PAUL SCHERRER INSTITUT

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Ultracold neutron production and extraction from the solid deuterium converter of the PSI UCN source

PhD Seminar 2019

Ingo Rienäcker on behalf of the PSI UCN group

Contents of this talk

1. What are ultracold neutrons …
   … and why are they useful for fundamental physics?

2. Ultracold neutron production (at PSI) …
   … and the challenges

3. Recent and upcoming studies to improve the performance of the PSI UCN source

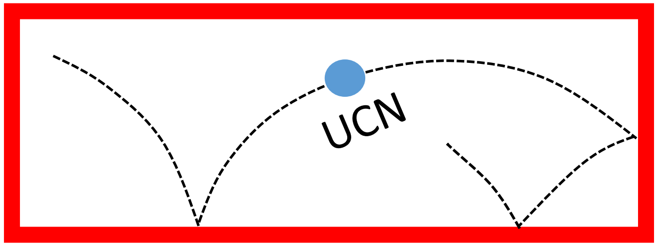
Ultracold neutrons (UCN)

Neutrons are called ultracold when they have very low (kinetic) energies

Quantity	Value
Energy	$E_{kin} \lesssim 300$ neV
Velocity	$v \lesssim 7.6$ m/s
Temperature	$T \lesssim 3.5$ mK
Wavelength	$\lambda \gtrsim 52$ nm

UCNs are totally reflected at all angles of incidence from many materials…
… and are thus **storable** in material bottles for long times

Long storage times in principal only limited by the beta-decay lifetime



$E_{grav} \approx 100$ neV/m

UCN in fundamental physics

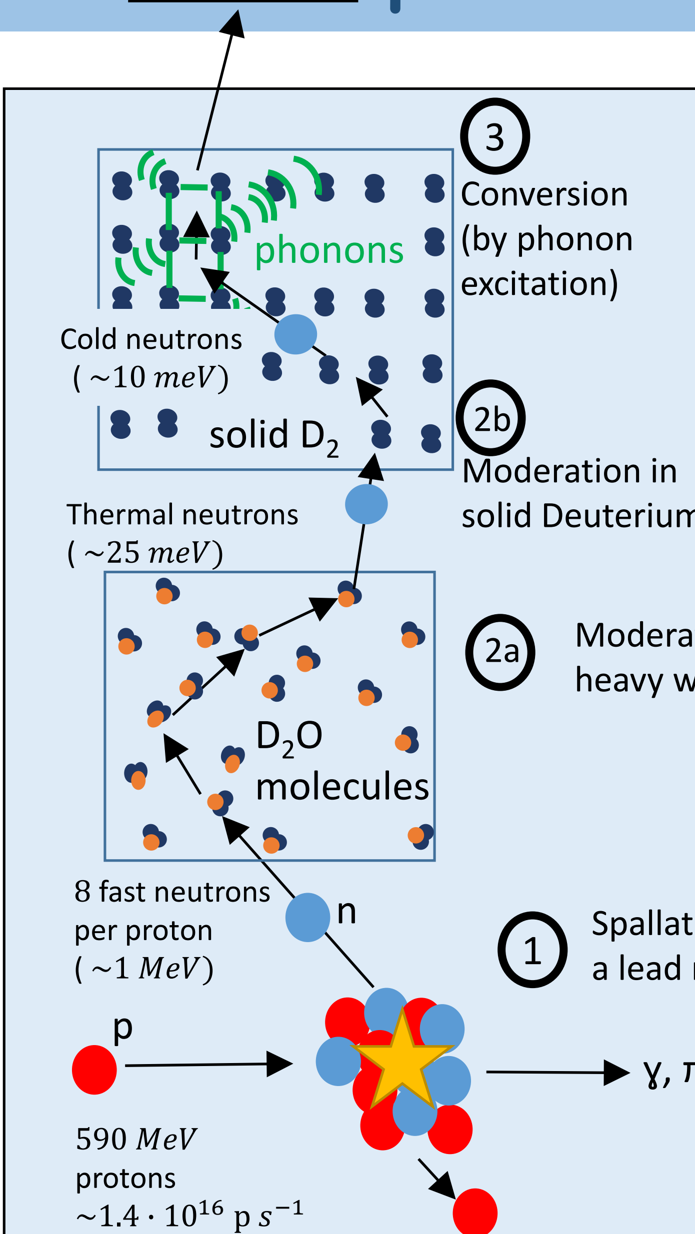
Some experiments using UCN

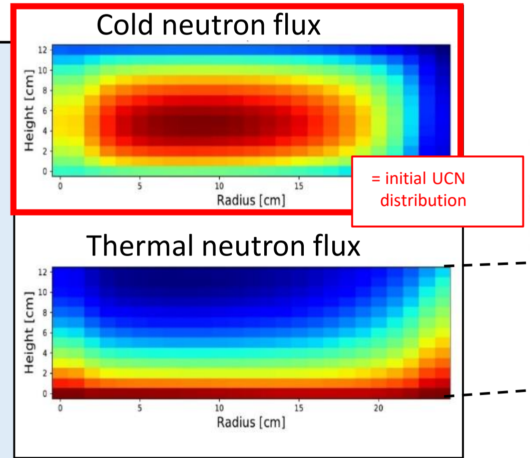
- **Neutron lifetime** measurements to determine weak interaction parameters
- Search for cold dark matter candidates – **axion** like particles
- Search for a **permanent electric dipole moment** of the neutron (nEDM)

