Cold and thermal neutron flux measurements at TRIUMF

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May 31st, 2017

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On behalf of Japan-Canada UCN collaboration

Outline

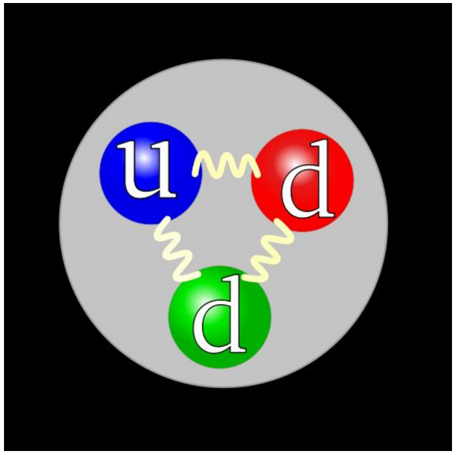
- Introduction
  - Neutron electric dipole moment
  - Ultra cold neutrons
  - Tests at TRIUMF
- Neutron flux experiments
  - Cold neutron measurement
  - Thermal and colder neutron measurement

	Ultra Cold	Very Cold	Cold	Thermal	Epithermal	Cadmium	Slow
Neutron Energy	< 300neV	300 – 500neV	500neV – 0.025eV	0.025eV	0.025 – 0.4eV	0.4 – 0.6eV	1 – 10eV

Neutron Electric Dipole Moment

- Baryogenesis
  - Baryon/antibaryon asymmetry in the early universe
  - Sakharov conditions (Sakharov, 1967)
    - Baryon number violation
    - CP-symmetry violation
    - Interactions outside of thermal equilibrium
- Extensions to Standard Model increase CP-violation
- How to measure this?
  - By measuring the neutron electric dipole moment (nEDM)
  - Probe for new sources of CP-violation
- (R3-4) Beatrice Franke's talk will cover more Thurs. at 1:30pm.

