Ultracold Neutrons at TRIUMF

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The University of Winnipeg

Outline:
- UCN Production and source
- Physics experiments at the UCN source: neutron EDM
- Materials science with UCN? with VCN?
- The future of neutron scattering in Canada?
International Spallation Ultracold Neutron Source

Spokespeople: Y. Masuda (KEK), J.W. Martin (Winnipeg)


(KEK, Titech, Winnipeg, Manitoba, ORNL, TRIUMF, NCSU, Caltech, RCNP, SFU, LANL, Tokyo, UNBC, Osaka, Kentucky)

We propose to construct the world's highest density source of ultracold neutrons and use it to conduct fundamental and applied physics research using neutrons.

Funding secured in Canada (CFI) and Japan
Ultracold Neutrons (UCN)

- UCN are neutrons that are moving so slowly that they are totally reflected from a variety of materials.
- So, they can be confined in material bottles for long periods of time.
- Typical parameters:
  - velocity < 8 m/s = 30 km/h = 20 mph
  - temperature < 4 mK
  - kinetic energy < 300 neV
- Interactions:
  - Gravity: \( V = mgh \) \( mg = 100 \text{ neV/m} \)
  - Magnetic: \( V = -\mu \cdot B \) \( \mu = 60 \text{ neV/T} \)
  - Strong: \( V = V_{\text{eff}} \) \( V_{\text{eff}} < 335 \text{ neV} \)
  - Weak: \( \tau = 885.7 \text{ s} = 15 \text{ mins} \)
How to make UCN

- Liberate neutrons by proton-induced spallation.
- Moderate (thermalize) in cold (20 K) D$_2$O.
- Cold neutrons then “downscatter” to near zero energy (4 mK) in superfluid helium through phonon production.
1 µa protons at 390 MeV
→ 15 UCN/cm³ to experiment.

Now accepting proposals for experiments. e.g. R. Golub, et al.
• Beam parameters for UCN source at TRIUMF:
  – 500 MeV protons at 40 μA
• At RCNP, Osaka:
  – 390 MeV protons at 1 μA
• A fifty-fold increase in beam power.
• Cyclotron operates ~ 8 months/yr.
New UCN Cryostat (Japan) Under Construction
## World's UCN projects

<table>
<thead>
<tr>
<th>Source Type</th>
<th>$E_c$ (neV)</th>
<th>$\rho_{\text{UCN}}$ (cm$^3$/s)</th>
<th>$T_s$ (s)</th>
<th>$\varepsilon_{\text{ext}}$</th>
<th>$\rho_{\text{UCN}}$ (source/exp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIUMF</td>
<td>spallation He-II</td>
<td>210</td>
<td>$0.4 \times 10^4$ (10L)</td>
<td>150</td>
<td>~1</td>
</tr>
<tr>
<td>ILL</td>
<td>n beam He-II</td>
<td>250</td>
<td>10</td>
<td>150</td>
<td>~1</td>
</tr>
<tr>
<td>SNS</td>
<td>n beam He-II</td>
<td>134</td>
<td>0.3 (7L)</td>
<td>500</td>
<td>1</td>
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<tr>
<td>LANL *</td>
<td>spallation SD2</td>
<td>250</td>
<td>$4.4 \times 10^4$ (240cm$^3$)</td>
<td>1.6</td>
<td>$1.3 \times 10^3/4.4 \times 10^4$</td>
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<tr>
<td>PSI</td>
<td>spallation SD2</td>
<td>250</td>
<td>$2.9 \times 10^5$ (27L*)</td>
<td>6</td>
<td>0.1</td>
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<tr>
<td>NCSU</td>
<td>reactor SD2</td>
<td>335</td>
<td>$2.7 \times 10^4$ (1L)</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Munich</td>
<td>reactor SD2</td>
<td>250</td>
<td>**</td>
<td>**</td>
<td>**</td>
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</tbody>
</table>
Location at TRIUMF

- Approx 20 x 20 m² box
- Pi-e-nu completion 2011
Layout, April 2010

- n-EDM experiment
- Cryo plant
- Spallation target + UCN source
- Radiation shielding
- Kicker
- Septum
- Bender
Physics Experiments for the TRIUMF UCN Source

- neutron lifetime
- gravity levels
- \textbf{n-EDM}
- n\bar{n}-oscillations
- Free n target
- Quantum mechanics / computing
- Surface physics / VCN line?

\textbf{Open for ideas / letters / proposals}
Neutron Electric Dipole Moment (n-EDM, $d_n$)

New sources of CP violation are required to explain the baryon asymmetry of the universe.

- Complementary to Rn-EDM TRIUMF ISAC.

Experimental technique:
- put UCN in a bottle with $E$-, $B$-fields
- search for a change in spin precession frequency upon $E$ reversal.

\[ h \nu = 2 \mu_n B \pm 2d_e E \]
EDMs, the SM, and beyond

- Ultimate goal: reach the SM limit

J.M. Pendlebury, E. Hinds

A. Ritz, M. Pospelov, et al

SUSY M = 1 TeV, tanβ = 3

Note: universality assumptions are now even being tested
Past and Future n-EDM efforts

- **Sussex-RAL-ILL expt.** \( (d_n < 3 \times 10^{-26} \text{ e-cm}) \)
  - 0.7 UCN/cc, room temp, in vacuo

- **CryoEDM (Sussex-RAL-ILL)**
  - 1000 UCN/cc, in superfluid \(^4\text{He}\)

- **SNS**
  - 430 UCN/cc, in superfluid \(^4\text{He}\)

- **PSI**
  - 1000 UCN/cc, in vacuo

- **TRIUMF:** 10,000 UCN/cc
n-EDM development in Japan


- Development of:
  - Comagnetometers
  - Ramsey resonance
  - New B-field geometry
Successful demonstration of the basic technique behind precision EDM measurements.

