Characterization of cold neutron fluxes for an advanced ultracold neutron source by using activation with borosilicate glass

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Neutron Electric Dipole Moment (nEDM)

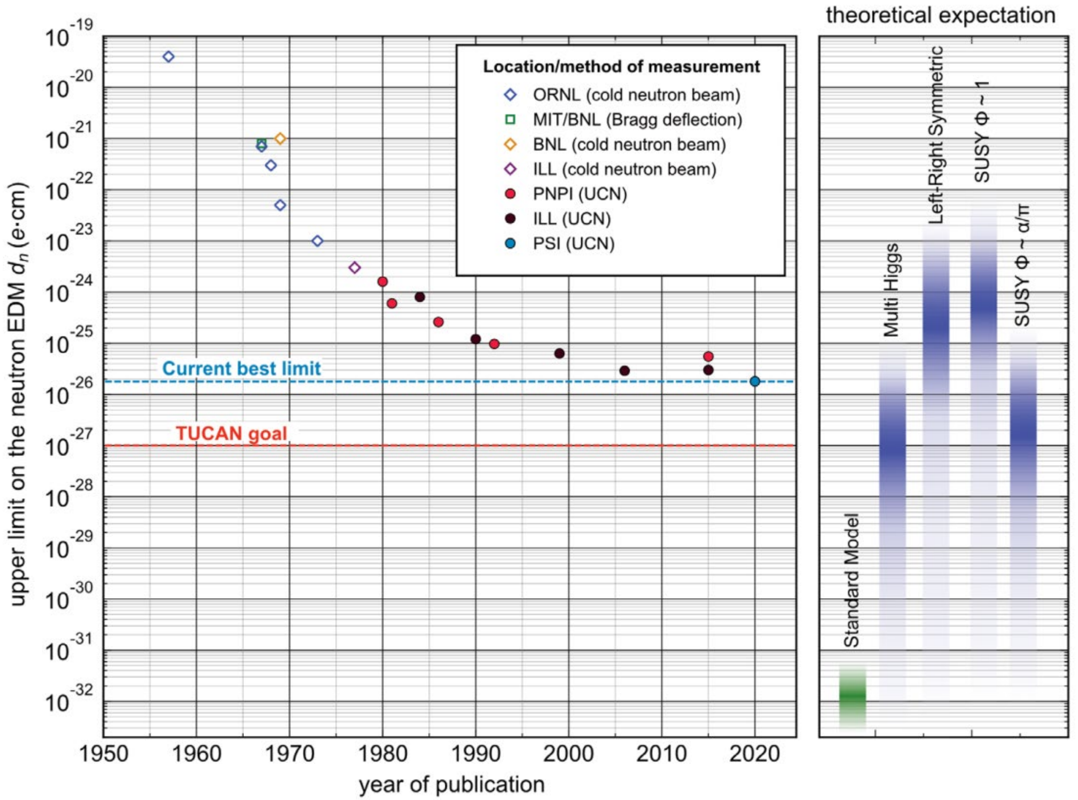
- **Neutron Electric Dipole Moment (nEDM)**
  - Electric Charge separation of the Neutron
  - The existence of a finite nEDM implies CP violation
  - Important in the context of resolving the origins of matter-antimatter asymmetry in the universe

- **Current status of nEDM measurements**
  - Latest experimental upper limit (PSI 2020):

$$d_n = \left(0.0 \pm 1.1_{\text{stat}} \pm 0.4_{\text{sys}}\right) \times 10^{-26} e\text{cm}$$

$$\Rightarrow |d_n| < 1.8 \times 10^{-26} e\text{cm} \ (90\% \ \text{C. L.})$$

  - Standard Model prediction: $d_n \sim 10^{-32}\ e\text{cm}$, stringent tests of theories beyond the Standard Model (BSM)



J. M. Pendlebury and E. A. Hinds, Nucl. Inst. Meth. A, 440, 471 (2000)

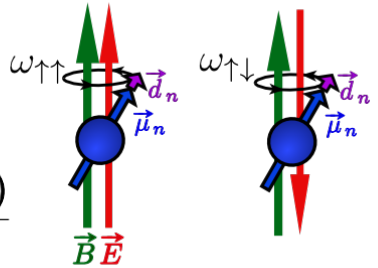
TRIUMF UltraCold Advanced Neutron collaboration

Developing a high-intensity ultracold neutron (UCN) source for an nEDM measurement

TUCAN

Principle of nEDM measurements

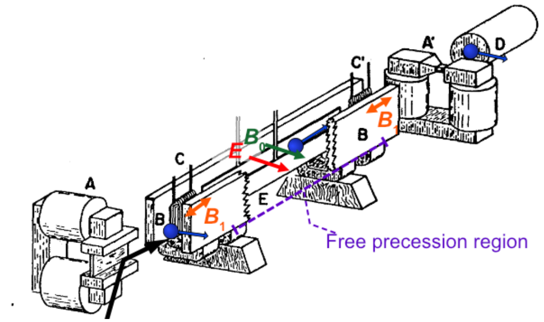
$$H = -\mu_n \vec{B} \cdot \frac{\vec{S}}{S} - d_n \vec{E} \cdot \frac{\vec{S}}{S}$$

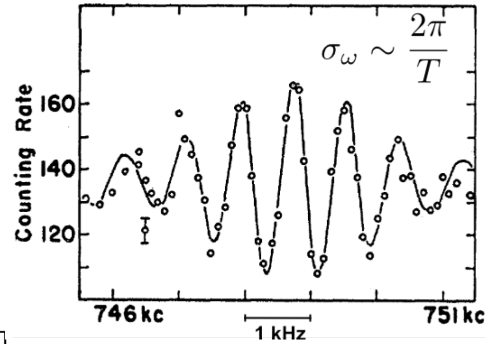


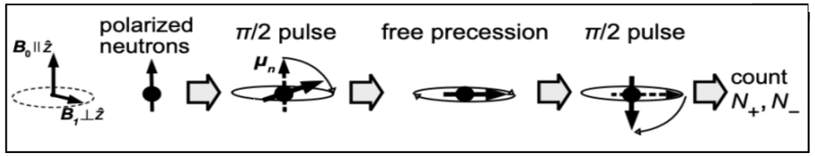
$\uparrow\uparrow$: $\vec{B} \parallel \vec{E}$
$\uparrow\downarrow$: $\vec{B} \parallel -\vec{E}$

$$d_n = \frac{\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}{4|E|}$$

Larmor frequency change due to electric field







$$d_n = (-0.1 \pm 2.4) \times 10^{-20}\ ecm$$

J.H. Smith, E.M. Purcell & N.F. Ramsey, Phys. Rev. **108**, 120 (1957)

- **Sensitivity of an nEDM measurement**

$$\sigma_d = \frac{\hbar}{2\alpha E T \sqrt{\boldsymbol{N}}}$$

PSI 2020:

E (electric field): 11 kV/cm
T (free precession time): 180 s
α (visibility, i.e. fringe amplitude): 0.76
N (# of detected neutrons): 11400/cycle