Ultra Cold Neutrons

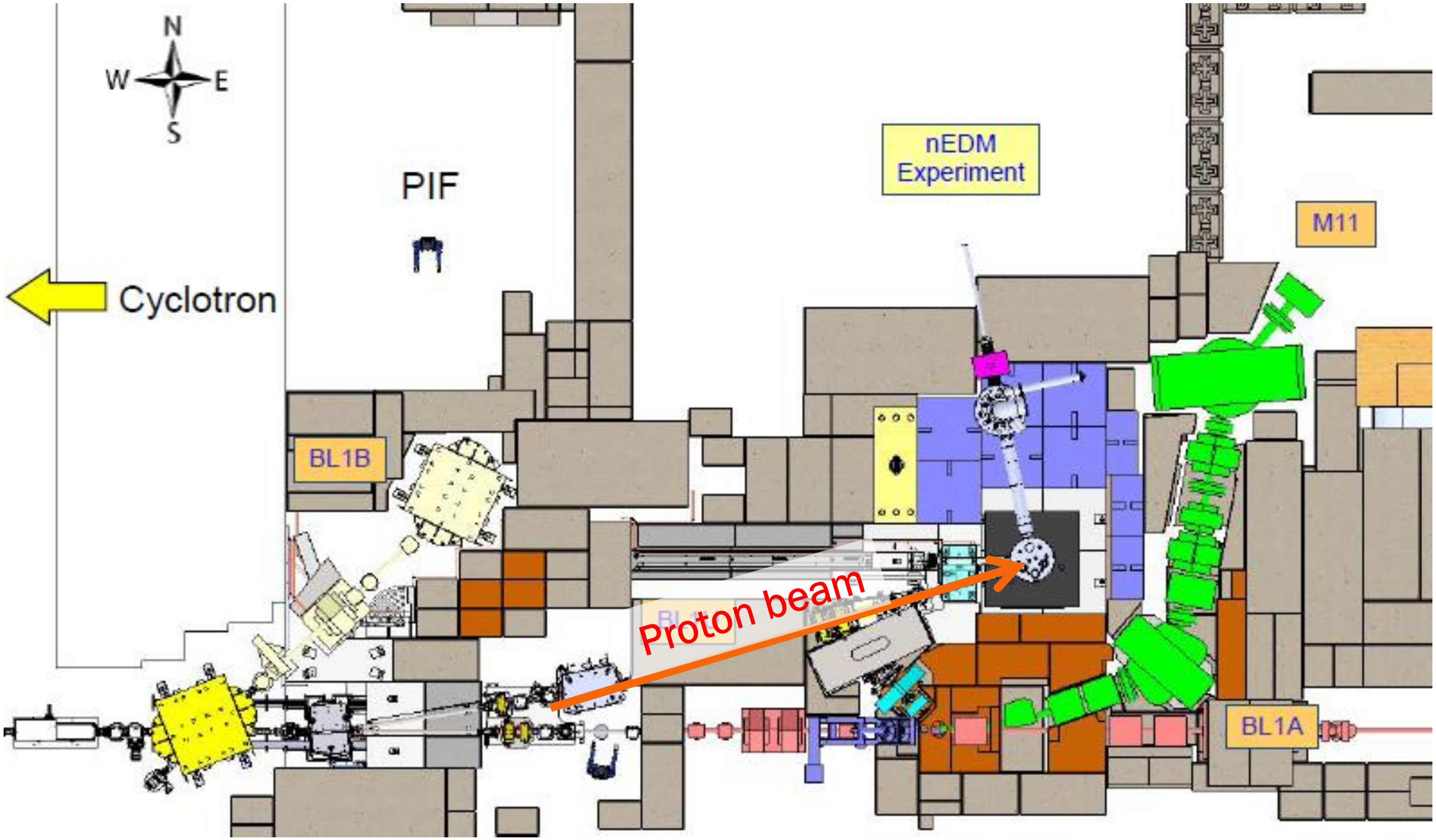


- Properties
  - < 3mK
  - ~7m/s
  - Subject to gravity
  - Polarizable
- Find neutron electric dipole moment (nEDM) by finding Larmor frequency

$$d_n = \frac{h}{4E}(f_{n\uparrow\uparrow} - f_{n\uparrow\downarrow})$$

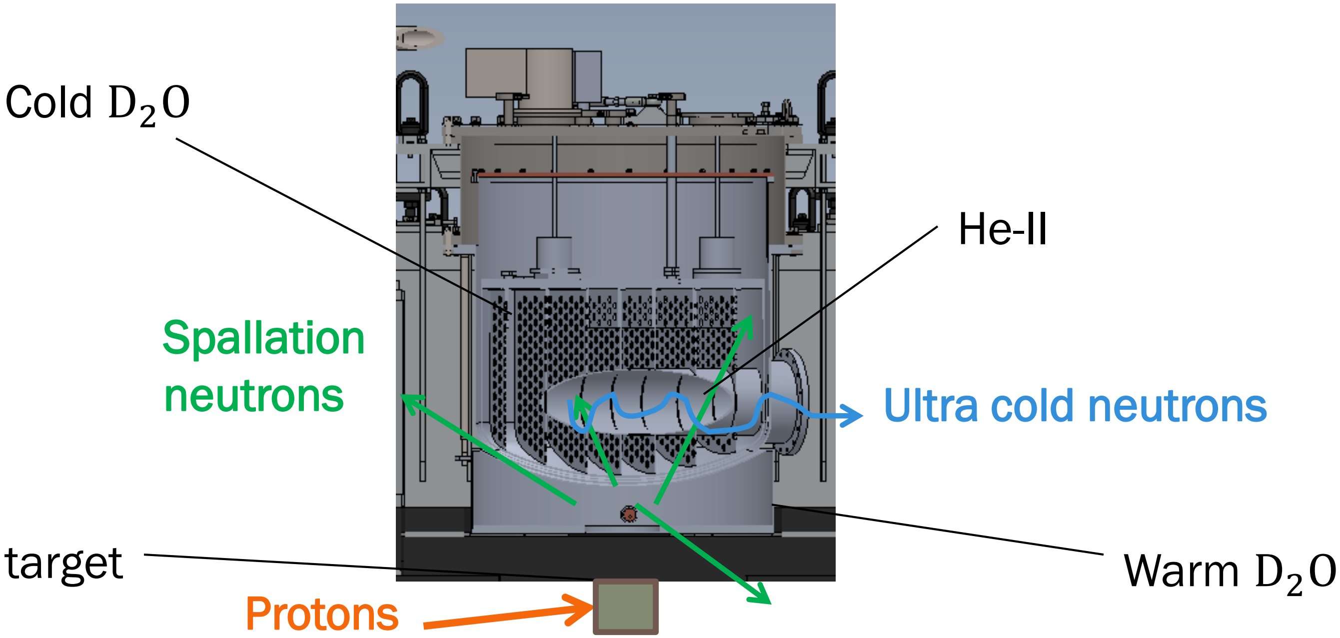
- $|d_n| \sim 3.0 \times 10^{-26}$ e-cm for current experimental limit (Pendlebury et. al)
- $|d_n| < 10^{-26}$ e-cm for new physics
- $|d_n| < 10^{-31}$ e-cm for CKM in Standard Model

UCN production layout at TRIUMF



UCN production layout

- Proton beam produces spallation neutrons on tungsten target
- Neutrons are thermalized by lead, and warm D_2O
- Cold D_2O further cools neutrons to cold temperatures
- Cold neutrons are further cooled to UCN level in the He-II volume and delivered to EDM apparatus



Beam on target at TRIUMF

Run Number	Temperature (K)	Date (in 2016)	Irradiation time	Integrated Beam (nA-s)
1	126	Nov 22nd	8 min	320605
2	87	Nov. 23rd	15 min	364380
3	8	Nov. 29th	8 min	274545
4	35	Nov. 29th	7 min	300995
5	8	Dec. 2nd	8 min	323907.5
6	65	Dec. 6th	9 min	351504
7	8	Dec. 12th	1 hr 42 min	306192
8	49	Dec. 13th	1 hr 58 min	284334
9	300	Dec. 20th	1 hr 6 min	303645
10	300	Dec. 20th	1 hr 35 min	312393
11	Empty	Dec. 21st	1 hr 17 min	349125

