Development of a Helium-3 Cryostat for Ultra-Cold Neutron Source

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Outline

• Ultra-Cold Neutron
  – Physics property
  – How to produce UCNs
    • Super-thermal method

• TUCAN experiment
  – TRIUMF Ultra-Cold Advanced Neutron
  – Development for high power helium-3 cryostat
    • Necessary cooling power
    • Heat Exchanger
    • Heat transfer in superfluid helium
      – Gorter-Millink heat transfer

• Summary
Ultra Cold Neutron (UCN)

extremely low kinetic energy neutrons

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

**Interaction of neutron**
- Gravity: 100 neV/m
- Magnetic field: 60 neV/T
- Weak interaction
  - $\beta$-decay: $n \rightarrow p + e$
- Strong interaction
  - Fermi potential: 335 neV ($^{58}$Ni)
  - Atom distance: $\sim 1$ Å
  - UCN feels average nuclear potential

**Unique property**
- UCN can be confined in material bottle
  - Use various experiments
    - nEDM, n lifetime, gravity ...

**High intensity UCN source is necessary to improve (statistical) sensitivity**
UCN production by super-thermal method

- phonon up-scattering of superfluid helium or solid D\(_2\)
- use large phase space of phonon
- free from Liouville’s theorem

We use superfluid helium as a UCN converter

UCN production cross section

\[
\frac{d\sigma}{dE} = 4\pi\hbar^2 \frac{k_f}{k_i} S(q, \hbar \omega)
\]

\(k_i, k_f\): wavenumber

\(S(q, \hbar \omega)\): Dynamic structure factor

resonant energy (single phonon excitation) 1 meV

UCN Production rate

\[
P(E_u) dE_u = \left[ \int \frac{d\Phi(E)}{dE} N_{\text{He}} \frac{d\sigma}{dE} (E_i \rightarrow E_u) dE_i \right] dE_u
\]

\[
P = \left[ \int p(E_u) dE_u = N_{\text{He}} 4\pi\hbar^2 \left( \frac{\hbar}{m_u} \right)^2 \frac{k_u^3}{3} \left[ \int \frac{d\Phi(q)}{dE} S(q, \hbar \omega = \frac{\hbar^2 q^2}{2m_u}) dq \right] \right]
\]
Schematic of our TUCAN source

TRIUMF Ultra-Cold Advanced UCN source

Feature: unique combination
- spallation neutron
  - High neutron flux
    - small distance between target and HeII
- Super-fluid Helium converter
  - long storage lifetime
    - up-scattering by phonon
      - $\tau_s = 36$ s at $T_{\text{HeII}} = 1.2$ K
      - $\tau_s = 600$ s at $T_{\text{HeII}} = 0.8$ K
(Cf. $SD_2 : T_s = 24\text{ms}$)

UCN production
- spallation neutron $\sim$ MeV
  - $D_2O$ Moderator ($300K, 20K$)
- cold neutron $\sim$ meV
  - Phonon scattering in He-II
- Ultra cold neutron $\sim 100\text{neV}$

$T_{\text{HeII}} \sim 1.0$ K is necessary under high radiation heat
UCN Storage time

UCN density
\[ \text{UCN density} = P \tau \left( 1 - \exp(-t/\tau) \right) \]
\[ \rightarrow P \tau \quad (t \to \infty) \]

- \( P \): UCN production rate
- \( \tau \): Storage time
- \( t \): proton irradiation time

long \( \tau \) is important

UCN Storage Life Time

\[ \frac{1}{\tau} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{abs}} + \frac{1}{\tau_{wall}} + \frac{1}{\tau_{phonon}} \]

- \( \tau_\beta \): \( \beta \) decay (886s)
- \( \tau_{abs} \): absorption by \(^3\text{He}\)
- > 1000 sec \(^3\text{He}/^4\text{He} < 10^{-11}\)
- \( \tau_{wall} \): wall loss
- 10 \sim 100 sec clean surface
- \( \tau_{phonon} \): phonon up-scattering
  \[ \propto T^{-7} \]
- > 50 sec \( T < 1.15 \text{ K} \)

requirement for cryo system

\[ \#\text{UCN} = P \tau \left( 1 - \exp(-t/\tau) \right) \]

UCN life time by phonon up-scattering
\[ \tau_{phonon} \propto T^{-7} \]