- **TUCAN**

2 orders of magnitudes improvement in UCN statistics

→ 10^{-27} ecm sensitivity in 400 days

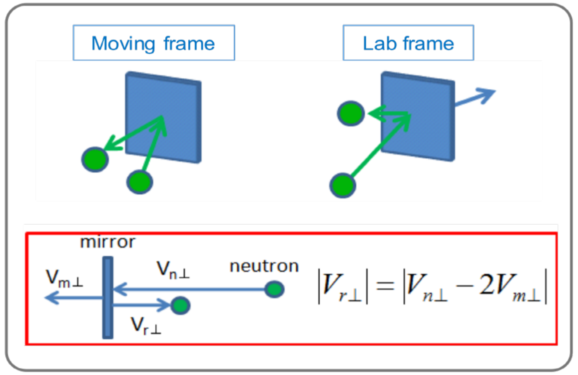
nEDM sensitivity is limited by the number of UCNs

UCN production methods

UCN : kinetic energies of < 300neV (c.f. Fermi potential of ^{nat}Ni: 245 neV)

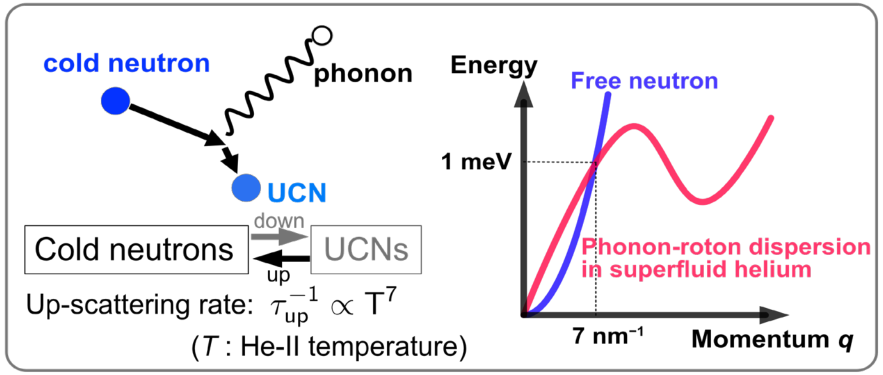
- **Production scheme**

Mechanical deceleration
(ILL/PF2, J-PARC/BL05)



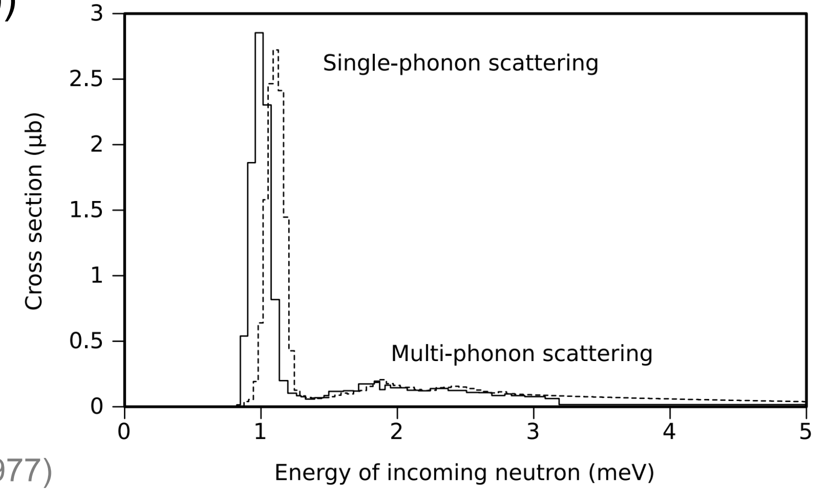
J-PARC/BL05: Prog. The. Exp. Phys. **2016**, 013C02 (2016)

Super-thermal production
(PSI, LANL (sD2), ILL/SuperSUN, TRIUMF (He-II))



R. Golub & J.M. Pendlebury, Phys Lett A 62, 337 (1977)

Cross section of super-thermal production (He-II)



1 meV

W. Schreyer et. al, Nucl. Inst. Meth. A 959 (2020)

➢ Limitation in density

Keys: - cold neutron flux at 1 meV
- temperature of He-II ≲1 K

TUCAN UCN production

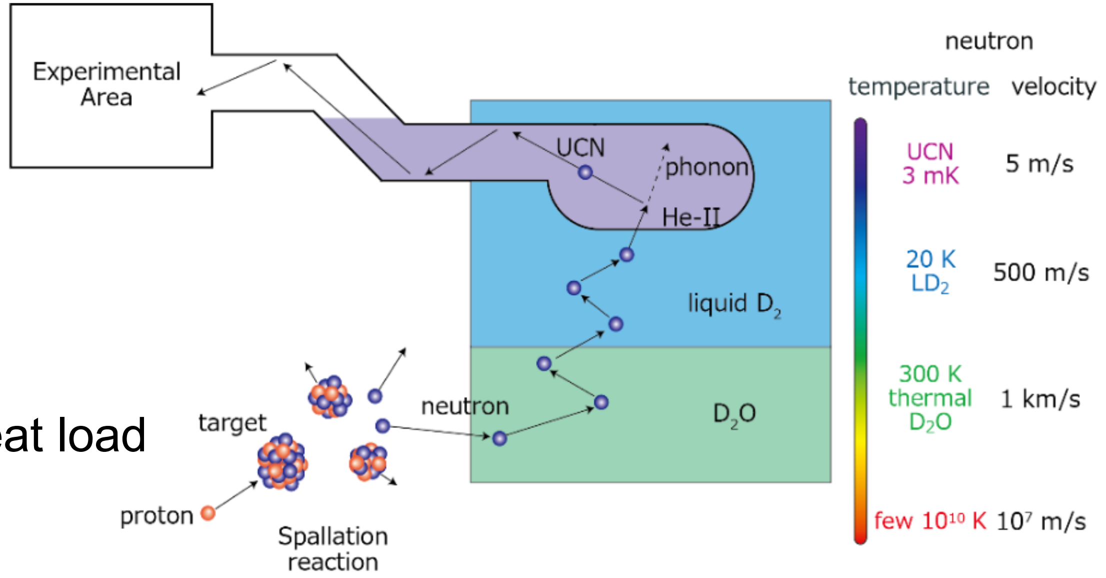
T̲RIUMF U̲ltraC̲old A̲dvanced N̲eutron source

- spallation neutron production by a cyclotron beam
- super-thermal UCN production with super fluid He (He-II)
- LD_2 for Cold neutron moderator

✓ Large solid angle coverage of the production target
✓ Lower up-scattering cross section of He-II over sD_2
✓ Optimized cold neutron flux around 1meV
→ **High UCN yield**