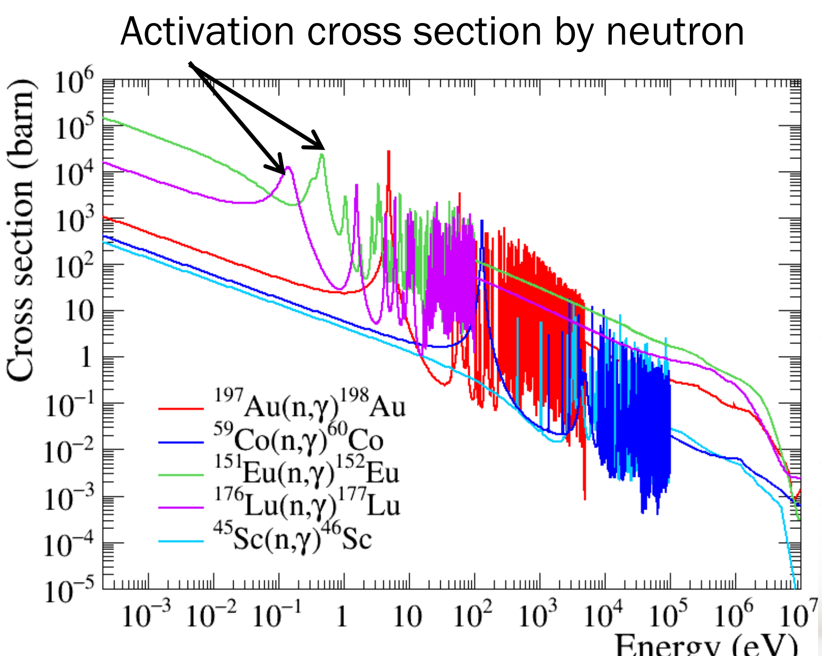
Measuring neutron flux

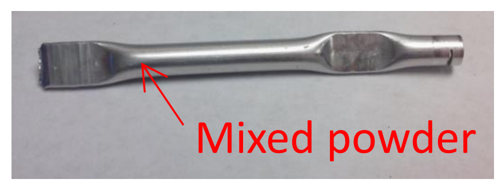
- Experiments to measure thermal and cold neutron production
  - Experiment to measure cold neutron flux using multiple activation foils
  - Experiment to test graphite reflector/moderator effect on thermal neutrons around cold source using gold foils
- Irradiation tests done at TRIUMF winter 2016

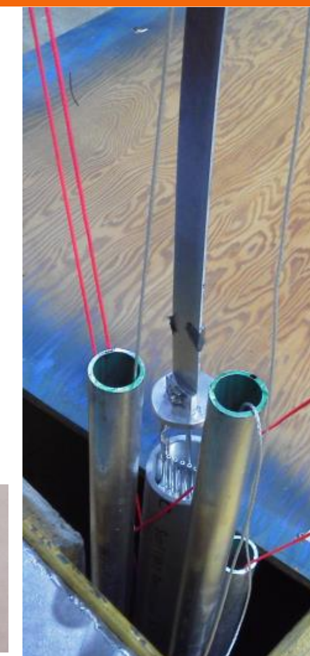
	Ultra Cold	Very Cold	Cold	Thermal	Epithermal	Cadmium	Slow
Neutron Energy	< 300neV	300 – 500neV	500neV – 0.025eV	0.025eV	0.025 – 0.4eV	0.4 – 0.6eV	1 – 10eV

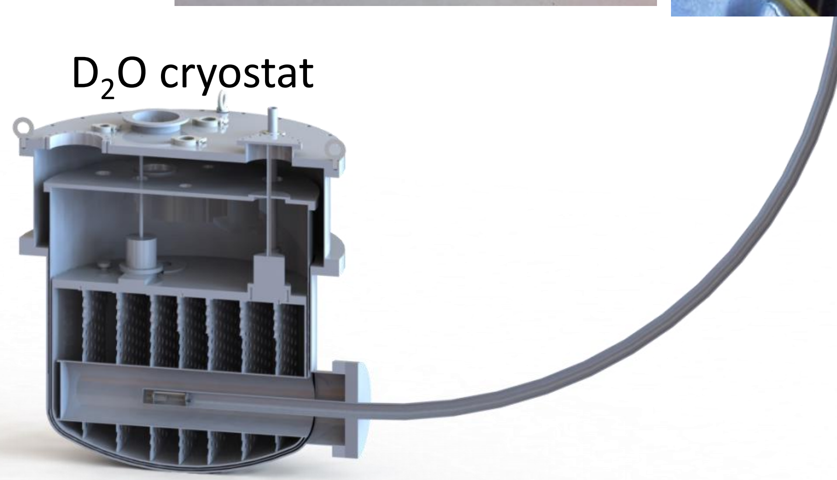
Cold neutron measurement

- Measure cold neutron flux (~1meV) inside cryostat
- 176Lu and 151Eu neutron capture resonance around 1meV
- Other metals for unfolding remaining spectrum





