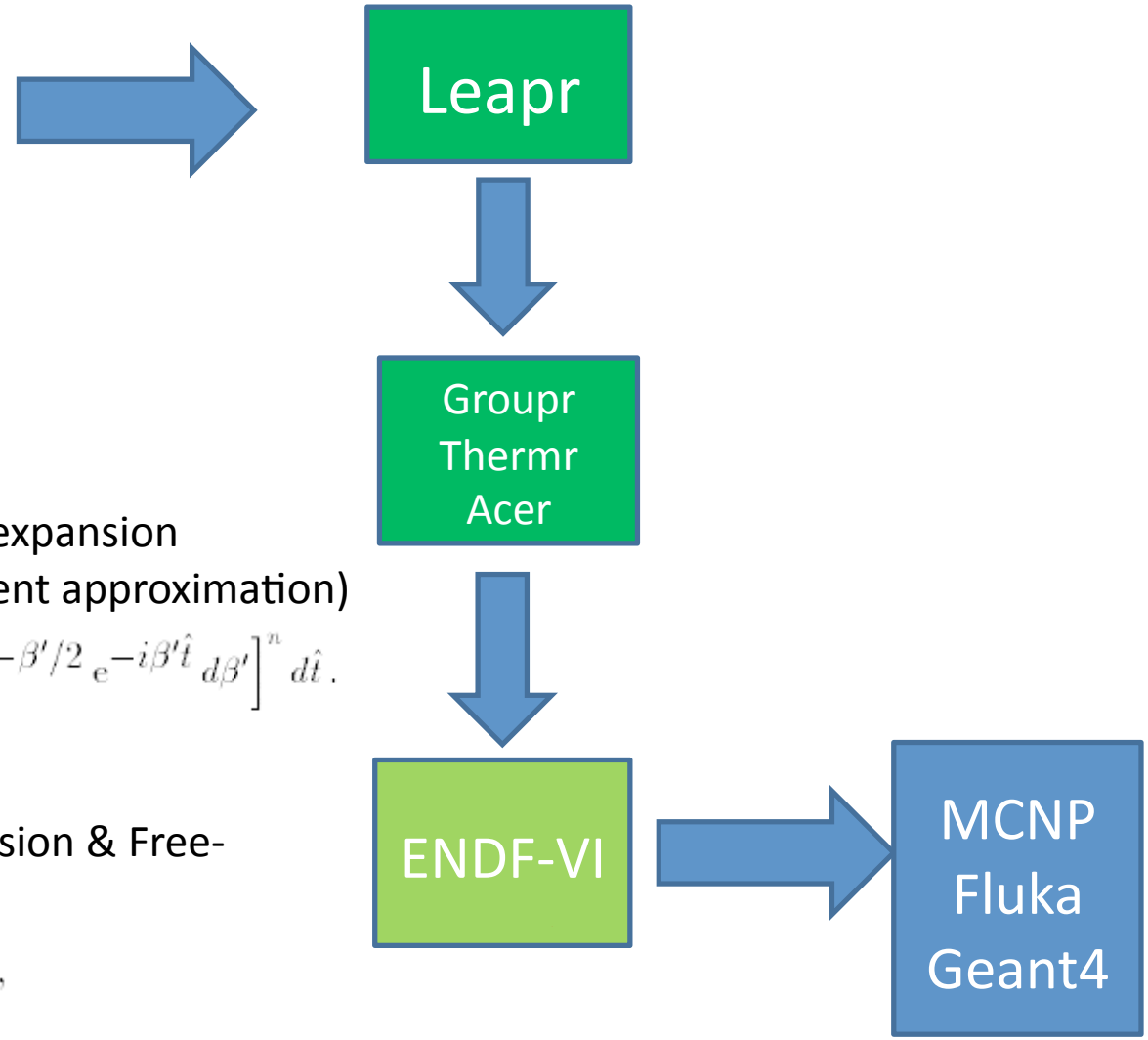
$$\sigma(E \to E', \mu) = \frac{\sigma_b}{2kT}\sqrt{\frac{E'}{E}}\,\mathcal{S}(\alpha, \beta)\,,$$

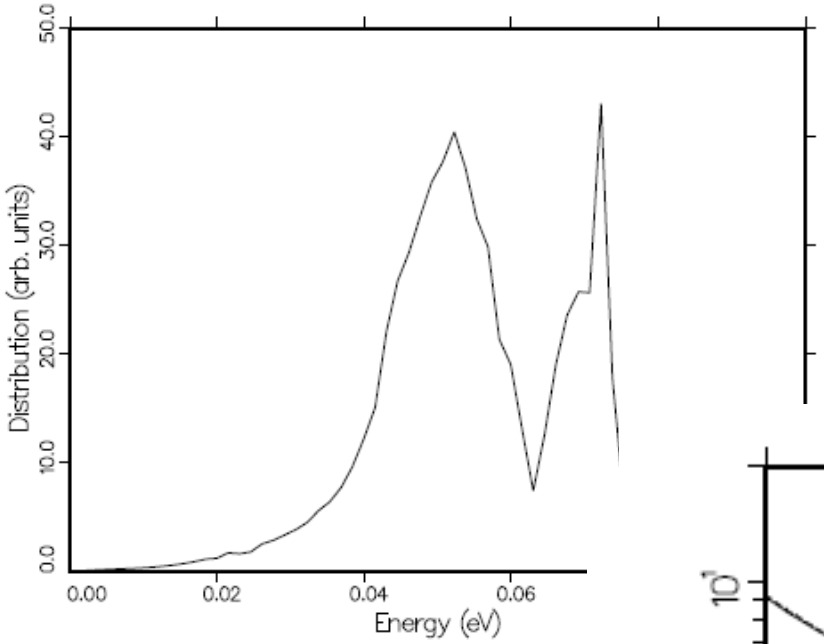
$$\mathcal{S}_s(\alpha, \beta) = e^{-\alpha\lambda_s}\sum_{n=0}^{\infty}\frac{1}{n!}\alpha^n \times \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{i\beta\hat{t}}\left[\int_{-\infty}^{\infty} P_s(\beta')\, e^{-\beta'/2}\, e^{-i\beta'\hat{t}}\, d\beta'\right]^n d\hat{t}\,.$$

Phonon expansion
(Incoherent approximation)

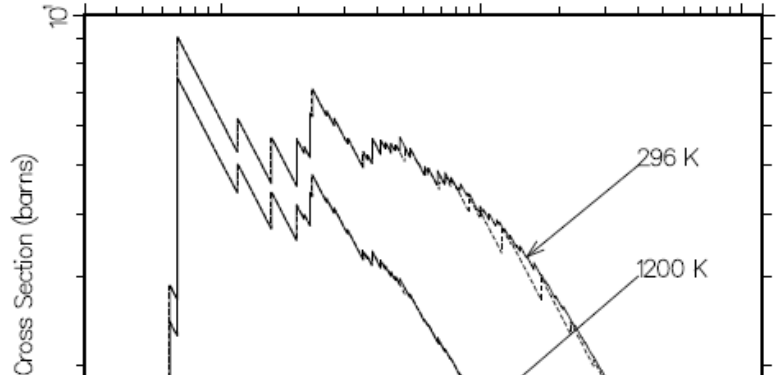
Other approximations:
Short-Collision-Time Approx., Diffusion & Free-gas translation, Discrete oscillators