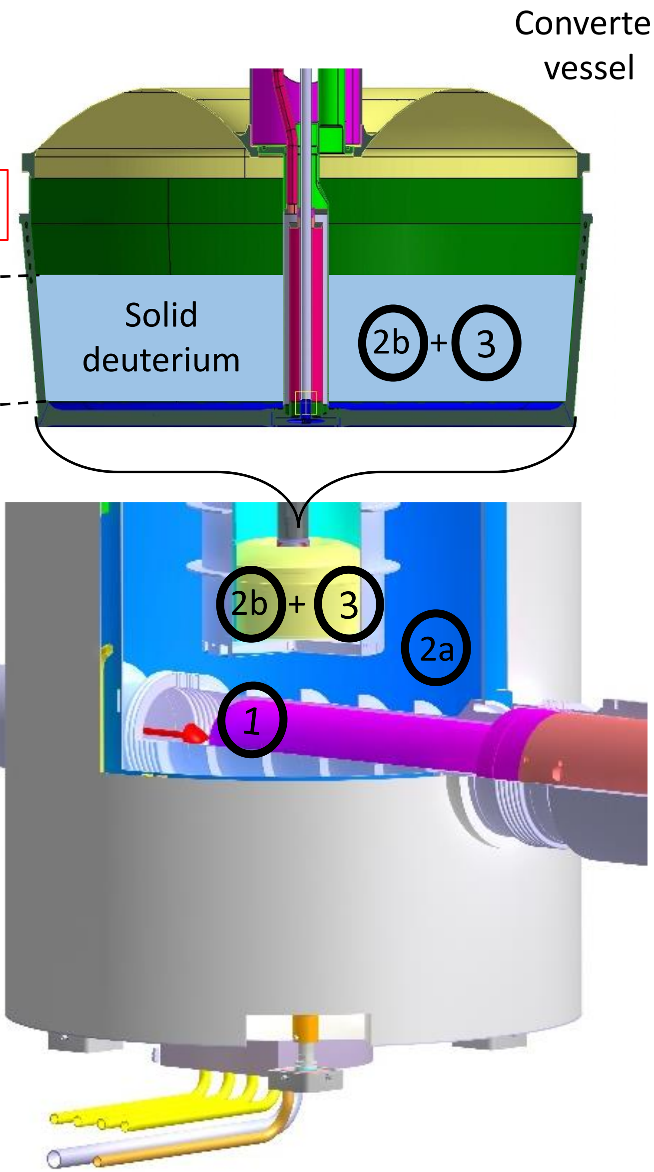
nEDM collaboration here at PSI

Experiments with UCN are limited by statistics
→Increase UCN output to improve experimental sensitivity

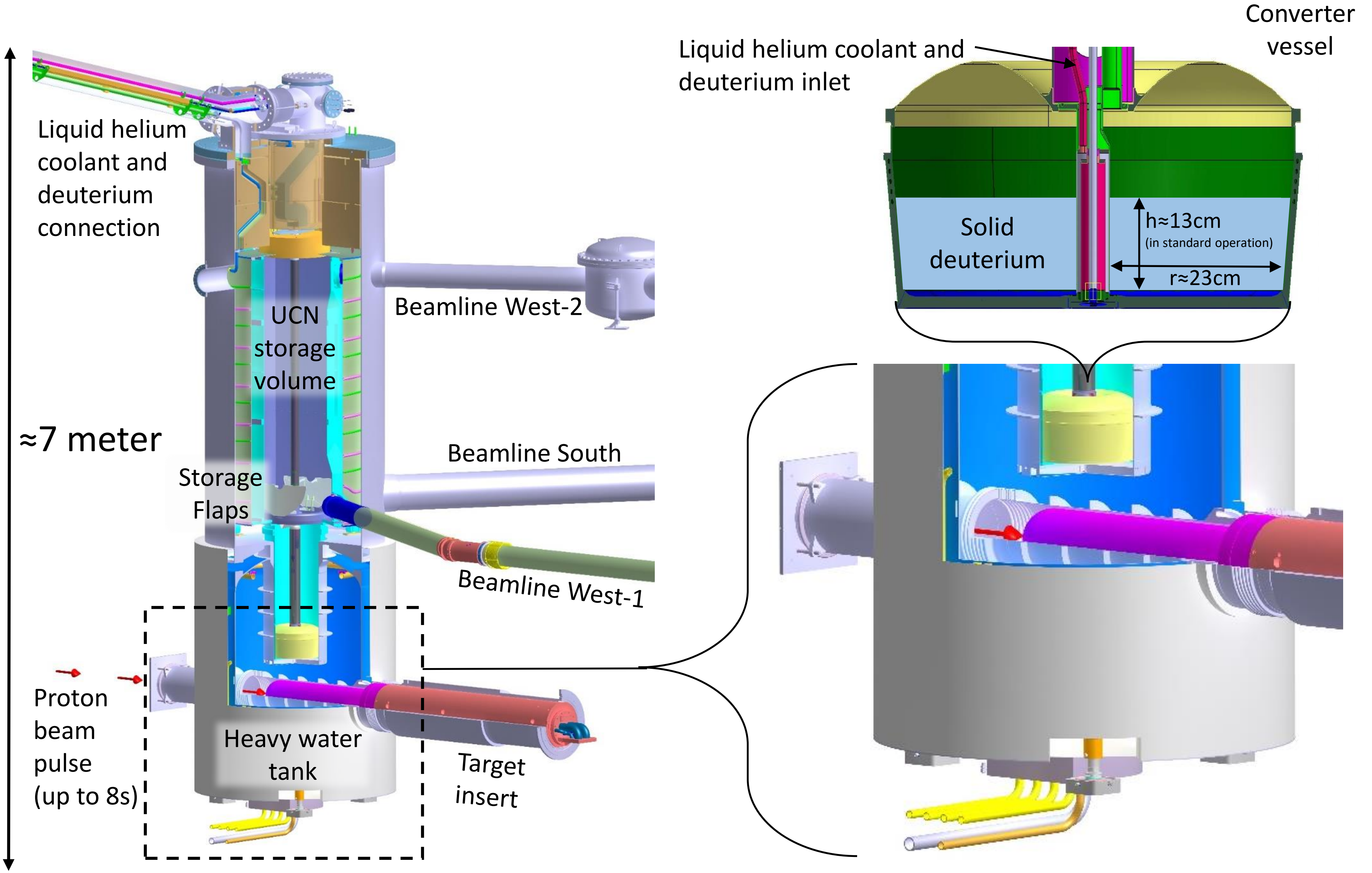
UCN production at PSI







The PSI UCN source

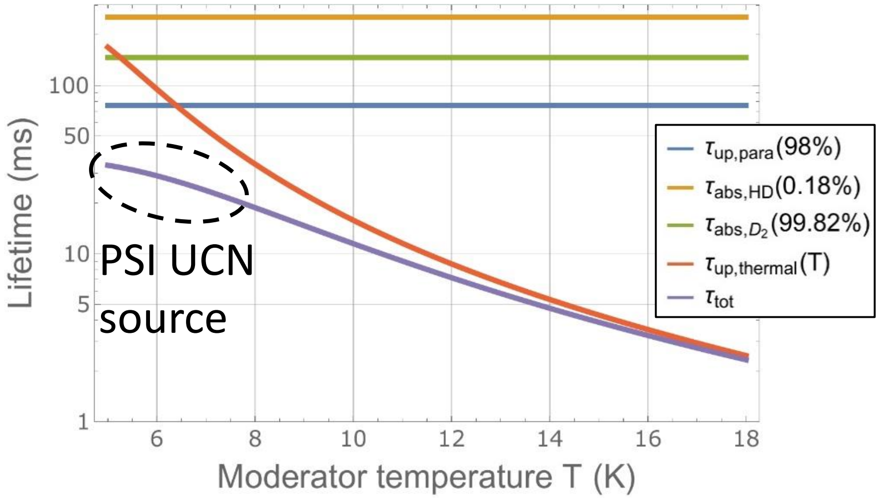


UCN extraction from solid D_2

UCN lifetime in the PSI solid D_2 converter expected to be $\tau \approx$ **30 ms**

[CL. Morris et al., Physical Review Letters 89(27) (2002)]

UCN lifetime $\tau = (\rho_{sD_2}\sigma_{loss}v)^{-1}$



How much time does it take for the UCN to escape from the D_2?