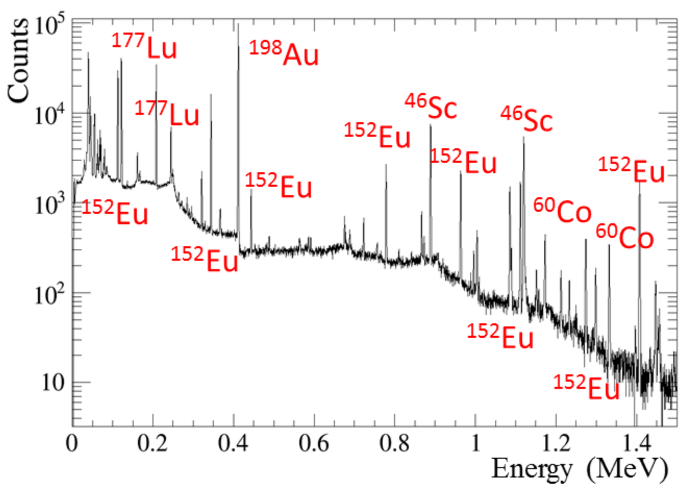




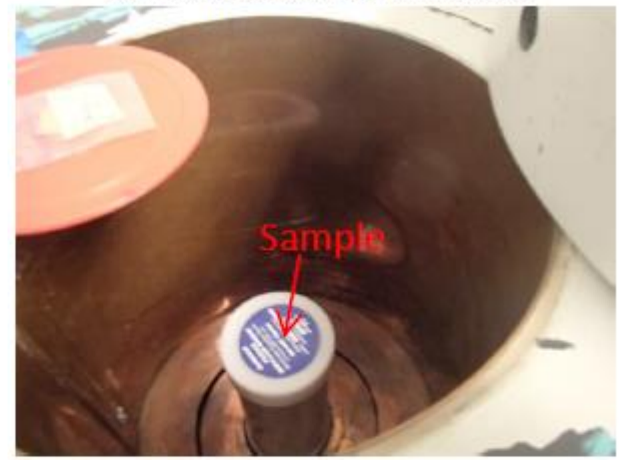
Measuring activation

- Gamma activity measured via HPGe detectors
- Two calibrations available
  - On surface of Ge crystal
  - 0.5 m above Ge crystal
- Systematic differences between calibrations

