neutron electric dipole search at TRIUMF

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for TUCAN collaboration
outline

• Neutron electric dipole moment
• Ultra-cold Neutron (UCN)
• UCN production by super thermal method
• UCN source at TRIUMF
  – Vertical source
    • developed at RCNP
    • first UCN production at TRIUMF on November 13, 2017
  – UCN source upgrade
    • LD2 moderator
    • High cooling power helium cryostat
    • expected statistics
Neutron Electric Dipole Moment (nEDM)

Sakharov conditions

1. Baryon number violation.
2. C-symmetry and CP-symmetry violation.
3. Interactions out of thermal equilibrium.

Electric Dipole moment

- Vector derived from charge distribution

\[ \vec{d} = d \frac{\vec{s}}{|\vec{s}|} \]

unit: e cm

\( d \neq 0 \rightarrow T \) violation

Assume CPT conservation

\[ \rightarrow CP \] violation

nEDM prediction

SM \( \sim 10^{-32} \) ecm

Probe of beyond SM physics

current upper limit of nEDM

\[ 3.0 \times 10^{-26} \text{ ecm} \quad @ILL, \ Grenoble \]

statistics \( 1.5 \times 10^{-26} \) ecm

systematics \( 0.7 \times 10^{-26} \) ecm

Statistically limited

\[ \rightarrow \] necessity of high intensity UCN source
How to measure nEDM?

Measure precession frequency under electro-magnetic field

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

precession frequency

\[ \hbar \omega = 2\mu_n B \pm 2d_n E \]

difference

\[ \Delta \omega = \omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow} = \frac{4dE}{\hbar} \]

in case of \( E = 10kV/cm, d = 10^{-27}ecm \)

\[ \Delta \omega = 4 \times 10^{-7}Hz \]

cf. Larmor frequency of neutron

30Hz @ \( B_0 = 1\mu T \)

accuracy of \( 10^8 \)

→ High frequency determination accuracy (Ramsey resonance technique)

and

→ High field stability
→ Co-magnetometer
frequency shift

\[ \Delta \omega = 4 \times 10^{-7} \text{Hz} \]

(\( E = 10\text{kV/cm}, \ d = 10^{-27}\text{ecm} \))

cf. Larmor frequency of neutron

30Hz @ \( B_0 = 1\mu\text{T} \)

required magnetic field stability : \(10^8!!\)

\(1\mu\text{T} \times 10^{-8} = 10\ f\text{T} \)

It is difficult to stabilize magnetic field to such an accuracy

-> monitor and correct magnetic field

co-magnetometer

• feels same magnetic field as UCN

ILL use \(^{199}\text{Hg}\) co-magnetometer

• polarization is measured by UV laser

Our plan : \(^{199}\text{Hg}, \ ^{129}\text{Xe}\) dual co-magnetometer

• monitor magnetic field strength and gradient
Ultra Cold Neutron

Ultra Cold Neutron
- Energy $\sim 100$ neV
- Velocity $\sim 5$ m/s
- Wave length $\sim 50$ nm

Interaction
- Gravity 100 neV/m
- Magnetic field 60 neV/T
- Weak interaction
  - $\beta$-decay $n \to p + e$
- Strong interaction
  - Fermi potential 335 neV ($^{58}$Ni)
    - atom distance $\sim 1\AA$
    - UCN feels average nuclear potential

UCN can be confined material bottle
→ Use in various experiments
  - nEDM, neutron lifetime, gravity, ...
UCN production by super fluid Helium

**UCN production**
- spallation neutron
  - \( \downarrow \) \( D_2O, LD2 \) Moderator (300K, 20K)
  - cold neutron \( \sim \) meV
  - \( \downarrow \) Phonon scattering in He-II

Ultra cold neutron \( \sim \) 100neV

**Feature of our source**
- spallation neutron
  - High neutron flux
  - small distance between target and UCN production volume
- Super-fluid Helium (He-II) converter
  - long storage lifetime
  - important to accumulate UCN

