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

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For the TUCAN Collaboration

Outline

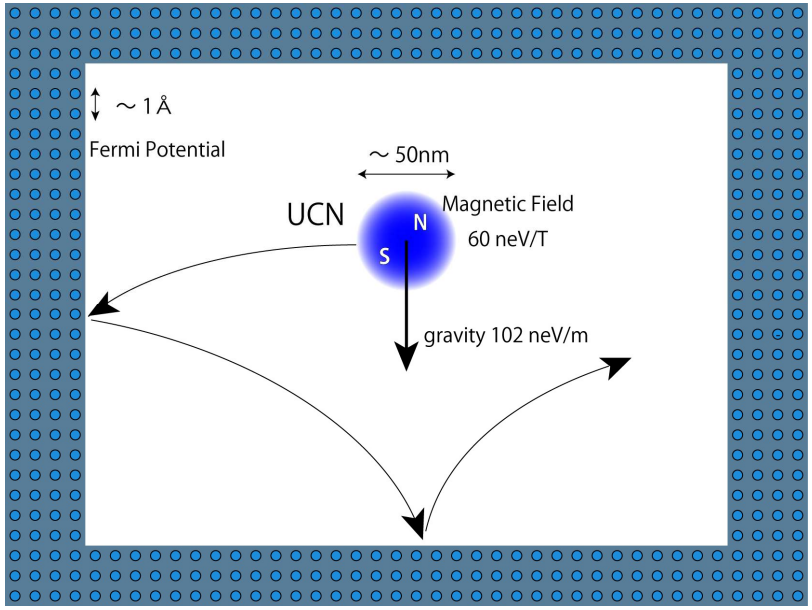
- Ultra-Cold Neutron
  - Physics property
  - How to produce UCNs
    - Super-thermal method
- TUCAN experiment
  - TRIUMF Ultra-Cold Advanced Neutron
  - Development for high power helium-3 cryostat
    - Necessary cooling power
    - Heat Exchanger
    - Heat transfer in superfluid helium
      - Gorter-Millink heat transfer
- Summary

Ultra Cold Neutron (UCN)

extremely low kinetic energy neutrons

Ultra Cold Neutron

Energy	～ 100 neV
Velocity	～ 5 m/s
Wave length	～ 50 nm



Interaction of neutron

- Gravity 100 neV/m
- Magnetic field 60 neV/T
- Weak interaction
  β-decay n → p + e
- Strong interaction
  Fermi potential 335 neV (^{58}Ni)
  atom distance : ~ Å
  UCN feels average nuclear potential

Unique property

UCN can be confined in material bottle

→ Use various experiments

nEDM, n lifetime, gravity ....

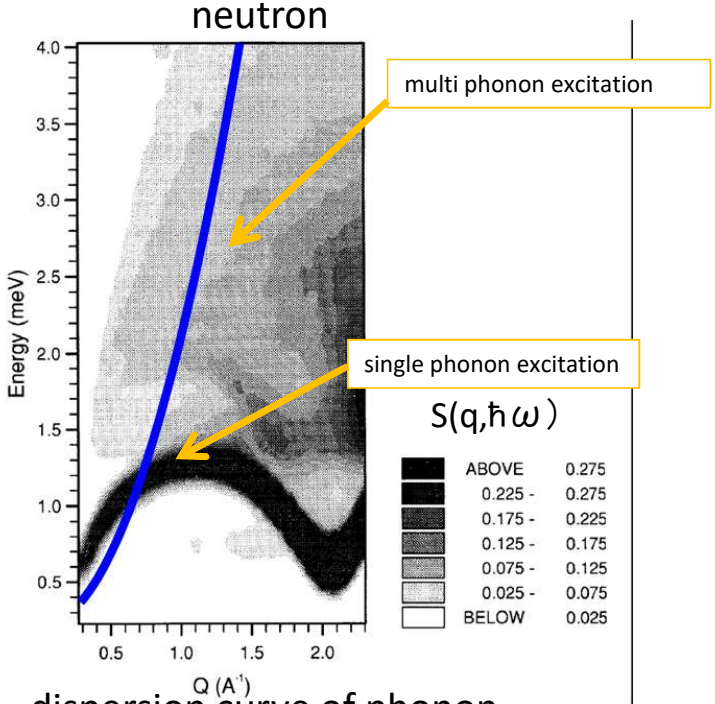
High intensity UCN source is necessary to improve (statistical) sensitivity

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

neutron



dispersion curve of phonon

M. R. Gibbs, et al
J. Low Temp. Phys. 120 (2000) 55

UCN production cross section

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

k_i, k_f : wavenumber

$S(q,\hbar\omega)$: Dynamic stracture factor

resonant energy (single phonon excitation)

1 meV

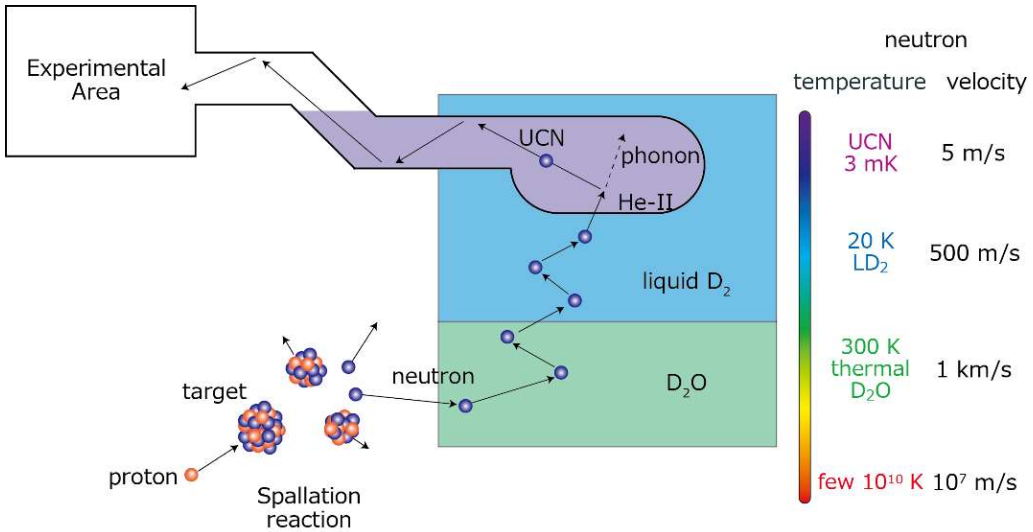
UCN Production rate

$$P(E_u)dE_u = \left[\int \frac{d\Phi(E_i)}{dE} N_{\mathrm{He}} \frac{d\sigma}{dE}(E_i \to E_u) dE_i\right] dE_u$$

$$P = \int p(E_u)dE_u = N_{\mathrm{He}} 4\pi b^2 \left(\frac{\hbar}{m_n}\right)^2 \frac{k_c^3}{3}\left[\int \frac{d\Phi(q)}{dE} S\left(q, \hbar\omega = \frac{\hbar^2 q^2}{2m_{\mathrm{n}}}\right) dq\right]$$