Prototype UCN source

- Prototype UCN source
  - developed at RCNP, Japan
    - $^3$He cryostat
      - $T_{\text{He-II}}$: 0.8 K
    - UCN life time: 81 sec
    - UCN density: 9 UCN/cm$^3$
      - $400 \text{ MeV} \times 1 \mu\text{A} = 0.4 \text{ kW}$
  - moved to TRIUMF, Canada
    - Dedicated beam line
      - Maximum beam power: $500 \text{ MeV} \times 40 \mu\text{A} = 20 \text{ kW} \ (\times 50)$
    - 2017 Jan. – Apr. install at Meson hall
    - 2017 Nov. First UCN production at TRIUMF
      - Beam power: $500 \text{ meV} \times 1 \mu\text{A} = 0.5 \text{ kW}$
UCN source upgrade

- Liquid deuterium (LD₂) Moderator
  - To get colder neutron in order to produce UCN effectively
- High power helium cryostat
  - Proton beam power
    - 0.4 kW at RCNP -> 20 kW at TRIUMF
  - Remove high radiation heat
    - Cooling power of 10 W around 1.0 K
Superfluid helium UCN converter cooling

Components

1. Helium-3 cryostat
   - Have to be placed behind radiation shield
     - $L = 2.0 \, \text{m}$
   - High cooling power: $\sim 11 \, \text{W} @ 1.0\, \text{K}$
     - 10 W: beam, 1 W: static

2. Heat Exchanger design
   - Kapitza conductance

3. Heat transport in superfluid helium
   - Flow pattern
     - Superfluid turbulent
     - Gorter-Millink heat transfer
1. Helium-3 cryostat

- **Design temperature**
  - $^3$He pot: 0.8 K
  - 1K pot: 1.6 K
  - $^3$He before 1K pot: 2.8 K
  - 4K reservoir: 4.2 K
  - $^3$He before 4K reservoir: 10 K
  - Detail of the heat exchanger design will be done at the next talk

- **Helium-3 mass flow rate:** 1.14 g/sec
  - Heat load: 11 W
  - $^3$He bath temperature: 0.8 K
    - Latent heat: 11.6 J/g
  - Liquid fraction after J-T expansion
    - $x = 0.83$
      - Supply pressure: 50 kPa
  - Necessary pumping speed
    - 8,800 m$^3$/hour
      - $P_{^3\text{He}} = 380$ Pa
2. Main Heat Exchanger design

Kapitza conductance

• Kapitza conductance between Cu and He-II
  \[ h_K(T) \sim 20 * K_G * T^3 \text{[W/m}^2\text{K]} \]
  \[ K_G = 20 - 60 \]

• Kapitza conductance between Ni and He-II
  \[ h_{K_{Ni}}(T) = f * h_K(T) \quad f = 0.61 \]

• Kapitza conductance between Cu and $^3$He
  \[ h_{K_3He}(T) = a * h_K(T) \quad a = 1.2 - 2.6 \]

Our recent measurement shows \( K_G = 45 - 48 \)

- Cylindrical shape
- Material: OFHC (RRR = 100)
- Inside: He-II
  - No fin
  - Surface area: \( S_i = 0.28 \text{ m}^2 \)
  - Ni plating
    - UCN friendly
- Outside: $^3$He
  - Fin structure
    - Fin gap = 1 mm
    - Fin length = 1 mm
  - Surface area: \( S_o = 0.89 \text{ m}^2 \)

\( \Delta T_{Cu-3He} = 0.078 \text{ K} \)
\( T_{Cu} = 0.878 \text{ K} \)
\( \Delta T_{Ni-HeII} = 0.118 \text{ K} \)
\( T_{He-II} = 0.996 \text{ K} \)

Temperature difference in the heat exchanger can be neglected.

\( K_G = 40, \ T_{3He} = 0.8 \text{ K}, \ Q = 11 \text{ W} \)

- junction between $^3$He and Cu
  - \( \Delta T_{Cu-3He} = 0.078 \text{ K} \)
  - \( T_{Cu} = 0.878 \text{ K} \)

- junction between Cu and He-II
  - \( \Delta T_{Ni-HeII} = 0.118 \text{ K} \)
  - \( T_{He-II} = 0.996 \text{ K} \)
3. Heat transport in superfluid helium