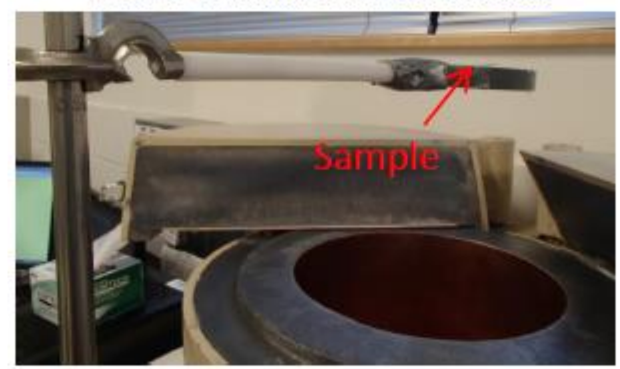
γ-ray spectrum measured by Ge detector



On contact with detector

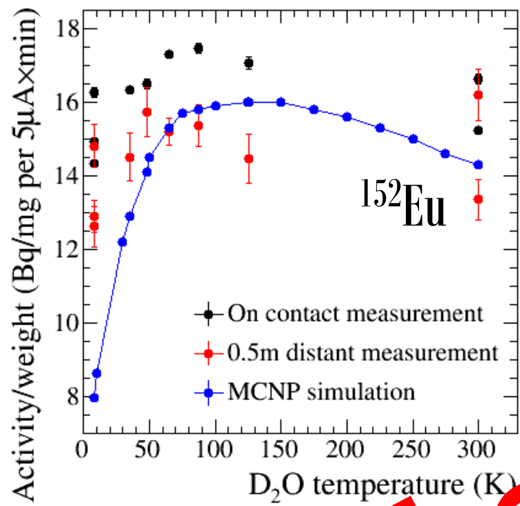


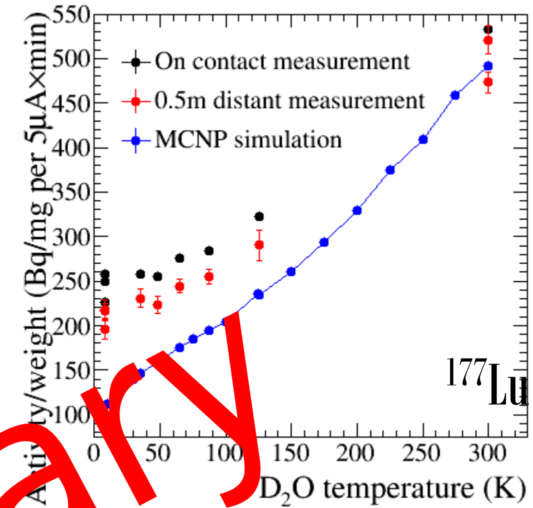
0.5m distant from detector

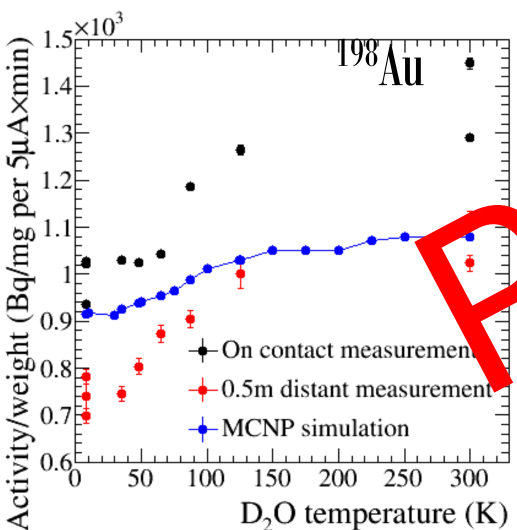


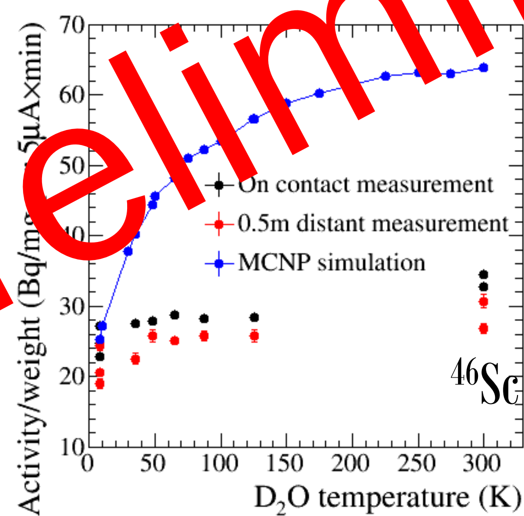
Activation results

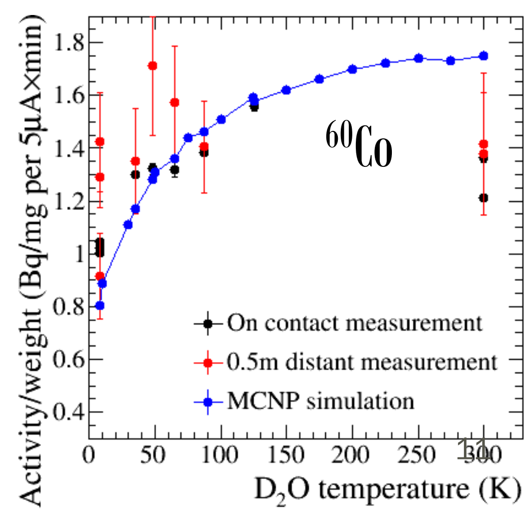
- Activation results for the multiple metals powder
- Foil activation measured with different HPGe calibrations
- Compared to MCNP simulation



