Wavelength resoluted ultra-cold neutron production in pressurized superfluid helium

Martin Fertl

Physik Department E18, Technische Universität München, Garching, Germany
Institut Laue-Langevin, Grenoble, France

June 12, 2009

NEUTRONS FOR SCIENCE

Outline

The experimental team

Jacques Bossy
Institut Neél, CNRS, Grenoble

Martin Fertl
Physik Department E18, Technische Universität München, Garching
Institut Laue-Langevin, Grenoble

Kent K. H. Leung
Institut Laue-Langevin, Grenoble
Physik Department E18, Technische Universität München, Garching

Amel Rahli
Université de Tizi Ouzou, Algeria

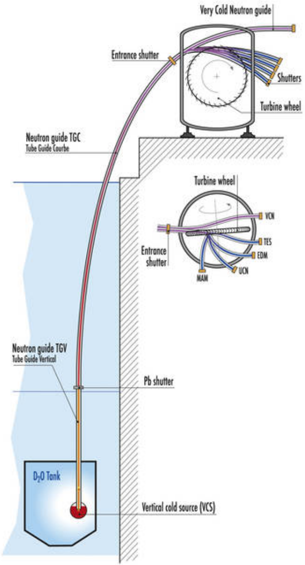
Philipp Schmidt-Wellenburg
Institut Laue-Langevin, Grenoble
Physik Department E18, Technische Universität München, Garching

Torsten Soldner
Institut Laue-Langevin, Grenoble

Oliver Zimmer
Institut Laue-Langevin, Grenoble
Physik Department E18, Technische Universität München, Garching

mechanical source, Steyerl 1975

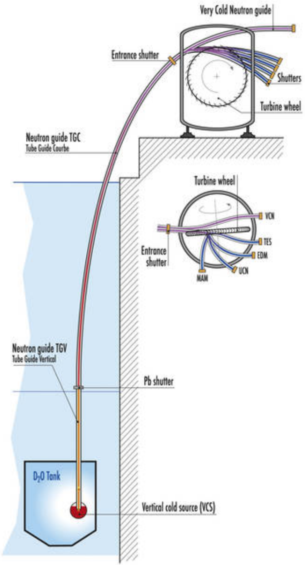
Doppler-shifting of very cold neutrons into the UCN range
e.g. Steyerl turbine on Level D at ILL
available density $\approx 50 cm^{-3}$



mechanical source, Steyerl 1975

Doppler-shifting of very cold neutrons into the UCN range
e.g. Steyerl turbine on Level D at ILL
available density $\approx 50cm^{-3}$

$\rightarrow$ worldwide efforts to achieve higher UCN densities



Ultra-cold neutrons
Superthermal sources

Superthermal sources, Golub and Pendlebury 1975

Inelastic downscattering of cold neutrons (CN) into the UCN regime by one excitation of phonons and suppression of upscattering by cooling the converter

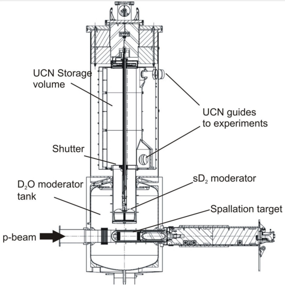
Ultra-cold neutrons

Superthermal sources

Superthermal sources, Golub and Pendlebury 1975

Inelastic downscattering of cold neutrons (CN) into the UCN regime by one excitation of phonons and suppression of upscattering by cooling the converter

solid deuterium
Uni Mainz, TUM, PSI



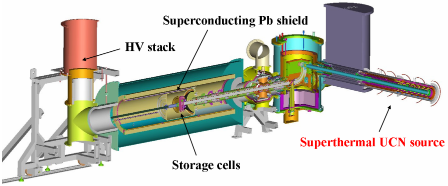
M. Kasperzak, Thesis (2008), Universität Wien