Schematic of our TUCAN source

TRIUMF Ultra-Cold Advanced UCN source



UCN production

spallation neutron ～ MeV

↓ D_2O Moderator (300K, 20K)

cold neutron ～meV

↓ Phonon scattering in He-II

Ultra cold neutron ～100neV

Feature : unique combination

- spallation neutron
  - High neutron flux
    - small distance between target and HeII
- Super-fluid Helium converter
  - long storage lifetime

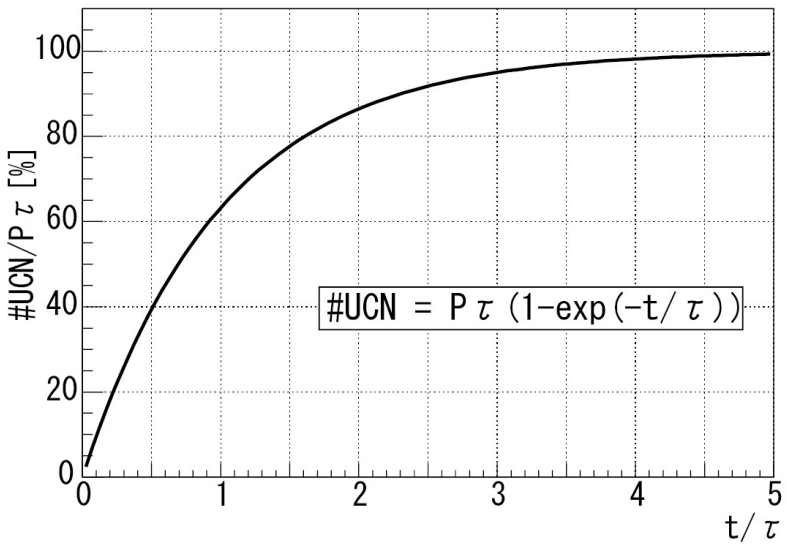
    up-scattering by phonon
    - τ_s = 36 s at T_{HeII} = 1.2 K
    - τ_s = 600 s at T_{HeII} = 0.8 K

(Cf. SD_2 : T_s = 24ms)

T_{HeII} ～ 1.0 K is necessary under high radiation heat

UCN Storage time

UCN density
= Pτ (1 – exp(-t/τ))
→ Pτ (t → ∞)
P : UCN production rate
τ : Storage time
t : proton irradiation time
long τ is important

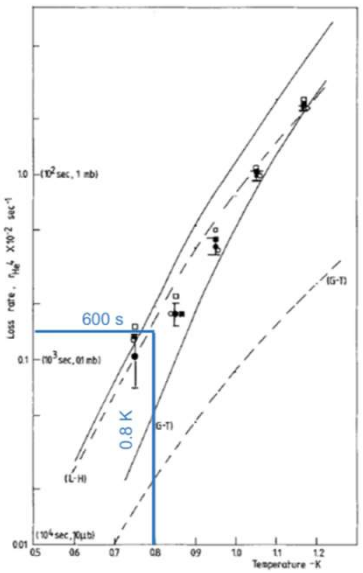


UCN density during proton irradiation

UCN Storage Life Time

$$1/\tau = 1/\tau_{\beta} + 1/\tau_{abs} + 1/\tau_{wall} + 1/\tau_{phonon}$$

τ_{β} : β decay (886s)
τ_{abs} : absorption by ^{3}He
> 1000 sec ^{3}He/^{4}He <10^{-11}
τ_{wall} : wall loss
10 ～ 100 sec clean surface
τ_{phonon} : phonon up-scattering
∝ T^{-7}
> 50 sec T < 1.15 K
requirement for cryo system



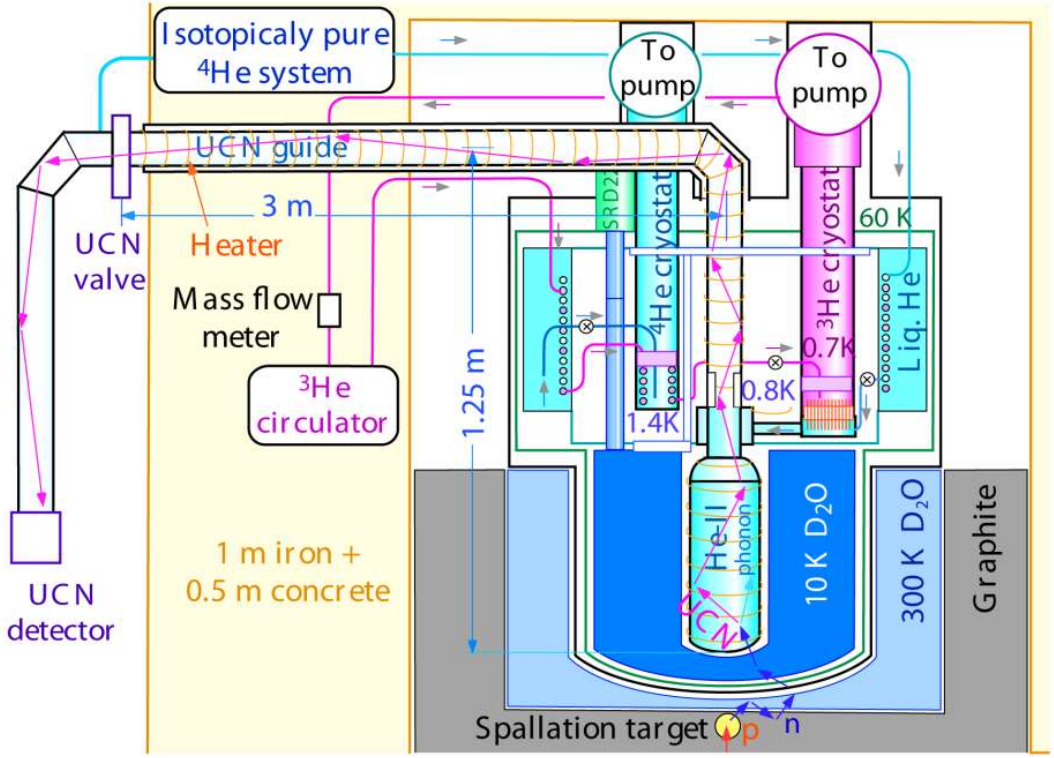
UCN life time by phonon up-scattering
τ_{phonon} ∝ T^{-7}

