Ultracold Neutrons and Neutron EDM

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Ultracold Neutrons (UCN)

• Neutrons that are moving so slowly that they bounce off surfaces and can be bottled.
  – $v < 8 \text{ m/s} = 30 \text{ km/h}$
  – $T < 4 \text{ mK}$
  – K.E. < 300 neV

• Interactions:
  – Gravity: $V = mgh$ \quad mg = 100 \text{ neV/m}$
  – Magnetic: $V = -\mu B$ \quad $\mu = 60 \text{ neV/T}$
  – Strong: $V = V_{\text{eff}}$ \quad $V_{\text{eff}} < 335 \text{ neV}$
  – Weak: $\tau = 886 \text{ s} = 15 \text{ mins.}$
What are the best experiments for UCN?

• Those best using their long storage/spin coherence time:
  – Neutron EDM (strong CP problem, SUSY CP problem, electroweak baryogenesis)
  – Neutron lifetime (BBN, $V_{ud}$/CKM unitarity)
  – Angular correlations, precision spectroscopy in beta decay ($V_{ud}$/CKM, scalar/tensor currents)
  – $n$-$\bar{n}$ oscillations? Quantum computing/error studies?

• Those best using their low energy
  – Neutron gravity levels above a mirror (gravity at μm scales, chameleon fields, fifth force, …)
  – Surface science of big organic molecules?

• Generally accepted that nEDM is top science priority for this field, given present UCN fluxes; it is our flagship experiment.

• Breakthrough in UCN production would improve precision of experiments, and open up new possibilities (free n target?)
Spallation-driven Superfluid He-II UCN Source

**UCN production recipe:**
- **Spallation** – Liberate neutrons from W target
- **Moderation** – Thermalize, cool neutrons in D$_2$O ice
- **Conversion** – Convert cold neutrons to UCN in He-II

General Layout of UCN Source at RCNP Osaka

- **Thermal, Cold & Ultra-Cold neutrons**
- **MeV neutrons**

Moderators
- Thermal: Graphite, 300K D$_2$O
- Cold: 10K D$_2$O ice

400 MeV protons
Source developed and tested in Japan, shipping to TRIUMF in Oct. 2015

Beamline prepared at TRIUMF, for extended running periods at ~40x higher intensity
Connection to Phase I nEDM experiment

2012-2014: Develop/Test Source (& nEDM) at RCNP [1+ μA]
2015: Source moves to TRIUMF
2016: Commission Source at TRIUMF [ramp to 40μA]
Sakharov’s Criteria and EW Baryogenesis Solutions

Criteria

• Departure from thermal equilibrium
• B-violation
• CP-violation

EW Baryogenesis

EW Baryogenesis Problems:

• EW phase transition not strong enough
• Not enough CP violation


Requires new physics and CP-violation near the EW scale
Sensitivity to new sources of CP violation

Induces: $d_q \sim \frac{\alpha}{\pi} \times \frac{m_q}{\Lambda^2_{SUSY}} \times \sin\theta_{CP}$

e.g. SUSY CP problem and relationship to LHC

M. Pospelov and A. Ritz,
A. Ritz, TRIUMF Summer Institute, 2012.
Sensitivity to SM sources of CP violation

• Strong sector may violate CP via $\theta$ term.
• Naively $\theta \sim 1$.
• Experimentally $\theta < 10^{-11}$, constrained mainly by nEDM.

Strong CP problem
Solution: Peccei-Quinn symmetry, axions(?)

• CKM CP violation is $10^{-31}$ e-cm background
Electric dipole moments and CP violation

\[ H = -\mu \cdot \vec{B} - d \cdot \vec{E} \]

• The EDM (\(d\)) term violates CP.
• New sources of CP violation required in e.g. electroweak baryogenesis.

\[ hv = 2\mu B \pm 2dE \]

• Precision goal \(\delta d_{\text{stat}} = 1.4 \times 10^{-25}\) e-cm/cycle, \(10^{-27}\) e-cm ultimately.
TRIUMF Neutron EDM Experiment