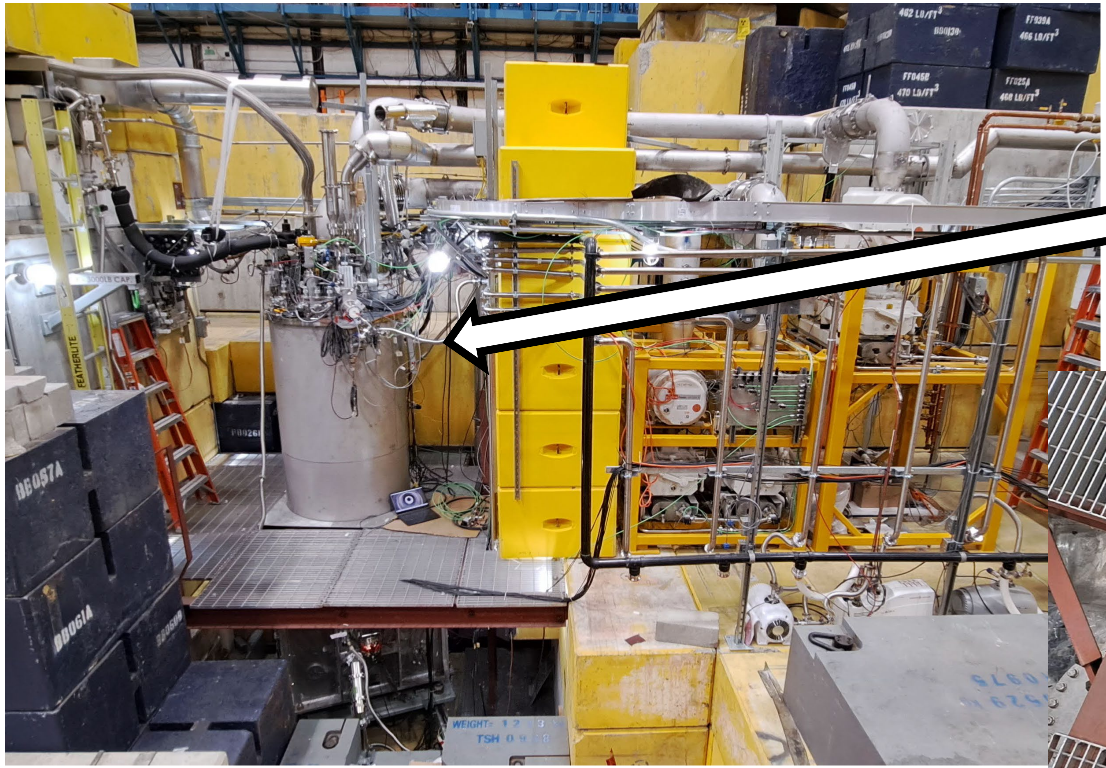
Challenge: Need to sustain He-II at ~1K under a 10 W heat load

J.W. Martin et al, arXve:2506.09064(2025)

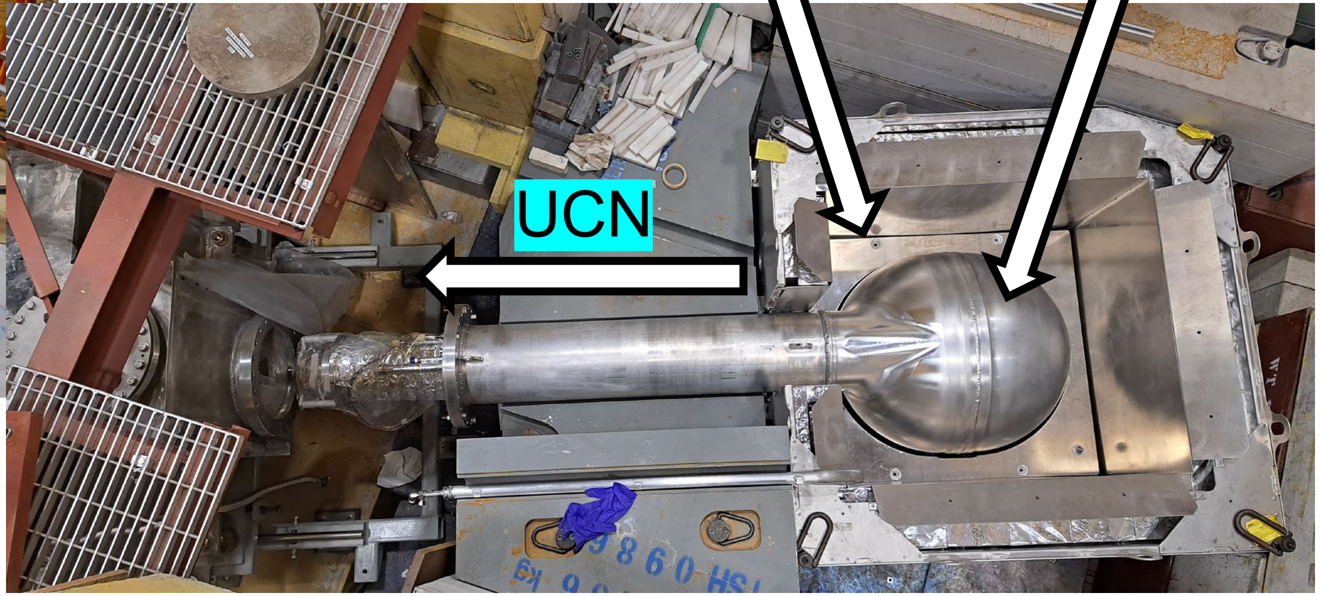


Key for UCN source: High power cryostat, 1meV neutrons

UCN source commissioning



cryostat



D2O

He-II and LD2

Cold neutron measurement

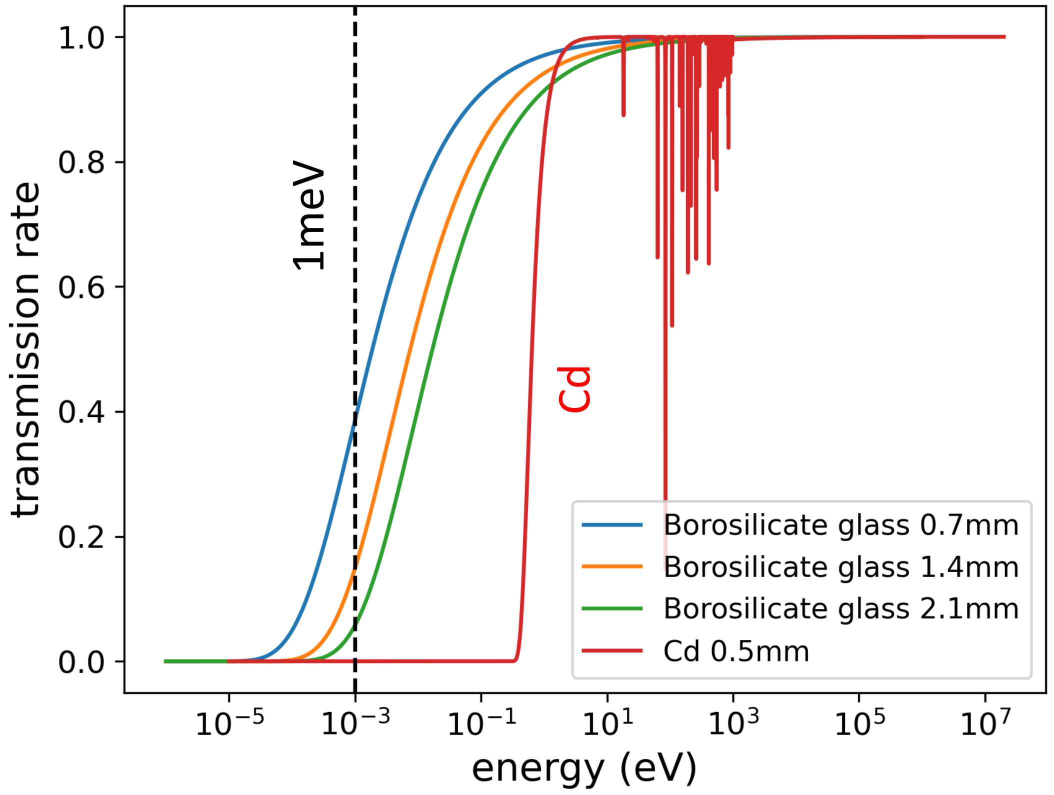
Cold neutron flux at 1meV is important for He-II super-thermal method