- Solid D_2 height ≈ 13cm
- typical UCN velocities ≈ 4m/s

→ extraction time ≈ life time

UCN extraction from solid D_2

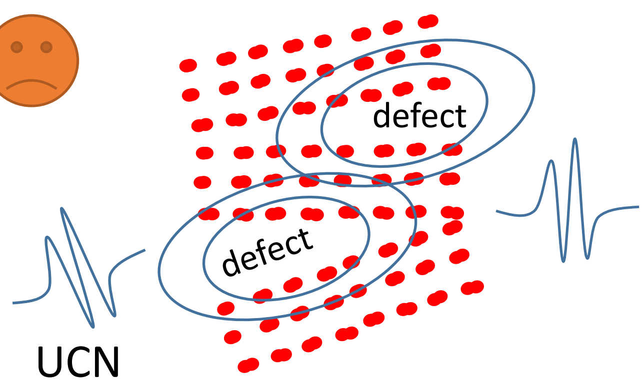
But UCN extraction time is increased by

1. elastic incoherent scattering
   - $\lambda_{MFP} = (\rho\, \sigma_{inc})^{-1} \approx 7.6\ \mathrm{cm}$
   - Isotropic

[NIST Centre for Neutron Research,Neutron News, Vol. 3, No. 3, 1992]
[I.I.Gurevich, L.V.Tarasov, Low-energy neutron physics, 1968]

2. elastic scattering on structural features
   - large scale defects in the D_2 crystal
   - Defects caused by thermal mechanical stress during cooling of the solid

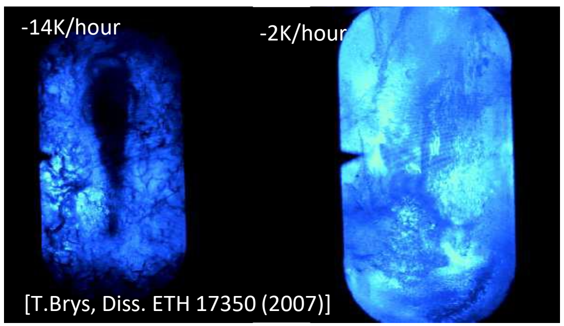
[T.Brys, Diss. ETH 17350 (2007)]



Solid D_2 freezing studies at PSI

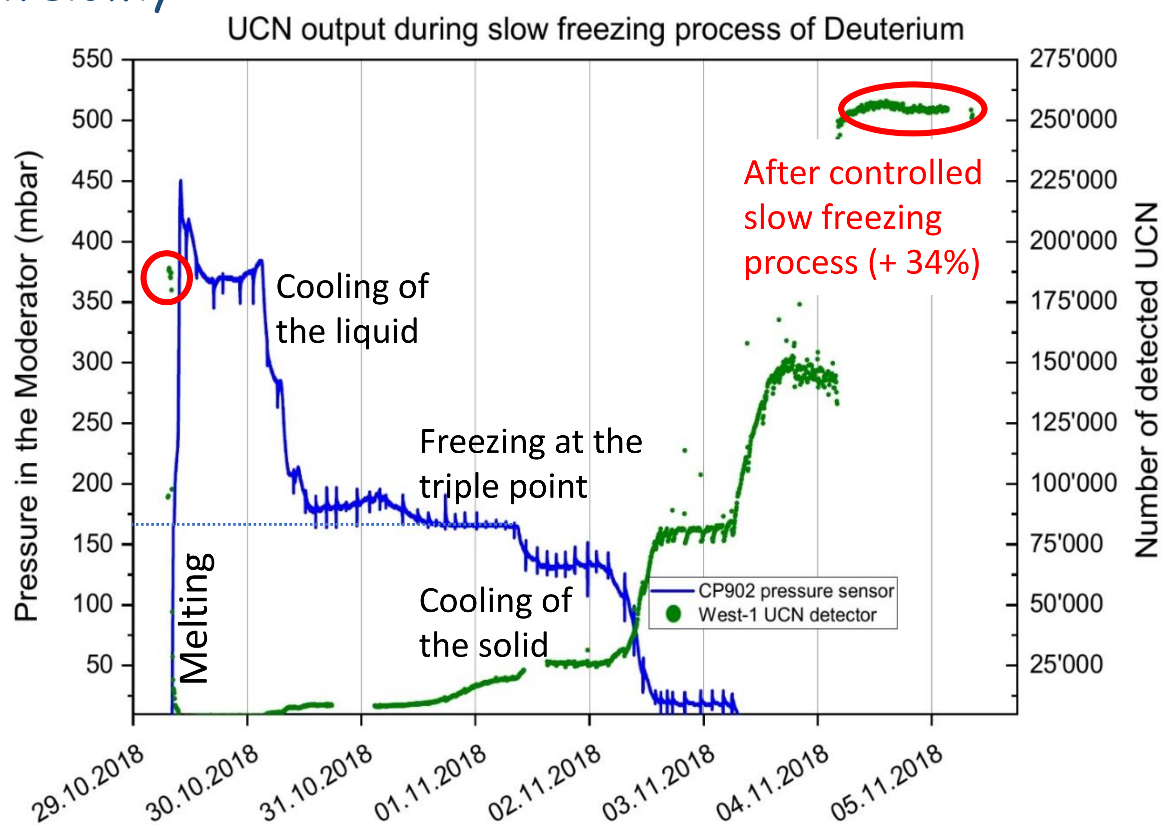
Access for direct measurements of the solid D_2 structure are not possible due to the high radiation environment close to the spallation target

Crysal growth in small sample container has lead to less defects when solid deuterium was cooled down slowly



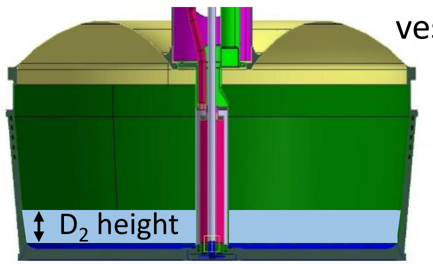
Optimize freezing process at the PSI UCN source