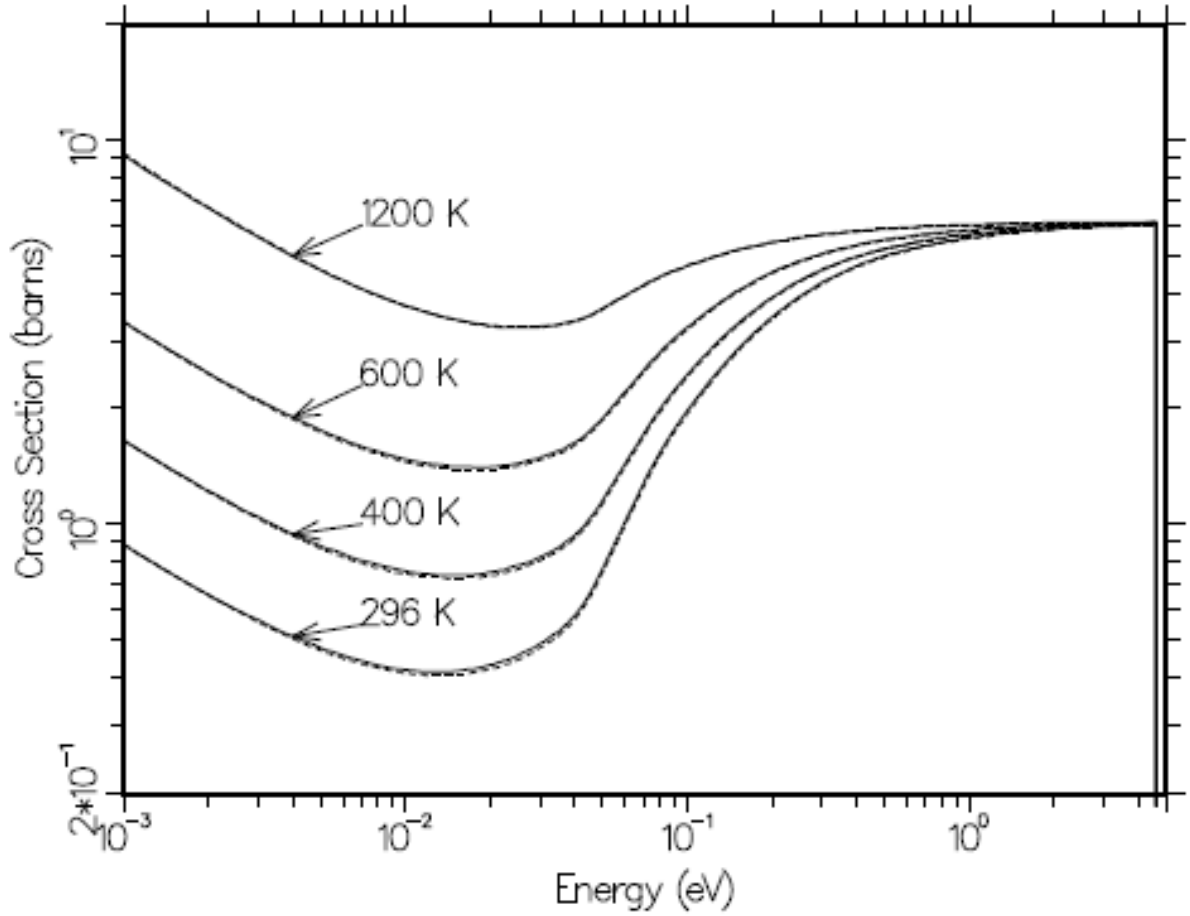
$$\sigma_{\rm coh}(E, \mu) = \frac{\sigma_c}{E}\sum_{E_i < E} f_i\, e^{-4WE_i}\delta(\mu - \mu_i)\,,$$