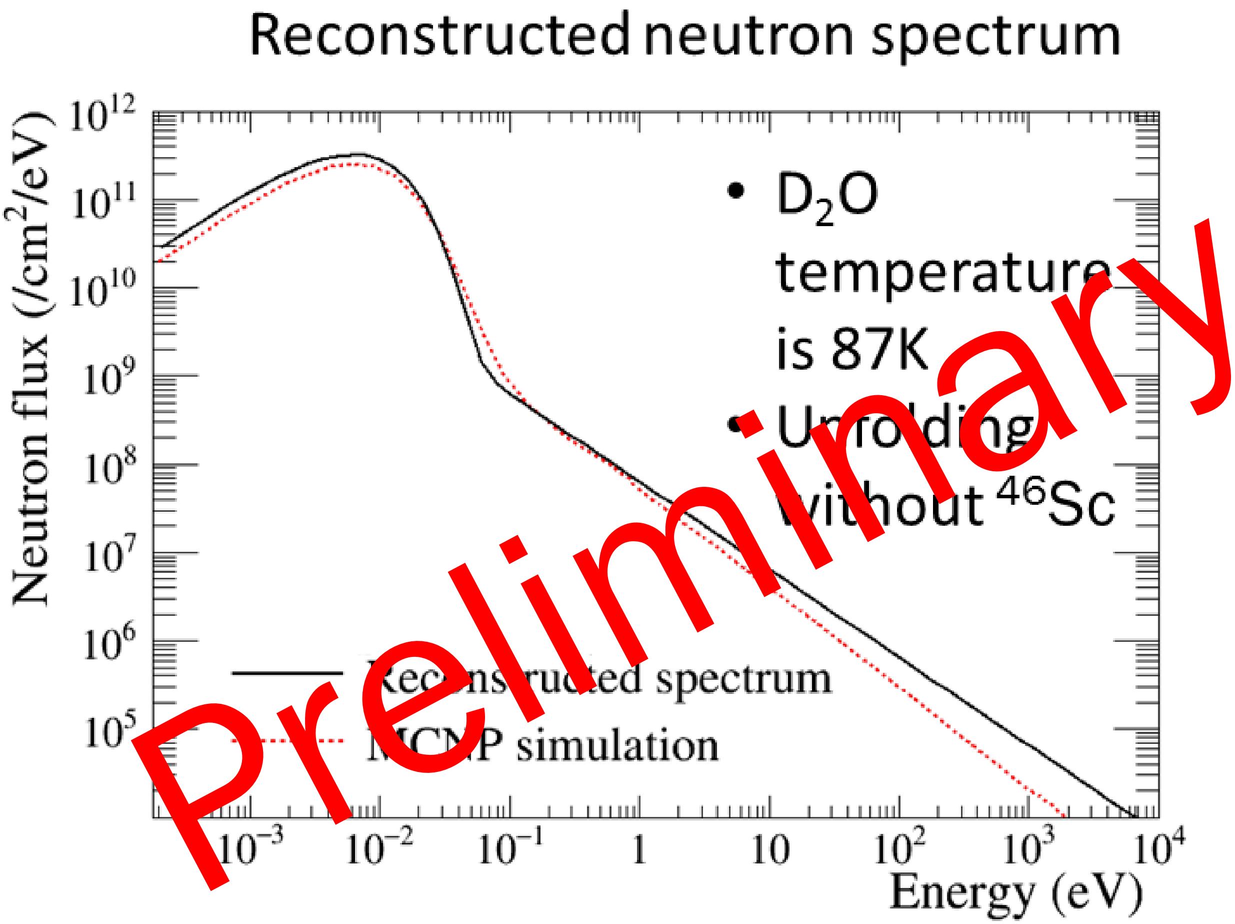




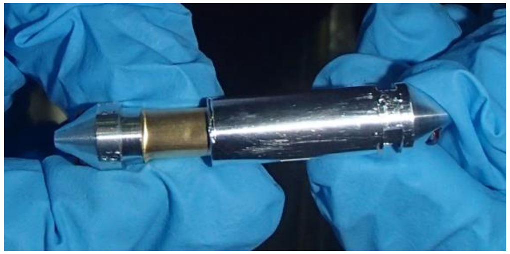


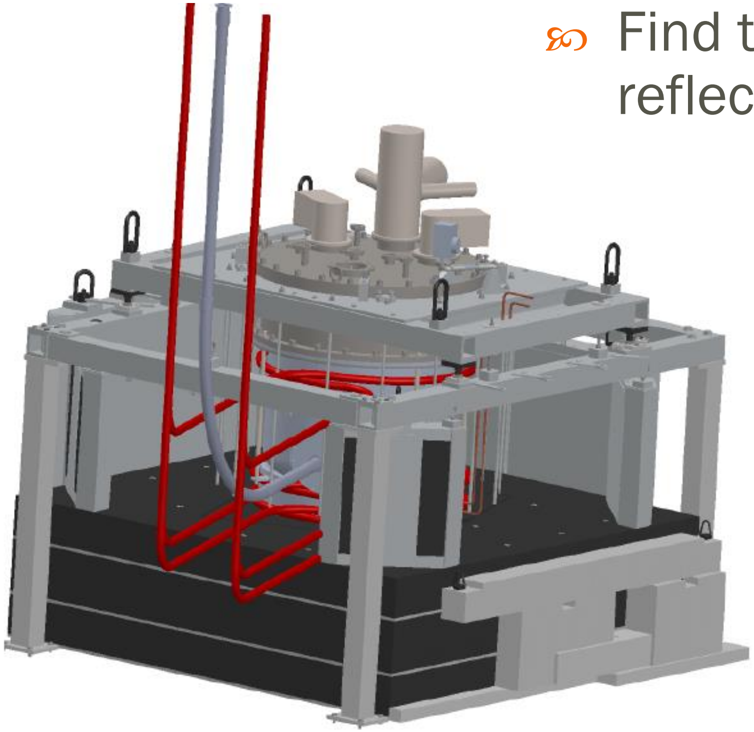


Calculated neutron spectrum in cryostat



Thermal neutron measurement

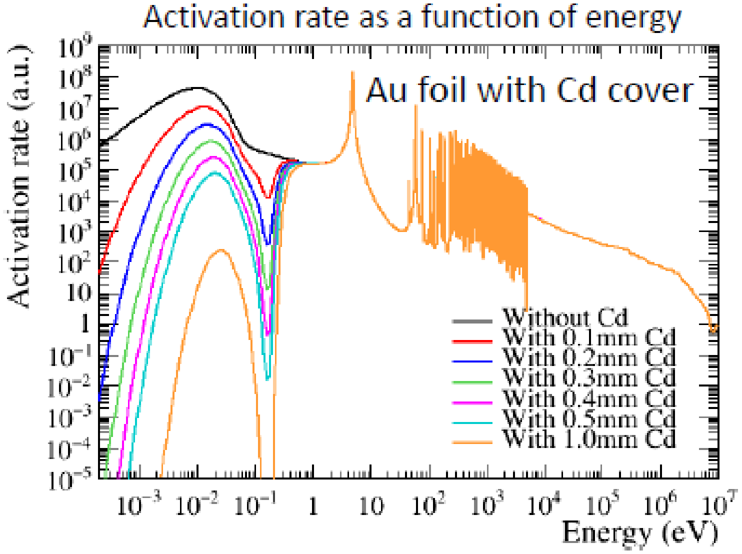




- Measure thermal and colder neutron flux outside cryostat
- Calculate total neutron flux for bare and Cd-covered 197Au