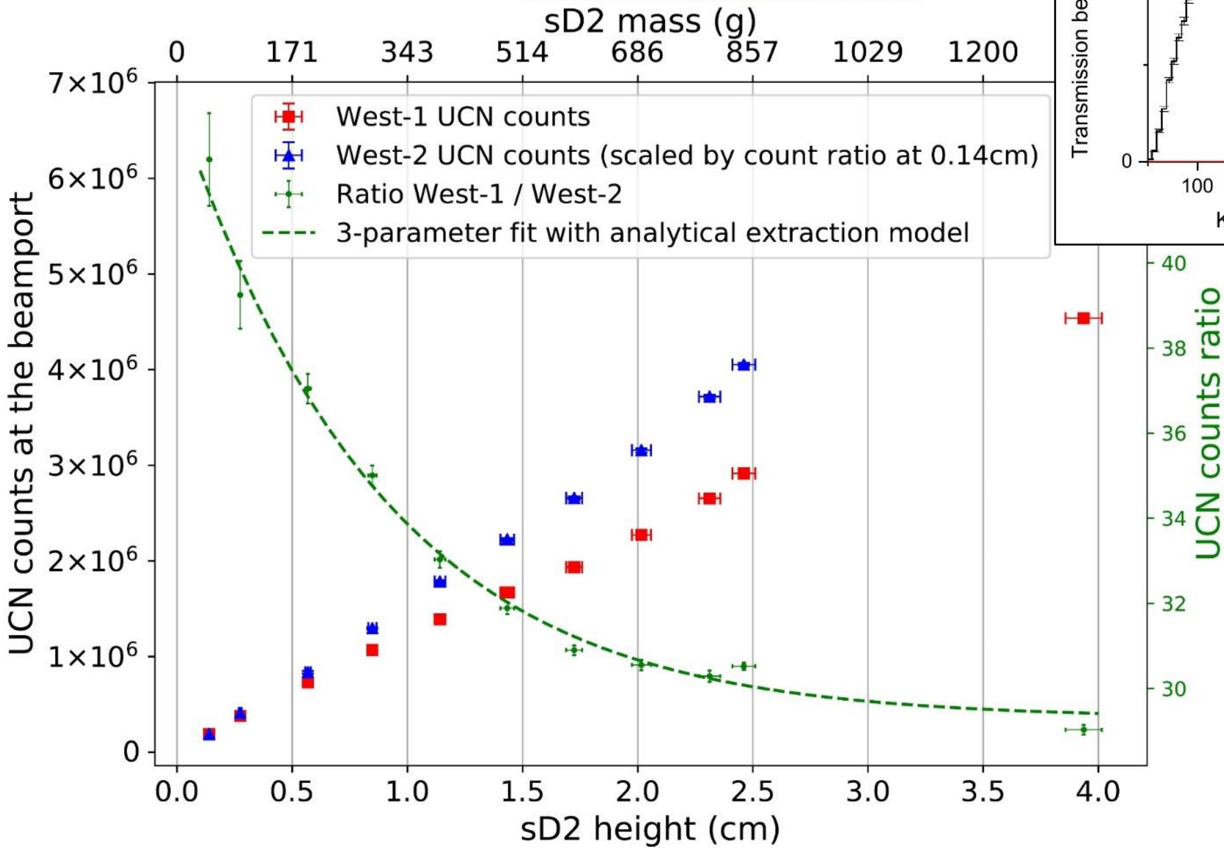
Observed increase of the UCN output due to the controlled slow freezing of deuterium

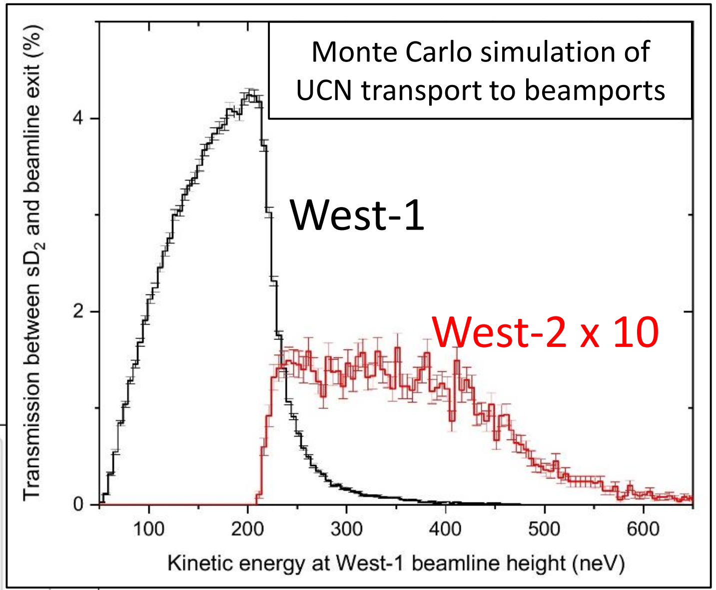


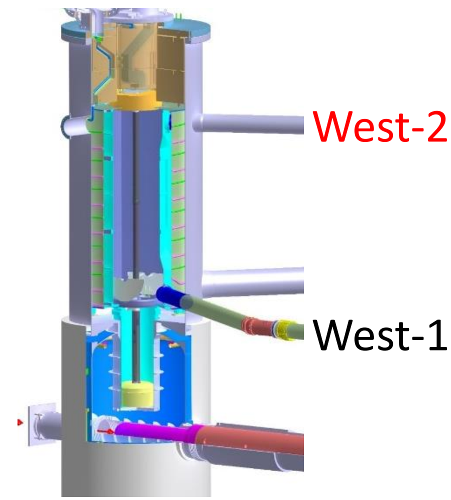
Studies on UCN extraction from solid D_2