re 1: The phonon frequency spectrum $\rho($

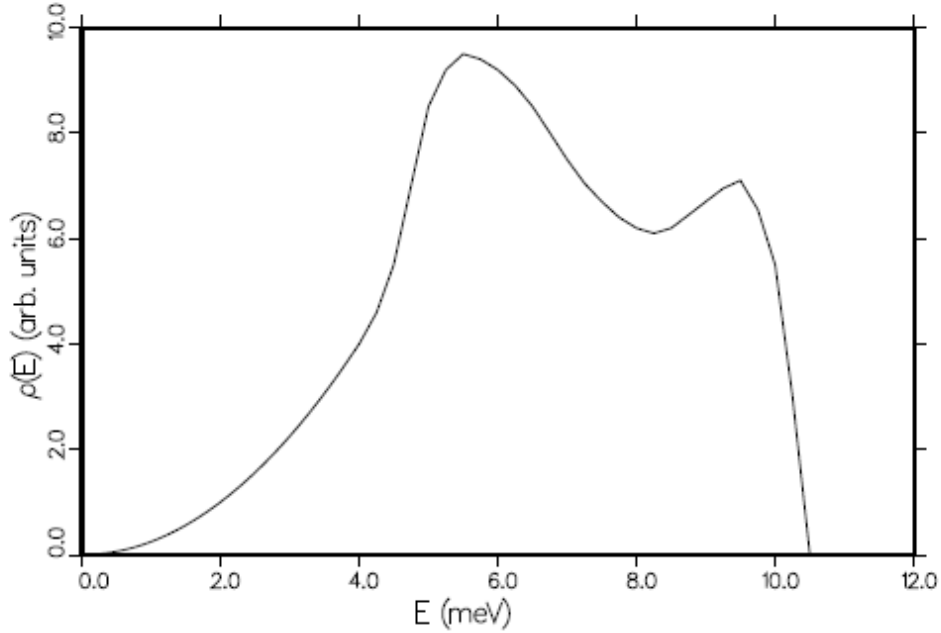


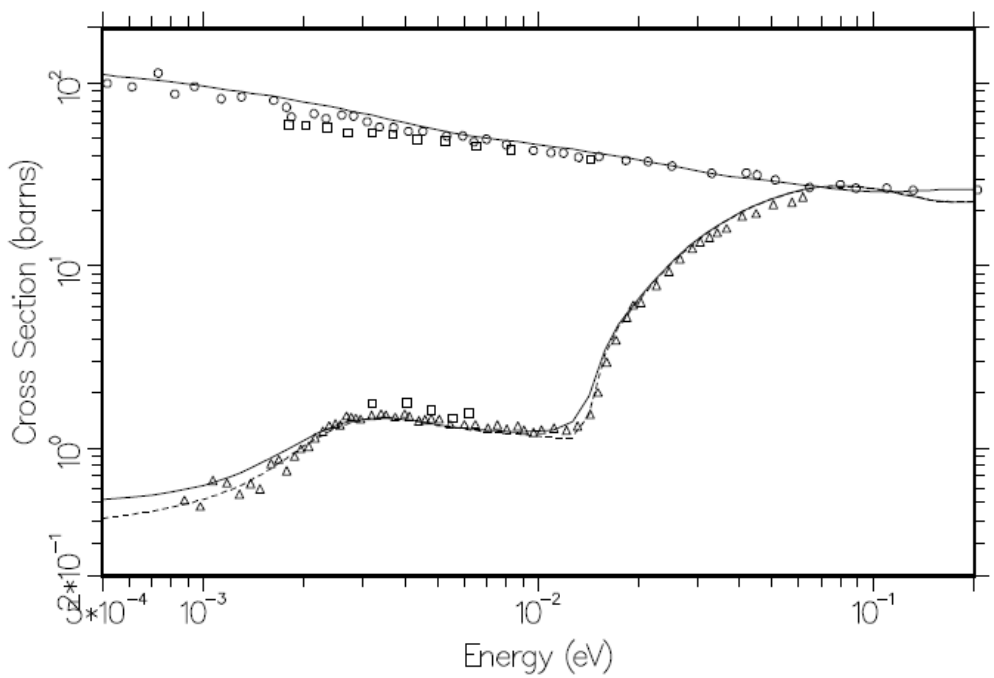


- Be
- hcp lattice

Figure 16: Perspective view of the secondary neutron spectra from

Liquid H_2





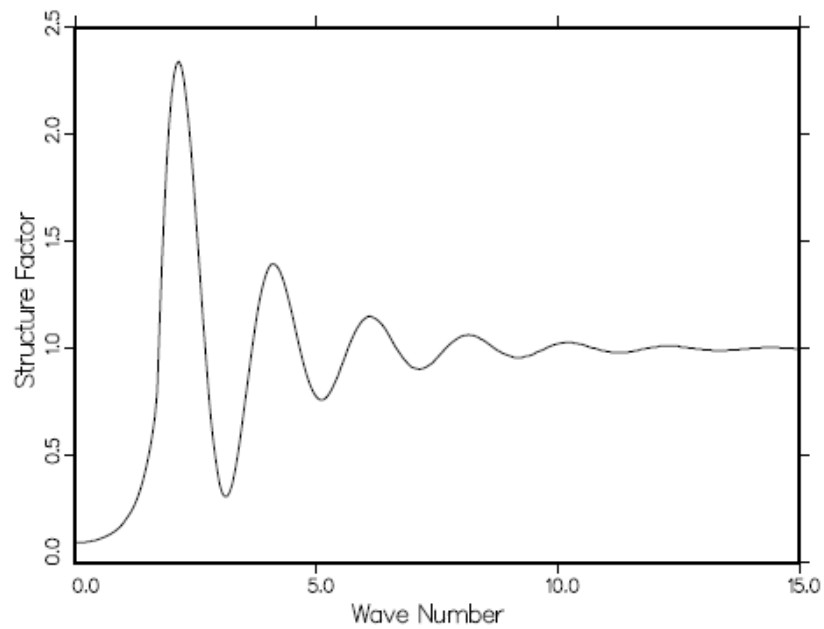
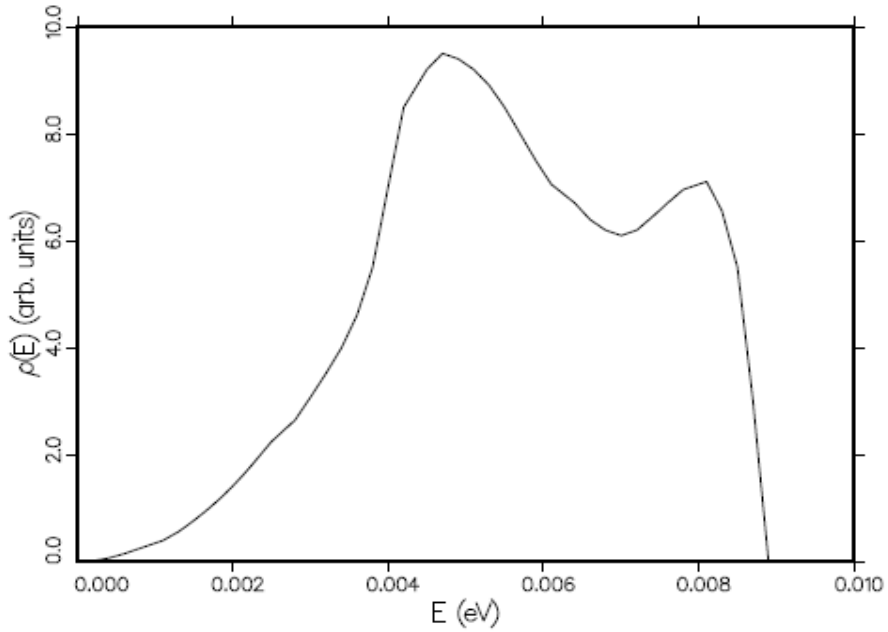
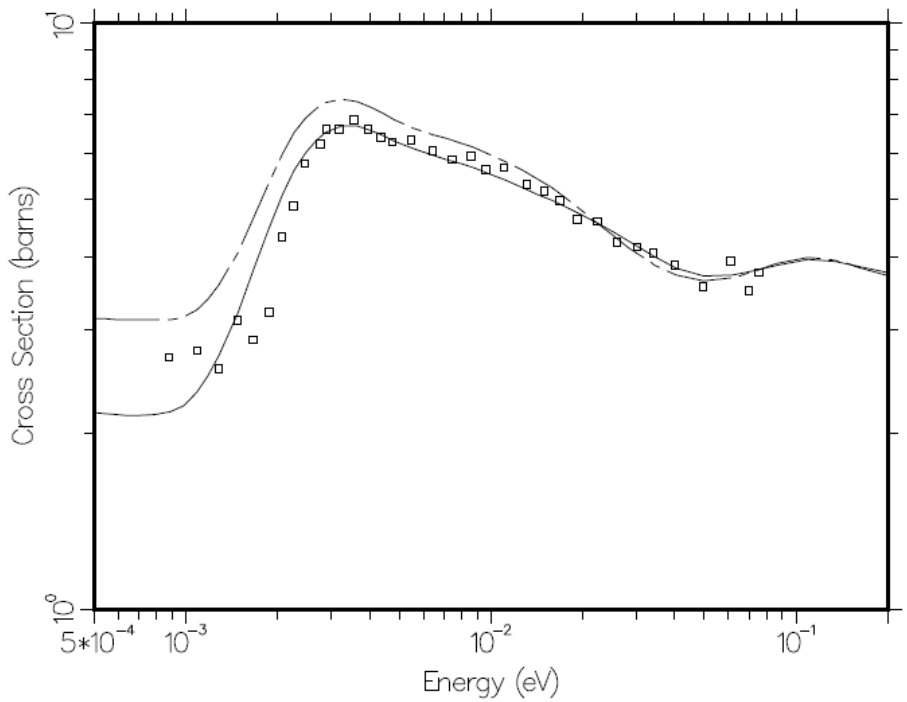


Fig
trar

ıre 82: The static structure factor $S(\kappa)$ for liquid hydrogen.

Liquid D_2





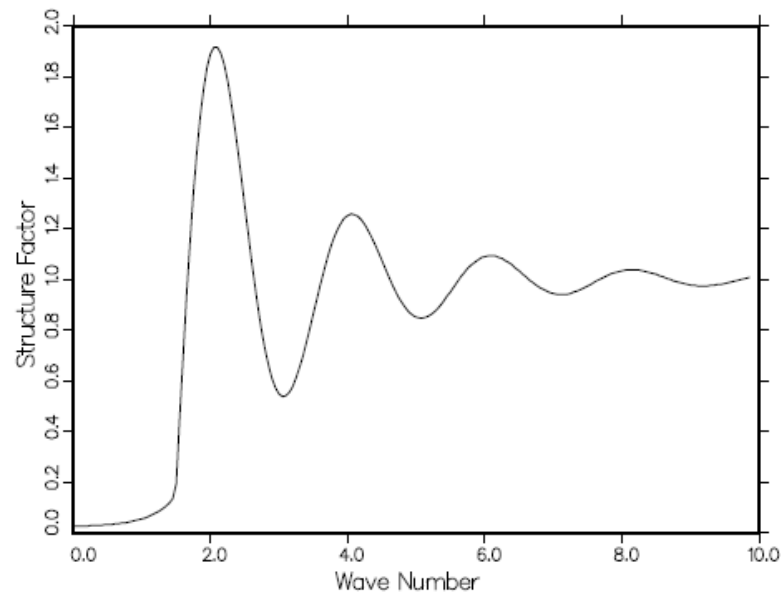
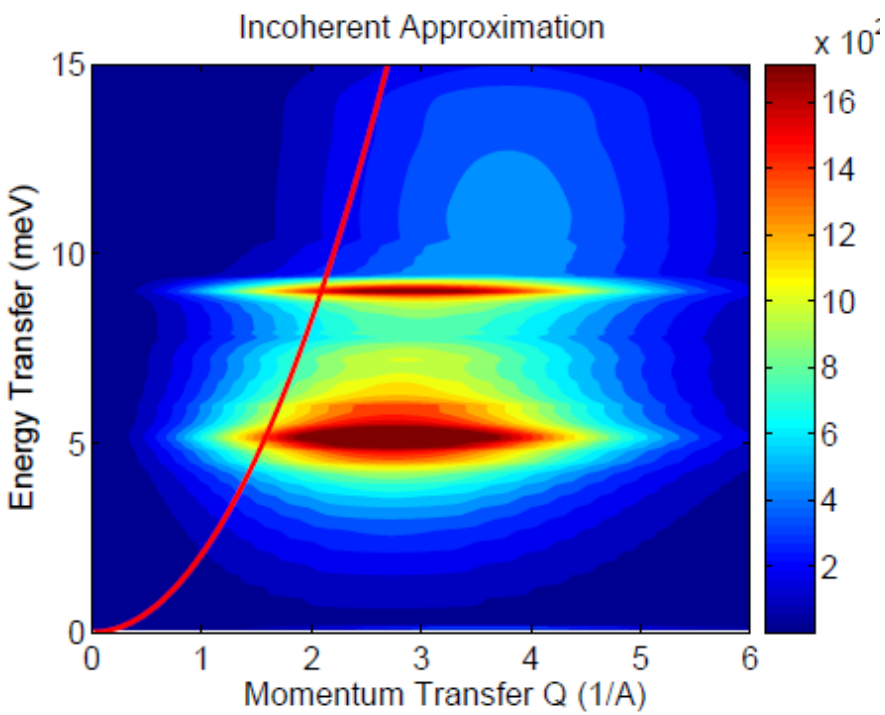