10 W @ \sim 1.0 K

- **Flow pattern**
  - Normal fluid component is dilute around 1.0 K region
    - Knudsen number \( K_n = \frac{\lambda}{D_{UCN}} < 1 \), \( \lambda \sim 0.5 \text{ mm}, D_{UCN} = 150 \text{ mm} \)
      - continuum flow
  - Superfluid laminar or turbulent?
    - Reynolds number of normal fluid component
      \[
      Re_n = \frac{|v_n - v_s| D_{UCN}}{v_n} \sim 10^6 \gg 1200 \sim 2600
      \]
      - superfluid turbulent

Gorter-Mellink turbulent model used to evaluate heat transport
Temperature difference in He-II

Temperature difference in superfluid helium can be calculated numerically using the following Gorter-Mellink equation:

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

- \( T_L \): He-II temperature at the heat exchanger
- \( T_H \): He-II temperature at the UCN production volume
- \( A \): cross section of He-II, diameter = 150 mm
- \( L \): distance of heat transfer, \( L = 2.0 \text{ m} \)

\( f(T) \): Heat transfer function

**Large ambiguity**
Temperature distribution in our system

Temperature distribution
- $^3$He pot
  - $T_{3He} = 0.800 \, \text{K}$
- Heat exchanger
  - $T_{HEX} = 0.878 \, \text{K}$
- He-II at HEX
  - $T_{He-II1} = 0.996 \, \text{K}$
- He-II at UCN prod.
  - $T_{He-II} = 1.14 \, \text{K (HEPAK)}$
  - $= 1.10 \, \text{K (Van Sciver)}$

Kapitza conductance
- $KG = 40$

GM heat transfer

Current design meets our requirement
  - Temperature at the production volume < 1.15 K

Future work: $f(T)$ measurement below 1.4 K
Summary

• UCNs are extremely slow neutrons
  – Can be confined material bottle

• High intensity UCN source
  – Developed by TUCAN
  – UCN converter : superfluid helium
  – $T_{\text{He-II}} < 1.15$ is necessary for effective UCN production
  – Cryostat design almost complete
  – Starting cryostat construction
Our goal

- Measure the neutron Electric Dipole Moment (nEDM) at a precision of $10^{-27}$ ecm
- Develop world-leading intense Ultra Cold Neutron (UCN) source at TRIUMF
Neutron Electric Dipole Moment (nEDM)

Sakharov conditions
Baryogenesis
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

T reversal

nEDM prediction
SM ~ 10^{-32} ecm

Probe of beyond SM physics

current upper limit of nEDM
3.0 \times 10^{-26} ecm @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
### Various neutrons

<table>
<thead>
<tr>
<th>Name</th>
<th>Energy</th>
<th>Wavelength</th>
<th>Velocity</th>
<th>Temperature</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast neutron</td>
<td>&gt;500 keV</td>
<td>40 fm</td>
<td>10⁷ m/s</td>
<td>6 × 10⁹ K</td>
<td>Nuclear physics, Astro physics</td>
</tr>
<tr>
<td>Epi-thermal neutron</td>
<td>10 eV</td>
<td>0.1 Å</td>
<td>44,000 m/s</td>
<td>1 × 10⁵ K</td>
<td>Resonance capture</td>
</tr>
<tr>
<td>Thermal neutron</td>
<td>25 meV</td>
<td>1.8 Å</td>
<td>2200 m/s</td>
<td>300 K</td>
<td>Neutron scattering</td>
</tr>
<tr>
<td>Cold neutron</td>
<td>2 meV</td>
<td>6 Å</td>
<td>600 m/s</td>
<td>23 K</td>
<td>Neutron scattering for condensed matter (nm)</td>
</tr>
<tr>
<td>Very cold neutron</td>
<td>50 μeV</td>
<td>40Å</td>
<td>100 m/s</td>
<td>0.6 K</td>
<td>Neutron interferometer</td>
</tr>
<tr>
<td>Ultra-cold neutron (UCN)</td>
<td>&lt;300 neV</td>
<td>500Å</td>
<td>8 m/s</td>
<td>3 mK</td>
<td>nEDM etc.</td>
</tr>
</tbody>
</table>

Slide by K. Mishima
Kapitza Conductance

- Kapitza conductance is Conductance at the surface 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 will be discussed T. Okamura

Kapitza conductance between Copper and He-II
Helium cryogenics, Steven W. Van Sciver
Kapitza conductance Measurement

first Kapitza conductance test at KEK
Sample
Material : OFHC
Heat
Temperature range : 1.82 - 2.15 K

Result
• Dependence of $T^3$
• Enough Kapitza conductance
Critical heat flux on the heat exchanger