TOF is not available due to space problem
→ **we select a gold foil activation**

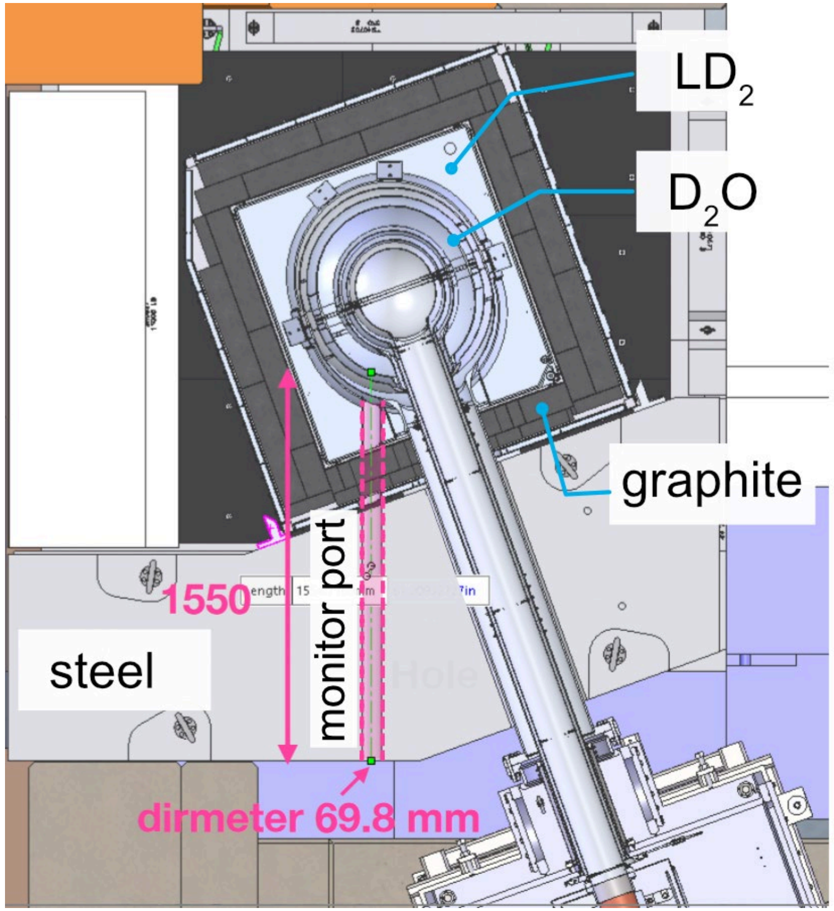
✓ **We used borosilicate glass as filters**

- Cd filter
  - ➢ Most standard
  - ➢ Thermal vs fast

- Borosilicate glass (contain B)
  - ➢ Sensitive to Cold Neutron (~1meV)
  - ➢ Transmission rate depends on its thickness



Cold neutron measurement method

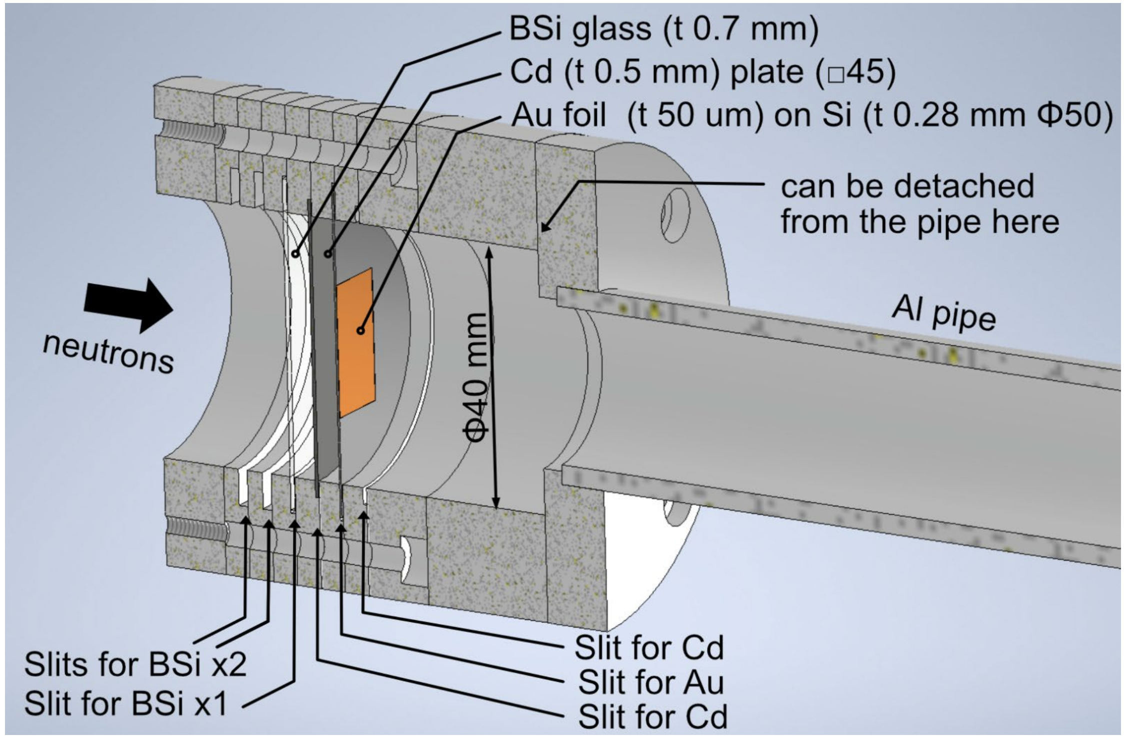


- different filter conditions

(Cd 0.5 mm, Borosilicate glass 0.7, 1.4, 2.1 mm)

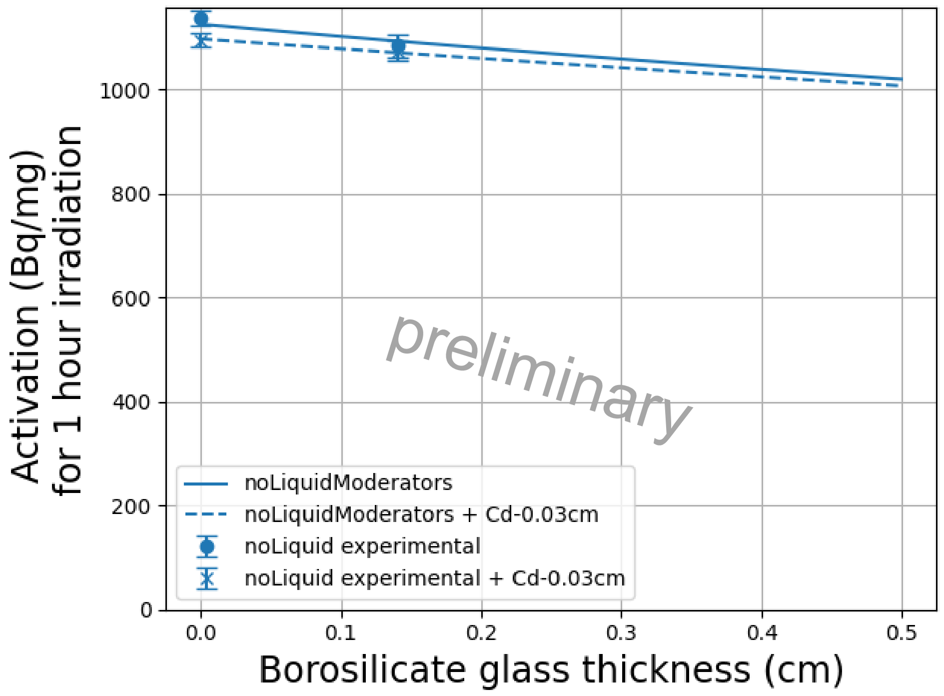
- with two moderator conditions:

i) No LD2, No D2O ii) No LD2, With D2O

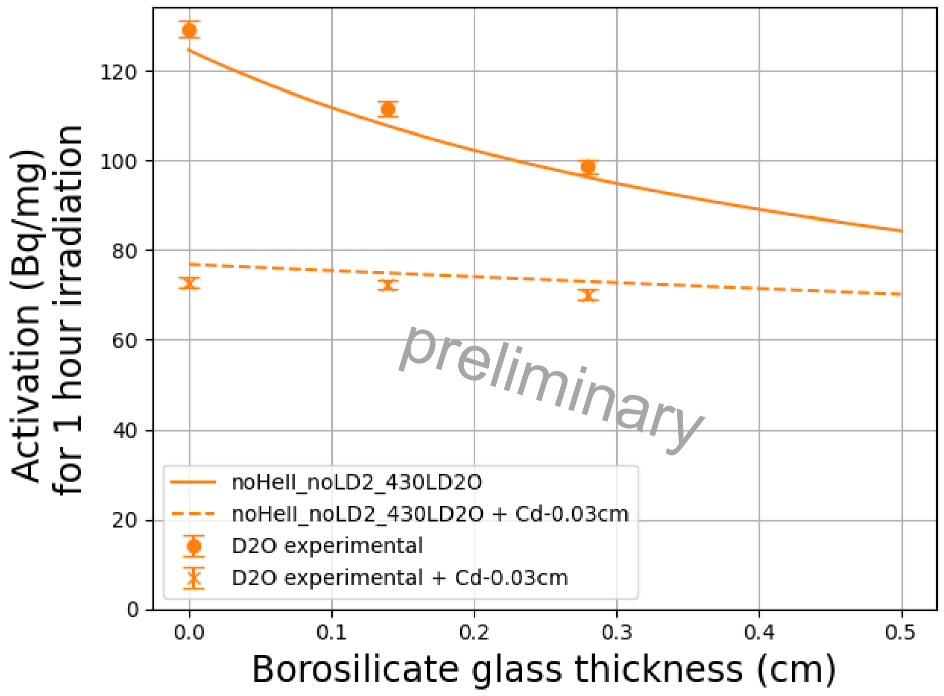


Results

No D2O, No LD2



430L D2O, No LD2



- Measurement reproduced the prediction by MCNP simulation (an extra scaling necessary to account for neutron flux uncertainty and germanium detector efficiency etc)
- Colder neutron spectrum from D2O → steeper curve as a function of borosilicate glass thickness

Summary and Outlook

- Developing an accelerator-driven, He-II super-thermal UCN source for a neutron EDM experiment with a 10^{-27} ecm sensitivity
- Cold neutron (~1meV) flux is important for He-II super-thermal method
- The neutron spectra are consistent between the simulation and actual activation measurements

TUCAN

Acknowledgements

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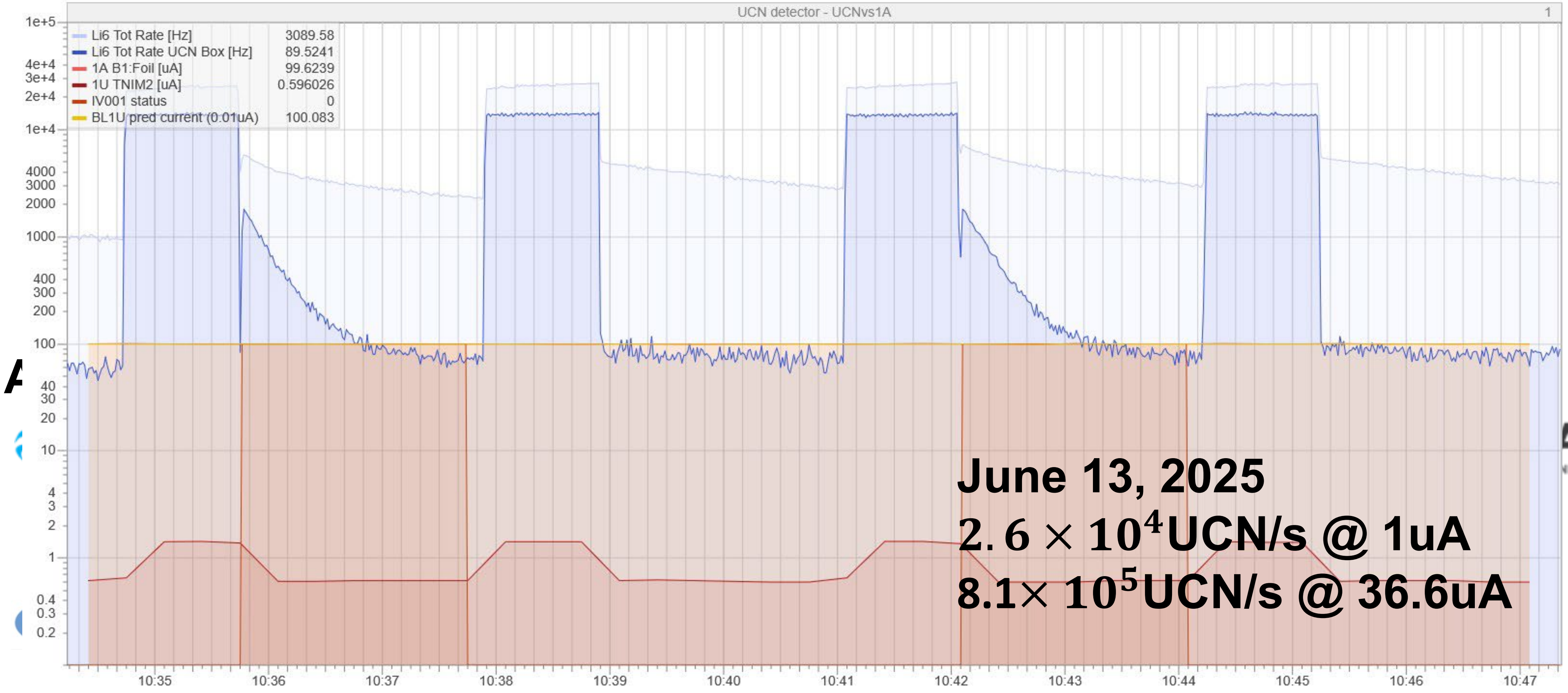
Japan Society for the Promotion of Science
JST