R. Golub and K. B¨oning, Z. Phys. B 51, 95 (1983)

Prototype UCN source

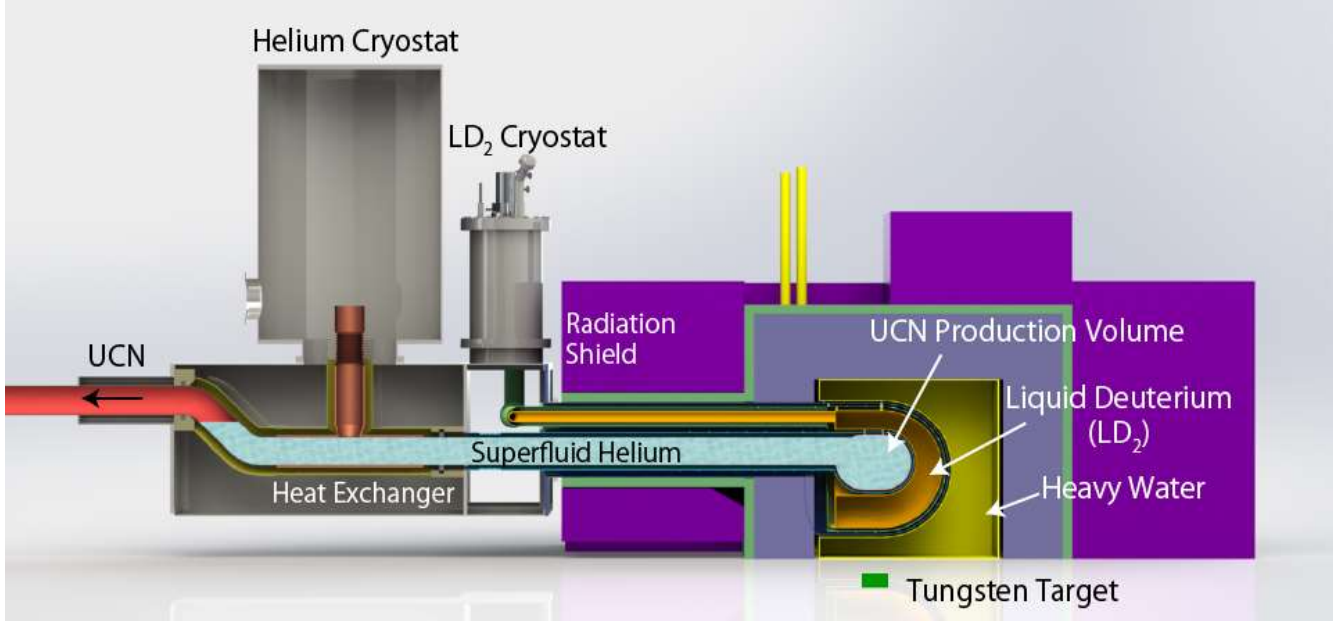
- Prototype UCN source
  - developed at RCNP, Japan
    - ^{3}He cryostat
      - $T_{He\text{-}II}$: 0.8 K
    - UCN life time: 81 sec
    - UCN density: 9 UCN/cm^3
      - 400 MeV × 1 μA = 0.4 kW

Y, Masuda et. al., Phys. Rev. Lett. 108, (2012), 134801



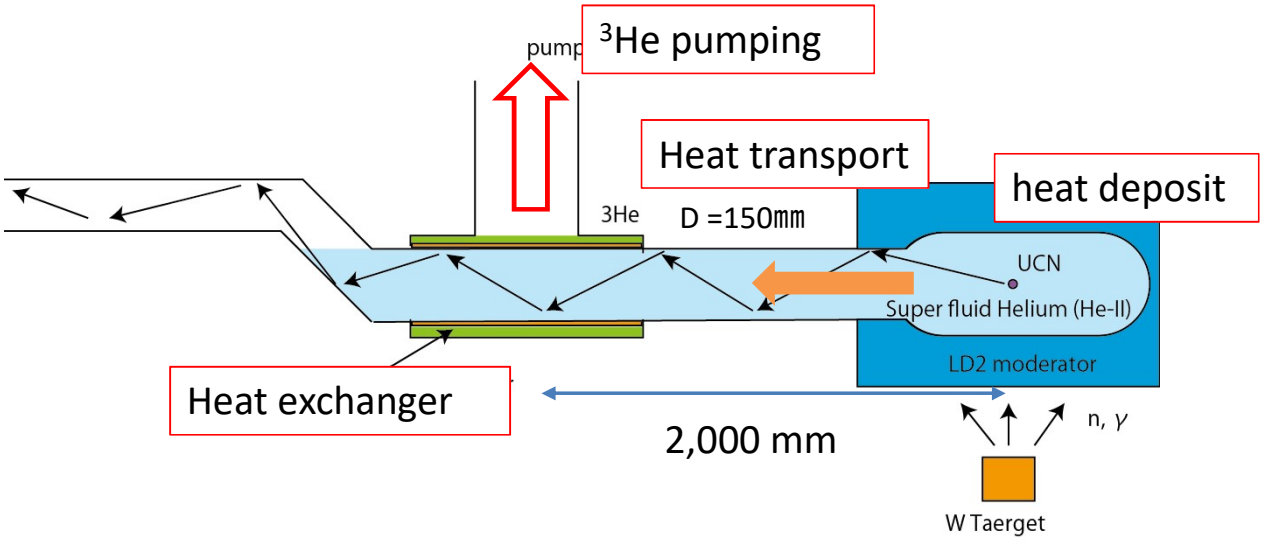
  - moved to TRIUMF, Canada
    - Dedicated beam line
      - Maximum beam power : 500 MeV × 40 μA = 20 kW (×50)
  - 2017 Jan. – Apr. install at Meson hall
  - 2017 Nov. First UCN production at TRIUMF
      - Beam power : 500 meV × 1 μA = 0.5 kW

UCN source upgrade



- Liquid deuterium (LD_2)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



$$T_{prod} = T_{3He} + \underbrace{\Delta T_{3He\text{-}Ni} + \Delta T_{Ni\text{-}HeII}}_{\text{Kapitza cond.}} + \Delta T_{HeII}$$

