Testing Fundamental Symmetries with the Next Generation Ultracold Neutron Source at TRIUMF

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THE STANDARD MODEL (SM)

- *soda can* → molecules → atom → neutron

- 1st generation: everyday matter
- 2nd generation: exotic matter
- 3rd generation: force particles
- Electroweak symmetry breaking (mass giving)
- Outside of standard model

**Particles:***

- **Quarks:**
  - u
  - c
  - t
  - d
  - s
  - b

- **Leptons:**
  - e
  - μ
  - τ

- **Bosons:**
  - γ (photon)
  - W^±
  - Z
  - H (Higgs boson)
  - γ (graviton)

**Properties:**

- Charge
- Color charge (red, green, or blue)
- Mass (eV)
- Spin

**Masses:**

- **Quarks:**
  - u, c, t: ~2.4 GeV
  - d, s, b: ~4.8 GeV
- **Leptons:**
  - e, μ, τ: ~0.51 GeV

**Nuclear Forces:**

- Strong nuclear force (color charge)
- Electromagnetic charge
- Weak nuclear force
- Gravitational force

**Fermions:**

- 12 fermions (+12 anti-matter)
  - Increasing mass

**Bosons:**

- 5 bosons (+1 opposite charged W)
  - Increasing mass

Infographic from CERN's 2012 WEBFEST
http://cds.cern.ch/journal/CERNBulletin/2012/35/News%20Articles/1473657
Continuous Symmetries:
• Translation in space → momentum conservation
• Translation in time → energy conservation
• Rotation → angular momentum conservation

Discrete Symmetries:
• Spatial Inversion (P) → P-invariance (parity)
• Charge Conjugation (C) → C-invariance
• Time reversal (T) → T-invariance

But Wait…
• Parity violation discovered in 1950s
• Charge parity (CP) violation discovered in 1960s
  • kaon sector (1964, 1990s)
  • B meson sector (2000’s)
    See. D. London’s talk Thursday

A neutron electric dipole moment would be a violation of both parity and time reversal invariance

parity (P) violation in β-decay (Madam Wu, 1957)

CPT still thought to be not violated (“good symmetry”)
THE BIG QUESTIONS

1. Baryon asymmetry of the universe
   - Sakarov Criteria
   - EW Baryogenesis (Sphalerons)
   - Departure from thermal equilibrium
   - CP violation – need more nEDM would help

2. Number of quark flavors/generations
   (CKM unitarity)

3. Predictions of elemental abundances
   in the universe

4. Testing Short-range Gravitation
   Interactions

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CKM Matrix

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
d' \\
s' \\
b'
\end{pmatrix}
= 
\begin{pmatrix}
d \\
s \\
b
\end{pmatrix}
\]

Unitarity

\[
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1
\]
**UCN EXPERIMENTS**

### Neutron decay correlations

\[ A = -2 \frac{\lambda^2 + R(\lambda)}{1 + 3|\lambda|^2} \]

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### Electric dipole moment

\[ V(r) = G \frac{m_1 m_2}{r} \left(1 + \alpha \cdot e^{-r/\lambda} \right) \]

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### Neutron lifetime

\[ |V_{ud}|^2 = \frac{4908.7(1.9) \text{ s}}{\tau_{\nu}(1 + 3\lambda^2)} \]

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### Gravity

**Magnet and field layout of PENelope**

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**Scintillator**

**UCN storage volume / decay trap**

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**Be-coated window**

**MWPC**

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**Detectors**

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**RAL Sussex EDM @ ILL**

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**Electric dipole moment**

---

**Participating institutions:**

- ORNL-Harvard
- BNL-MIT
- ORNL-ILL...
- ILL-Sussex-RAL...
- LNPI St Petersburg

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**Year of Publication**

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**West**

**East**

---

**UCNA @ LANL**

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**Neutron decay correlations**

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**Magnetic field**

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**storage volume**

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**Electric dipole moment**

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**Scintillator**

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**UCN storage volume / decay trap**

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**Be-coated window**

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**Year of Publication**

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**Electric dipole moment**

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ULTRACOLD NEUTRONS (UCN)

Neutrons moving so slowly that they bounce off surfaces and can be bottled.

Interactions

- **Strong interaction**
  
  long wavelength samples over many atoms in materials
  
  $\Rightarrow$ average Fermi potential, total reflection

- **Electromagnetic Interaction**
  
  $V_m = -\mu \cdot B = \pm 60 \text{ neV per Tesla}$
  
  We can make beam beam of 100% polarized UCN !!!

- **Gravity**
  
  $V_g = mgh \approx 100 \text{ neV per meter}$

- **Weak Interaction**
  
  $\beta$-decay
  
  $n \rightarrow p + e + \bar{\nu}_e, 728 \text{ keV lifetime } \sim 15\text{min}$

Can store/transport UCN on times comparable to lifetime
HOW DO WE MAKE UCN AT TRIUMF?

