Cold and thermal neutron flux measurements at TRIUMF

May 31\textsuperscript{st}, 2017

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On behalf of Japan-Canada UCN collaboration
Introduction
  - Neutron electric dipole moment
  - Ultra cold neutrons
  - Tests at TRIUMF

Neutron flux experiments
  - Cold neutron measurement
  - Thermal and colder neutron measurement

<table>
<thead>
<tr>
<th>Neutron Energy</th>
<th>Ultra Cold</th>
<th>Very Cold</th>
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<th>Cadmium</th>
<th>Slow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 300neV</td>
<td>300 – 500neV</td>
<td>500neV – 0.025eV</td>
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<td>0.025 – 0.4eV</td>
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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.
Properties
- < 3mK
- ~7m/s
- Subject to gravity
- Polarizable

Find neutron electric dipole moment (nEDM) by finding Larmor frequency

$$d_n = \frac{h}{4E} (f_{n↑↑} - f_{n↑↓})$$

- $|d_n| \sim 3.0 \times 10^{-26}$ 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
Proton beam produces spallation neutrons on tungsten target.

- Neutrons are thermalized by lead, and warm D$_2$O.
- Cold D$_2$O further cools neutrons to cold temperatures.
- Cold neutrons are further cooled to UCN level in the He-II volume and delivered to EDM apparatus.
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Temperature (K)</th>
<th>Date (in 2016)</th>
<th>Irradiation time</th>
<th>Integrated Beam (nA-s)</th>
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</thead>
<tbody>
<tr>
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<td>126</td>
<td>Nov 22\textsuperscript{nd}</td>
<td>8 min</td>
<td>320605</td>
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<tr>
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<td>Nov. 29\textsuperscript{th}</td>
<td>8 min</td>
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<td>Empty</td>
<td>Dec. 21\textsuperscript{st}</td>
<td>1 hr 17 min</td>
<td>349125</td>
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</table>
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

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

![Activation cross section by neutron](image)

![D$_2$O cryostat](image)

![Mixed powder](image)
Gamma activity measured via HPGe detectors

Two calibrations available
  - On surface of Ge crystal
  - 0.5 m above Ge crystal

Systematic differences between calibrations
Activation results for the multiple metals powder

Foil activation measured with different HPGe calibrations

Compared to MCNP simulation

![Graphs showing activation results for different metals like Eu, Au, Co, Sc, and Lu.](image)
Calculated neutron spectrum in cryostat

Reconstructed neutron spectrum

- $D_2O$ temperature is 87K
- Unfolding without $^{46}Sc$

Reconstructed spectrum

NCNP simulation
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
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
Peak valley structure noted

Systematic errors in different HPGe calibrations (see previous)
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.
Thank you
Back up
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: \( V_f = 233 \) neV

Focus on 1 meV neutrons

Figure 2. \( S(q, h\omega) \) at SVP for (a) \( q = 0.90 A^{-1} \) and (b) \( q = 0.95 A^{-1} \). The vertical lines indicate the energy of an incident neutron with \( E = h^2 q^2 / 2m_n \) 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 has 1/ν activation

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

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

\gamma \text{ energies}
- 411.8 keV – main transition
- 675.9 keV
- 1087.7 keV

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

\[ \phi_{th} = \phi_b - \phi_c \]