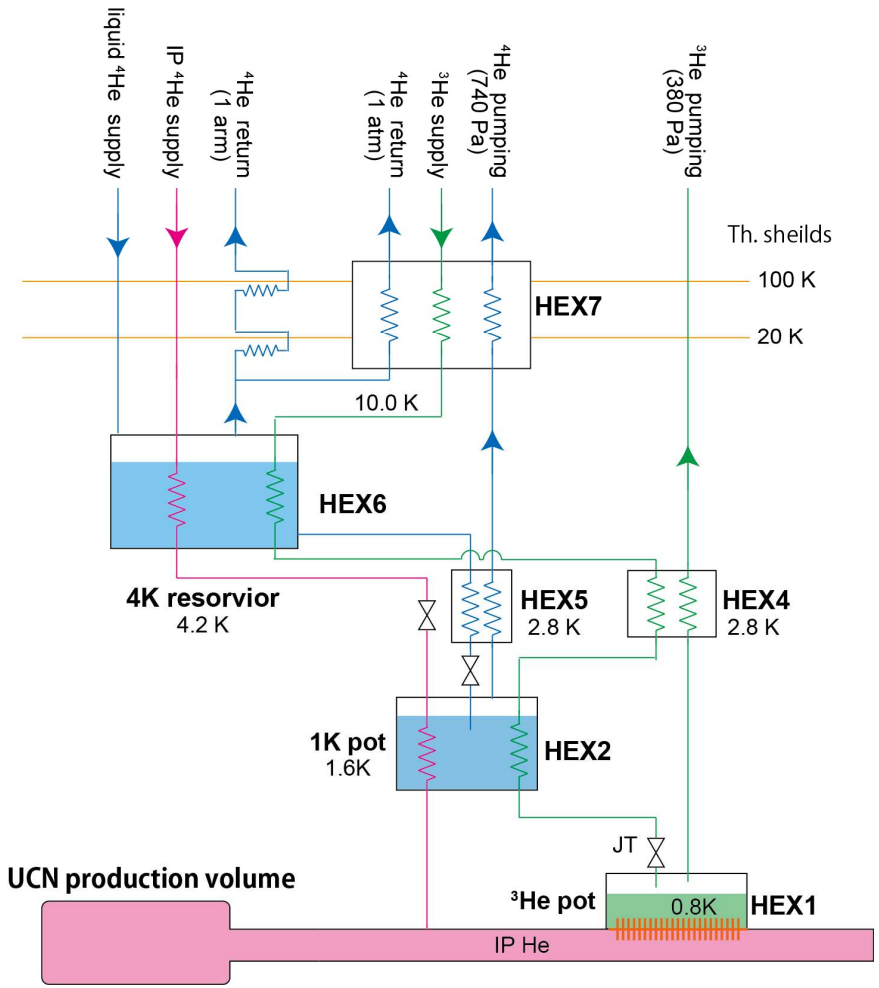
^{3}He pumping

Heat transfer in He-II

Components

1. Helium-3 cryostat
   - Have to be placed behind radiation shield
     - L = 2.0 m
   - High cooling power : ～11 W @1.0K,
     - 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 tansfer

1. Helium-3 cryostat



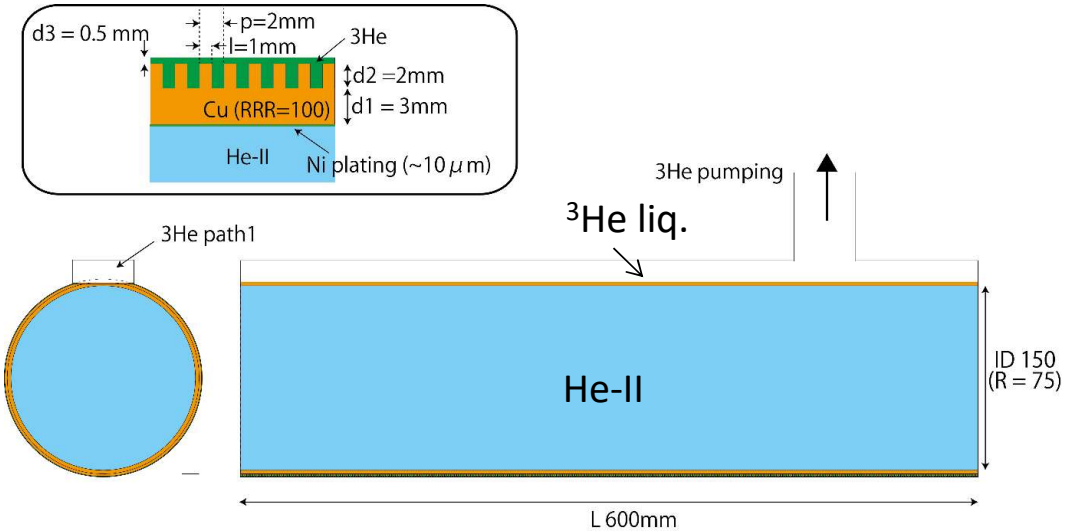
Flow diagram

- 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 m3/hour
      - P_{3He} = 380 Pa

2. Main Heat Exchanger design



- Cylindrical shape
- Material : OFHC (RRR = 100)
- Inside : He-II
  - No fin
  - Surface area :Si = 0.28 m^2
  - Ni plating
    - UCN friendly
- Outside : ^{3}He
  - Fin structure
    - Fin gap = 1 mm
    - Fin length = 1 mm
  - Surface area : So = 0.89 m_2

Kapitza conductance

- Kapitza conductance between Cu and He-II

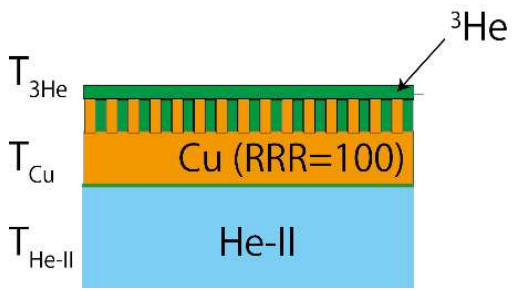
  $h_K(T) \sim 20 * K_G * T^3$ [W/m^{2}K]

  K_G = 20 - 60
- Kapitza conductance between Ni and He-II

  $h_{K\,Ni}(T) = f * h_K(T)$ f = 0.61
- Kapitza conductance between Cu and ^{3}He

  $h_{K\_3He}(T) = a * h_K(T)$ a = 1.2 – 2.6

Our recent measurement shows K_G = 45 -48

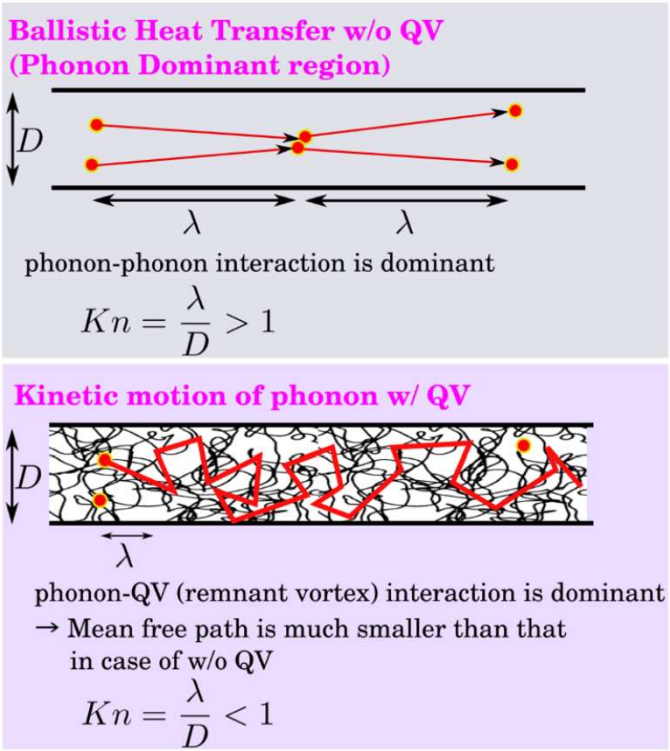


ex) K_G = 40 , T_{3He} = 0.8 K, Q = 11 W

- junction between 3He and Cu
  - ΔT_{Cu-3He} = 0.078 K
  - T_{Cu} = 0.878 K
- junction between Cu and He-II
  - ΔTNi-HeII = 0.118
  - T_{He-II} = 0.996 K