UCN output for different solid D_2 filling levels in the converter vessel



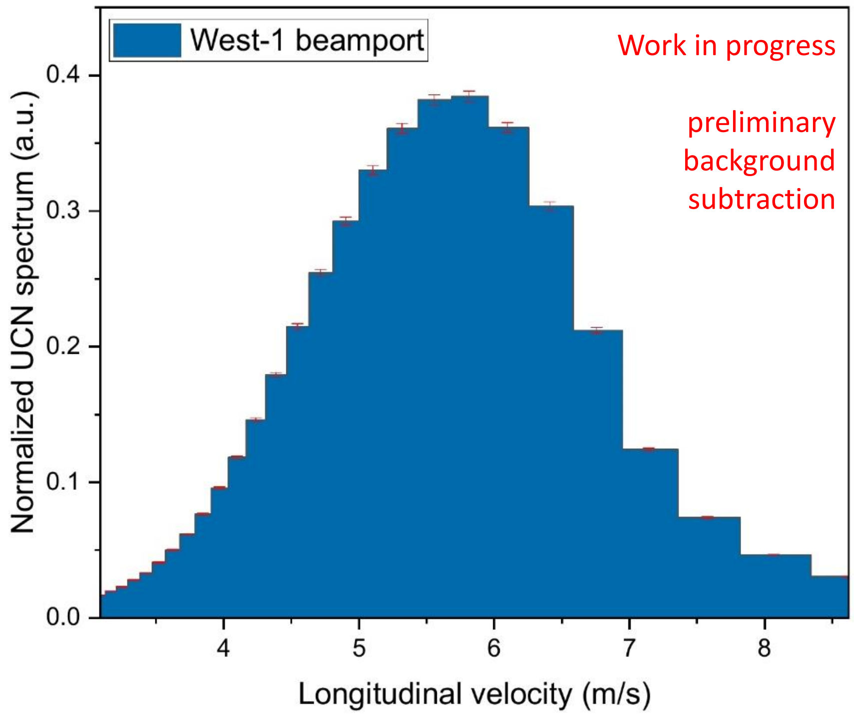




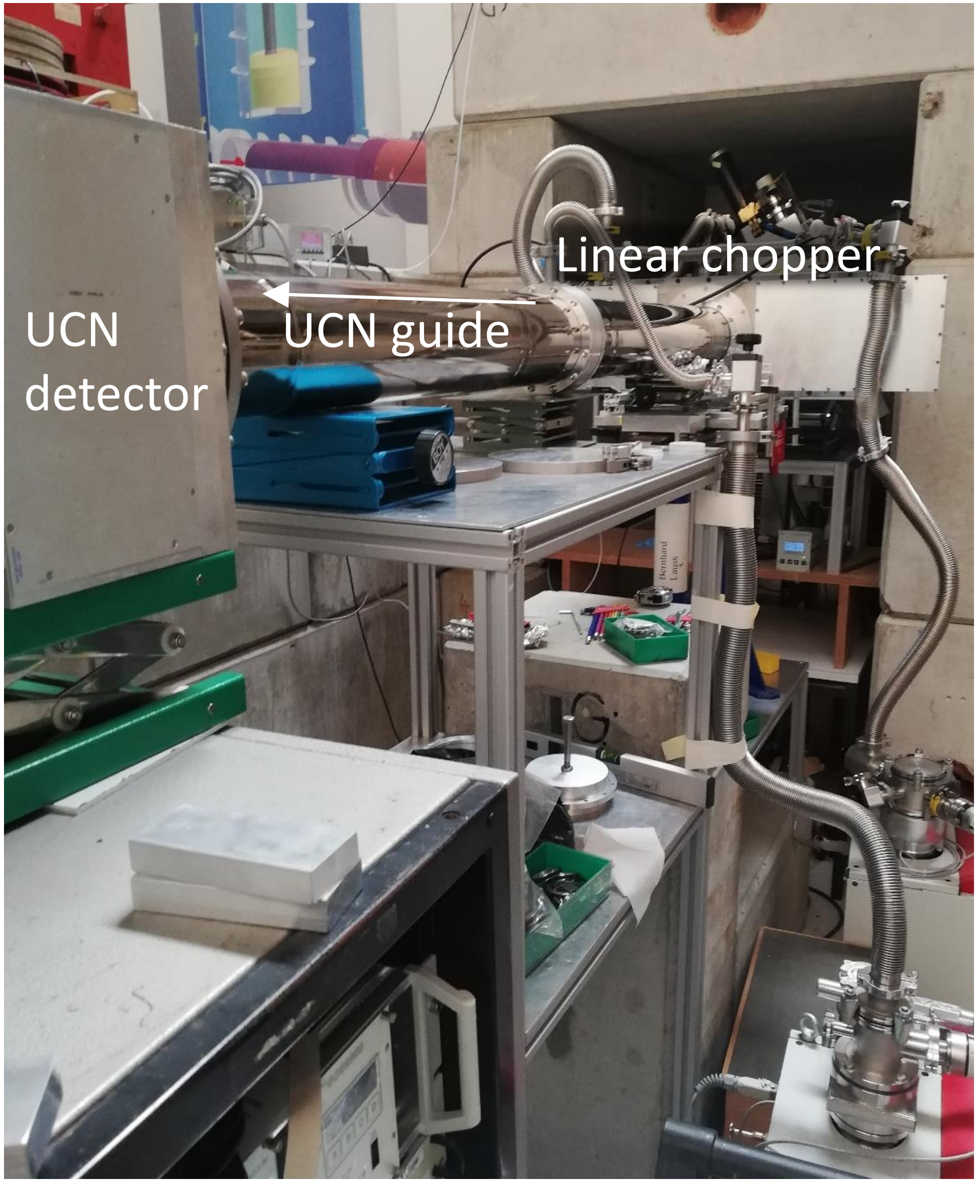


UCN energy spectrum measurement

Determined UCN energy spectrum at the West-1 beamport by a time of flight measurement



Infer energy dependence of UCN extraction

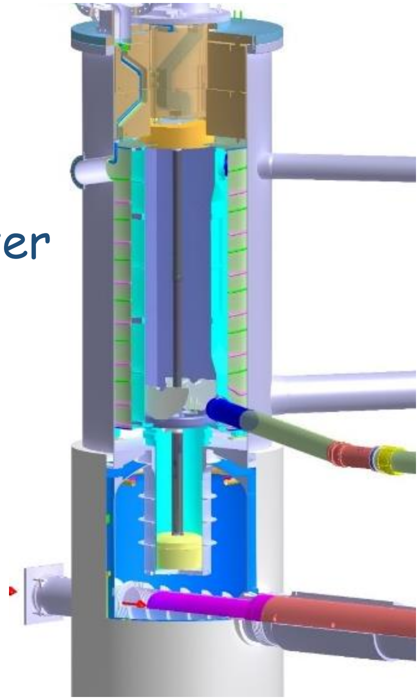


Conclusion and outlook

UCNs can be stored for long times which makes them useful tools for fundamental physics

Since experimental sensitivity is limited by statistics we are working on improving the output of the PSI UCN source by

1. Dedicated measurements of the performance of the source
2. Energy dependent models and simulations of the UCN extraction from the solid deuterium converter
3. Combine information to propose conclusive possible design upgrades of the source and in particular the central insert containing
   - parts of the cryogenic system
   - storage flaps
   - converter vessel



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Thank You

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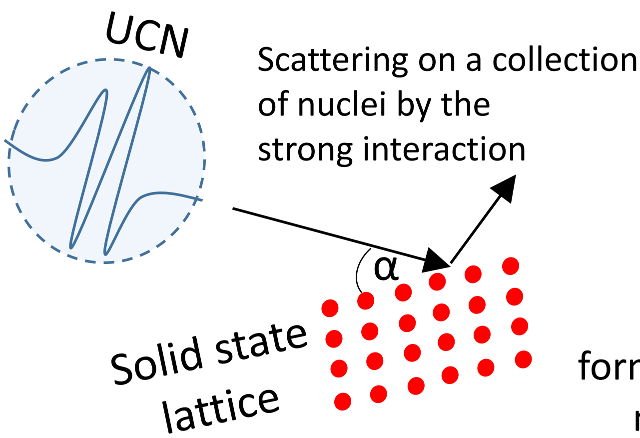
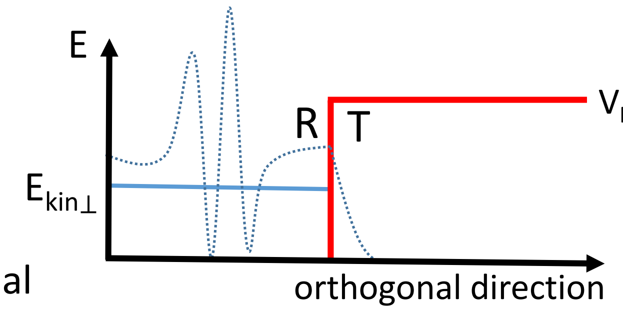
Fermi potential



Effective potential V_F
formulated in one-dimensional
non-relativistic quantum
mechanics by Fermi in 1936