Helium 4
- no neutron absorption cross section
- up-scattering by phonon
  - \( \tau_s = 600 \text{ s at } T_{\text{HeII}} = 0.8 \text{ K} \)
  - \( \tau_s = 36 \text{ s at } T_{\text{HeII}} = 1.2 \text{ K} \)
  - \( 1/\tau_s \propto T^7 \)
Vertical UCN source

- Vertical UCN source
  - developed at RCNP
    - $T_{\text{He-II}}$ : 0.8 K
    - UCN life time: 81 sec
    - UCN density: 9 UCN/cm$^3$
      - $400 \text{ MeV} \times 1 \mu\text{A} = 0.4 \text{ kW}$
- move to TRIUMF
  - modification for safety requirement
  - 2017 Jan. – Apr. install at Meson hall
  - 2017 Nov. UCN production SUCCEEDED!!
UCN Source @ TRIUMF

Major Milestone
✓ - 2016  proton beam line for UCN source (BL1U 500MeV, 40μA)
✓ 2016  commissioning proton beam line and cold neutron production
✓ 2017  UCN production by Vertical source (~ 1μA)
- 2020  High intensity UCN source (40μA)
First UCN production at TRIUMF

- 2014 - 2017: installation of beamline and source
- **Nov 13, 2017: first UCN produced at TRIUMF**
- Approx. $5 \times 10^4$ per shot at 1 $\mu$A and $> 3 \times 10^5$ at 10 $\mu$A
- experimental program: source and UCN hardware characterization
- UCN source is quite stable for more than one month
- Detailed analysis is ongoing

UCN will be used for R&D for Upgrading facility and EDM apparatus
UCN yield linearity in beam current

- Maximum UCN count rate 47000 at 1µA (RCNP best shot 80000)
- We have non optimized UCN valve, longer UCN guides and an aluminum foil before the detector
- By far enough UCN to do our measurement program
- Vertical Source is capable of sustaining higher currents and the UCN yield can be increased significantly.
- Highest number for 60 s irradiation and 10 µA: $3.25 \times 10^5$
Other experimental program

Storage lifetime evolution

- NO catastrophic deterioration

UCN production in higher temperature

\[ \frac{1}{\tau} \propto T^7 \]

This is the first time we run the vertical source for more than 1 week

- Detector characteristic \((^3\text{He gas}, \, ^6\text{Li grass})\)
- UCN guide characteristic
- and so on, detailed analysis is ongoing
proton beam power
0.4 kW at RCNP  ->  20 kW at TRIUMF
A new helium cryostat which has high cooling power is necessary

Heat load on He-II depends on geometry
• distance between target and He-II
• cold moderator
• gamma shield and so on

• higher cold neutron flux
cause higher heat load
• ratio of this is constant in some region

Optimization is necessary
5 – 9 times larger cold neutron flux is achievable compared with ice D₂O
Heat load on UCN production volume

- Radial LD$_2$ layer more important than lower
- Best He-II-bottle height 30-40 cm, radius 15-20 cm (for current cooling scheme)
- Limited by amount of LD$_2$!
- For He-II height 30 cm, radius 15 cm, 40 μA beam:
  - 20.6 l He-II, 115 l LD$_2$
  - $3.9\cdot10^7$ UCN/s
  - 7.9 W max. heat in He-II
  - 65 W max. heat in LD$_2$
- Best strategy to reduce LD$_2$:
  reduce He-II size and go closer to target

2017-10-18

deal with such a huge heat load around 1 K
He cryostat

• to keep He-II temp. ~ 1.0 K
• decompressed Helium 3
• $^3$He vs $^4$He
  – vapor pressure @ 0.8K
    • $^3$He: 3 Torr
    • $^4$He: 0.01 Torr
  – cooling power
    @ 0.8K with 10,000 m$^3$/hour pumping
    • $^3$He: 15W
    • $^4$He: 0.13 W
Heat transfer between heating point and cooling point

- Heat transfer in He-II
  - below 1 K, heat transfer is not good because of low fraction of normal fluid which convey heat (two fluid model)

- Kapitza conductance of heat exchanger
  - Conductance at the surface between liquid and solid is small at low temperature
Superfluid Helium

Two Fluid Model

<table>
<thead>
<tr>
<th>Normal fluid</th>
<th>Superfluid</th>
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<tbody>
<tr>
<td>Viscosity</td>
<td>$H_n$</td>
</tr>
<tr>
<td>Entropy</td>
<td>$S_n$</td>
</tr>
</tbody>
</table>

- Ratio of super/normal component depends on temperature.
- Fraction of normal mode become small in low temperature.