Ultra-cold neutrons
Superthermal sources

Superthermal sources, Golub and Pendlebury 1975

Inelastic downscattering of cold neutrons (CN) into the UCN regime by one excitation of phonons and suppression of upscattering by cooling the converter

superfluid helium
NIST, Cryo-EDM, ILL, PNPI, KEK



Cryo-EDM collaboration

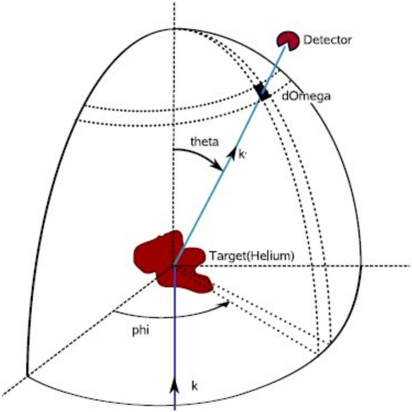
UCN production in superfluid helium

inelastic neutron scattering

inelastic scattering

double differential cross section

$$\frac{d\Sigma}{dE' d\Omega} = Na^2 \frac{k'}{k} S(q, \hbar\omega)$$



Ph. Schmidt-Wellenburg (PSW)

UCN production in superfluid helium

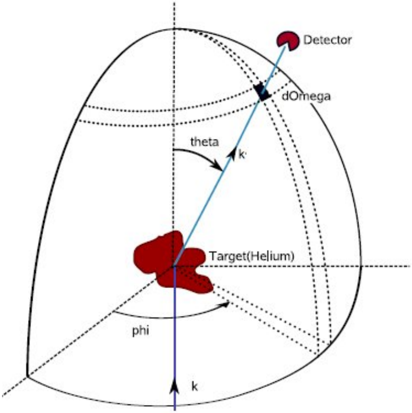
inelastic neutron scattering

inelastic scattering

double differential cross section

$$\frac{d\Sigma}{dE'd\Omega} = Na^2 \frac{k'}{k} S(q, \hbar\omega)$$

- scattering function $S(q,\hbar\omega)$ describes system dynamics



Ph. Schmidt-Wellenburg (PSW)

UCN production in superfluid helium

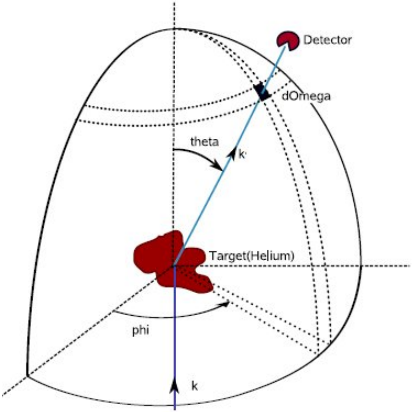
inelastic neutron scattering

inelastic scattering

double differential cross section

$$\frac{d\Sigma}{dE' d\Omega} = Na^2 \frac{k'}{k} S(q, \hbar\omega)$$

- scattering function S(q,$\hbar\omega$) describes system dynamics
- $\vec{q} = \vec{k} - \vec{k'}$
  $\hbar\omega = E - E'$

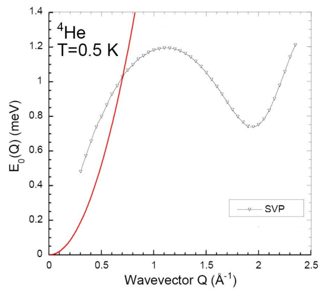


Ph. Schmidt-Wellenburg (PSW)

UCN production in superfluid helium

dispersion relation of He-II and production rate

Single excitation spectrum

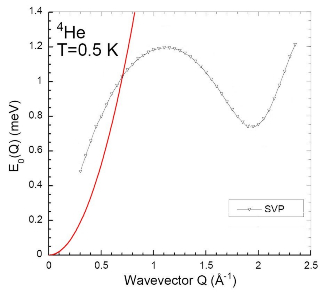


M.R. Gibbs et al., J. Phys.: Condens. Matter **11** 603-628 (January 1999)