Temperature difference in the heat exchanger can be neglected

3. Heat transport in superfluid helium
10 W @ ~ 1.0 K



- Flow pattern
  - Normal fluid component is dilute around 1.0 K region
    - Knudsen number $K_n = \frac{\lambda}{D_{UCN}} < 1,$

      $\lambda \sim 0.5\ mm,\ D_{UCN} = 150\ mm$

      continuum flow
  - Superfluid laminar or turbulent ?
    - Reynolds number of normal fluid component

$$R_{e_n} = \frac{|v_n - v_s| D_{UCN}}{\upsilon_n} \sim 10^6 \gg 1200 \sim 2600$$

superfluid turbulent

Gorter-Mellink turbulent model used to evaluate heat transport

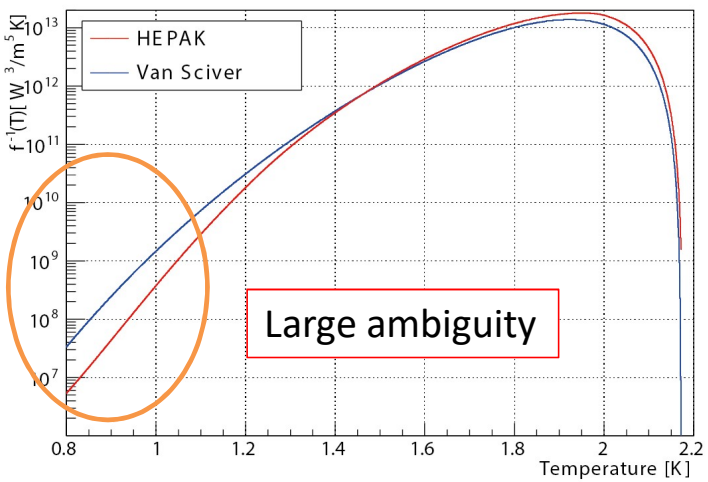
Temperature difference in He-II

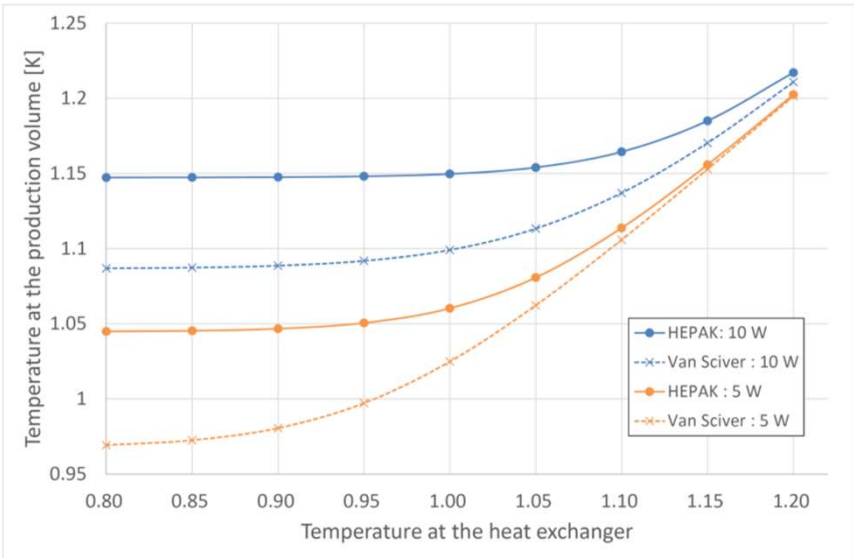
Temperature difference in superfluid helium can be calculated numerically using following Gorter-Mellink equation

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

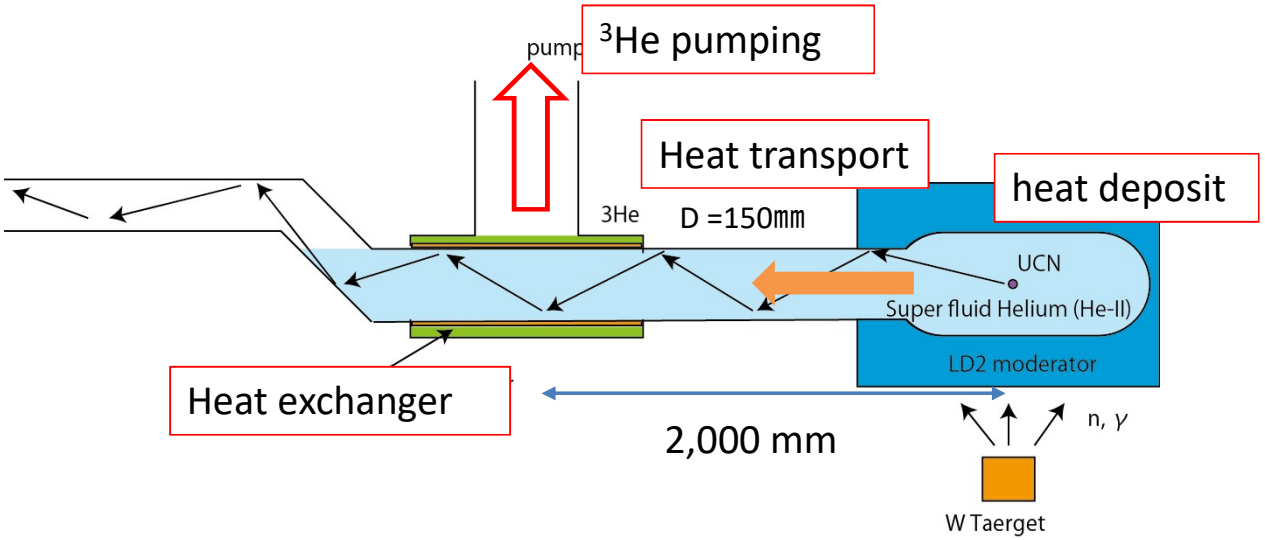
T_L : He-II temperature at the heat exchanger
T_H : He-II temperature at the UCN production volume
A : cross section of He-II
diameter = 150 mm
L : distance of heat transfer (L = 2.0 m)

f(T) : Heat transfer function





Temperature distribution in our system



Temperature distribution

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

Kapitza conductance (KG = 40)

GM heat transfer

$$T_{prod} = T_{3He} + \Delta T_{3He\text{-}Ni} + \Delta T_{Ni\text{-}HeII} + \Delta T_{HeII}$$

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
  - $T_{He\text{-}II} < 1.15$ is necessary for effective UCN production
  - Cryostat design almost complete
  - Starting cryostat construction