- **Spallation** — Free the neutrons from W target
- **Moderation** — Cool the neutrons in D$_2$/D$_2$O
- **Conversion** — Really cool the neutrons in He-II

Spallation target, thermal and cold moderator and He-II converter

Technology developed at RCNP Osaka
TRIUMF UCN HISTORY SO FAR

2006: UCN project was first introduced into the TRIUMF 5Y planning

2007: International Workshop UCN sources and Experiments at TRIUMF

2008: Positive review by TRIUMF’s Experiments Evaluation Committee (EEC)

2009: CFI-NIF Award for UCN Source

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

2012 Two new hires in Winnipeg that work on UCN

2013: TRIUMF hires are research scientist for UCN

2014: First substantial installations occurred this spring

Seeking CFI-IF for nEDM experiment, 2\textsuperscript{nd} experiment port, & my coating facility
UCN FACILITY AT TRIUMF: MESON HALL

BL1B: UCN Beamline (EDM, $\tau$, gravity, ...) removed

M11: Beam deflects beam facility (radial of left) when space needed

BL1B/PIF: remains operational when BL1A/U off (Cyc. cooldown)
2014:
• septum
• dipole
• replacement of shielding towards cyclotron

2015:
• kicker
• decommissioning of existing beamline
• quads
• source shielding

2015/16:
• target
• moderators
• He-II cryostat
• UCN guides
• UCN polarizer
• finish shielding
Primary goals for 2014 installation met

- Reconfigure Cyclotron shielding (Shield-Plug)
- Septum subsystem (1AM5: vacuum vessel only)
- Rough-in (trench) services
- BL1U → UCN-Dipole, girder, reconfiguration of BL1A

“Best Efforts” goals 90-95 %

- Rough-in (non-trench) services
- Complete services
- BL1U girder components
Experimental limit today:
\[ d_n < 2.9 \cdot 10^{-26} e \cdot cm \]

Goals for next experiments:
\[ d_n < 10^{-27(28)} e \cdot cm \]
nEDM EXPERIMENTAL SITES
RAMSEY’S METHOD

1. prepare a sample of polarized neutrons

2. make a $\pi/2$ spin flip (“start clock”)

3. allow free spin precession in (anti-)parallel $B$ and $E$ static fields

4. make a $\pi/2$ spin flip (“stop clock”)

5. analyze direction of neutron spin

look at energy (frequency) shift under Electric field inversion:

$$\Delta \varepsilon = h |\Delta \nu| = 4Ed_n$$

N. F. Ramsey, Phys.Rev. 76 996 (1949)
Look at energy (frequency) shift under E field inversion:
\[ \Delta \varepsilon = h |\Delta \nu| = 4Ed_0 \]


**ERROR BUDGET**

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

**EDM statistical sensitivity:**

$$\sigma_d = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

- $\alpha$: visibility
- $E$: electric field
- $T$: observation time
- $N$: # of neutrons

ultra-cold neutrons are:

...totally reflected*

$\Rightarrow$ long observation time $T$

...enough from our new source

$\Rightarrow$ sufficient statistics $\sqrt{N}$

...polarizable to 100%

$\Rightarrow$ good visibility $\alpha$

Expect in one year

$$\sigma_d \sim 10^{-27} \text{ e} \cdot \text{cm}$$

**Systematics Errors are Key**

Biggest Error due in-homogeneities in the magnetic field (GPE effect)

Requirements for $10^{-27}$ e·cm

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

*by suitable materials under all angles of incidence
**CANADIAN EDM R&D**

**Magnetic environment**
- active shielding
- passive shielding
- creation of stable and homogeneous B field
- magnetometry

**UCN detection**
\[ n + ^6\text{Li} \rightarrow ^3\text{H} \ (2.74 \text{ MeV}) + ^4\text{He} \ (2.05 \text{ MeV}) \]
- conventional $^3\text{He}$ detectors too slow
- high rate capability
- Li glass scintillators + lightguide + PMTs

**Dual Co-magnetometer**

<table>
<thead>
<tr>
<th></th>
<th>$^{199}\text{Hg}$</th>
<th>$^{129}\text{Xe}$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>$\gamma$(MHz/T)</td>
<td>7.65</td>
<td>29.16</td>
<td>29.16</td>
</tr>
<tr>
<td>UCN capt. $\sigma$ (barns)</td>
<td>2150</td>
<td>21.0</td>
<td>21.0</td>
</tr>
<tr>
<td>transition (nm)</td>
<td>253.7</td>
<td>252.4</td>
<td>252.4</td>
</tr>
<tr>
<td>transition process</td>
<td>one-photon</td>
<td>two-photon</td>
<td>two-photon</td>
</tr>
</tbody>
</table>