Heat transport

- Since superfluid has no entropy, heat is transported only by normal fluid.
- Heat transport in low temperature (< 1K) become small because of small fraction of normal fluid.
Gorter-Mellink Equation

\[ q_j(r) = -\left( \frac{f(T)^{-1}}{1/3} \frac{\partial T(r)}{\partial x_j} \right)^{1/3}, \quad f(T) = \frac{A_{gm} \rho_n}{\rho_s s^3 s^4 T^3} \]

- \( q_j(r) \): [W/m²] Heat Flux vector at \( r \).
- \( f^{-1}(T) \): [W³/m⁵ K] Heat transfer function. (⇔ \( q_j = -\lambda \partial_j T \))
- \( A_{gm} \): Gorter-Mellink mutual friction parameter, [m·sec].

\( f(T)^{-1} \): Heat transfer function of He-II based on Two fluid model
Temperature difference in He-II

Chamber temperature, $T_H$, can be solved numerically using the following Gorter-Mellink equation.

$$Q_{in} = \left( \frac{A^3}{L} \int_{T_L}^{T_H} f(T)^{-1}dT \right)^{1/3}$$

- $A$ : cross section of He-II
- $L$ : distance of heat transfer

Temperature increase in He-II
10 W heat load

$L = 1000\text{mm}$

*detail will be discussed by T. Okamura*
Kapitza Conductance

- Kapitza conductance is Conductance at the junction between liquid and solid is small at low temperature.
- Kapitza conductance, $h_K(T)$ is a function of temperature.
- There are several theory on Kapitza conductance.
  - Phonon limit
    - $h_K(T) \sim 4500 \, T^3 \, [W/m^2K]$  
      - 2 - 10 times larger than measured
  - Khalatnikov theory
    - $h_K(T) \sim 20 \, T^3 \, [W/m^2K]$  
      - 10 - 100 times smaller than measured
- Experimental data strongly depends on surface quality
  - plan to measure Kapitza conductance at KEK

Kapitza conductance between Copper and He-II

Helium cryogenics, Steven W. Van Sciver
Cu Heat exchanger should be plated by Ni

Kapitza conductance between Cu-Ni is large enough since junction is solid-solid

- Kapitza conductance between Ni and He-II
  \[ h_{K_{Ni}}(T) = f \cdot h_{K_{Cu}}(T) \quad \text{f} = 0.61 \]

- Kapitza conductance between Cu and 3He
  \[ h_K(\text{He-II}) = (1.2 - 2.6) \cdot h_K(3\text{He}) \]

ex) average quality of Cu, 10 W heat load

- junction between He-II and Ni
  - \[ h_{K_{Ni}}(1.0K) = 244 \text{ [w/m2 K]} \]
  - \[ \Delta T_{\text{He-II-Ni}} = 0.16 \text{ K} \]
  - \[ T_{\text{Ni}} = 0.84 \text{ K} \]

- junction between Cu and 3He
  - \[ h_{K_{Ni}}(0.84K) = 232 \text{ [w/m2 K]} \]
  - \[ \Delta T_{\text{He-II-Ni}} = 0.09 \text{ K} \]
  - \[ T_{3\text{He}} = 0.75 \text{ K} \]
Equilibrium temperature

Equilibrium temperature can be calculated as a function of heat load.

