The UCN source and EDM experiment at TRIUMF

Overview and Status

R. Picker

for the TRIUMF nEDM collaboration
• TRIUMF UCN source design
• Status
• EDM strategy and R&D
TRIUMF on UBC campus
The UCN source at TRIUMF

the cyclotron during construction
Recipe:
1. 500 meV protons on tungsten create spallation neutrons
2. lead, graphite, heavy water, deuterium moderate fast neutrons to cold neutrons
3. $^4$He at 0.7 K converts them to UCN
4. Extraction to experiments via material guides
The UCN source at TRIUMF

Beam sharing in the meson hall at TRIUMF

Micro structure of the proton beam

planned UCN facility in the Meson hall at TRIUMF
**Kicker magnet:**
- deflects every third proton bunch upwards
- ordered from Danfysik 2013
- installation 2016

**Bending dipole**
- provided by KEK
- deflects beam by 7° more
- Installed

**Lambertson septum:**
- beam separation in center 70 mm
- deflects upper beam by 9° to the left into BL1U
- Installed

**upstream section of BL1U**
BL1U downstream

SC polarizer

He-II cryostat
- 0.8 K
- pumping on $^3$He

Cold moderator cryostat
- Warm D$_2$O and sD$_2$O or ID$_2$

$^3$He-4He heat exchanger

EDM experiment

Spallation target
- beam power: 20 kW (during 1 min beam on target) and 5 kW (average)
- tungsten (Ta cladded)
- water cooled
- cladded target blocks have been fabricated in Japan

Bending dipole

nEDM

temp profiles
Layout of the UCN area

- Proton Irradiation Facility
- Beamline components
- EDM cell, magnetic shielding
- Laser lab For EDM
- Laser lab 4.5 m x 5 m
- 2nd port 3 m x 3 m
- EDM space 6 m x 9 m
- Laser lab for EDM
- Second experiment port
- M11: e, μ, π up to 400 MeV/c
- UCN source cryostat
- Spallation target and moderators
- UCN source
- EDM Layout of the UCN area
Where do we stand?

2014, TRIUMF:
- septum
- dipole
- replacement of shielding towards cyclotron

2013,14 RCNP, Osaka:
- successful cooldown of new cryostat to 0.7 K
- first UCN beam time
- UCN production and extraction demonstrated despite large $^3$He fraction

Source commissioning

proposed UCN facility in the Meson hall at TRIUMF
Beamline 1U work in the Meson hall
Closed-up & ready for beam on time
Primary goals for installation all met
“Best Efforts” goals mostly met
What is next?

2014:
• septum
• dipole
• replacement of shielding towards cyclotron

2015:
• Installation of kicker quartz beam tube
• quads and downstream beam diagnostics
• bottom layer of source shielding
• decommissioning of existing beamline M13

November 3, 2014
2015: Removal of M13 pion beam line

Before

Dipole 1 (hot!) is reused in UCN shielding (solves storage problem)

After

Move dipole 2 here as shielding block (coils removed)

cyclotron

pion production target

pion production target

beam line BL1A

beam line BL1U

M13B1

M13B2
What is next?

2014:
- septum
- dipole
- replacement of shielding towards cyclotron

2015:
- decommissioning of existing beamline M13
- quads
- source shielding

2015/16:
- kicker
- target
- moderators
- He-II cryostat
- UCN guides
- UCN polarizer
- finish shielding

2015 Non-Shutdown & 2016 Shutdown

2016 Shutdown
a lot of steel and concrete...
Optimization of moderators for TRIUMF phase

(Acsion, Uwpg, TRIUMF)

- after Fukushima: rules in Japan have changed
  ⇒ activated cold moderator cryostat cannot be shipped to Canada
- existing design for a few $\mu$A at RCNP has a few problems for 40 $\mu$A at TRIUMF
  ⇒ Wigner energy from graphite
  ⇒ high dose rate for maintenance

- using liquid D$_2$ instead of solid D$_2$O increases UCN yield significantly
  ⇒ optimization using MC tools: proton beam on target, spallation, secondary products, gamma heating

Moderator layout at RCNP

November 3, 2014
Moderator optimization

- MCNPX and MicroShield® are been used (Acsion Industries)
- Figure of merit: UCN production taking heating into account ($T^7$)

**Figure of merit:** UCN production taking heating into account ($T^7$)

- **features**
  - all relevant distances, positions optimized
    - e.g. target vertical distance decrease increases UCN yield, but also He-II heating 5 times as much
  - UCN bulb: Al $\rightarrow$ Be: $-2.4$ W
  - sD$_2$O $\rightarrow$ lD$_2$: 6 x UCN prod
  - production rate $> 10^7$ UCN/s

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proposed moderator layout at TRIUMF (preliminary) – side view
Principles:

- high UCN density
  - fingers crossed…

- room-temperature experiment enabling rapid optimization
  - Ramsey technique
  - EDM cell size flexible until UCN density is known