**Optical Magnetometry**
- Conventional Sensors
  - $\sim 1-10 \text{ pT sensitivity}$
- NMOR $^{85/87}\text{Rb}$ Sensor
  - All $n=1$
  - $\sim fT$ Sensitivity
CONCLUSIONS

- Good physics can be done with neutrons
  - Search for new sector of CP violation (nEDM)
  - Search for beyond standard model interactions (via neutron decay)
- TRIUMF will have the best UCN source in the world
  - Proton beamline installation started this year
  - On track to do commissioning in 2016
  - first measurements in 2017
- nEDM at TRIUMF
  - Subsystem R&D well underway
  - Seeking CFI-IF
  - High discovery potential of a nEDM
UCN CANADIAN COLLABORATION


1KEK, 2UBC, 3Winnipeg, 4Manitoba, 5TRIUMF, 6RCNP Osaka, 7UNBC, 8Osaka, 9SFU, 10Beihan
BACKUP SLIDES
EDM CELL AND ELECTRIC FIELD

• dielectric strength of Xe at $10^{-3}$ mbar unknown
• HV test setup at TRIUMF
• 50x100 mm cylindrical test cell
• field strength goal > 10 kV/cm
• test of different cell materials
• commissioned 8/2013

HV/EDM cell mock-up at TRIUMF
the particle data group (PDG) reviews all major particle properties annually [http://pdg.lbl.gov/]

PDG „world“ averages of the neutron lifetime for the last 50 years

⇒ PENeLOPE

(Precision Experiment on the Neutron Lifetime Operating with Proton Extraction)

- Combination of magnetic storage of ultra-cold neutrons and in-situ proton detection
- Large volume
- Blind analysis
- Many knobs to turn to investigate systematic effects

Parameter s of Big Bang Nucleosynthesis

\[ Y_P = 0.228 + 0.023 \log\eta_{10} + 0.012 N_v + 0.018(\tau_n - 10.28) \]

- cosmic helium abundance \( \text{He/p} \) from old stars
- cosmic baryon density \( (n_c/n_B) \cdot 10^{-10} \)
- WMAP, Planck
- \# of neutrino flavors 3
- neutron lifetime PENeLOPE

"Exponential fit" of averages:

\[ \tau_n(t) = \tau_{n0} + Ne^{-t/\tau_{PDG}} \]

\[ \tau_{n0} = 880.4 \pm 1.4 \text{ s} \]

\[ \tau_{PDG} = 11.6 \pm 1.5 \text{ years} \]
Transport and Storage of UCN

Fermi (Material) Potential

\[ V = \frac{2\pi\hbar^2}{m} \quad \text{UCN flux } \propto (V)^{3/2} \]

UCN Loss Probability
-- Neutron absorption
-- Inelastic upscattering

Depolarization Probability
Roughness/Specular Reflection

Usually means applying a coating on industrial, machined components

Need dedicated facility

a lot of steel and concrete...

Expected completion date ~late 2016
Neutron Decay

Proton

Neutron

"Master Formula"

\[
\frac{1}{\tau_n} = W = \left( G_V V_{ud} \right)^2 g_V \left( 1 + 3 \left( \frac{g_A}{g_V} \right)^2 \right) \left( 1 + \Delta_R \right) f_n p_e E_e (E_0 - E_e)^2 \left[ 1 + m_e b \frac{j_h}{f_n} \right]
\]

Angular Correlations (directional distribution shown)

\[
\frac{dW}{d\Omega_e d\Omega_v dE_e} \propto p_e E_e (E_0 - E_e)^2 \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_v}{E_e E_v} + b \frac{m_e}{E_e} + \left( \frac{\vec{J}_n}{J_n} \right) \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_v}{E_v} + D \frac{\vec{p}_e \times \vec{p}_v}{E_e E_v} \right) \right]
\]

Big Bang Nucleosynthesis – neutron lifetime matters

**Parameter s of Big Bang Nucleosynthesis**

\[
Y_P = 0.228 + 0.023 \log_{10} n_H / n_e + 0.012 N_{\nu} + 0.018 (\tau_n - 10.28)
\]
Conclusion

1) **Current Exps & Th:** $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999(4)_{V_{ud}}(4)_{V_{us}}$
   Great Unitarity Test & Success → No New Physics!
   Nuclear Isospin Breaking? Needs Resolution
   Radiative Corrections Stable (Unchallenged!)