UCN production in superfluid helium

dispersion relation of He-II and production rate

Single excitation spectrum



M.R. Gibbs et al., J. Phys.: Condens. Matter **11** 603-628 (January 1999)

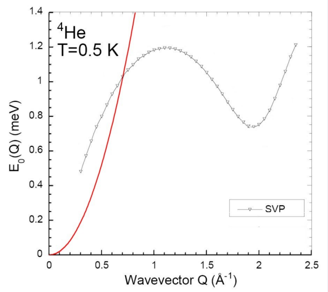
UCN production rate

$$P_{UCN}(V_c) = N\sigma k_c \frac{V_c\hbar}{3\pi} \int_0^\infty \frac{d\phi}{d\lambda_i}\left(\int S(q,\hbar\omega)\delta(\hbar\omega - \frac{\hbar^2 k^2}{2m_n})d\omega\right)\lambda_i d\lambda_i$$

UCN production in superfluid helium

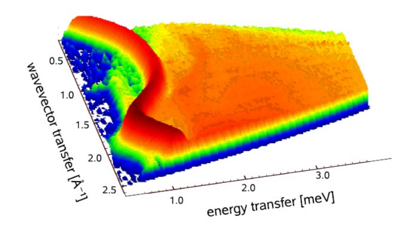
dispersion relation of He-II and production rate

Single excitation spectrum



M.R. Gibbs et al., J. Phys.: Condens. Matter **11** 603-628 (January 1999)

multiphonons @ 10 bar and 0.5 K



PSW, Thesis (2009), TUM

UCN production rate

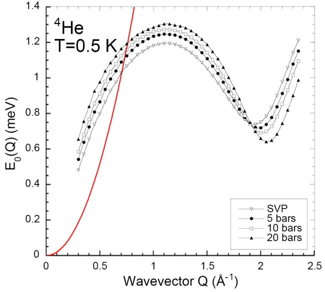
$$P_{UCN}(V_c) = N\sigma k_c \frac{V_c \hbar}{3\pi} \int_0^\infty \frac{d\phi}{d\lambda_i} (\int S(q, \hbar\omega) \delta(\hbar\omega - \frac{\hbar^2 k^2}{2m_n}) d\omega) \lambda_i d\lambda_i$$

UCN production in pressurized superfluid helium

calculation single phonon contribution

calculation single phonon contribution

$$P_I \propto N\lambda^{*4}\beta S^*$$



PSW, Thesis (2009), TUM

UCN production in pressurized superfluid helium
calculation single phonon contribution

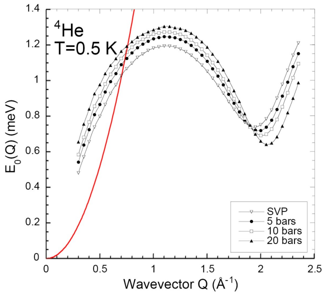
calculation single phonon contribution

$$P_I \propto N\lambda^{*4}\beta S^*$$

SVP to 20 bar

$$P_{I,20bar} = P_{I,SVP} \cdot 1.16$$

- helium density N increases



PSW, Thesis (2009), TUM

UCN production in pressurized superfluid helium

calculation single phonon contribution

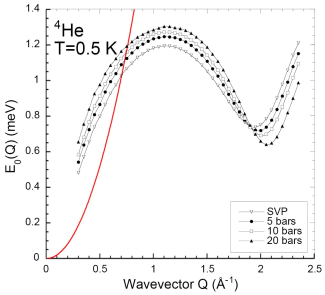
calculation single phonon contribution

$$P_I \propto N\lambda^{*4}\beta S^*$$

SVP to 20 bar

$$P_{I,20bar} = P_{I,SVP} \cdot 0.99$$

- helium density N increases
- β decreases ($1.42 \rightarrow 1.21$)