- improved magnetic environment
  - big ticket item…

- dual-species xenon-129/mercury-199 comagnetometer
  - cancels magnetic field inhomogeneities to first (second) order

- ongoing extensive R&D program
  - Magnetics
  - UCN detector
  - Comagnetometer
  - HV/EDM cell
  - Simulations
Dominant systematic uncertainties are related to magnetics

Best nEDM limit so far (ILL/RAL/SUSSEX): $2.9 \cdot 10^{-26} \text{ e-cm}$

<table>
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<tr>
<th>Effect</th>
<th>Shift</th>
<th>$\sigma$</th>
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<tr>
<td>Door cavity dipole</td>
<td>−5.6</td>
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<tr>
<td>Other dipole fields</td>
<td>0.0</td>
<td>6.0</td>
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<tr>
<td>Quadrupole difference</td>
<td>−1.3</td>
<td>2.0</td>
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<tr>
<td>$v \times E$ translational</td>
<td>0.0</td>
<td>0.03</td>
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<tr>
<td>$v \times E$ rotational</td>
<td>0.0</td>
<td>1.0</td>
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<tr>
<td>Second-order $v \times E$</td>
<td>0.0</td>
<td>0.02</td>
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<tr>
<td>$\nu_{\text{Hg}}$ light shift (geo phase)</td>
<td>3.5</td>
<td>0.8</td>
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<td>$\nu_{\text{Hg}}$ light shift (direct)</td>
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<td>Uncompensated $B$ drift</td>
<td>0.0</td>
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<td>Hg atom EDM</td>
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<tr>
<td>Electric forces</td>
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<td>0.4</td>
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<tr>
<td>Leakage currents</td>
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<tr>
<td>ac fields</td>
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<td>0.01</td>
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<tr>
<td>Total</td>
<td>−3.8</td>
<td>7.2</td>
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PRL 97, 131801 (2006)

Requirements for $10^{-27} \text{ ecm}$

- $B_0$ ca 1 $\mu$T
- Homogeneity < nT/m
  \[ < 100 \text{ pT across the cell} \]
- Stability controlled to < pT

active compensation coils

magnetometers
Magnetic environment R&D

- **Active magnetic shielding**
- **Passive magnetic shielding**
  - magnetically shielded room
  - 3-4 layer shield inside
- **Magnetic field generation**
  - B0, B1, shim coils

### Magnetometers
- Xe/Hg co-magnetometer
- Flux gates
- Giant magnetoresistance sensors
- Squids
- Optical (NMOR)

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Active shielding coils

Winnipeg Passive Shield prototype

B0 coil simulation

NMOR
### 129Xe/199Hg comagnetometer

<table>
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<tr>
<th></th>
<th>199Hg</th>
<th>129Xe</th>
<th>n</th>
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<tr>
<td>Spin</td>
<td>½</td>
<td>½</td>
<td>½</td>
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<tr>
<td>$\gamma$(MHz/T)</td>
<td>7.65</td>
<td>-11.77</td>
<td>-29.16</td>
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<tr>
<td>UCN capture $\sigma$ (barns)</td>
<td>2150</td>
<td>21.0</td>
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<tr>
<td>transition (nm)</td>
<td>253.7 nm</td>
<td>252.4 nm</td>
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<tr>
<td>transition process</td>
<td>one-photon</td>
<td>two-photon</td>
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**Benefits of dual co-magnetometer**

1. Handle on magnetic gradient!
2. The laser requirements for Hg and Xe are very similar. Development of the required lasers can proceed along the same path.
3. The Xe atomic EDM may also be measured with Hg co-magnetometer in the same setup.
- conventional $^3$He detectors too slow
- principle $n + ^6\text{Li} \rightarrow ^3\text{H} (2.74 \text{ MeV}) + ^4\text{He} (2.05 \text{ MeV})$
- high rate capability
- Li glass scintillators + lightguide + PMTs
- first assembly of full detector done, first tests ongoing

$\rightarrow \text{Blair Jamieson, Tuesday 16:20}$
• dielectric strength of Xe at $10^{-3}$ mbar unknown
• HV test setup at TRIUMF
• 50x100 mm cylindrical test cell
• test of gases, different cell materials, geometries
• field strength goal > 10 kV/cm
MC Simulation: understanding and optimizing source and experiment

- Goal: full EDM cycle simulation

- Recreating UCN lifetime including He effects
  - Helium $V_F(i) = 2 \times 10^{-17}$ eV
  - Lifetime = 18.8 s
  - RCNP Lifetime = ~19 s

- Detailed modelling of RCNP source run Nov 2013 to understand results
- Geometry is meshed and used in PENTrack
- E. Barre, R. Picker, P. Yapa, E. Lloyd
Concentrating on development of necessary techniques
Keep layout as flexible as possible
Funding application for full experiment submitted June 2014, decision spring 2015
First Ramsey cycles at TRIUMF 2017-18