Example:
- $d = 150 \text{ mm}$, $L = 1,500 \text{ mm}$
- Pumping speed: $10,000 \text{ m}^3/\text{hour}$
- Heat load: $10 \text{ W}$

Temperature distribution:
- $T_{\text{He-II H}} = 1.15 \text{ K}$ ($\tau_{\text{up-scatt}} = 50 \text{ sec}$)
- $T_{\text{He-II L}} = 1.00 \text{ K}$
- $T_{\text{Cu H}} = 0.84 \text{ K}$
- $T_{\text{Cu L}} = 0.83 \text{ K}$
- $T_{3\text{He}} = 0.75 \text{ K}$
- $\Delta T = 0.40 \text{ K}$

Large uncertainty in parameter (Kapitza, GM)
- $\rightarrow$ have to be tested
- $\rightarrow$ we will have experiments at the beginning 2018
Alternative plan: direct pumping

- direct pumping of He-II
  - another way to cooldown He-II
    - There is no effect of Kapitza conductance since they have no heat exchanger
      - if Kapitza conductance is found to be smaller than expected, the direct pumping have large advantage
    - He-II volume can be small
      - temperature difference in He-II become small
  - Cooling power: 7 W at 1.2 K with 10,000 m³/hour pumping
    - upscattering life time at 1.2 K: 36 sec
High cooling power cryostat

• A new He-II cryostat is being developed
  – TRIUMF proton beam line BL1U
    $500 \text{ MeV} \times 40 \mu\text{A} = 20 \text{ kW}$
  – necessary cooling power is around 10 W at 1.0 K
  – Heat conductance is important
    • inside He-II
    • Kapitza conductance between He-II/3He and heat exchanger

• Isopure $^4\text{He}$ direct pumping is an alternative method
Expected statistics after UCN source upgrade

- New He cryostat will be made for 20 kW operation
- LD2 moderator increase cold neutron flux by factor 5 – 9
- UCN guide coating facility will be established at U. Winnipeg

<table>
<thead>
<tr>
<th></th>
<th>vertical source</th>
<th>horizontal source</th>
<th>factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton beam</td>
<td>0.4 kW</td>
<td>20 kW</td>
<td>× 50</td>
</tr>
<tr>
<td>production volume</td>
<td>8 L</td>
<td>12 L</td>
<td>× 1.5</td>
</tr>
<tr>
<td>LD2 moderator</td>
<td>-</td>
<td>-</td>
<td>× 5 – 9</td>
</tr>
<tr>
<td>UCN production rate</td>
<td>3.2 × 10^4 UCNs</td>
<td>2.3 × 10^7 UCN/s</td>
<td>~ 700</td>
</tr>
</tbody>
</table>

statistical sensitivity

\[ \sigma_d = \frac{\hbar}{2\alpha E t_c \sqrt{N}} \]

- \( E = 10\text{kV/cm} \)
- \( t_c = 130\text{s} \)
- \( \alpha = 0.8 \) (visibility)

\[ N : \text{number of UCN} \]
\[ \rho = 680 \text{ Pol. UCN/cm}^3 \] @20kW operation, TRIUMF
in cell of \( \phi 36 \text{ cm and H 15 cm (15L)} \) × double cell
\[ N = 2.1 \times 10^7 \text{ UCN/batch} \]

\[ \sigma_d = 5.6 \times 10^{-26} \text{ ecm/cycle} \]
(1 cycle : 8 fill to determine the resonant frequency)
assume stable running of 14 hours/day
\[ \sigma_d = 1 \times 10^{-27} \text{ ecm/100 MT day} \]
Second UCN port : Y switch

- Bend is necessary for radiation protection
  - to not see target area directly
- Y switch can divert UCN to second area.
  - R&D for UCN guide, detector and so on
  - open for user facility in future

If you have an interest idea to use UCN, please contact us!!
Summary

• High UCN density is essential to overcome current limit of neutron EDM measurement sensitivity
• UCN production in superfluid helium is a viable way to achieve a high density UCN source
• UCN production with the vertical UCN source succeeded
  – will use UCN produced for R&D for source and nEDM experiment
• High intensity UCN source is being developed
  – proton beam power : 500 MeV * 40 μA = 20 kW
  – new cryostat with higher cooling power
    • necessary cooling power : ~10 W at 1.0 K
      – 3He pumping, isopure 4He pumping
  – Final optimization is ongoing
    • statistical error of $10^{-27}$ ecm / 100 MT day
  – Plan to produce UCN from 2021