If $E_{kin} < V_F$ the UCN will be totally reflected under all angles of incidence

Material (solid)	Fermi Potential
Aluminium	V_F=54 neV
Nickel	V_F=252 neV
Diamond	V_F=304 neV

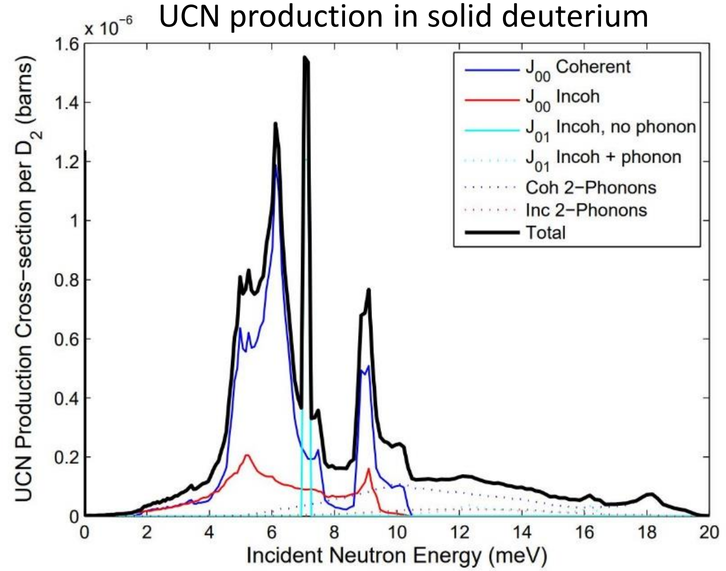
Storage volume dimensions ≫ UCN wavelength

- ➢ classical trajectories
- ➢ ultracold gas in free molecular flow

[R. Golub, D. Richardson, S.K. Lamoreaux, Ultra-Cold Neutrons, Adam Hilger, 1991]

Superthermal UCN production

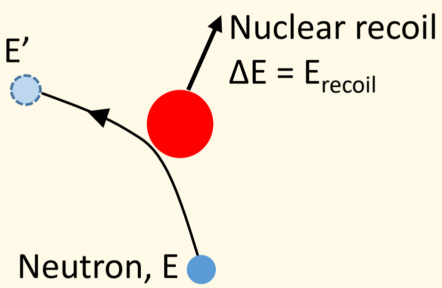
1. Create free neutrons by nuclear fission or **spallation** (using PSI HIPA beam)
2. Thermalize (slow down) neutrons by elastic scattering in a moderator at like liquid hydrogen, light water, … or **heavy water**
3. Convert moderated neutrons to UCN by inelastic superthermal moderation in liquid helium or **solid deuterium**



C.-Y. Liu, A.R. Young, C. Lavelle, and D. Salvat, arxiv 1005.1016, 2010

Elastic moderation

At higher energies (≫ 1eV) bound nuclei are quasi-free

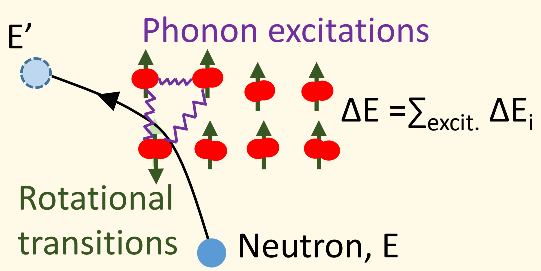


Many interactions

$E'_{min} \sim k_B T$

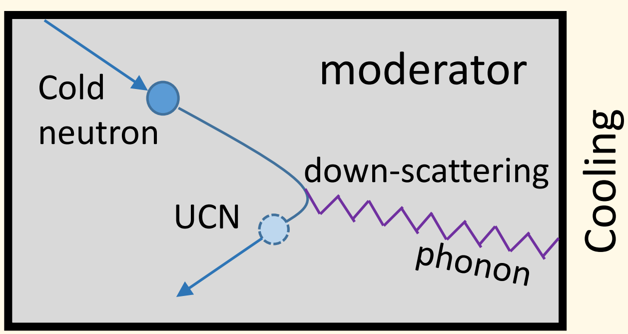
Inelastic superthermal moderation

At lower energies (10^{-3}eV – 1eV) the neutron interacts with bound system and can transfer energy to internal and lattice excitations (phonons)



Single interaction

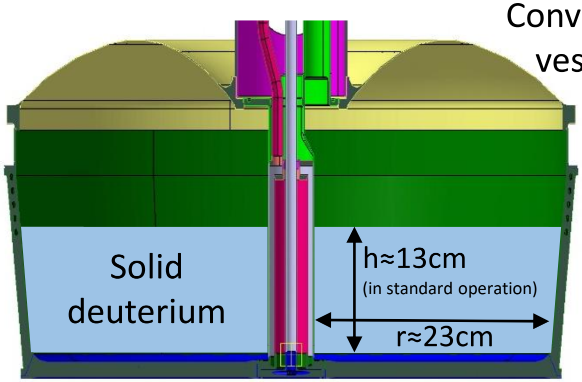
$\Delta E_{max} \approx E$ (suppressed by available phase space)



up-scattering suppressed by 'cooling away' phonon population

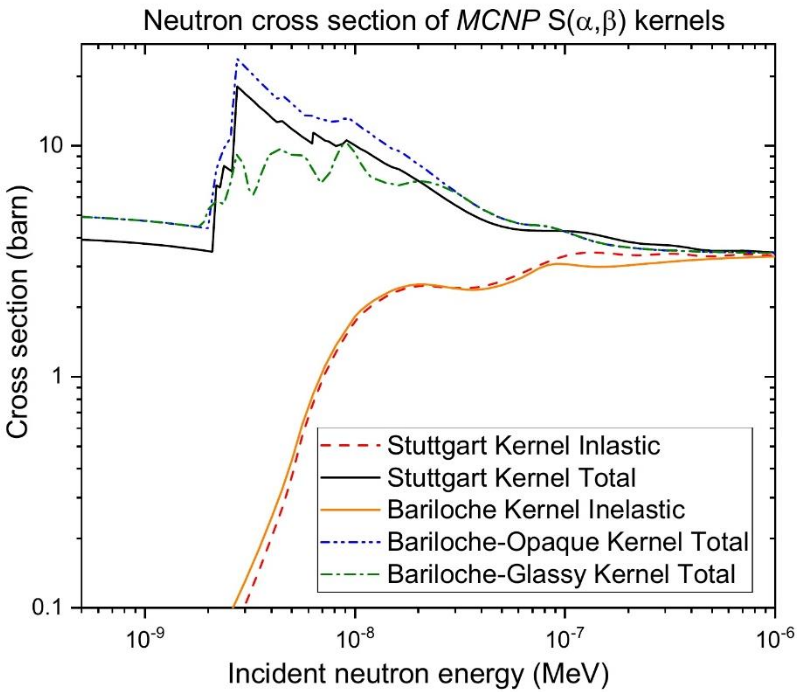
Simulation of neutron moderation

MCNP6 Monte Carlo simulation of spallation process and moderation benchmarked by gold foil activation measurements [H.Becker et. al., NIM A 777 (2015)]