PSW, Thesis (2009), TUM

UCN production in pressurized superfluid helium

calculation single phonon contribution

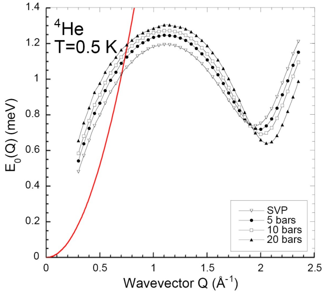
calculation single phonon contribution

$$P_I \propto N\lambda^{*4}\beta S^*$$

SVP to 20 bar

$$P_{I,20bar} = P_{I,SVP} \cdot 0.73$$

- helium density N increases
- β decreases (1.42 $\rightarrow$ 1.21)
- λ^* decreases (8.92 Å$\rightarrow$ 8.26 Å)



PSW, Thesis (2009), TUM

UCN production in pressurized superfluid helium

calculation single phonon contribution

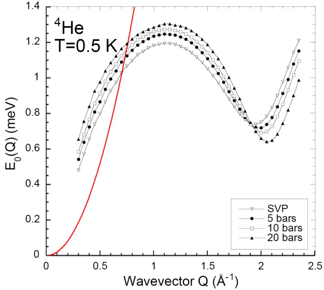
calculation single phonon contribution

$$P_I \propto N\lambda^{*4}\beta S^*$$

SVP to 20 bar

$$P_{I,20bar} = P_{I,SVP} \cdot 0.41$$

- helium density N increases
- β decreases ($1.42 \rightarrow 1.21$)
- λ^* decreases (8.92 Å$\rightarrow$ 8.26 Å)
- S^* decreases ($0.118(8) \rightarrow 0.066(7)$)



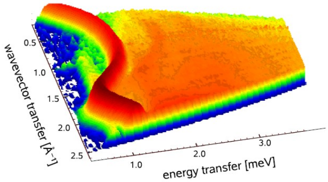
PSW, Thesis (2009), TUM

UCN production in pressurized superfluid helium

calculation multiphonon contribution

Production from multiphonons

$$\frac{P_{II}(V_c)}{d\lambda_i} = N\sigma \frac{h^2}{3m_n{\lambda_c}^3} \frac{d\Phi}{d\lambda_i} \lambda_i s_{II}(\lambda_i)$$



PSW, Thesis (2009), TUM

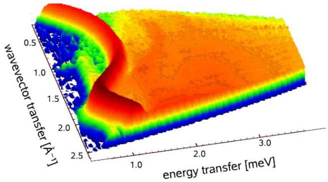
UCN production in pressurized superfluid helium

calculation multiphonon contribution

Production from multiphonons

$$\frac{P_{II}(V_c)}{d\lambda_i} = N\sigma \frac{h^2}{3m_n{\lambda_c}^3} \frac{d\Phi}{d\lambda_i} \lambda_i s_{II}(\lambda_i)$$

integral depends on shape of incident cold neutron spectrum
→ numerical calculations



PSW, Thesis (2009), TUM

UCN production in pressurized superfluid helium

calculation multiphonon contribution

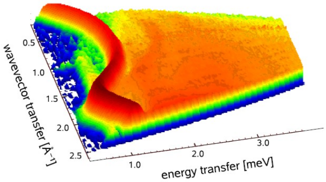
Production from multiphonons

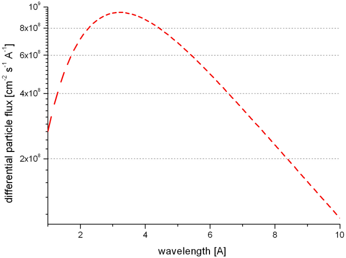
$$\frac{P_{II}(V_c)}{d\lambda_i} = N\sigma \frac{h^2}{3m_n\lambda_c{}^3}\frac{d\Phi}{d\lambda_i}\lambda_i s_{II}(\lambda_i)$$

integral depends on shape of incident cold neutron spectrum
$\rightarrow$ numerical calculations

calculated production rate for PF1b:
$P(SVP) = (9.5 + 4.4) \pm (0,9) cm^{-3}s^{-1}$
$P(20bar) = (5.3 + 5.8) \pm (0,8) cm^{-3}s^{-1}$