Summary and Outlook



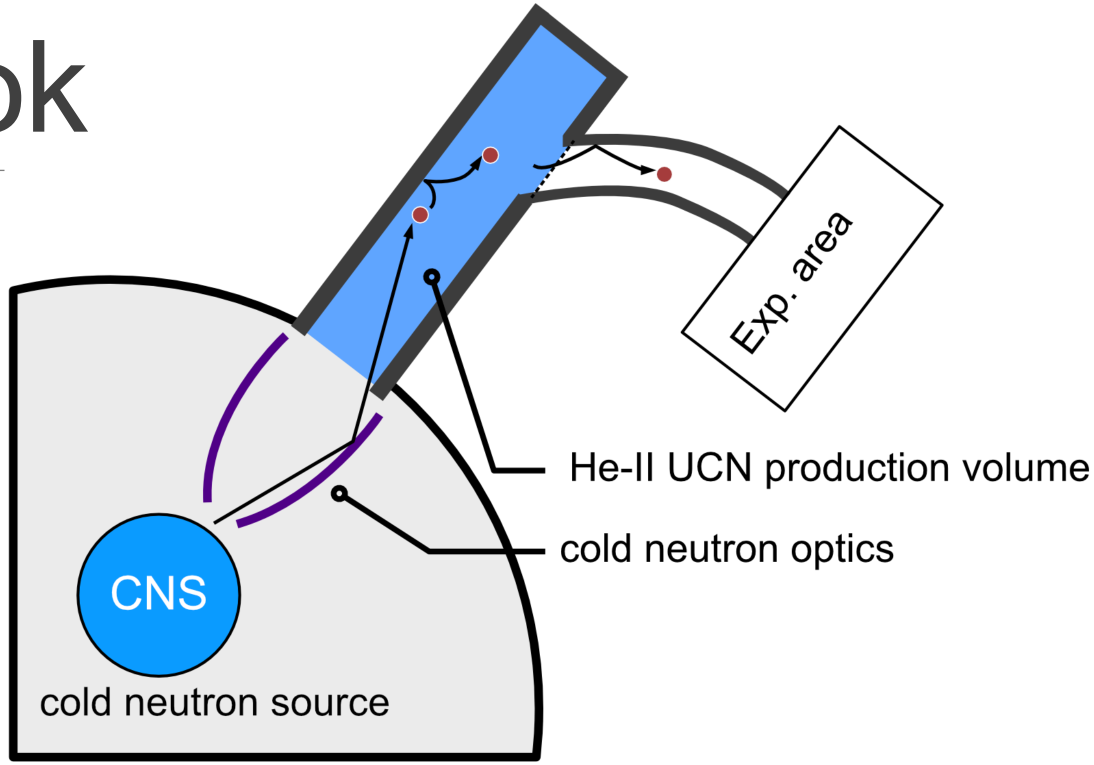
June 13, 2025

2.6×10^4 UCN/s @ 1uA

8.1×10^5 UCN/s @ 36.6uA

Summary and Outlook

Based on experience of TUCAN, Reactor-based He-II super-thermal UCN source is also proposed for the New Research Reactor



Acknowledgements

TRIUMF UBC UNBC SFU University of Manitoba The University of Winnipeg NSERC CRSNG INNOVATION.CA Canada Foundation for Innovation Fondation canadienne pour l'innovation

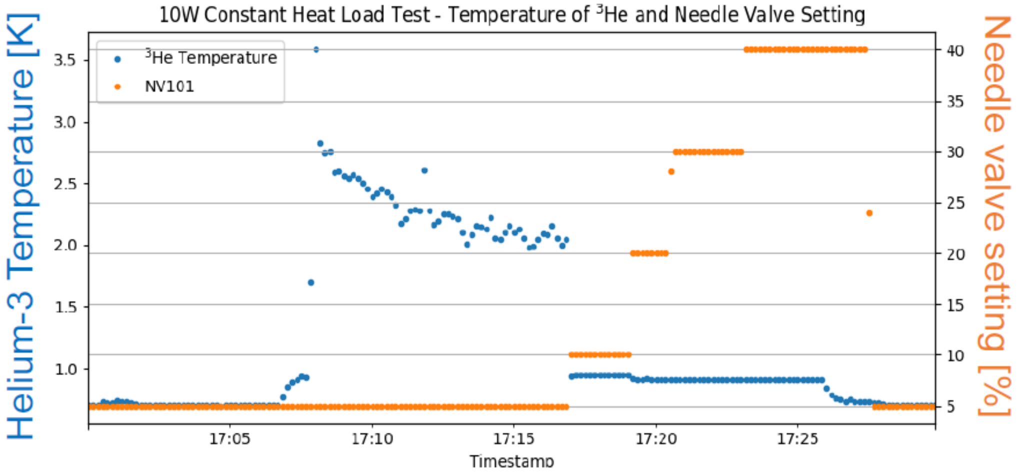
NC State University Oak Ridge National Laboratory University of Saskatchewan

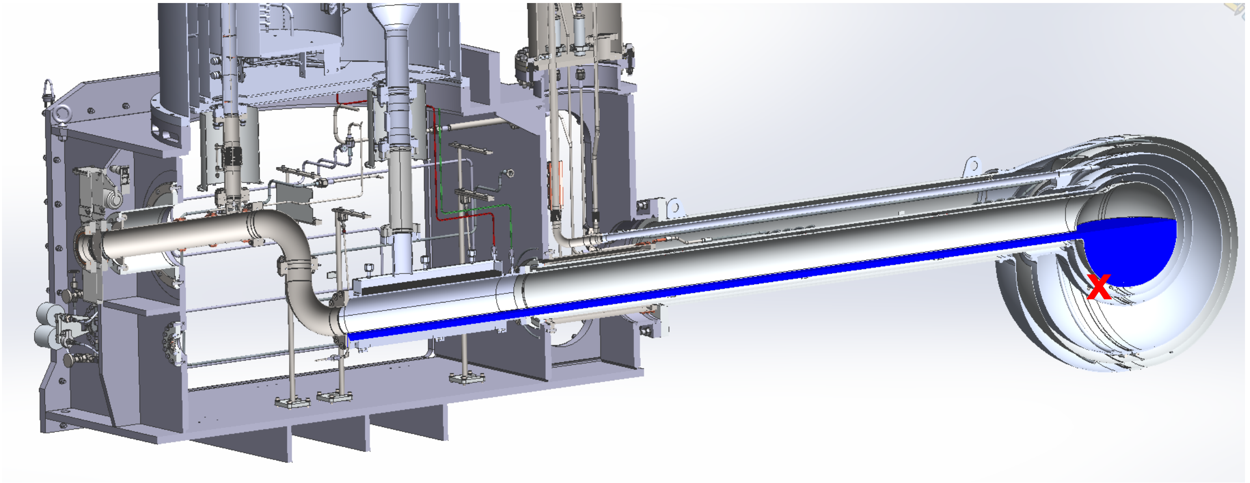
KEK RCNP Nagoya University KURNS

Thank you for your attention!