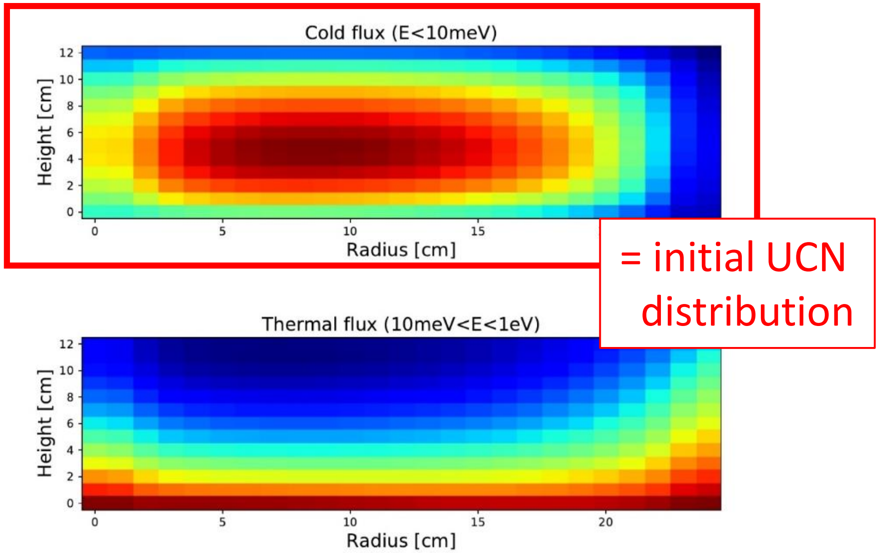


Low-energy neutron scattering kernels

'Bariloche'-Kernel [R. Granada, EPL 86, 2009]
'Stuttgart'-Kernel [W. Bernant et. al., Nuclear Science Technology, 2002]



Neutron flux density distribution

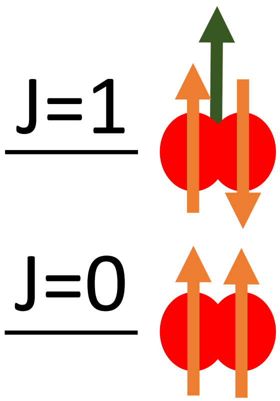


D_2 spin isomers

J=odd: «para-D_2»

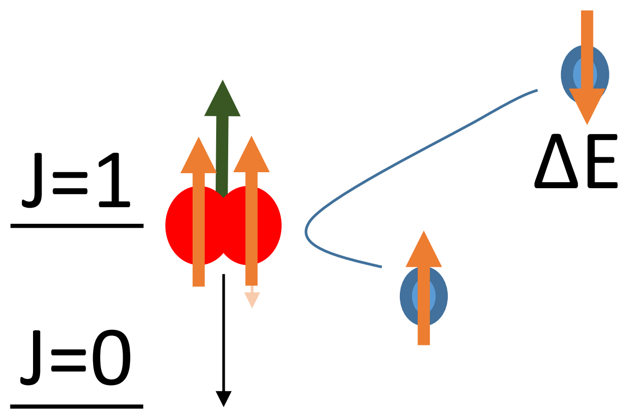
J=even: «ortho-D_2»

ΔE = -7meV



Transition forbidden due to the permutational symmetric wave function of the D_2 molecule

A Neutron can induce a spin flip and gain the transition energy



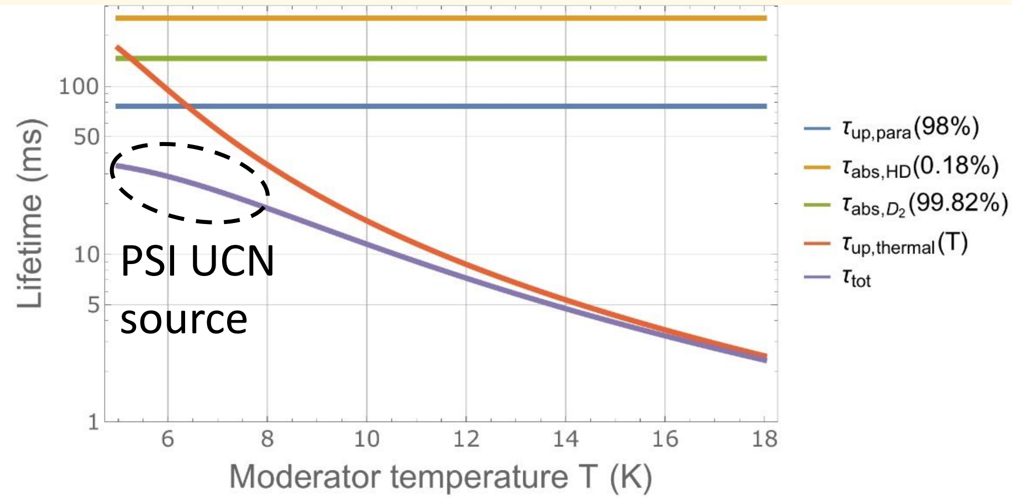
UCN losses in solid D_2

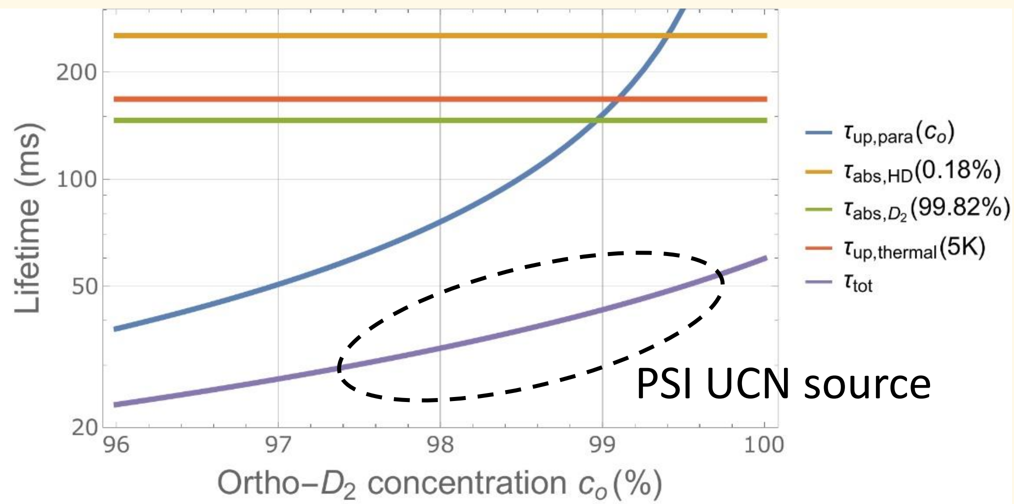
UCN are lost by:

- Thermal phonon up-scattering
  Solution: Cool moderator to low temperatures
- Neutron induced J=1→0 transition of D_2 angular momentum eigenstate
  Solution: Reduce J=1 population
  → increase J=0 ortho-D_2 concentration
- Absorption on hydrogen nucleus
  Solution: Reduce hydrogen contamination
- Absorption on deuterium nucleus
  Solution: None

[C.-Y. Liu, A.R. Young, S.K Lamoreaux, Phys. Rev. B, Vol62]
[NIST Centre for Neutron Research, Neutron News, Vol. 3, No. 3, 1992]

UCN lifetime $\tau = (\rho_{sD_2}\sigma_{loss}v)^{-1}$





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How much time does it take for the UCN to escape from the sD_2?