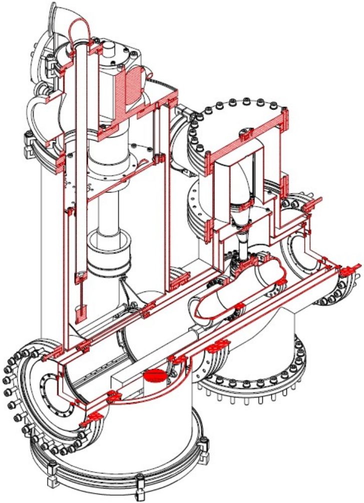
PSW, Thesis (2009), TUM





Experimental setup
Cryostat

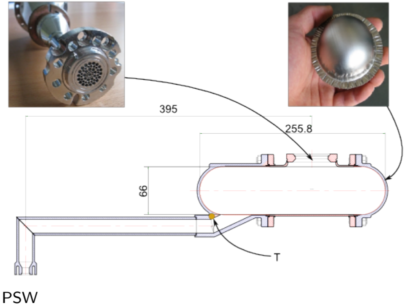
prototype cryostat with modified Al volume



Experimental setup
Cryostat

prototype cryostat with modified Al volume

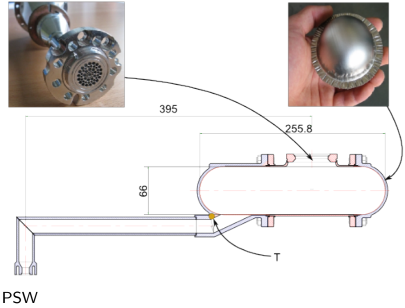
- pressure resistant ($\leq$ 50 bar)



Experimental setup
Cryostat

prototype cryostat with modified Al volume

- pressure resistant ($\leq$ 50 bar)
- Ni coated central piece and 2 Ni end caps

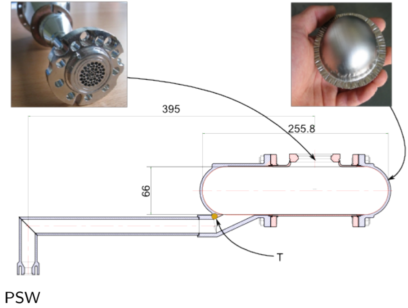


Experimental setup

Cryostat

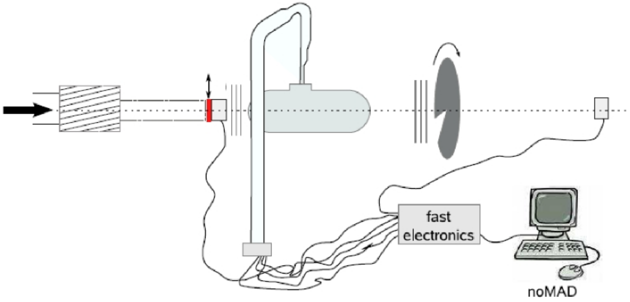
prototype cryostat with modified Al volume

- pressure resistant ($\leq$ 50 bar)
- Ni coated central piece and 2 Ni end caps
- no UCN valve, 100 μm Al extraction window