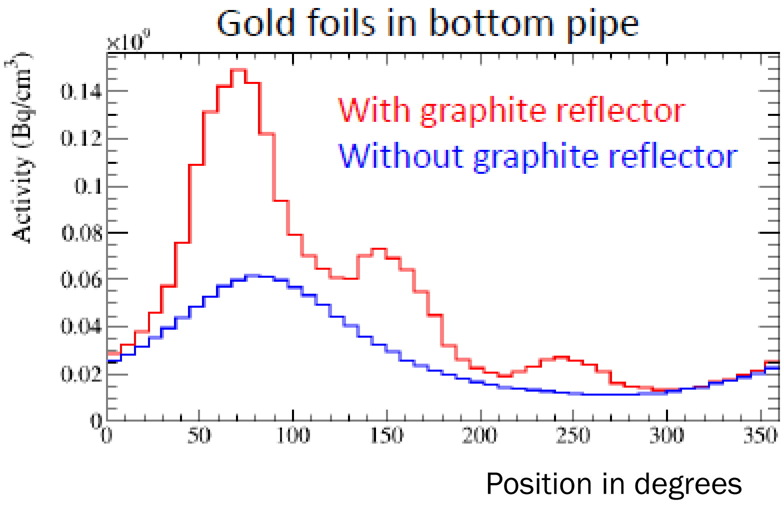
$$\phi_{th} = \phi_b - \phi_c$$

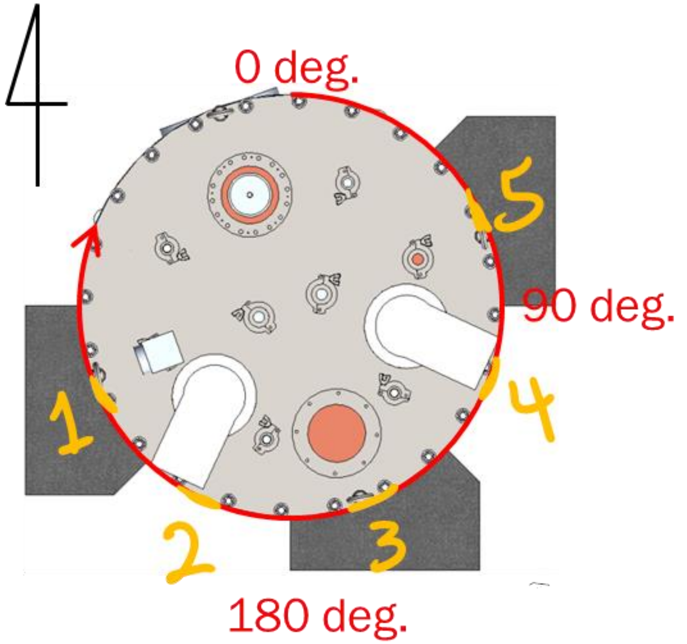
- Find thermalizing effect of graphite reflectors



Au foil placement determination

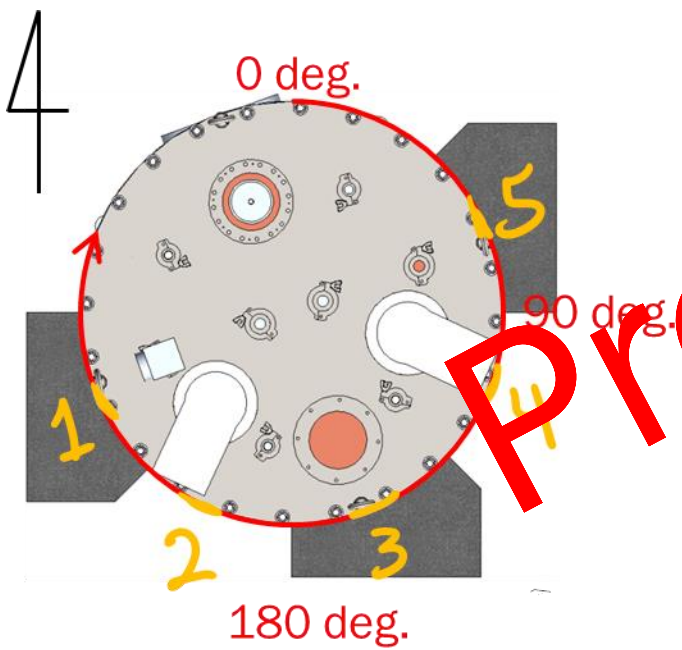
- Placement of foils determined via FLUKA simulations
- Due to presence of graphite columns, activation has peaks between cryostat and graphite
- Foils placed in expected peak and valley positions