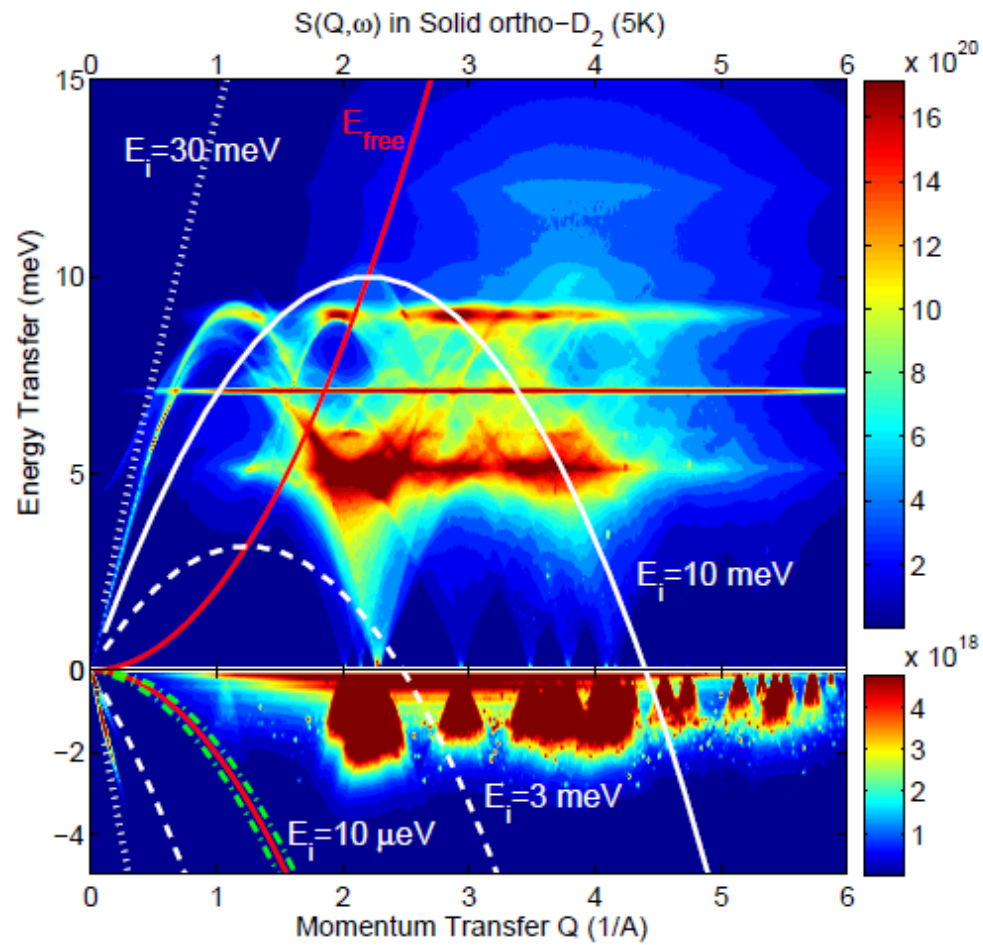
Figure 95: The static structure factor $S(\kappa)$ for liquid deuterium.

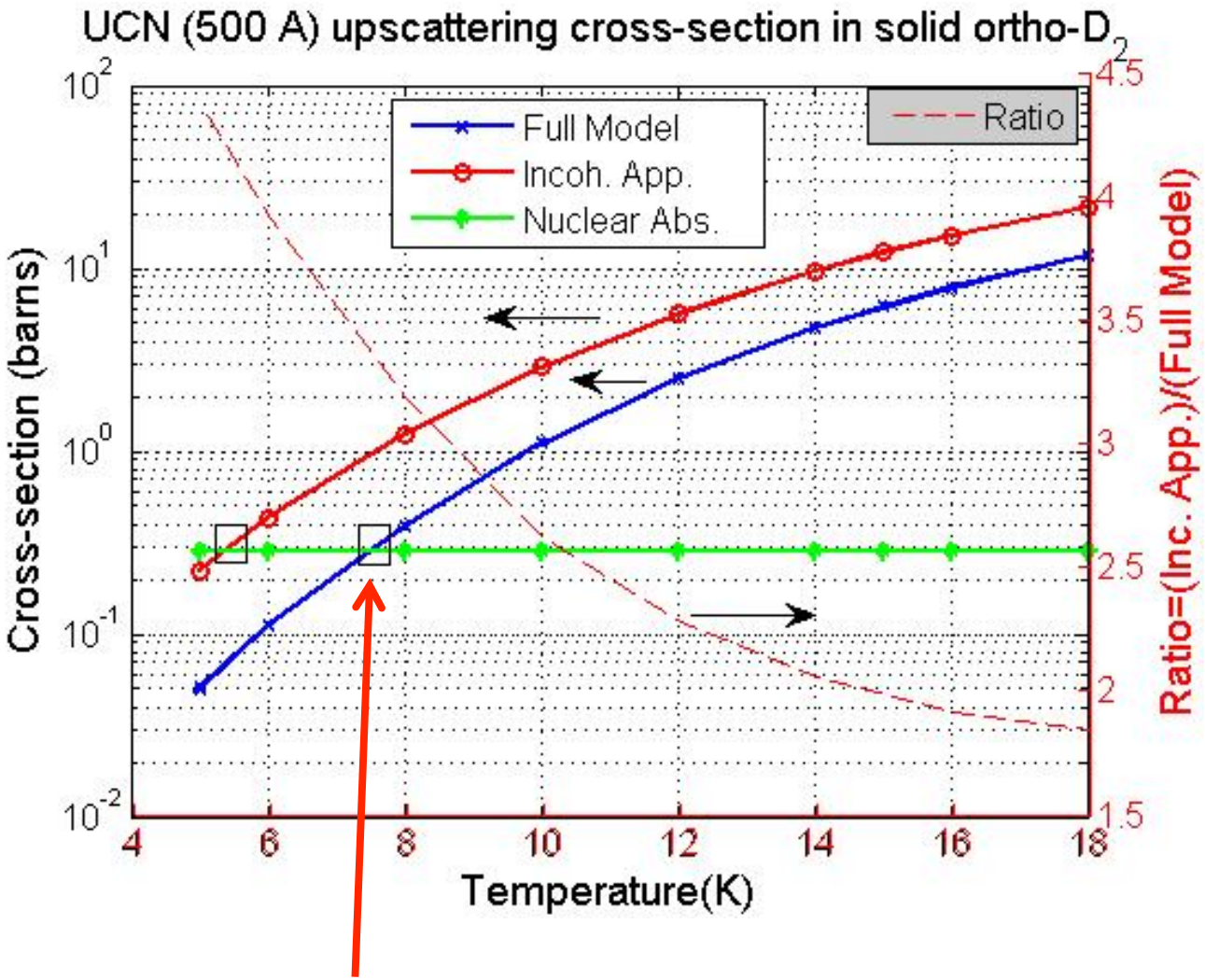
Incoherent Approximation

- Inc. Approx.

Semi-ab initio calculatoin





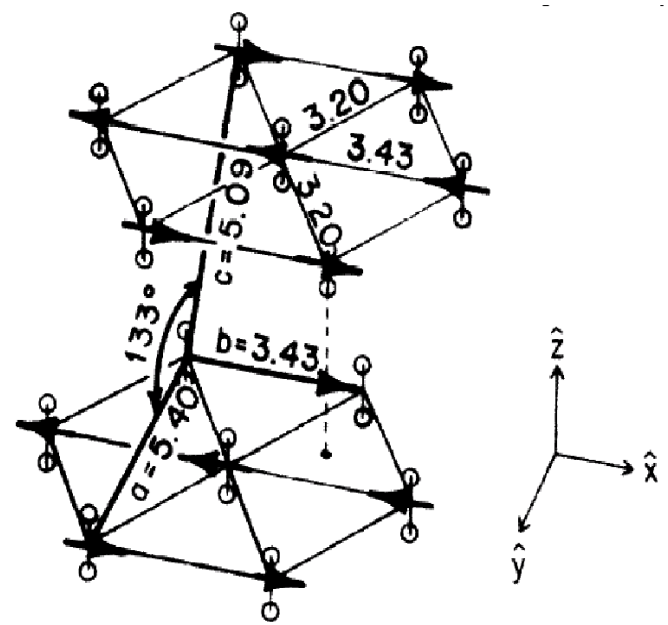


Higher saturation temperature!

Solid Oxygen as a UCN Source

σ_{coh} =4.232 barn, σ_{inc} = 0 barn,
σ_{abs} = 0.0001 barn

- Electronic spin S=1 in O_2 molecules.
- Nuclear spin = 0 in $_{16}O$
- Collinear Anti-ferromagnetic in 2-D
  - α-phase, T < 24K.



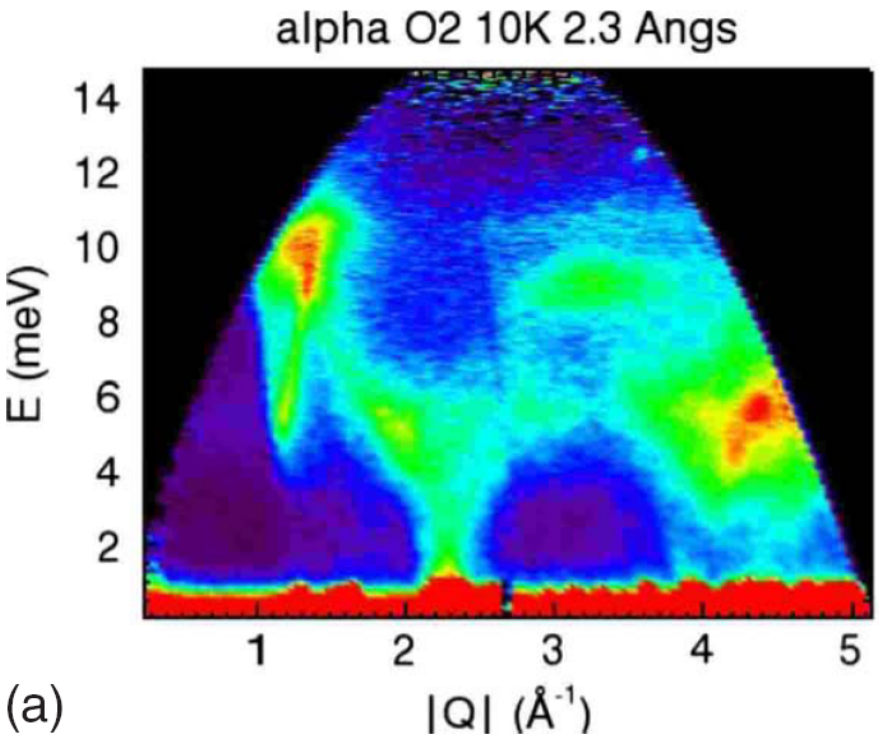
Stephens & Majkrzak, PRB **33**, 1 (1986)

UCN Production in alpha S-O_2

- Produce UCN through magnon excitations.
  - Magnetic scattering length ~ 5.4 fm.
- Null incoherent scattering length.
- Small nuclear absorption probability.