Experimental setup
Infrastructure

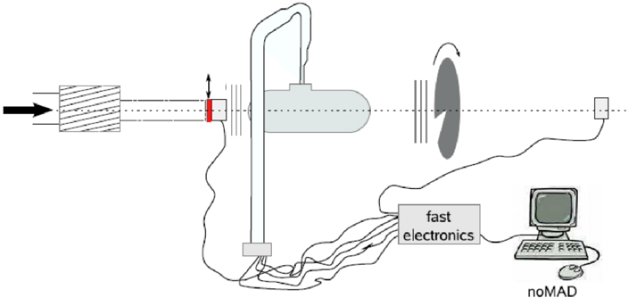
- velocity selector (3.5 Å→ 9.7 Å)



PSW

Experimental setup
Infrastructure

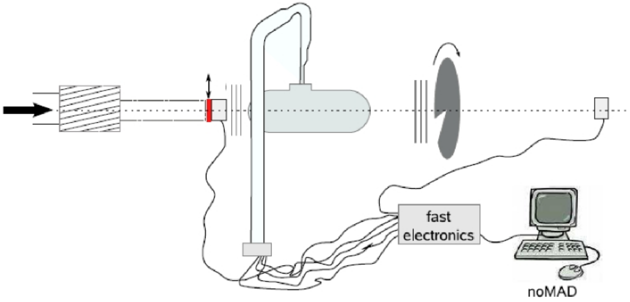
- velocity selector (3.5 Å→ 9.7 Å)
- fast cold neutron shutter



PSW

Experimental setup
Infrastructure

- velocity selector (3.5 Å→ 9.7 Å)
- fast cold neutron shutter
- time of flight



PSW

Measurement results
Measurement scheme

- wavelength scans for 5 pressures: SVP, 5, 11, 16 and 20 bar

Measurement results
Measurement scheme

- wavelength scans for 5 pressures: SVP, 5, 11, 16 and 20 bar
- temperature range: 1.08 K $\leq$ T $\leq$ 1.12 K, stability $\leq$ 0.02 K

Measurement results
Measurement scheme

- wavelength scans for 5 pressures: SVP, 5, 11, 16 and 20 bar
- temperature range: 1.08 K $\leq$ T $\leq$ 1.12 K, stability $\leq$ 0.02 K
- several control measurements at SVP

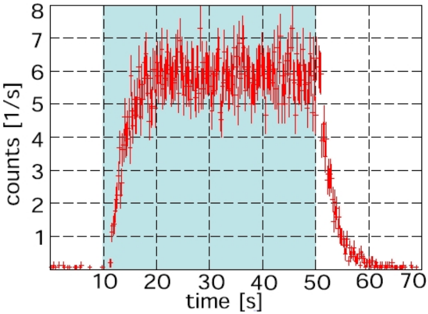
Measurement results

Measurement scheme

- wavelength scans for 5 pressures: SVP, 5, 11, 16 and 20 bar
- temperature range: 1.08 K $\leq$ T $\leq$ 1.12 K, stability $\leq$ 0.02 K
- several control measurements at SVP