One possible design:
Second experiment port

Short term:
- detector and guide development

Long term:
- real user facility
- evaluation through TRIUMF SAP-EEC
- everybody’s welcome

Laser lab for EDM

Spallation target and moderators

Second experiment port
• first UCN hardware installations at TRIUMF on time/budget/schedule
• next installation steps well underway
• large EDM funding request submitted
• EDM R&D very lively in Canada
• first UCN at TRIUMF 2016
• EDM result $< 10^{-27}$ ecm before the end of the decade

Towards our physics goals, one brick at a time...
Optimization details

TAROFF - default 10 - Offset of target center in x direction (along axis of beam)
TARYOF - Default 20 - Offset of Target along y axis (positive or negative)
ANGBG Default 117 - Angle (degrees) between beam and guide outlet - keep fixed due to layout geometry
TARTAN - Default 10 - Distance along z from target center to D2O tank bottom
RADTNK - Default 50 - keep fixed - One Half the Length of Rectangular tank including walls
D2TH300 - Default 10.5 - Distance from 300K D2O tank bottom to LD2 tank bottom
D2HETP - Default 30 - keep fixed - Distance from He-II center to top of 300K Tank
WSD2O - Default 97.9 - Inside Width of D2O Region in Rectangular 300K tank
RADED2 - Default 15 - keep fixed - Radial depth of LD2 layer outside of He-II bulb

Optimization parameters \( I_x \)
- relative and not absolute values
- rational:
  - highest UCN output is proportional to the UCN density, rather than UCN production rate
  - He-II heating increases \( \Rightarrow \) UCN losses also increase.
  - UCN optimization parameter intended to be proportional to the UCN density in the He-II bulb
  - The constant of proportionality, to convert the optimization parameter to UCN/cc in the He-II bulb is unknown and is different for each optimization parameter.

Poor cooling performance - \( I_1 : n_{UCN} \propto \frac{P_{UCN}}{Q_{He}} \)
Average cooling performance - \( I_2 : n_{UCN} \propto \frac{P_{UCN}}{Q_{He}^{2/3}} \)
Good cooling performance - \( I_3 : n_{UCN} \propto \frac{P_{UCN}}{Q_{He}^{1/2}} \)
The main changes are:
- Replace all graphite near the beam with lead, which multiplies and reflects fast neutrons.
- The lead also shields personnel from activated steel below the target during service access from above.
- Replace all Al vessels with Be or Mg, which have smaller neutron absorption cross sections (0.008 or 0.063 vs. 0.23 b).
- Replace D$_2$O ice with liquid LD$_2$ (similar D density), which has a much higher molecular density of states in 1-25 meV.

Results before optimization of the cold moderator geometry

- Al→Be, C→Pb: UCN production increased by a factor of 2.5
- 20°K D$_2$O → LD$_2$: UCN production increased by a factor of 6
- 20°K heating reduced by a factor of 2
- He-II wall heating reduced by a factor of 3; Al→Be bottle: -2.4 W
- Service dose above cryostats reduced by a factor of 10
• new paragraph detailing sensitivity
  • production rate $7 \times 10^7$ UCN/s
  • 35 s storage time in source
  • transport efficiency 3.3%
  • 400 UCN/cm$^3$ in one cylindrical cell (d=36 cm, h=15 cm)
  • $T_1 = 2000$ s, $T_2 = 1000$ s, $T_{\text{prec}} = 150$ s
  • $E = 12$ kV/cm
  • sensitivity per cycle $1.17 \times 10^{-25}$ ecm
Which height of EDM cell is best at what storage time?

\[ \sigma_{d_n} = \frac{\hbar}{2\alpha E T \sqrt{N}} \rightarrow \text{figure of merit} \]

\[ \sqrt{N(T,h)} \cdot T = \sum_{\text{bin}=0}^{n} N_{0,\text{bin}}(h) \exp \left( -\frac{T}{\tau_{s,\text{bin}}} \right) \cdot T \]

Plans to simulate:
⇒ depolarization
⇒ spin evolution
⇒ various GPEs

2006: UCN project was first introduced into the 5Y planning
2007: International Workshop UCN sources and Experiments at TRIUMF
2008: Positive review by TRIUMF’s Experiments Evaluation Committee (EEC)
2010: International Review endorses UCN program strongly
2011: MoU between Uwpg, KEK, RCNP and TRIUMF was signed…
   ➢ to build a He-II spallation source at KEK/RCNP and move it to TRIUMF
   ➢ to develop and conduct a neutron EDM experiment
   ➢ to build a dedicated beam line and target at TRIUMF
2011-2013: development of beam line in Meson hall
   ➢ Kicker, septum, bender, focusing elements, diagnostics, target
   ➢ Shielding upgrade
   ➢ clean-up of Meson hall has started
2013: TRIUMF hires are research scientist for UCN (that would be me…)
2014: first substantial installations during the 2014 shutdown