TUCAN UCN source 2024

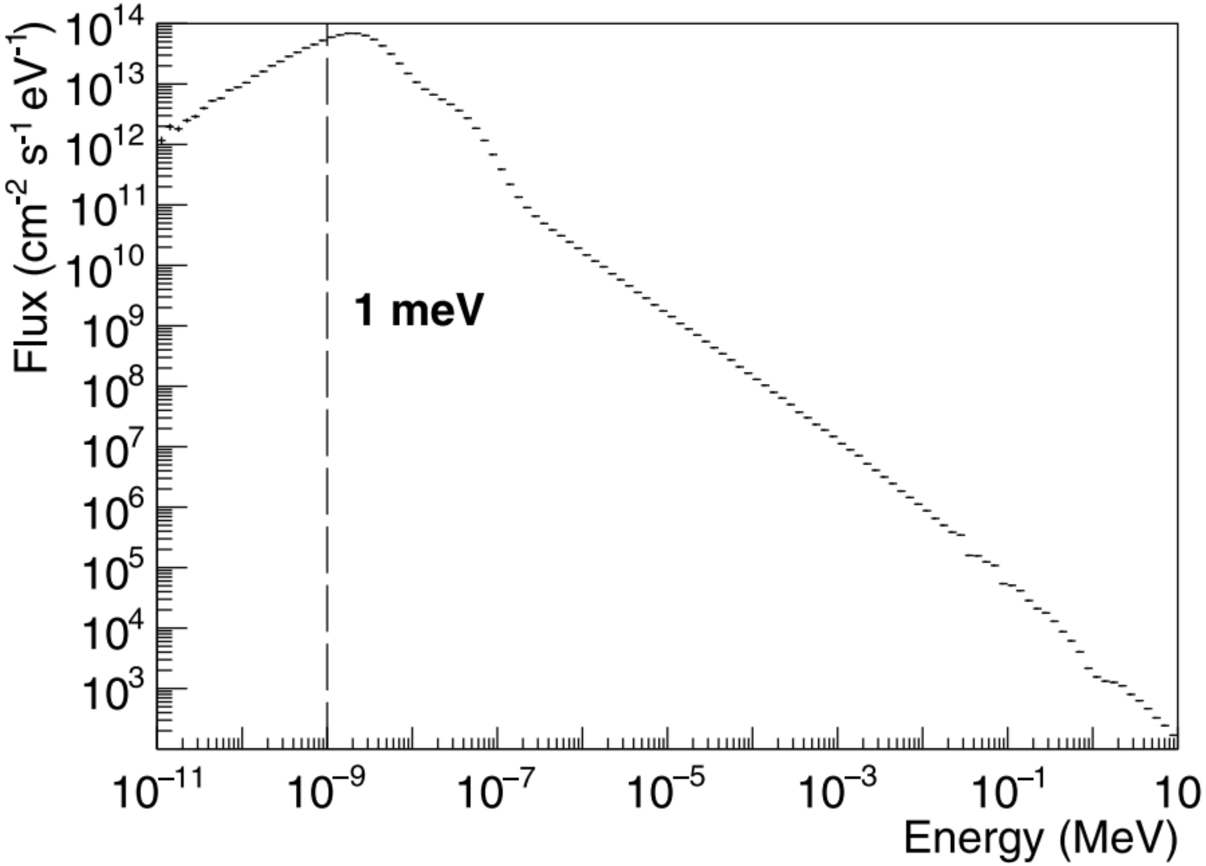
- Built and commissioned all major components of the UCN source by November 2024
- Attempted the first UCN production → no UCN observed due to contamination of He system
- Demonstrated cryogenic performance sufficient for 40 μA beam operation





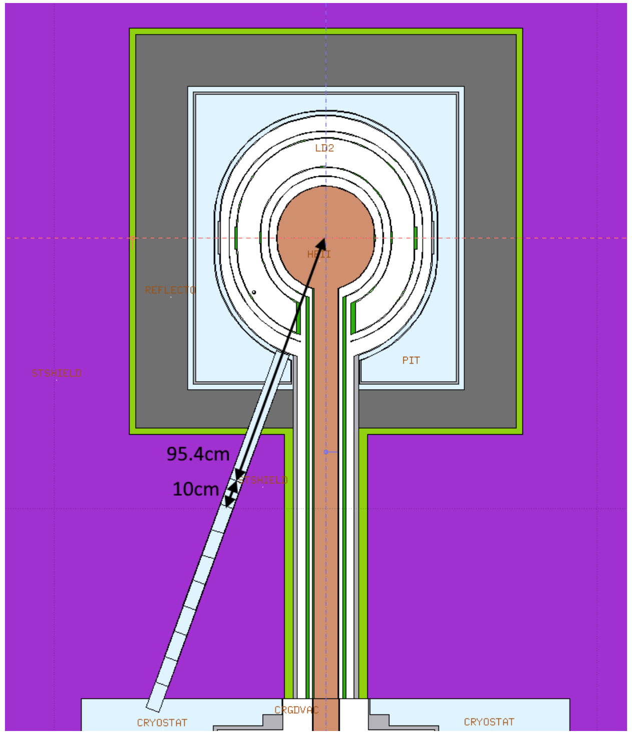
Sustained 1.2 K under 10 W heat load (↔ 40 μA proton beam)

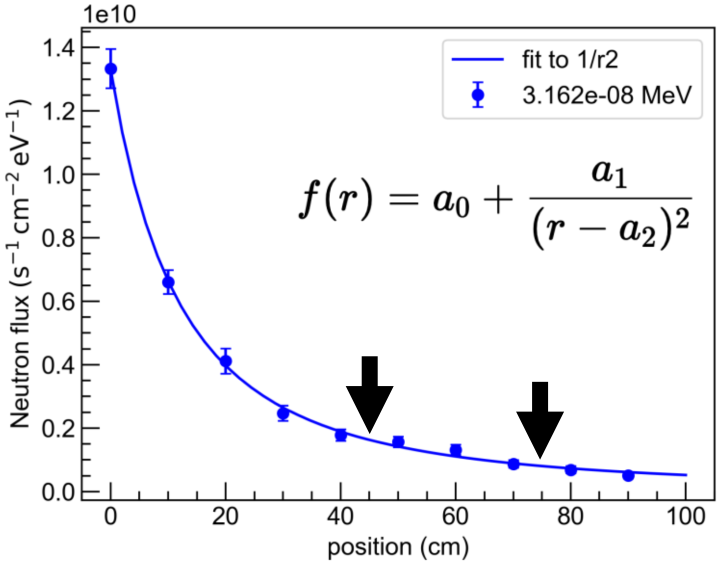
Appendix

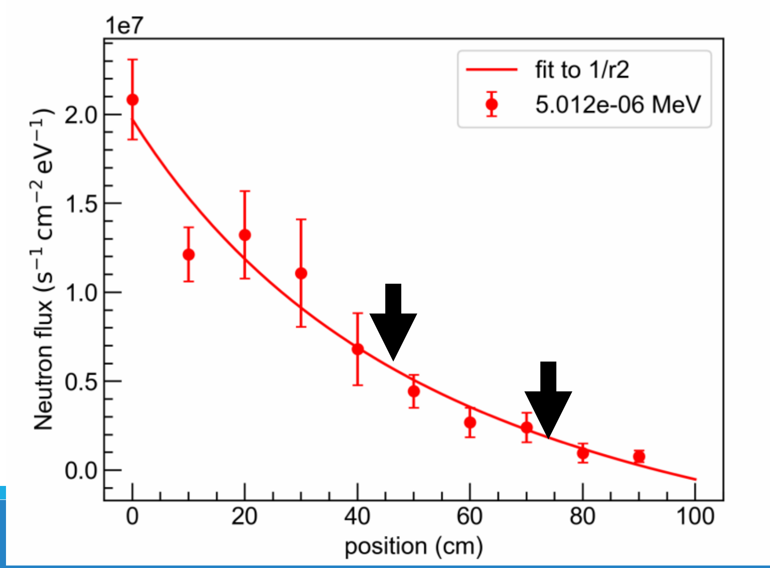


Flux (cm^{-2} s^{-1} eV^{-1})
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
1 meV
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10
Energy (MeV)

Appendix





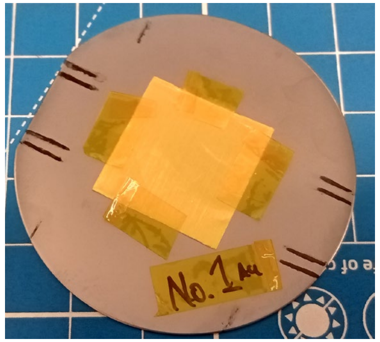


- 27mm(noD2O), 67mm(430LD2O)