⇒ A very large source possible.

Inelastic neutron scattering data

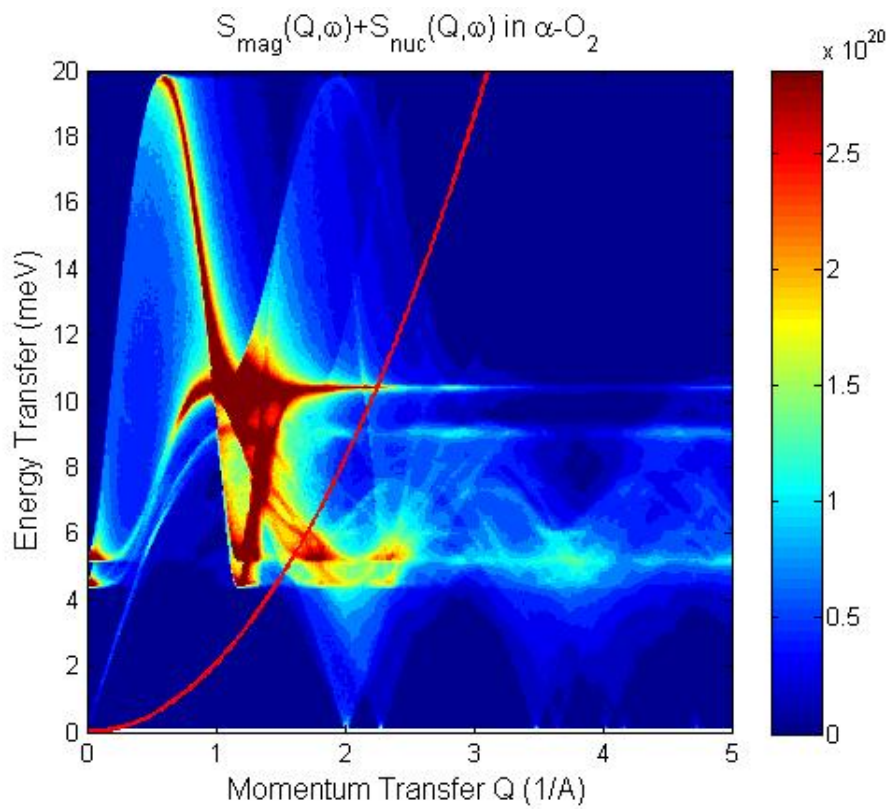


Calculations

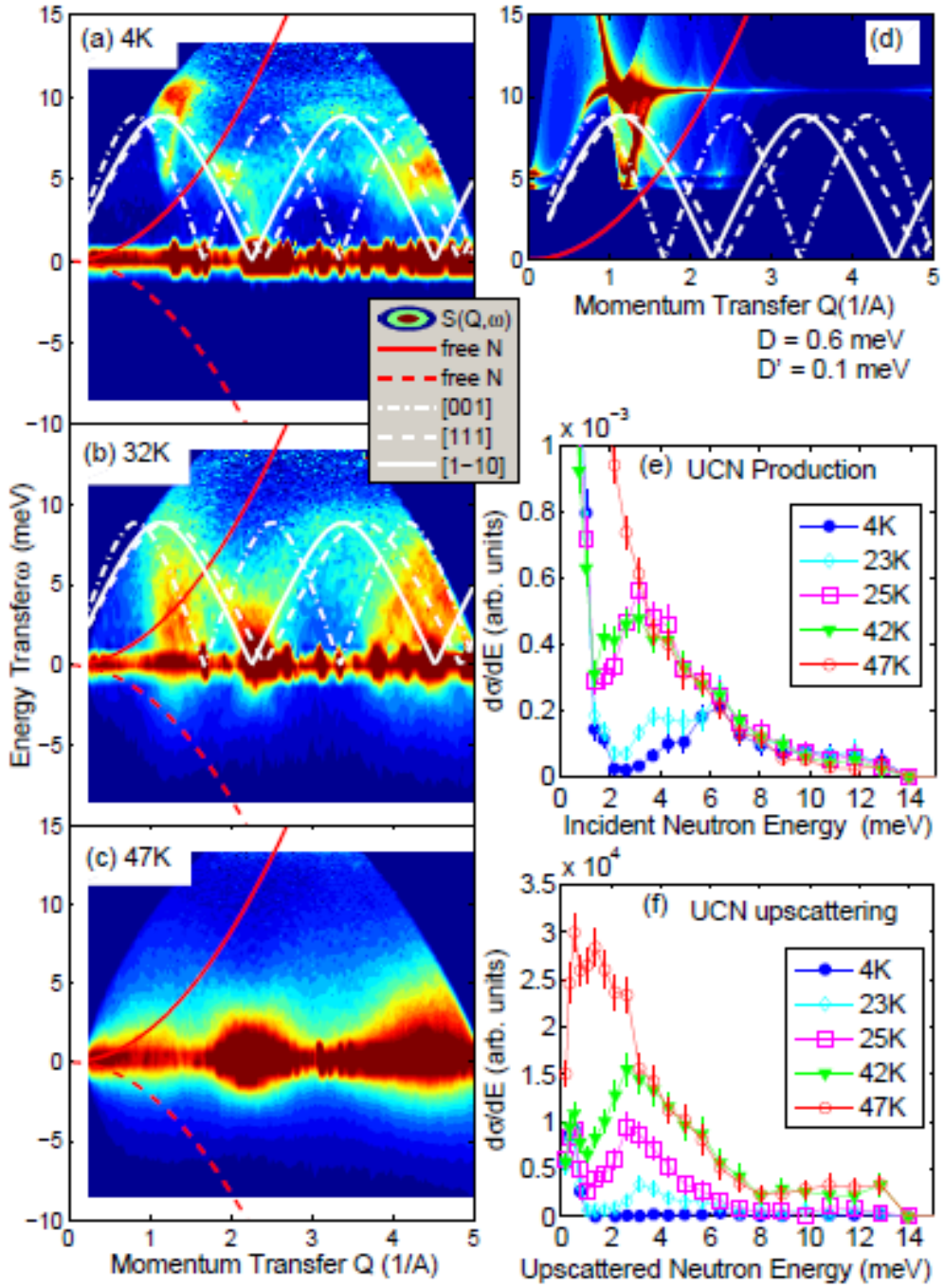
$$H = -2\sum_{\langle ij \rangle} J_{ij}\mathbf{S}_i\cdot\mathbf{S}_j + \sum_i (-DS_{xi}^2 - D'S_{yi}^2 + D'S_{zi}^2)$$