• Overview/Goals:
  – Our approach: Spallation-driven superfluid-helium UCN source connected to room-temperature nEDM experiment.
  – Present world’s best limit (Sussex/RAL/ILL)
    \[ d_n < 3 \times 10^{-26} \text{ e-cm} \]
  – SM (CKM) lower bound
    \[ d_n > \sim 10^{-31} \text{ e-cm} \]
  – Our goal sensitivity:
    \[ \delta d_n \sim 10^{-27} \text{ e-cm ("phase 2") } \]
    \[ \delta d_n \sim 10^{-28} \text{ e-cm (possible with source upgrades)} \]

• Features of nEDM expt.:
  – New UCN source with potential world-leading density
  – Room temperature with flexibility e.g. to modify cell size in light of systematics vs. stats.
  – New dual \(^{129}\text{Xe}\) 2-photon + \(^{199}\text{Hg}\) comagnetometers
  – Improved magnetic field control, diagnostics.

\[ \pm E \rightarrow B \]
\[ \nu \rightarrow J \]
\[ h\nu = 2\mu_n B \pm 2d_n E \]
Recent UCN highlights

2014, TRIUMF (completed):
• 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

Source commissioned (in Japan)
Plan for TRIUMF Installation periods: ~Jan-Apr each year

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

2014 Shutdown

2015 Shutdown

2016 Shutdown
Present Status of UCN Facility

UCN Source (2013-14, RCNP)
- successful cool down of new cryostat to 0.7 K \(\rightarrow\) 0.58 K
- ext. heat load from 1 \(\rightarrow\) 0.2 W
- first UCN beam time
- UCN prod.\(^n\) in \(^4\)He (natural) and extraction demonstrated (despite large \(^3\)He fraction)

2014
- Septum
- Dipole & Girder
- Shielding Plug

2015
- Vault Components
- M13 Decommission
- Quads & D/S section
- Shield Pyramid Base

Kicker in 2016

Vault section

D/S section

Pyramid base

Target in 2016

U/S section

BL1U

BL1A
2015 Highlights and 2016 plans

1. Design/safety review June 2015
2. Target design review July 2015
3. UCN source shipment Oct. 2015
4. More reviews
nEDM experiment first priority (after UCN source commissioning)

### UCN
- **@RCNP**
  - UCN development
- **@TRIUMF**
  - Beamline, target, shielding installation

### EDM
- **@RCNP**
  - EDM development
- **@TRIUMF**
  - EDM R&D for Phase 2
  - EDM Phase 1

#### Timeline
- **2015**
  - 1st Quarter: UCN development
  - 2nd Quarter: Beamline, target, shielding installation
- **2016**
  - 1st Quarter: Source install
  - 2nd Quarter: Source commission
  - 3rd Quarter: LD₂ upgrade, Be bottle
- **2017**
  - 1st Quarter: Commission B/L & CN Spring ‘16
- **2018**
  - 1st Quarter: EDM Phase 2
nEDM Phase 1

- use **existing** EDM Ramsey **apparatus** from RCNP, Osaka
- exploit **higher UCN density** at TRIUMF (also more beamtime available)
- room temperature, **1 small cell**, vertical loading, spherical $B_0$ coil
- small incremental improvements until replaced by Phase 2
  - Active magnetic compensation system
  - high voltage
  - comagnetometer
  - high-flux detector
Phase 2: Cold Moderator Upgrade to LD$_2$

MCNPX Studies:
UCN yield increased by 5-7 when D$_2$O ice replaced by LD$_2$ and heat load on He-II cut in half!

LD$_2$ Cryostat System
- Aluminum Cryostat
- 125 Liquid Litres of D$_2$
- 90 W Heat Load
- Circulate LD$_2$ to remote condenser + cryo-cooler
nEDM Phase 2 – circa 2019?

- Room temperature
- Improvements
  - Higher UCN density with LD$_2$ moderator
  - 2 cells, probably “horizontal” loading
  - Dual Xe/Hg comagnetometer
  - Improved magnetic environment
  - Simultaneous counting of both polarizations
- Sensitivity goal: $d_n < 10^{-27} \text{ e} \cdot \text{cm}$

- Ongoing extensive R&D program
  - Magnetic fields
  - UCN detector
  - Comagnetometer
  - HV/EDM cell
  - Simulations

Possible topology

- Magnetically shielded room
- Inner passive shielding
- EDM cell(s)
- HV feed
- UCN switch
- SC polarizer
- He-II volume
- Spallation target
- Moderator cryostat
- Protons
- 2.5 m
- 4 UCN detectors
- Spin flipper/Analyzer
Canadian EDM R&D