TRIUMF Ultra-Cold Advanced Neutron

S. Ahmed[3,4], T. Andalib[3,4], C. Bidinosti[3,8], J. Birchall[4], M. Das[3,4], C. Davis[5], E. Cudmore[5] A. Ezzat[2], B. Franke[5], M. Gericke[4], S. Hansen-Romu[3,4], K. Hatanaka[6], B. Jamieson[3], K. Katsika[5], S. Kawasaki[1], T. Kikawa[5], M. Kitaguchi[10], A. Konaka[5,8], F. Kuchler[5], E. Korkmaz[7], M. Lang[3,4], L. Lee[5], T. Lindner[3,5], Y. Makida[1], J. Mammei[4], R. Mammei[3], C. Marshall[5], J. W. Martin[3], R. Matsumiya[5], K. Mishima[1], T. Momose[2], R. Nagimov[5], T. Okamura[1], H. J. Ong[6], S. Page[4], R. Picker[5,9], E. Pierre[6,5], W. D. Ramsey[5], L. Rebenitsch[3,4], W. Schreyer[5], H. SHimizu[10], S. Sidhu[9], J. Sonier[9], I. Tanihata[6], W. T. H. van Oers[4,5], and Y. Watanabe[1]–

[1]KEK
[2]The University of British Columbia
[3]The University of Winnipeg
[4]The University of Manitoba
[5]TRIUMF
[6]RCNP
[7]The University of Northern BC
[8]Osaka University
[9]Simon Fraser University
[10]Nagoya University

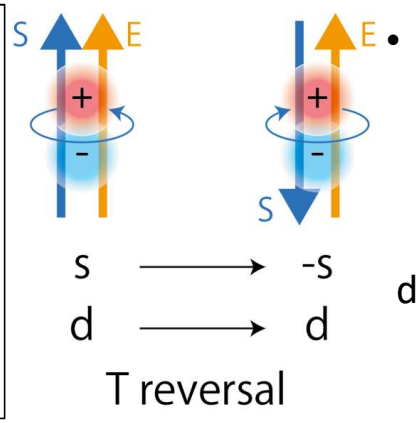
Our goal

- **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

d≠0 → T violation

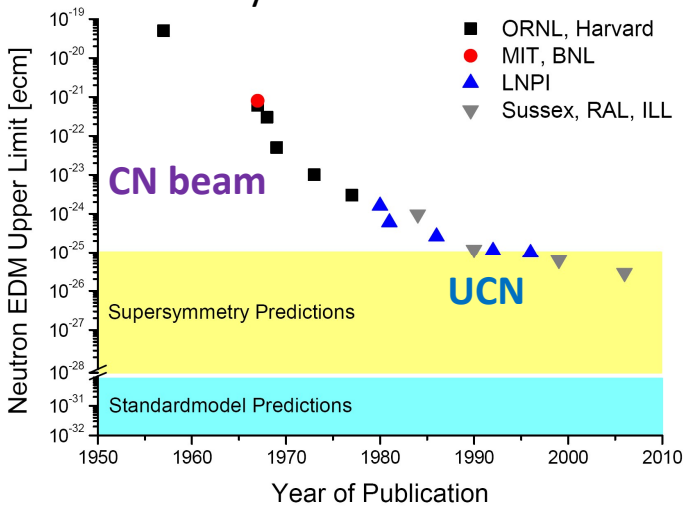
Assume CPT conservation

→ CP Vioration

nEDM prediction
SM ～10^{-32} ecm

Probe of beyond SM physics

history nEDM measurement



current upper limit of nEDM
3.0 × 10^{-26} ecm **@ILL, Grenoble**
statistics 1.5 × 10^{-26} ecm
systematics 0.7 × 10^{-26} ecm

Statistically limited
–> necessity of high intensity UCN source

Various neutrons

Fast

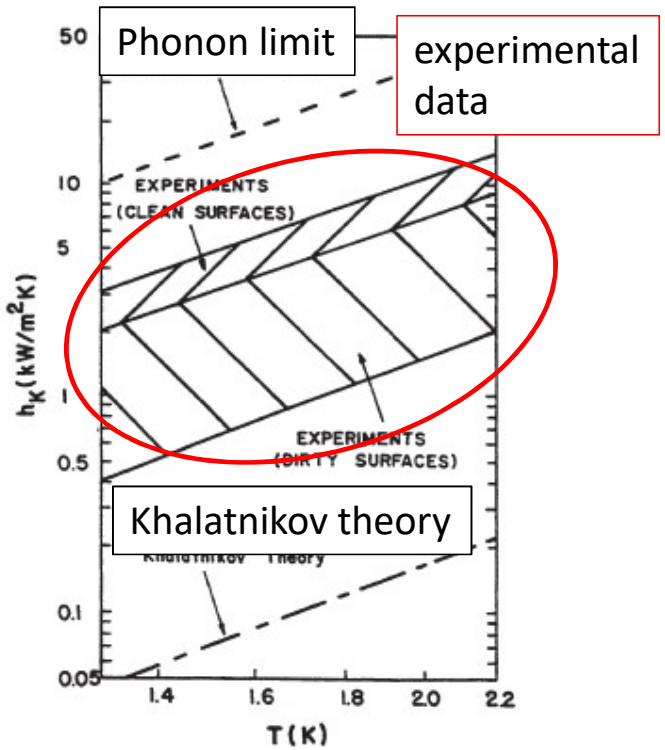
Slow

Name	Energy	Wavelength	Velocity	Temperature	Application
Fast neutron	>500 keV	40 fm	10^7 m/s	6×10^9 K	Nuclear physics Astro physics
Epi-themral neutron	10 eV	0.1 Å	44,000 m/s	1×10^5 K	Resonance capture
Thermal neutron	25 meV	1.8 Å	2200 m/s	300 K	Neutron scattering
Cold neutron	2 meV	6 Å	600 m/s	23 K	Neutron scattering for condensed matter (nm)
Very cold neutron	50 μeV	40Å	100 m/s	0.6 K	Neutron interferometer
Ultra-cold netruon UCN	**<300 neV**	**500Å**	**8 m/s**	**3 mK**	**nEDM etc.**

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
    - $h_K(T)$ ~ 4500 T^3 [W/m^{2}K]
      - 2 - 10 times larger than measured
  - Khalatnikov theory
    - $h_K(T)$ ~ 20 T^3 [W/m^{2}K]
      - 10 - 100 times smaller than measured
- Experimental data strongly depends on surface quality
  - plan to measure Kapitza conductance will be discussed T. Okamura