Jnn=-2.44 meV
Jnnn=-1.22 meV

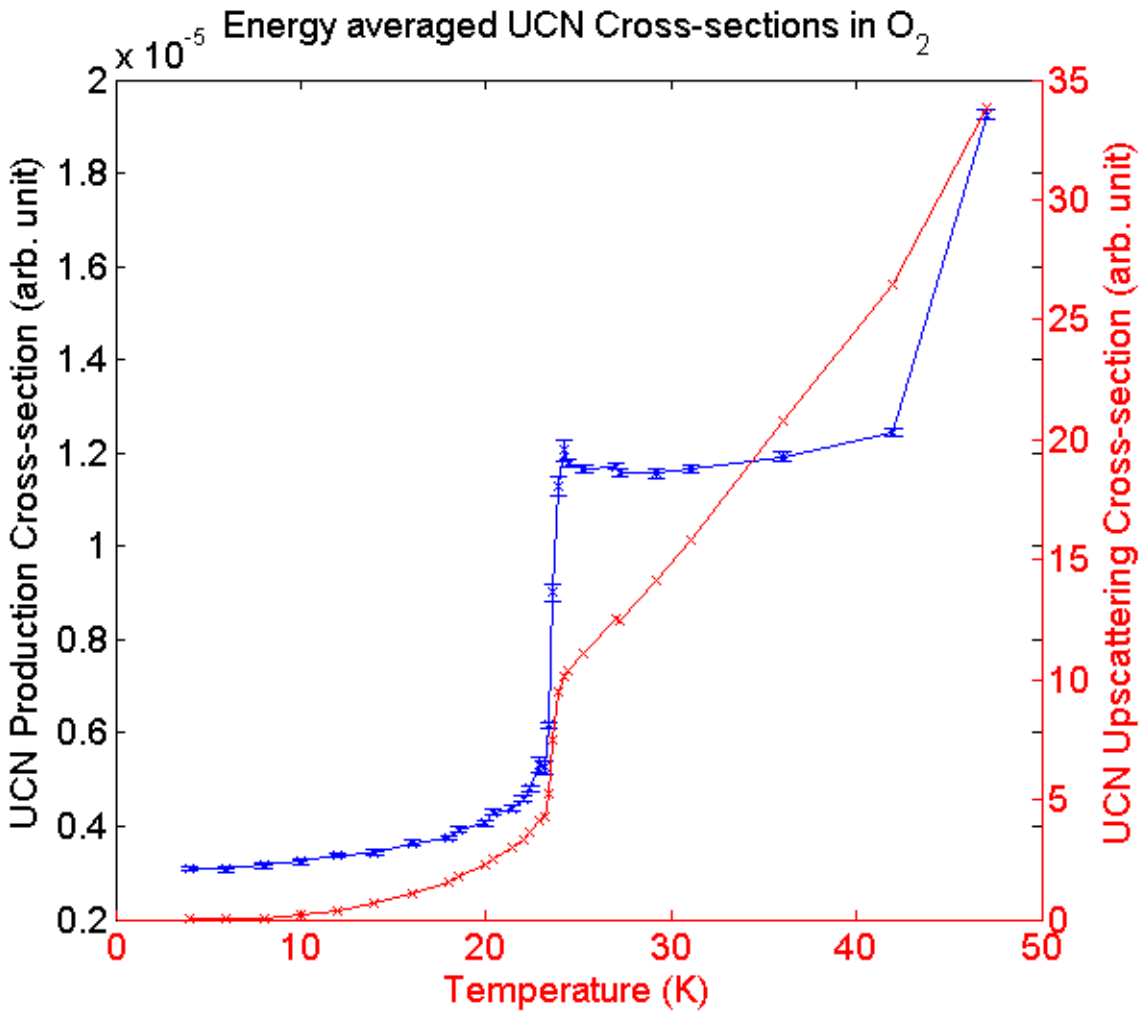
D=0.6 meV (updated)
D'=0.1 meV

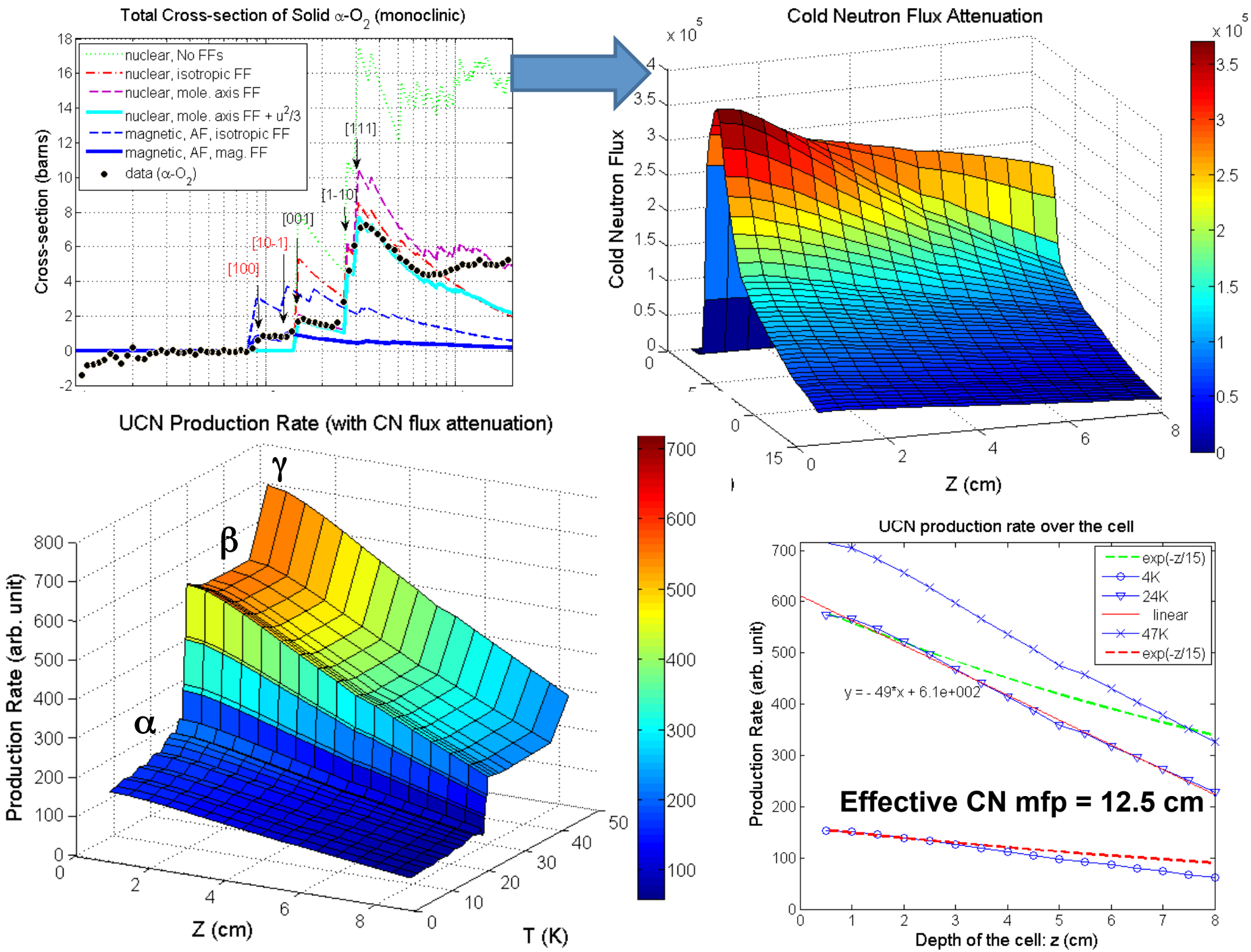


Spin self-energy is very strong along the direction of spin alignment!


(a) 4K
(b) 32K
(c) 47K
(d)
S(Q,ω)
free N
free N
[001]
[111]
[1−10]
Energy Transferω (meV)
Momentum Transfer Q (1/A)
Momentum Transfer Q(1/A)
D = 0.6 meV
D' = 0.1 meV
(e) UCN Production
dσ/dE (arb. units)
Incident Neutron Energy (meV)
(f) UCN upscattering
Upscattered Neutron Energy (meV)
4K
23K
25K
42K
47K