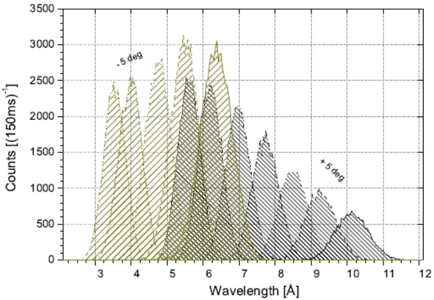
measuring time for 1 point: 70 s

- 10 s CN shutter closed
- 40 s CN shutter open
- 20 s CN shutter closed



PSW

Measurement results
Time of flight



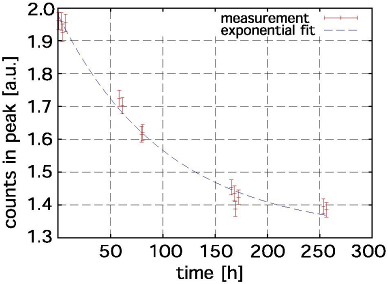
PSW

- selector speed ↔ neutron wavelength
- CN spectrum in converter volume

Measurement results
temporal decrease of UCN count rate

Control measurements

14 control measurements at SVP $\rightarrow$ temporal decrease of UCN count rate



PSW

Measurement results
temporal decrease of UCN count rate

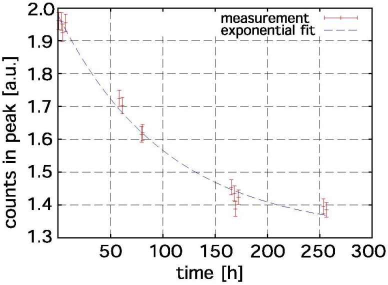
Control measurements

14 control measurements at SVP $\longrightarrow$ temporal decrease of UCN count rate

$$N(t) = N_0(e^{(-\frac{t}{\tau})} + \kappa)$$

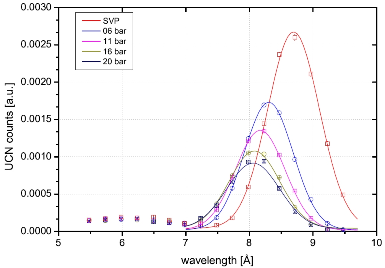
$\tau = 102(12)$h and $\kappa = 1.96(3)$

$\chi^2_{red} = 1.19$



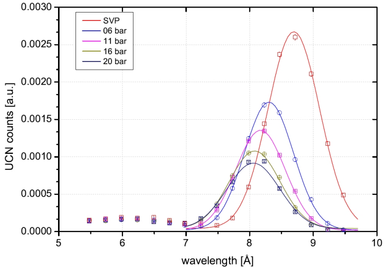
PSW

Measurement results
UCN Production rate



[PSW]
Count rates corrected for background and temporal decrease, normalized to CN monitor count rate

Measurement results
UCN Production rate

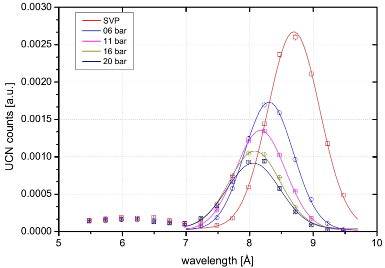


[PSW]
Count rates corrected for background and temporal decrease, normalized to CN monitor count rate

Results

- shift of the single phonon peak to shorter wavelength

Measurement results
UCN Production rate

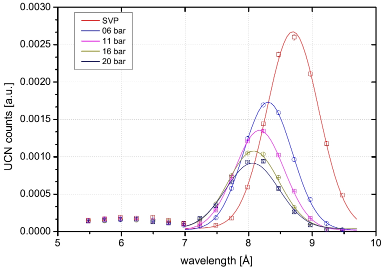


[PSW]
Count rates corrected for background and temporal decrease, normalized to CN monitor count rate

Results

- shift of the single phonon peak to shorter wavelength
- UCN count rate in single phonon peak decreases

Measurement results
UCN Production rate



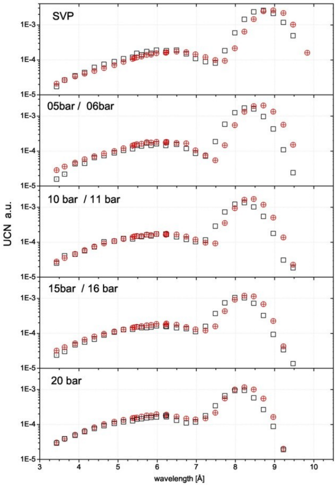
[PSW]
Count rates corrected for background and temporal decrease, normalized to CN monitor count rate

Results

- shift of the single phonon peak to shorter wavelength
- UCN count rate in single phonon peak decreases
- slight increase in multiphonon region