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- typical UCN velocities ≈ 4m/s

→ extraction time ≈ life time

But UCN extraction time is increased by

1. elastic incoherent scattering

   $\lambda_{MFP} = (\rho\,\sigma_{inc})^{-1} \approx 7.6\text{ cm}$

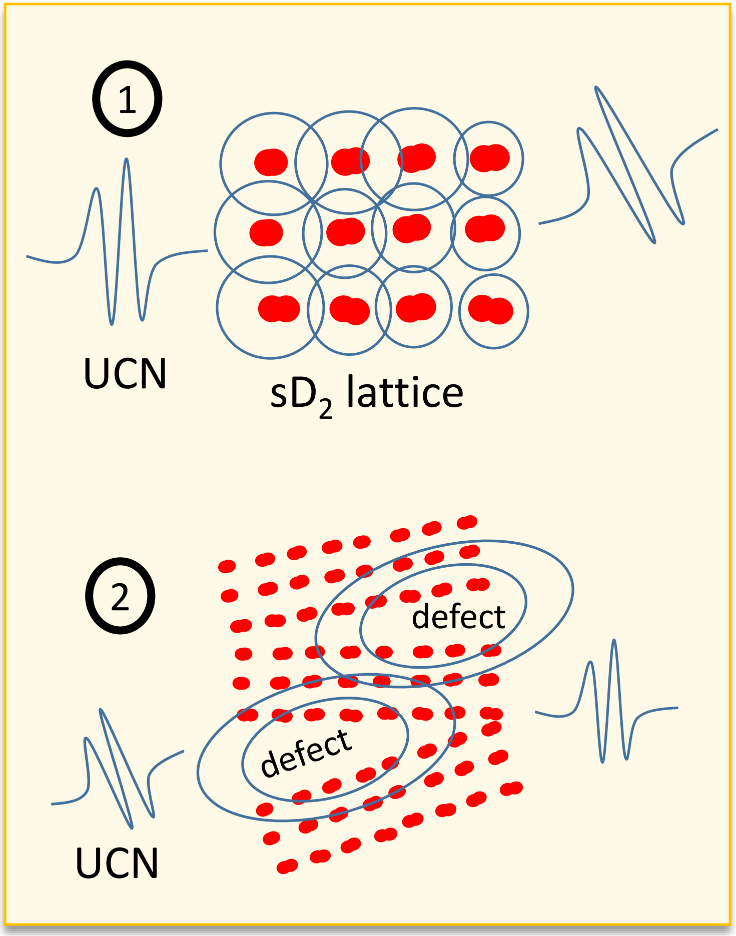
   - isotropic
   - no coherent interference $\lambda_{UCN} \gg$ lattice distances

   [NIST Centre for Neutron Research,Neutron News, Vol. 3, No. 3, 1992]
   [I.I.Gurevich, L.V.Tarasov, Low-energy neutron physics, 1968]

2. elastic scattering on structural features

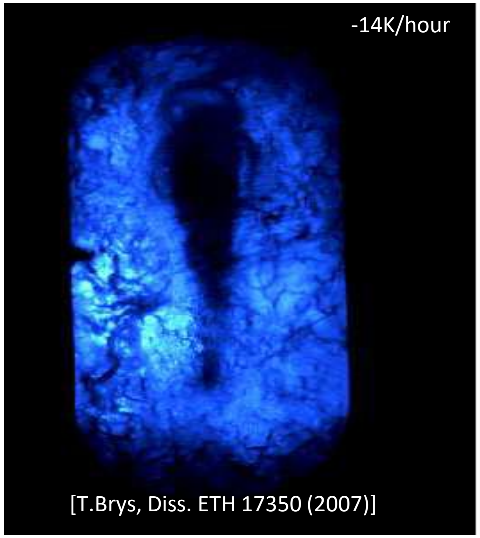
   - large scale defects in the D_2 crystal
   - surface frost

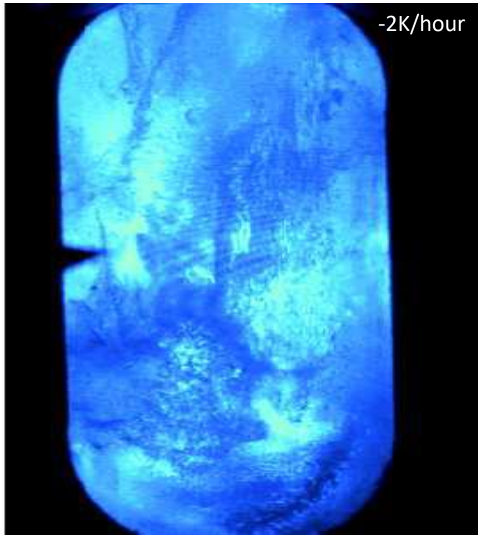
   [A.Anghel et. al., EPJ **54**: 148 (2018)]
   [R. Golub, D. Richardson, S.K. Lamoreaux, Ultra-Cold Neutrons, Adam Hilger, 1991]

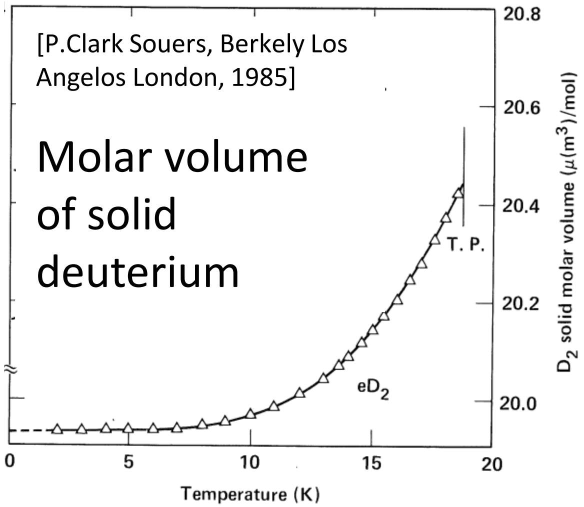


Solid D_2 structure studies

D_2 crystals at 5K grown from the liquid in a $40cm^2$ sample container at different cooling rates







Low light transmission indicates more structural defects

Defects caused by thermal stress during cooling of the solid