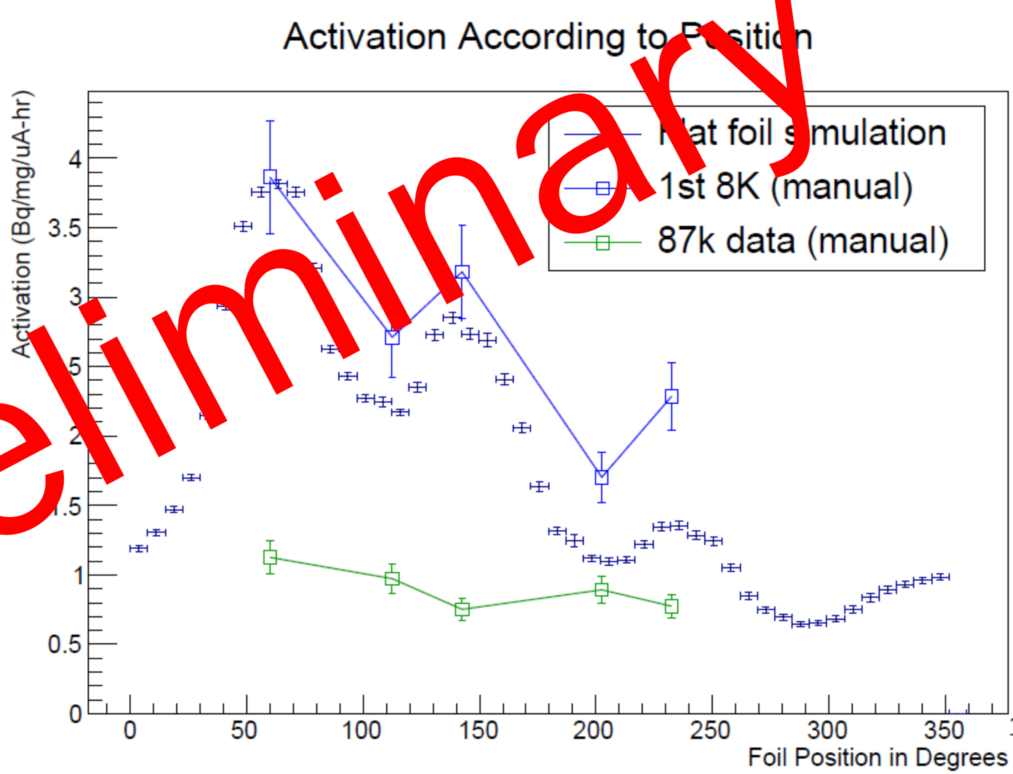




Sample Activation

- Peak valley structure noted
- Systematic errors in different HPGe calibrations (see previous)





To be continued…

- Cold neutron tests: Activation cross section measurement at J-PARC MLF planned for Nov. 2017 to reduce cross section uncertainty for the cold neutron analysis
- Thermal neutron tests
  - Material activations are being analyzed for various temperatures, from 8K to 300K
  - Systematic effects from the HPGe measurements to be finalized.

NSERC, CFI

Thank you

Back up

Optimizing UCN production

Figure from Schmidt-Wellenburg, et al.

- Cold neutrons downscattered to UCN in He-II

$$P(V_f) = \int_0^{\infty} dE \int_0^{V_f} N \frac{d\varphi}{dE} \cdot \frac{d\sigma}{dE'} (E \to E')dE'$$

- Fermi potential of He-II: $V_f = 233 \text{ neV}$
- Focus on 1 meV neutrons

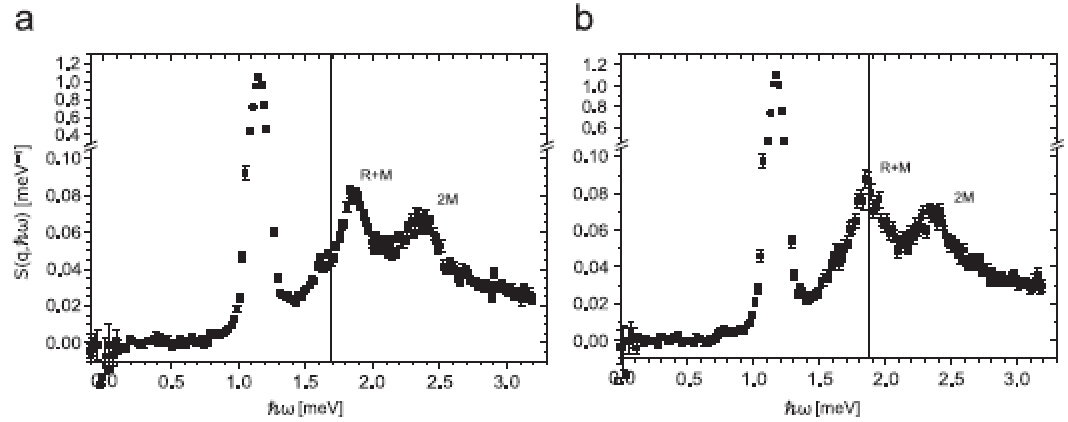


Fig. 2. $S(q, \hbar\omega)$ at SVP for (a) $q = 0.90\,\text{A}^{-1}$ and (b) $q = 0.95\,\text{A}^{-1}$. The vertical lines indicate the energy of an incident neutron with $E = \hbar^2 q^2/2m_n$ that can be down-scattered to the UCN energy range. The width of the single phonon excitation is dominated by the finite resolution of the instrument. The roton–maxon (R+M) and two maxon (2M) resonances at higher energies are significantly lower in intensity.

Au foil activation

- Au has 1/v activation

$$\#UCN \propto \#n_{spallation} \text{ and } \#n_{thermal}$$

$$^{197}Au + n \rightarrow {}^{198}Au \rightarrow {}^{198}Hg + e^- + \gamma$$

- γ energies
  - 411.8 keV – main transition
  - 675.9 keV
  - 1087.7 keV

$$\phi_i = A_i \frac{t}{A\sigma_{abs}N(1 - e^{-t/\tau})}$$

$$\phi_{th} = \phi_b - \phi_c$$