Magnetic environment
- active shielding
- passive shielding
- creation of stable, homogeneous B fields
- Precision atomic magnetometry and SQUIDs

UCN detection
- Need faster detectors
- Li glass scintillators + lightguide + PMTs
- Test run in August 2015 at PSI
- R&D towards dual detectors which count both spin states simultaneously.

\[ n^+\text{Li} \rightarrow ^3\text{H} \ (2.74 \text{ MeV}) + ^4\text{He} \ (2.05 \text{ MeV}) \]

Dual Co-magnetometer
- Hg, Xe polarisation
- laser development
- 2-photon transition requires development of intense CW UV lasers.
- Xe EDM measurement

Electric field, UCN cell
- dielectric strength of Xe at \(10^{-3}\) mbar unknown
- 50x100 mm cylindrical test cell
- gas breakdown studies
- material studies
Long-Range Plan

• **2017-2021**: improvements to UCN source and nEDM experiment
  – 2017-2018 CFI proposal for major upgrade to UCN source and nEDM experiment ($12M) leveraged by Japan support and TRIUMF 5YP support ($1.6M)
  – NSERC support ~$800k/yr (presently ~$500k/yr)

• **2022-2026**: development of facility and other UCN experiments
  – Neutron lifetime in a magnetic trap
  – Neutron gravity levels
  – Cost scale ~$5M/expt. Expect new international users and support for these experiments.
Summary

• UCN source testing (RCNP) and installation of beamline components (TRIUMF) proceeding on schedule.

• R&D progress for the neutron EDM experiment.

• Phase I nEDM operating by 2016-17

• Phase II application aiming at sub-$10^{-27}$ e-cm precision planned for 2017-18.
More info and backups
Recent achievements

• Recent publications on magnetic field R&D and UCN detector (see our draft brief)
• Recent MSc theses (several MSc and PhD in progress) (see draft brief)
• Conference proceedings/presentations (most recent one is Larry Lee at SSP2015, Victoria, BC, several others this week at CAP)
• Facility, installation at TRIUMF (see this talk and Larry’s talk at SSP)
Example nEDM R&D achievement:

Precision atomic magnetometry with Rb

- Magnetometer at 20 fT precision!
- (Your brain thinking ~ 1000 fT)
- Shielding factor = $1.3 \times 10^7$ couldn’t have been measured with any other magnetometer.

Optical rotation sees shielded field and calibration field

Wolfgang Klassen (UM/UW) installing external coils.

$\pm 475$ fT applied internally (calibration)

$\pm 1.45$ uT applied externally

NSERC Faculty Research FTE’s

- This is list expected for our next renewal April 2015
- Also ~4 Japan faculty FTE’s
- Expect 1-2 more Canadians to join over next 5YP period, and some Japanese
- More international users once facility is operational and time can be dedicated to other experiments (2022-)

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<tr>
<th>Name</th>
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<td>C. Bidinosti</td>
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Full Collaboration List (06/2015)

T. Adachi¹, E. Altiere², T. Andalib³, C. Bidinosti³, J. Birchall⁴, M. Chin⁵, C. Davis⁵, F. Doresty⁴, M. Gericke⁴, S. Hansen-Romu³, K. Hatanaka⁶, B. Jamieson³, S. Jeong¹, D. Jones², K. Katsika⁵, S. Kawasaki¹, T Kikawa⁵, A. Konaka⁵, E. Korkmaz⁷, M. Lang³, T. Lindner⁵, L. Lee⁴, K. Madison², J. Mammei⁴, R. Mammei³, J.W. Martin³, Y. Masuda¹, R. Matsumiya⁶, K. Matsuta⁸, M. Mihara⁸, E. Miller², T. Momose², S. Page⁴, R. Picker⁵, E. Pierre⁶, W.D. Ramsay⁵, L. Rebenitsch³, J. Sonier⁹, I. Tanihata⁶, W.T.H. van Oers⁴, Y. Watanabe¹, and J. Weinands²

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⁸Osaka University, Osaka, Japan
⁹Simon Fraser University, Burnaby, BC, Canada

Grad students highlighted in red
Typically 8-10 undergraduates per year (not listed)

More collaborators always welcome:
- nEDM R&D, future UCN source R&D, future experiments R&D