2) **Neutron Decay:** $|V_{ud}| = [4908.7(1.9) \text{s}/\tau_n (1+3g_A^2)]^{1/2}$ clean & precise
   Neutron Lifetime Controversy (6σ discrepancies)
   2010 $\tau_n^{\text{PDG}}=885.7(8)\text{s}$ vs $\tau_n=878.5(8)\text{s}$ Needs Resolution
   $g_A$ larger? Perkeo Ave. 1.2755(13) vs 2010 $g_A^{\text{PDG}}=1.2695(29)$
   Larger $g_A$ & smaller $\tau_n$ → Unitarity, solar neutrino flux, primordial nuclear abundances, proton spin, Goldberger-Treiman/Muon Capture, Bjorken Sum Rule, lattice calculation benchmark...

**$V_{ud}$, $\tau_n$ and $g_A$ must be precisely determined!**
Gravity

\[ V(r) = G \frac{m_1 m_2}{r} (1 + \alpha \cdot e^{-r/\lambda}) \]

Material science

Molecular rotor  UCN inelastic scattering reflectometer get pictures
Neutron Decay ($n \rightarrow p e^\nu$) & $V_{ud}$

$|V_{ud}|^2 = 4908.7(1.9)\text{sec}$ Master Relation

$\tau_n(1+3g_A^2)$

Measure $\tau_n$ and $g_A = G_A/G_V$ (decay asymmetries)

2008 PDG $\tau_n^{\text{ave}} = 885.7(8)\text{sec}$, $g_A^{\text{ave}} = 1.2695(29)$

$\Rightarrow |V_{ud}|^{\text{ave}} = 0.9746(4)\tau_n(18)g_A(2)_{RC}$ reasonable but ...

2012 PDG $\tau_n^{\text{PDG}} = 880.1(1.1)\text{sec}$? & $g_A = 1.2755(13)$ Perkeo II

$\Rightarrow |V_{ud}| = 0.9739(6)\tau_n(8)g_A(2)_{RC}$

Agrees with superallowed! $0^+ \rightarrow 0^+$ Nuclear Beta $V_{ud} = 0.97425(22)$

(Are $\tau_n$ & $g_A$ both shifting?)

History $g_A = 1.18 \rightarrow 1.23 \rightarrow 1.25 \rightarrow 1.26 \rightarrow 1.27 \rightarrow 1.275$?

Many New $\tau_n$ & $g_A$ Experiments Planned
Neutron Electric Dipole Moment (nEDM)

Non-zero nEDM implies violation of time-reversal symmetry (T).
In QFT, this is equivalent to CP violation. (CPT=1)
The nEDM is sensitive to sources of CP violation:

- within the Standard Model, via $\theta_{\text{QCD}}$ $\text{nEDM} \approx 10^{-32}$ ecm
- beyond the Standard Model, e.g. as required by Electroweak Baryogenesis in order to generate the baryon asymmetry of the universe

Where is all the antimatter

**Sakharov Conditions:** (A.D. Sakharov, JETP Lett. 5, 24-27, 1967)

1) Baryon number violation (may imply proton decay)
   - Baryon: particle made out of 3 quarks (proton, neutron, lambda...)
   - proton is lightest baryon (uud), could only decay to leptons or mesons (2 quarks)

2) Departure from thermal equilibrium
   - Phase transitions
   - Expansion of the Universe (Inflation)

3) Time reversal violation ($\Rightarrow$ CP violation)
   - not enough in Standard Model $\Rightarrow$ electric dipole moment would help
MONTE CARLO SIMULATION: ONE EXAMPLE

Which height of EDM cell is best at what storage time?

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

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

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

Monte Carlo Simulation: Reproducing RCNP experiment

- detailed modelling of RCNP source run Nov 2013 to understand results
- geometry is meshed and used in PENTrack, our MC code

UCN detector

He-II cryostat

polarizer & windows

Magnetic field along guide

3D field maps of polarizer

recreating UCN lifetime including He effects

Helium $V_p(i) = 2 \times 10^{-17} \text{ eV}$
Lifetime = $18.8 \text{ s}$

RCNP Lifetime $\approx 19 \text{ s}$
second UCN experiment port very valuable
- short term: for beam development, detector and guide tests
- long term: for experiments besides EDM: lifetime, neutron decay, charge, gravity

included in our upcoming CFI request
big step towards a real user facility
will attract UCN physicists from around the world
PHYSICS WITH SLOW NEUTRONS

\( \beta \)-decay

Charge and Moments

Short range Forces

\( n \rightarrow \bar{n} \) Oscillation

**Charged Current parameters**

BSM (S,V,A,T) \( \geq 7 \) TeV

**best limits/values are possible**

\textbf{nEDM: best constraints}

CP, T violation

\textbf{best limits}

\( \sim \) nm scale

Probes \( \Delta B=2 \)

\( >100 \) TeV

M.I. scale

\textbf{Best limits are possible}

Charge: GUT-level effects

Grav. states: \( \sim \) \( \mu \)m scale