Improvements in field homogeneity, profile, magnitude, shielding for longer $T_2$.

Ramsey Resonance Results


Dec. 2009, achieved:

$T_2 \sim 300$ ms

April 2010, achieved:

$T_2 > 30$ s !!!

becoming competitive with ILL, where $T_2 = 120$ s (typ.)

Nearing state-of-the-art in low-field NMR!

- Successful demonstration of the basic technique behind precision EDM measurements.
- Improvements in field homogeneity, profile, magnitude, shielding for longer $T_2$. 
EDM Statistics

- **ILL:**
  - $\alpha = 0.64$, $\tau = 130$ s, $E = 10$ kV, $N = 14000$ UCN/cycle
  - 1 UCN/cc: $\sigma(d_n) = 1.7 \times 10^{-25}$ e-cm/day
  - Final stat. error: $\sigma(d_n) = 1.5 \times 10^{-26}$ e-cm

- **TRIUMF with increased UCN density:**
  - $10^4$ UCN/cc: $\sigma(d_n) = 1.7 \times 10^{-27}$ e-cm/day

- **e.g. SNS projected:**
  - $\sigma(d_n) \sim 3 \times 10^{-27}$ e-cm/day (B. Filippone, FNAL seminar 06)

\[
\sigma(d_n) = \frac{\hbar}{2\alpha ET \sqrt{N}}
\]
n-EDM Systematics

- magnetic field variations
- leakage currents
- geometric phase effect
  - false EDM arising from field inhomogeneity and E x v.

(co)magnetometry

Comagnetometry

False EDM (GP) effect

Magnetic field down
n-EDM at TRIUMF

- Complete experiments in Japan, 2009-2012.
- Develop LOI/proposal for TRIUMF ~ 2010-11.
- Unique aspects of the EDM work in Japan:
  - New UCN production mechanism aiming for highest density
  - Higher UCN density allows smaller cell size
  - New DC coil geometry
  - Xe comagnetometer

We gratefully welcome new collaborators to this exciting experiment!!!
UCN and you!
research opportunities

- Development state-of-the-art technology in low-field NMR, related to medical MRI's. Precision (co)magnetometry, shielding.
- Quantum mechanics and quantum computing studies using UCN spins.
- Development of UCN detectors.
- Electronics, DAQ (MIDAS), data collection, analysis, and simulation.
- Development of future UCN experiments - lifetime, gravity, quantum computing, surface physics, others.
Timeline

- **June 2009:** Source funded in Canada and Japan
  - JSPS, CFI, TRIUMF, Acsion Ind., Govt of MB, UWpg.
- **2009-12:**
  - develop UCN source in Japan, EDM experiment
  - preparations and design at TRIUMF
  - develop collaborations and proposals for experiments
- **2012-14:** Install, commission at TRIUMF
- **2014-15:** First experiments
Surface Chemistry and Physics

• Use UCN to study 10 nm thin surface films
  – UCN microscope
  – inelastic scattering reflectometry (UCN ISR)
    • UCN upscattering off a big molecule
UCN ISR apparatus for TRIUMF

- Design of cryostat and first proof-of-principle experiments have been carried out. (Hahn-Meitner Inst., ILL)
- Need higher UCN flux.
- R. Golub, E. Korobkina, L. Clarke (NCSU)

Needs clever physics and chemistry ideas!
UCN potential as new probe of surfaces.
VCN line is possible ...
The future of neutrons in Canada?

- New nuclear reactor for neutron scattering.
- A new UCN source should be proposed, too!
  - could be based on TRIUMF UCN source

People are already thinking about a “Super-UCN Source” at a facility like this.

e.g. Serebrov, et al,
At the WWR-M reactor, Gatchina, Russia

e.g. similar concept explored for the FRM-II reactor in Munich, Germany
Thank you!
Kicker Concept

- Downstream users affected only at 7% level.
- UCN data when cyclotron is on (8 months/yr.)
### Summary of CFI request

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
<th>Funding Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCN cryostat system</td>
<td>$4M</td>
<td>Japanese collaborators</td>
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<tr>
<td>Beamline</td>
<td>$2M</td>
<td>TRIUMF 5YP request</td>
</tr>
<tr>
<td>Kickers, shielding, spallation target</td>
<td>$4.225M</td>
<td>CFI NIF</td>
</tr>
<tr>
<td>Moderator design</td>
<td>$0.675M</td>
<td>Manitoba + Acsion Industries</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$10.9M</strong></td>
<td>+$0.25 M UWpg</td>
</tr>
</tbody>
</table>

- UCN cryostat system includes:
  - Existing UCN source ($2M)
  - Modifications to source for TRIUMF ($2M)
    - Horizontal extraction, improved guide technology, etc.

- Canadian money for physics experiments:
  - separate budget from NSERC.

TRIUMF support for University Initiatives