The solid-deuterium-moderator-based ultracold neutron source at PSI

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on behalf of the PSI UCN Team

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What are ultracold neutrons - UCN

UCN < 300 neV ~ 8 m/s ~ 3 mK

\[ \lambda = \frac{\hbar}{m \cdot v} \]

> 50 nm !

\[ E_{\text{kin}} = \frac{mv^2}{2} = \frac{3}{2} kT \]

e.g. air molecules at 20 °C: ~400 m/s

<table>
<thead>
<tr>
<th>Type</th>
<th>Velocity</th>
<th>Temperature</th>
<th>Temperature</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal (25 meV)</td>
<td>2200 m/s</td>
<td>300 K</td>
<td>0.18 nm</td>
<td></td>
</tr>
<tr>
<td>cold (5 meV)</td>
<td>1000 m/s</td>
<td>60 K</td>
<td>0.4 nm</td>
<td></td>
</tr>
<tr>
<td>UCN (&lt; 260 neV)</td>
<td>&lt; 7 m/s</td>
<td>0.003 K</td>
<td>&gt; 50 nm</td>
<td></td>
</tr>
</tbody>
</table>

Neutrons with \( E_{\text{kin}} < 300 \text{ neV} \) reflect under any angle of incidence => can be stored (E. Fermi, 1946)
UCN reflect under any angle of incidence → can be manipulated and stored

- storage properties are material dependent e.g. Ni, Ni$^{58}$, Be, DLC, steel
  \[ V_F = 150 - 300 \text{ neV} \]
  (neutron optical potential)

**Standard Storage Bottle**

magnetic

\[ V_m = -\mu B \]

60 neV T$^{-1}$

gravitation

\[ V_g = m_n g h \]

100 neV m$^{-1}$
UCN reflect under any angle of incidence → can be stored

Relevant parameter for UCN sources and storage experiments

UCN density

e.g. ~30 UCN/cm³ in experiment at PSI

- fundamental physics experiments
e.g. search for a permanent electric dipole moment of the neutron

Comparison of ultracold neutron sources for fundamental physics measurements

Suggestion of "standard" method and device for UCN density measurement and comparison:

Standard storage bottle
High Intensity Proton Accelerator (HIPA) complex

Proton Accelerator
590 MeV Cyclotron
2.2/2.4 mA beam current

kicker to UCN

2 experimental areas / 3 beamlines

UCN Source

SINQ

Ultra Cold Neutron Source
The PSI UCN source

UCN optics arXiv:1907.05730

- Pulsed 1.3 MW p-beam
- 590 MeV, 2.2 mA, 1% duty cycle

- Heavy water moderator → thermal neutrons 3.6m³ D₂O

- Spallation target (Pb/Zr) (~8 neutrons/proton)

- Cold UCN-converter 5 kg solid D₂ at 5 K

- DLC coated UCN storage vessel height 2.5 m, ~2 m³

- Cryo-pump

- UCN guides towards experimental areas 8.6m(S) / 6.9m(W)

- Important: UCN source operation by ASQ Group (B. Blau et al.)

- n²EDM experiment

- UCN delivery at beam port
Understanding the thermal neutron flux

- Fully detailed MCNP-X model and simulation by Vadim Talanov + Michael Wohlmuther
- comparison to gold foil measurements

756 Zr/Pb Canelloni Target
~7.5 n/p
by M. Wohlmuther
Understanding the cold flux via tritium activation monitoring

Measurement of tritium in gaseous D2 at KIT Karlsruhe - cooperation with Robin Groessle / Tritiumlab

PhD work of Nicolas Hild

Input - detailed history of
- D2 mass in moderator vessel
- proton beam current

\[ \sigma \text{-capture} \sim \frac{1}{v_n} \]
Why solid deuterium?
Superthermal UCN production

Why solid deuterium?
Superthermal UCN production

D_2

UCN production per molecule in sD2
multiphonon Debye-Model

4He

Golub & Pendlebury

"maxon"
"roton"

sD2-based UCN sources
at LANL, TRIGA Mainz,
NCSU
and planned for TUM

F. Atchison et al., PRL99(2007)262502 (measurement at SINQ)
Beat the losses - go to 5K

loss cross-sections

- Nuclear capture on hydrogen → isotopically clean D2
- Up-Scattering via p→o conversion → high ortho D2 concentration
- Nuclear capture on the deuteron → cool to 5 K

Thermal effect
(better cooling = less losses)

Para Deuterium effect
(less para = less losses)

Modified plot from
Raman measurement of: para D2 content and H2/HD content

Result (preliminary):
99.3 % Ortho-D2 (>98%) during standard operation
0.33±0.03 % HD-molecules

PhD work of Nicolas Hild
Para-ortho D2 conversion via radiation

PhD work of Nicolas Hild

at SINQ - liquid D2 - 76% ortho D2 equilibrium

Para-ortho D2 conversion via radiation

![Graph showing the conversion of para-ortho D2 over time](image)
Time behavior of UCN intensity - frost formation

- Conditioning procedure regains full intensity
- Standard data taking week - Sept. 2017

Frost disks isotropically oriented in vacuum

Pressure during pulsing

Pressure (Pa)

Time

MCUCN simulation by G. Zsigmond

E (neV)  \( r_{\text{cap}} \) (cm)
- 150  1.0
- 150  0.25
- 250  1.0
- 250  0.5
- 350  1.0
- 500  1.0

UCN exited on top) / (UCN started below snow)

(33 \( s_{\text{D}_2} \) disks) / (converter cross section)
Time behavior of UCN intensity - frost formation

- Frost disks isotropically oriented in vacuum
- UCN source & Absorbing layer

standard data taking week - Sept. 2017

similar effect observed at other UCN sources - work with LANL and NCSU

conditioning procedure regains full intensity
Slow freeze sD2 test

- longest ever freezing time done at PSI UCN source

UCN output during slow freezing process of Deuterium

Preliminary

~40% increase in UCN intensity

Triplepoint

PhD Ingo Rienäcker

Sep. 2019
- observe behavior of UCN output at the triplepoint (no pressure ambiguity)

preliminary
highest number of UCN registered at beamport West-1

Production pulse measured at West-1 beamport

- Normalized to 2.2 mA

UCN Counts

- 2018: specific other studies
Summary:

- Successful operation of the PSI UCN source has been achieved in the last years - world leading facility.

- Better understanding of all source parameters and increase of UCN intensity has been achieved.

- Further developments are ahead.

- Many thanks to all PhD students for their hard work and to the UCN source operating crew.
thanks for your attention