Measurement results

Comparison with theory

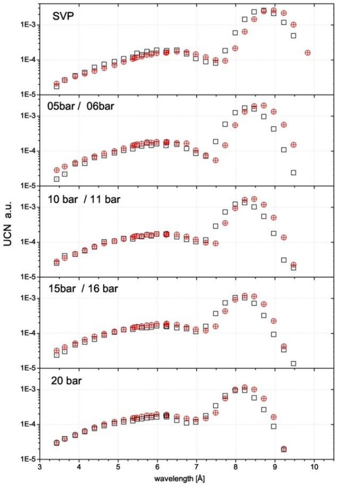


PSW

Experiment vs. theory

- intensity decrease agrees

Measurement results
Comparison with theory

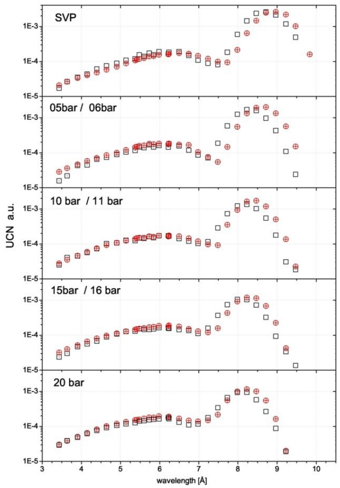


PSW

Experiment vs. theory

- intensity decrease agrees
- relative peak position shift agrees

Measurement results
Comparison with theory

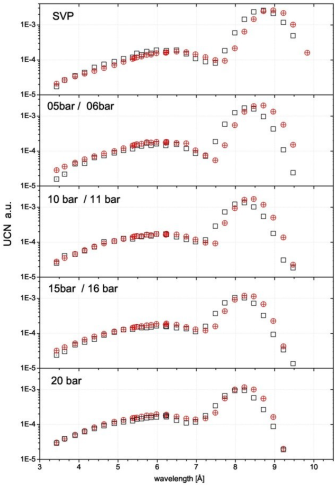


PSW

Experiment vs. theory

- intensity decrease agrees
- relative peak position shift agrees
- absolute peak position differs

Measurement results
Comparison with theory



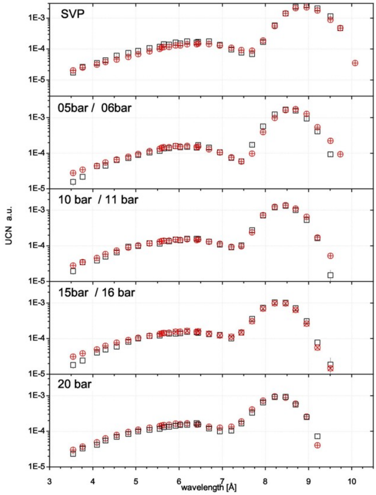
PSW

Experiment vs. theory

- intensity decrease agrees
- relative peak position shift agrees
- absolute peak position differs

systematic shift of the peak positions to shorter wavelength

Measurement results
Comparison with theory



PSW

Experiment vs. theory

- intensity decrease agrees
- relative peak position shift agrees
- absolute peak position differs

fit of flight path

Measurement results

Implication for further He-II UCN sources

Saturated vapor pressure is best suited for He-II UCN sources at a 8.9 Å neutron beam

Measurement results

Implication for further He-II UCN sources

Saturated vapor pressure is best suited for He-II UCN sources at a 8.9 Å neutron beam

- application of pressure reduces the total UCN production rate at a typical cold beam

Measurement results

Implication for further He-II UCN sources

Saturated vapor pressure is best suited for He-II UCN sources at a 8.9 Å neutron beam

- application of pressure reduces the total UCN production rate at a typical cold beam
- windowless UCN extraction remains possible

Measurement results

Implication for further He-II UCN sources

Saturated vapor pressure is best suited for He-II UCN sources at a 8.9 Å neutron beam

- application of pressure reduces the total UCN production rate at a typical cold beam
- windowless UCN extraction remains possible
- no need for an enforced pressure volume