UCN Production & Upscattering Cross Sections

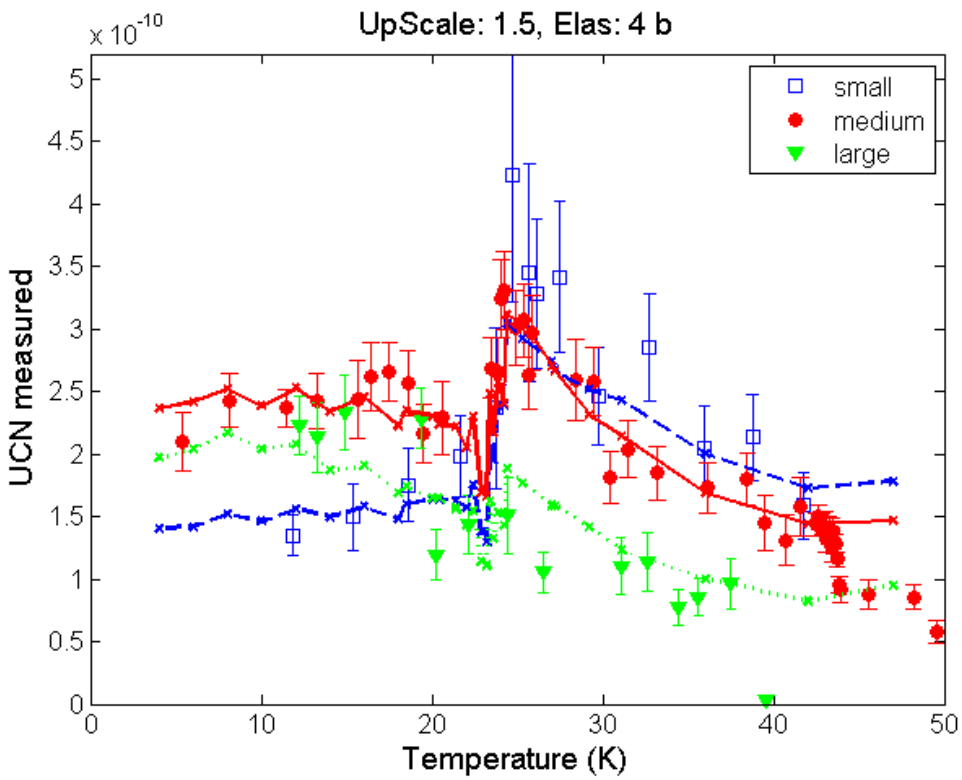


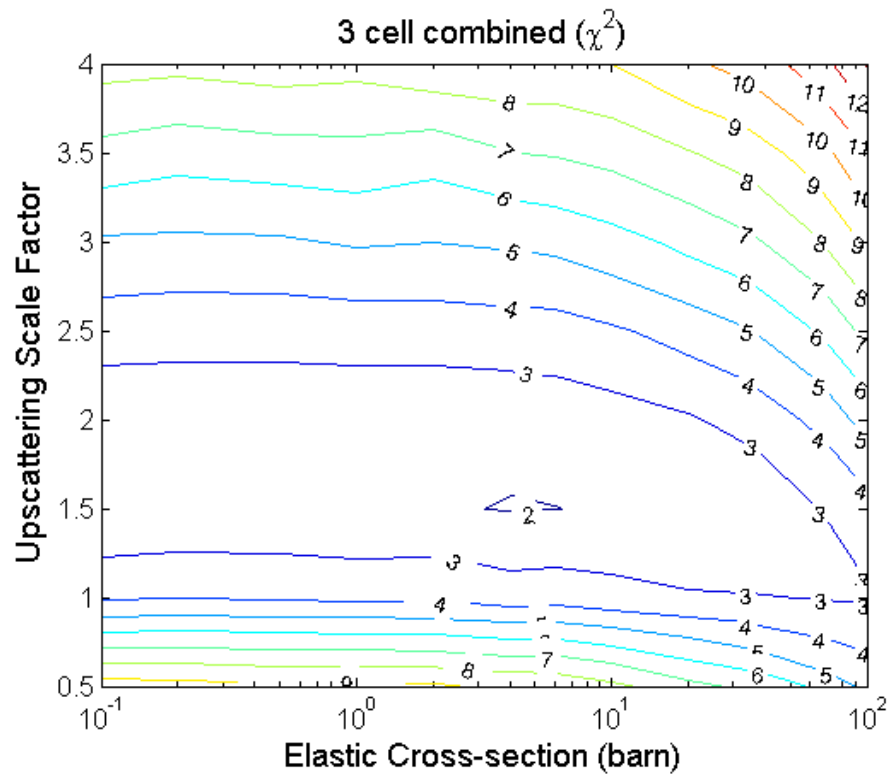

Total Cross-section of Solid α-O2 (monoclinic)
nuclear, No FFs
nuclear, isotropic FF
nuclear, mole. axis FF
nuclear, mole. axis FF + u2/3
magnetic, AF, isotropic FF
magnetic, AF, mag. FF
data (α-O2)
Cross-section (barns)
[111]
[1-10]
[001]
[10-1]
[100]
Cold Neutron Flux Attenuation
Cold Neutron Flux
Z (cm)
UCN Production Rate (with CN flux attenuation)
Production Rate (arb. unit)
Z (cm)
T (K)
γ
β
α
UCN production rate over the cell
exp(-z/15)
4K
24K
linear
47K
exp(-z/15)
y = - 49*x + 6.1e+002
Effective CN mfp = 12.5 cm
Production Rate (arb. unit)
Depth of the cell: z (cm)

Combined analysis

Monte-Carlo study with multivariable fit to the data from 3 cells of different size.

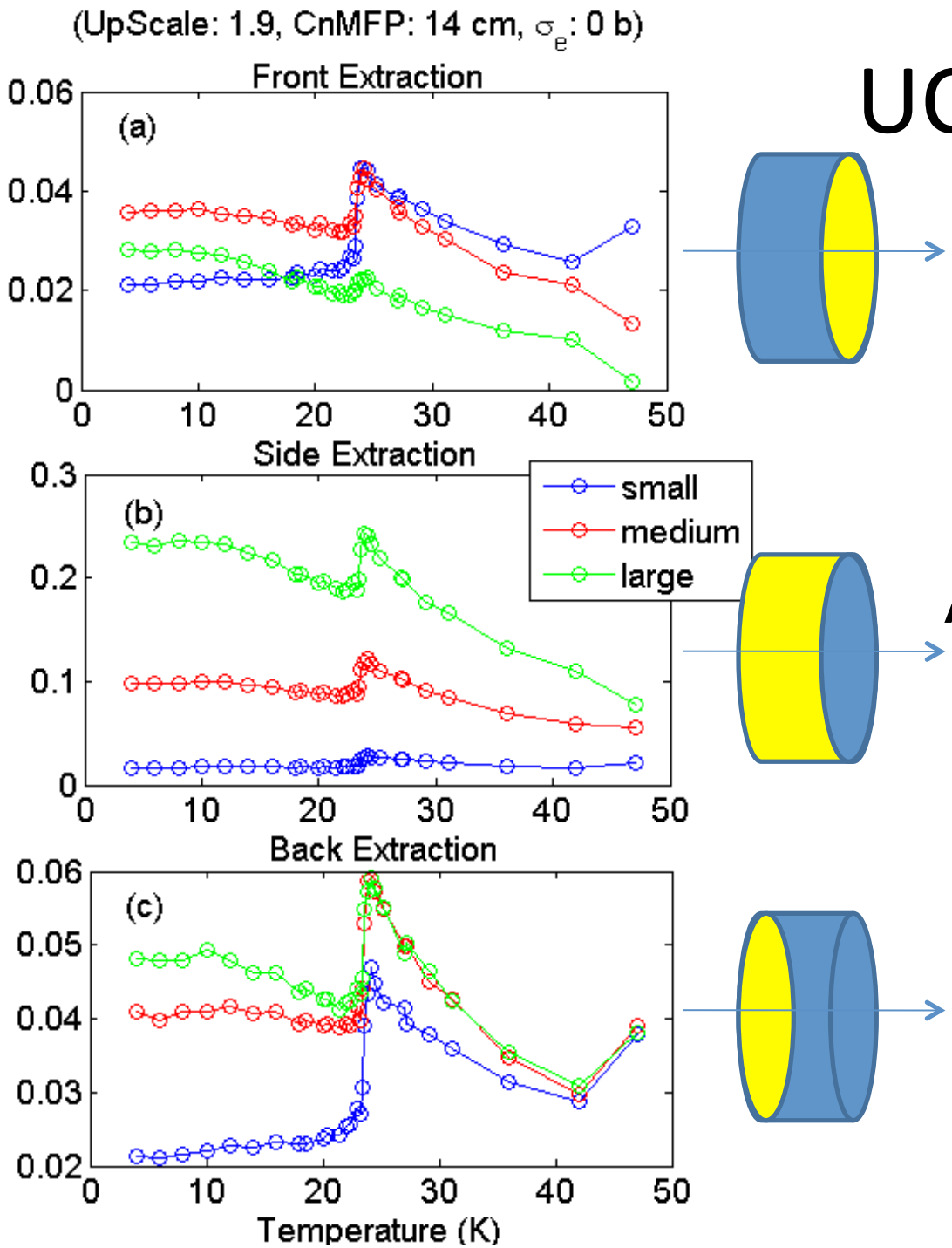
3 free parameters
- **rescale factor**
- **upscattering scale**
- **UCN elastic mfp**





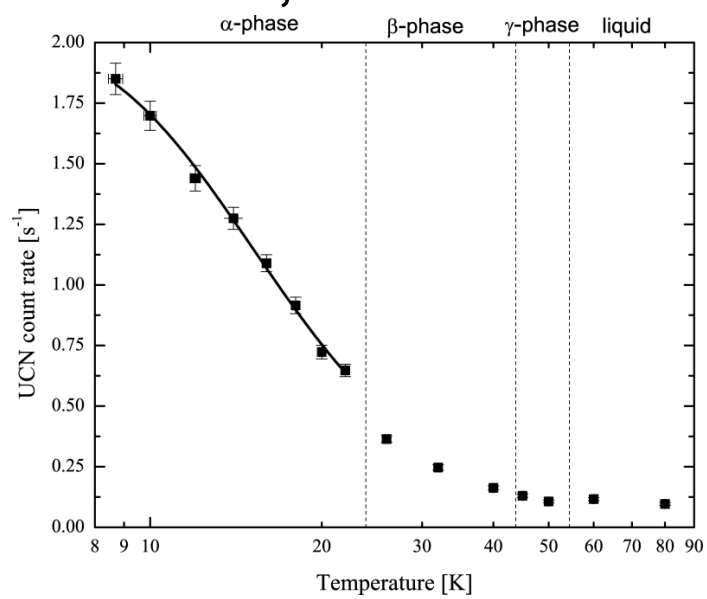
C.-Y. Liu, et. al., submitted to *Phys. Rev. Lett.*, March 2011