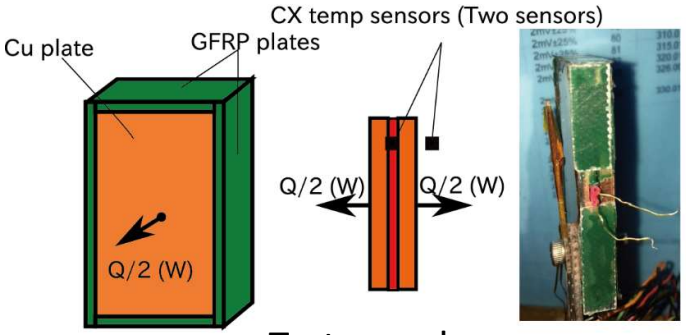


Kapitza conductance between Copper and He-II

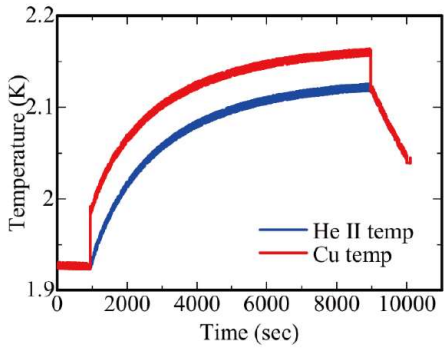
Helium cryogenics, Steven W. Van Sciver

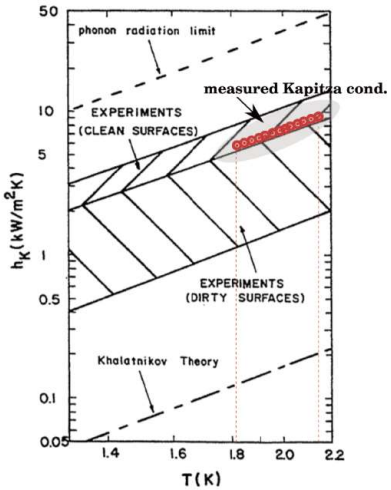
Kapitza conductance Measurement

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



Test sample





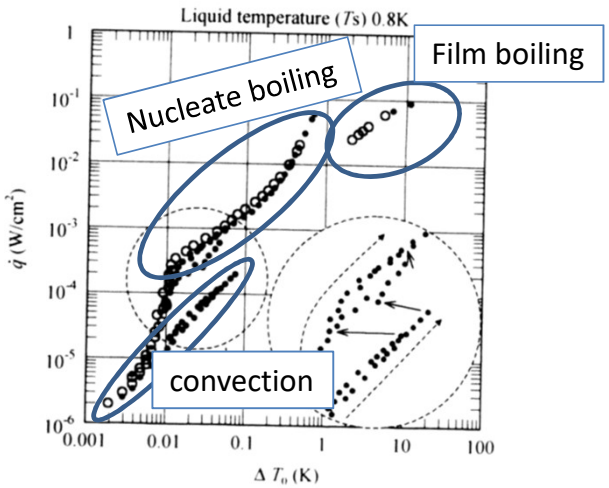
Van Sciver, Helium cryogenics

<u>Result</u>

- 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 W
  - Surface area : So = 0.89 m^2
  - Heat flux : 1.2 $\times 10^{-3}$ W/cm^2



Boing curve of helium-3 at 0.8 K

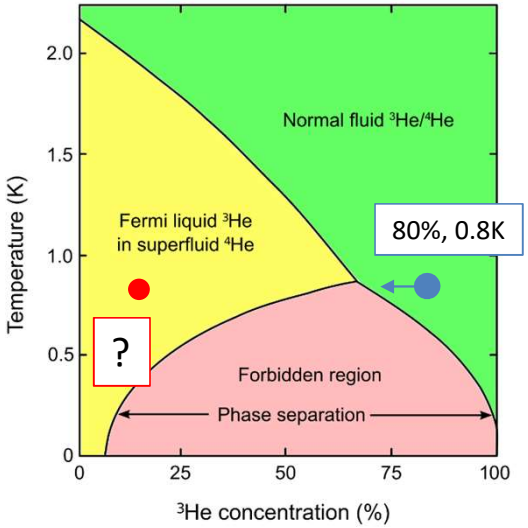
  - Heat flux of no fin design is still lower than the critical heat flux of 2 x 10^{-2} W/cm^2 for the transition from nucleate boiling to film boiling
  - However, critical heat in narrow channel might be different
    - Will be measured by the HEX test piece using helium-4

3He – 4He mixture

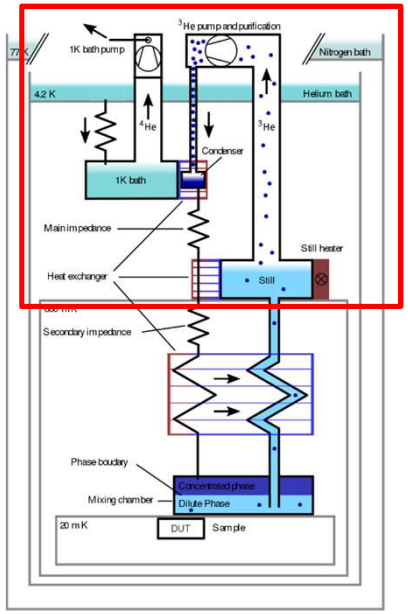
- In order to reduce necessary amount of 3He, 3He and 4He mixture might work
  - 80% of 3He and 20% of 4He mixed helium works for the vertical cryostat
    - 4He concentration of liquid in 3He pot should be larger, since main component of circulating gas is 3He
  - 80%, 0.8 K : normal fluid