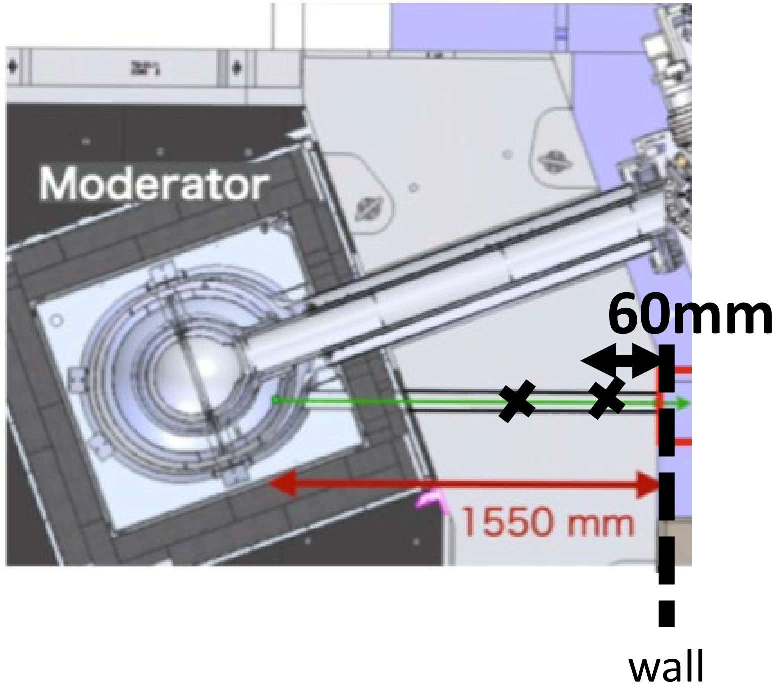
Appendix

We had 2 beam times

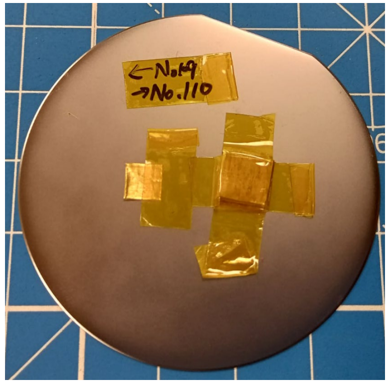
No D2O, No LD2 (Oct 14, 2024)



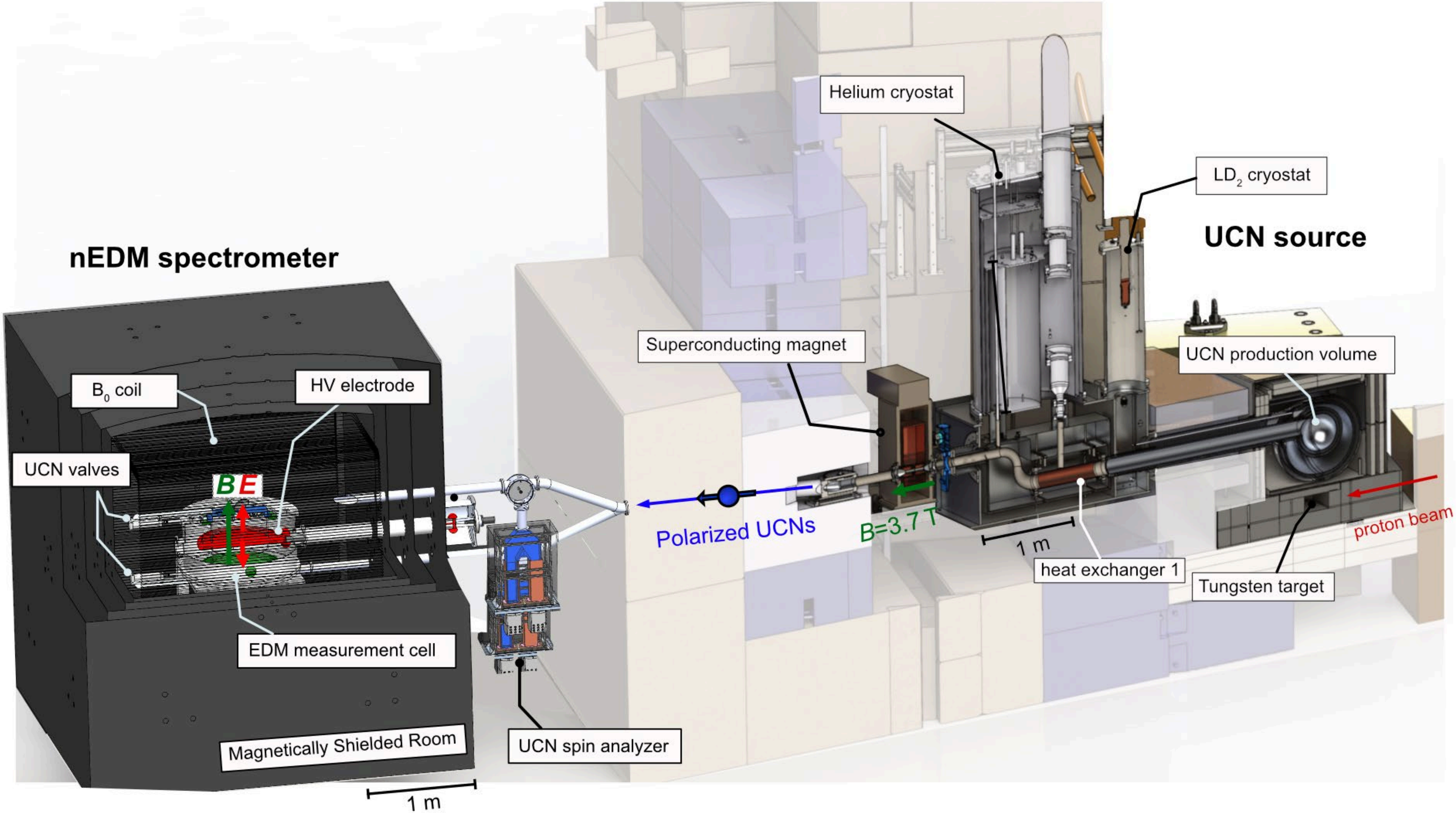
- 2cmX2cm gold foil
- set Cd and noCd separately
- Irradiated for 60min by 10uA beam
- Inserted at 500mm from the wall
- (1381mm from centre)
- The activation is **~470kBq**



430L D2O, No LD2 (Nov 11, 2024)



- 0.5cmX0.5cm gold foil
- set Cd and noCd at the same time
- Irradiated for 5min by 10uA beam
- Inserted at 60mm from the wall
- (1821mm from centre)
- The activation is ~300Bq



nEDM spectrometer
UCN source
Helium cryostat
LD_2 cryostat
Superconducting magnet
UCN production volume
B_0 coil
HV electrode
UCN valves
B E
Polarized UCNs
B=3.7 T
1 m
heat exchanger 1
Tungsten target
proton beam
EDM measurement cell
Magnetically Shielded Room
UCN spin analyzer
1 m

	nEDM 2016	n2EDM
chamber diameter D	DLC & dPS 47 cm	DLC & dPS 80 cm
N (per cycle) T E α	15'000 180 s 11 kV/cm 0.75	121'000 180 s 15 kV/cm 0.8
$\sigma(f_n)$ per cycle	9.6 μHz	3.2 μHz
$\sigma(d_n)$ per day	11×10^{-26} e cm	2.6×10^{-26} e cm
$\sigma(d_n)$ (final)	9.5×10^{-27} e cm	1.1×10^{-27} e cm