UCN Extraction



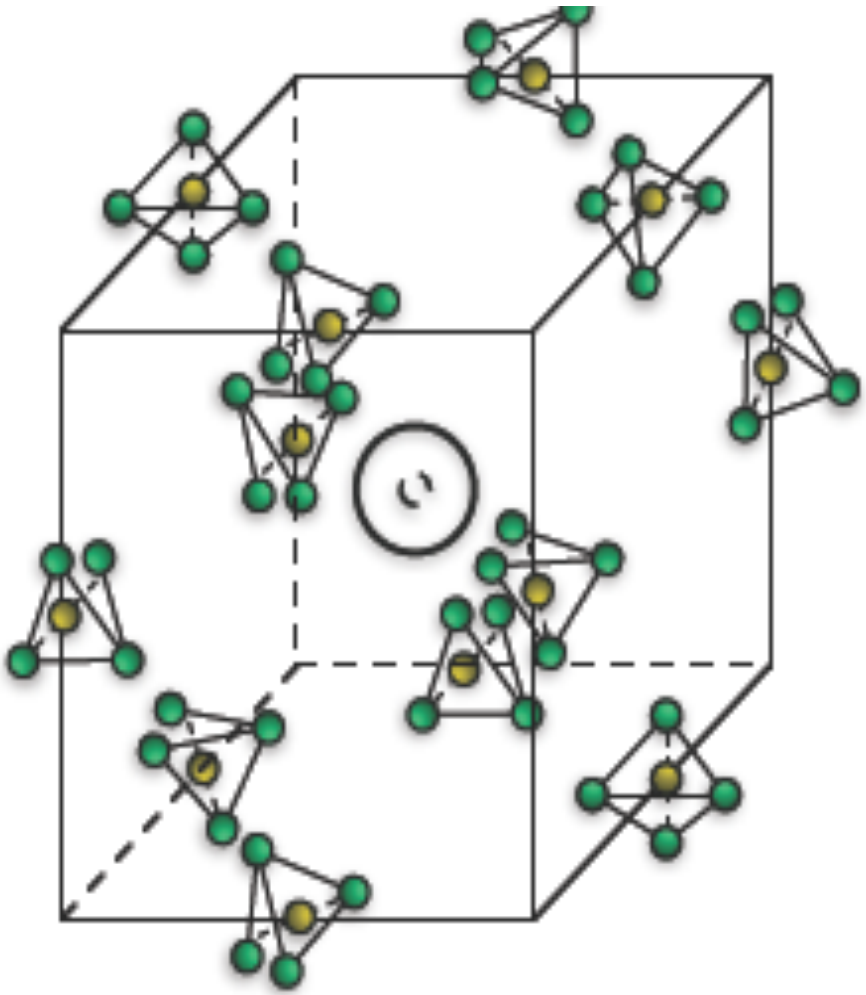
Yellow: extraction surface

A. Frei et al., arXiv:1006.2970v1



Vertical extraction (side)

Phase II Structure of Solid Methane



CH4 is the brightest-known cold neutron moderator (BUT not useable at high power sources due to rad damage)

<u>Below 20 K</u>

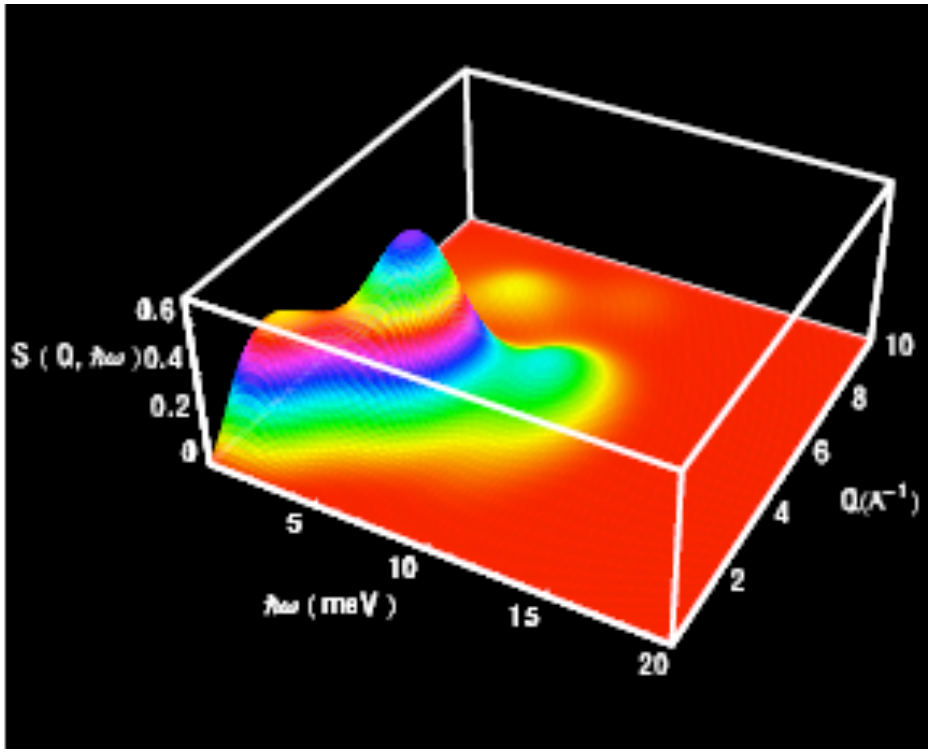
¼ of the CH4 are free rotors

¾ are hindered rotors

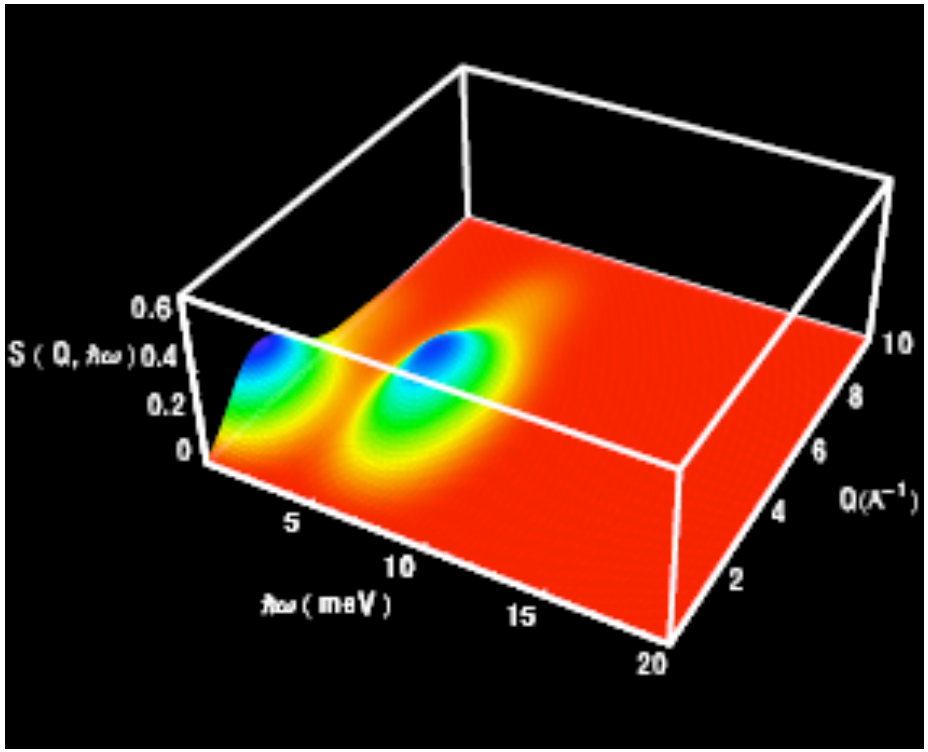
<u>Above 20K</u>

All sites are free rotors

S(q,omega) for CH4



Free Rotational modes



Tunneling, Librational modes

Yun Shin developed a new MCNP kernel for CH_4 at various temperatures (including below 20K, in phase II) and used in with MCNP to reproduce the observed LENS n spectrum (in NIM)

Summary

- Need to expand the library of scattering kernels to optimize cold neutron sources.
- Take INS data (high resolution, CN + thermal) (+ total cross-section measurement) to streamline production of ENDF-VI files, needed for the above task.