- 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



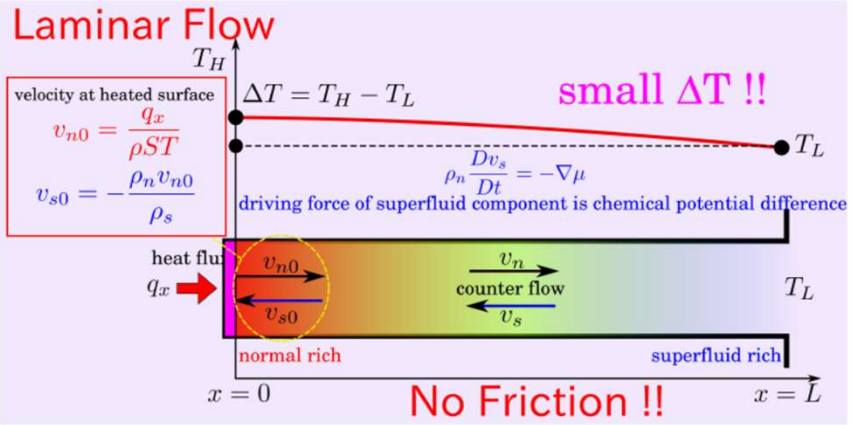
Phase diagram of 3He/4He mixture

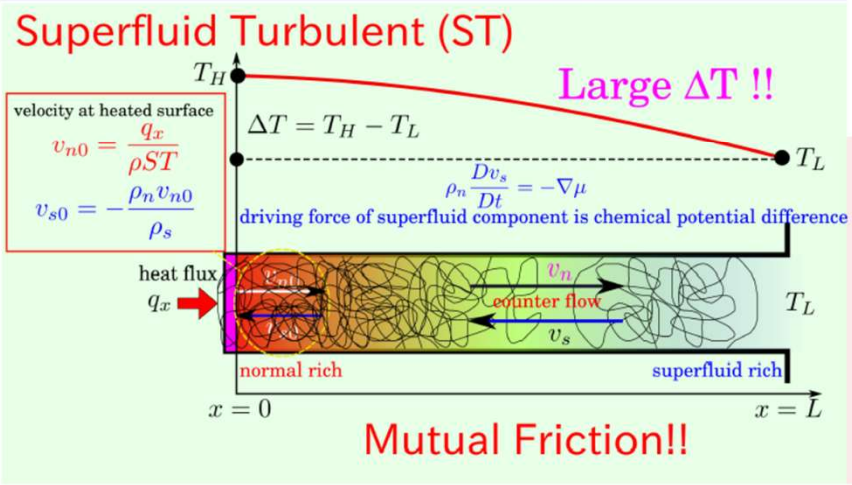


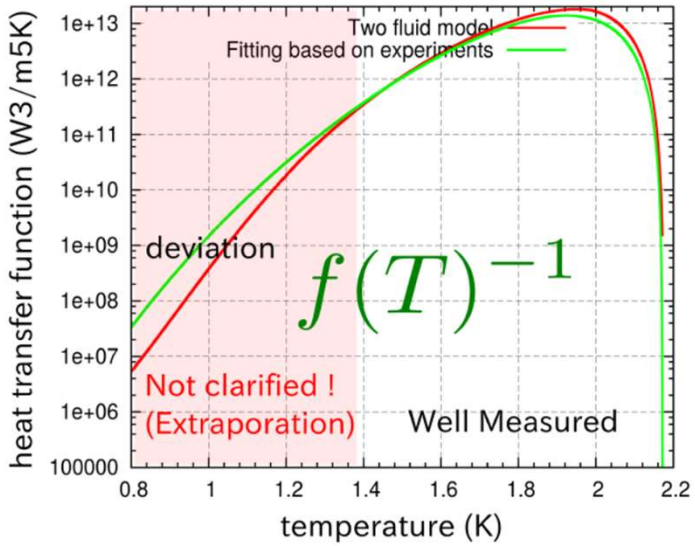
Use here

Dilution refrigerator

He IIの熱流動特性 (1)
超流動乱流 vs 層流





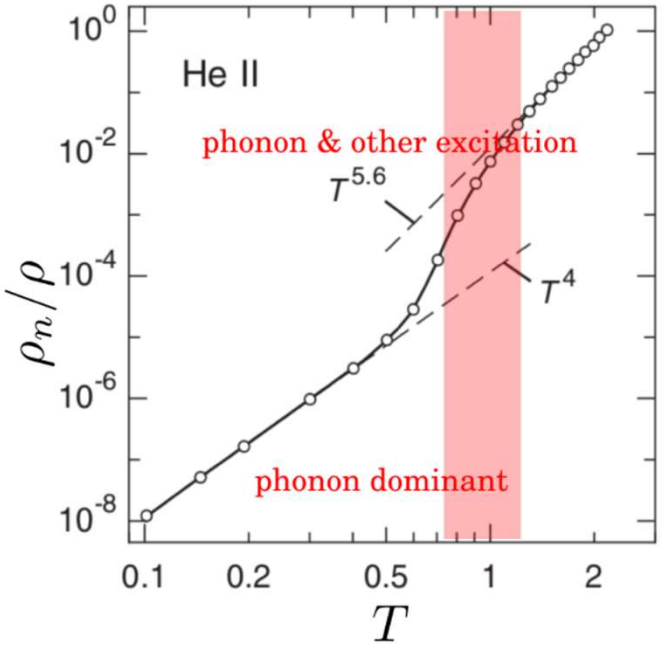


Gorter-Mellink Equation at ST

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

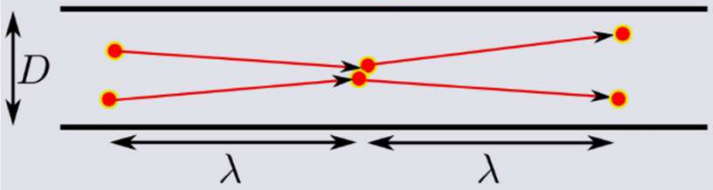
Heat transfer function, f(T)-inv, at sub K to 1K is not sufficiently clarified.

He IIの熱流動特性 (2)
バリスティック領域



power of 4 : phonon dominant
power of 5.6 : phonon + other excitation (roton)
(Quantized Vortex,QV)

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
→ Mean free path is much smaller than that in case of w/o QV

$$Kn = \frac{\lambda}{D} < 1$$

He IIの流動状態の判別

- "バリステック領域"か"連続体"かの判別

$$Kn = \frac{\lambda}{D_{UCN}} \tag{1}$$

⇒ 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

$$v_{sc} \sim D_{eff}^{-0.25} \tag{2}$$

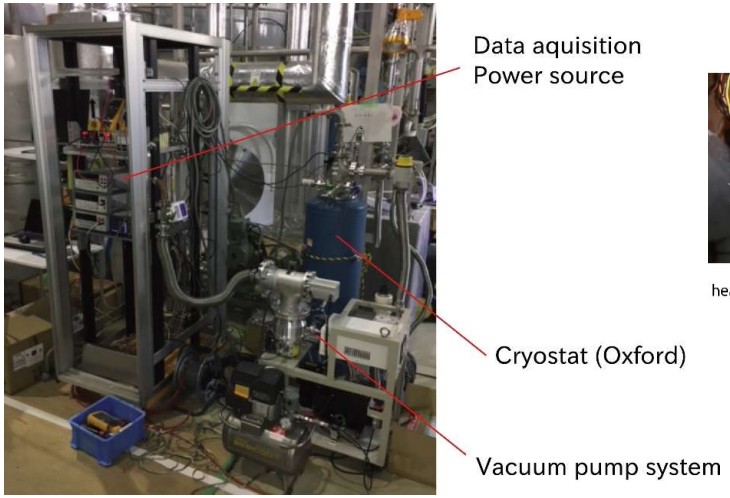
  - 常流動成分に着目した判別

$$Re_{n1} = \frac{v_n D_{UCN}}{\nu_n} > 1200 \sim 2600, \quad \nu_n = \frac{\eta_n}{\rho} \tag{3}$$

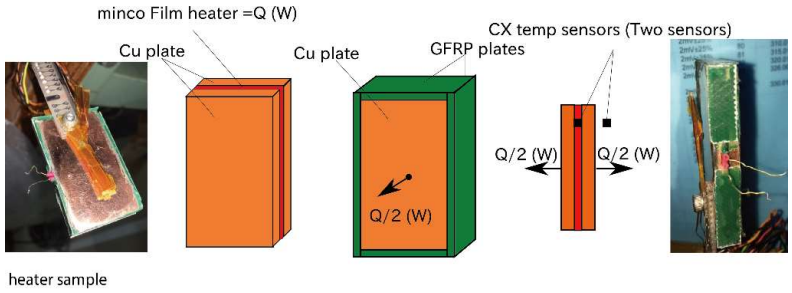
$$Re_{n2} = \frac{|v_n - v_s| D_{UCN}}{\nu_n} > 1200 \sim 2600, \quad \nu_n = \frac{\eta_n}{\rho} \tag{4}$$

⇒ 判別結果：$v_s \sim v_{sc}$, $Re_n \gg Re_{n1}, Re_{n2}$ ⇒ 超流動乱流

Kapitza conductance measurement



Setup



sample