- Boiling curve
  - Free convection (no boiling)
  - Nucleate boiling
    - Maximum heat transfer
  - Film boiling

- Heat flux
  - Total heat: $Q = 11 \text{ W}$
  - Surface area: $S_0 = 0.89 \text{ m}^2$
  - Heat flux: $1.2 \times 10^{-3} \text{ W/cm}^2$

- Heat flux of no fin design is still lower than the critical heat flux of $2 \times 10^{-2} \text{ W/cm}^2$ for the transition from nucleate boiling to film boiling
- However, critical heat in narrow channel might be different
  - Will be measured by the HEX test piece using helium-4
3He – 4He mixture

- In order to reduce necessary amount of 3He, 3He and 4He mixture might work
  - 80% of 3He and 20% of 4He mixed helium works for the vertical cryostat
    - 4He concentration of liquid in 3He pot should be larger, since main component of circulating gas is 3He
  - 80%, 0.8 K: normal fluid

- Does 20%(for example), 0.8 K work?
  - Maybe yes.
    - Heat load
      - by film flow: < 100 mW
      - Negligible from total heat load of 10 W
    - 4He has no contribution for heat transfer at 0.8K
      - Analogy of dilution refrigerator, 4He can be treated as vacuum
    - “low density liquid 3He” convey the heat

- Is it possible to test by using vertical source?
  - If 3He purification work well, we can introduce more 4He into 3He gas
He IIの熱流動特性 (1)
超流動乱流 vs 層流

Laminar Flow

\[ T_H \]

\[ \Delta T = T_H - T_L \]

small \( \Delta T \) !!

\[ v_{n0} = \frac{q_x}{\rho S \Delta T} \]

\[ v_{a0} = -\frac{\rho_n v_{n0}}{\rho_s} \]

driving force of superfluid component is chemical potential difference

No Friction !!

Superfluid Turbulent (ST)

\[ T_H \]

\[ \Delta T = T_H - T_L \]

Large \( \Delta T \) !!

\[ v_{n0} = \frac{q_x}{\rho S \Delta T} \]

\[ v_{a0} = -\frac{\rho_n v_{n0}}{\rho_s} \]

driving force of superfluid component is chemical potential difference

Mutual Friction!!

Gorter-Mellink Equation at ST

\[ q_x^3 = -f(T)^{-1} \frac{dT}{dx} \]

Heat transfer function, \( f(T) \)-inv, at sub K to 1K is not sufficiently clarified.
He IIの熱流動特性 (2)

バリスティック領域

Ballistic Heat Transfer w/o QV
(Phonon Dominant region)

 Phonon-phonon interaction is dominant

\[ Kn = \frac{\lambda}{D} > 1 \]

Kinetic motion of phonon w/ QV

 Phonon-QV (remnant vortex) interaction is dominant
\[ Kn = \frac{\lambda}{D} < 1 \]

power of 4: phonon dominant
power of 5.6: phonon + other excitation  
(roton)  
(Quantized Vortex, QV)
He IIの流動状態の判別

"パリステック領域"か"連続体"かの判別

\[ Kn = \frac{\lambda}{D_{UCN}} \]  \hspace{1cm} (1)

⇒ 判別結果：連続体近似が成立
⇒ 超流動乱流か層流かの判別が必要！

"超流動乱流"か"層流"かの判別

- 超流動成分に着目した判別

\[ v_{sc} \sim D_{eff}^{-0.25} \]  \hspace{1cm} (2)

- 常流動成分に着目した判別

\[ Re_{n1} = \frac{v_n D_{UCN}}{\nu_n} > 1200 \sim 2600, \quad \nu_n = \frac{\eta_n}{\rho} \]  \hspace{1cm} (3)

\[ Re_{n2} = \left| v_n - v_s \right| D_{UCN} \nu_n > 1200 \sim 2600, \quad v_n = \frac{\eta_n}{\rho} \]  \hspace{1cm} (4)

⇒ 判別結果：\( v_s \sim v_{sc} \), \( Re_n \Rightarrow Re_{n1}, Re_{n2} \Rightarrow 超流動乱流 \)
Kapitza conductance measurement

Setup

Data acquisition
Power source
Cryostat (Oxford)
Vacuum pump system

sample

He II temp
Cu temp

Temperature (K) vs. Time (sec)

measured Kapitza cond.

Kholostnov Theory

phonon radiation limit

EXPERIMENTS (CLEAN SURFACES)

EXPERIMENTS (DIRTY SURFACES)