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

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Abstract. Ultra-cold neutrons (UCNs) have a very small kinetic energy as a level of a few hundred neV and can be confined in a material bottle. The TUCAN (TRIUMF Ultra-Cold Advanced Neutron) collaboration established for aiming to build a high-intensity UCN source on a dedicated proton beamline at TRIUMF. The source is composed of a combination of a spallation neutron target and a superfluid helium UCN converter. Estimated heat deposit from spallation reaction on the superfluid helium is approximately 10 W. In order to achieve the requirement of superfluid helium temperature, a high-power helium-3 cryostat has been developed. Heat transport property in superfluid helium at 1.0 K is also a key element of the UCN source cryogenics.

1. Introduction
Ultra-cold Neutrons (UCNs) are extremely slow neutrons of which the kinetic energy is below several hundred neV. As a consequence, UCNs are totally reflected at the surface of certain materials and can be confined in a material bottle. Using this unique property, UCNs are used for various experiments such as neutron electric dipole moment searches, neutron lifetime measurements, gravity experiments, and others. In order to improve the statistical uncertainty of those experiments, a high-intensity UCN source is required.

In 1977, Golub and Pendlebury proposed to use superfluid helium as a converter for the production of UCNs [1] . Cold neutrons lose almost all of their energy by phonon scattering in the superfluid helium, then turn into UCNs. The way to produce UCNs by using phonon excitation is called superthermal method. So far, superfluid helium and solid deuterium have been realized. Solid deuterium has a high UCN-production cross section, but also high absorb cross section [2]. On the other hand, superfluid helium has a lower UCN-production cross section but can have much lower absorption.

2. UCN production in superfluid helium
The dispersion relations of free neutrons and phonons in superfluid helium cross at an energy of $E$ of around 1 meV. A neutron with that energy excites a single phonon and lose almost all of its energy and momentum. Neutrons which have slightly higher than the energy excite multiples phonons in the same process [3][4]. The UCN production rate $P$ is given by the cold-neutron
flux $\Phi(E)$ and scattering cross section $\sigma(E)$:

$$P = \int \Phi(E)\sigma(E)dE. \quad (1)$$

The UCN lifetime $\tau$ in superfluid helium is given by the lifetime of up-scattering $\tau_{\text{He}}$, wall loss $\tau_{\text{wall}}$, absorption of $\tau_{\text{abs}}$, and beta decay $\tau_{\beta}$:

$$\tau^{-1} = \tau_{\text{He}}^{-1} + \tau_{\text{wall}}^{-1} + \tau_{\text{abs}}^{-1} + \tau_{\beta}^{-1}. \quad (2)$$

The wall-storage lifetime is determined by the material, cleanness, and roughness of the wall surface of the vessel material and it is typically on the order of tens to hundreds of seconds. The absorption lifetime is dominated by the contamination of $^3\text{He}$ which has a high neutron-absorption crosssection. In natural helium which has a $^3\text{He}$ abundance of $10^{-6}$ the absorption lifetime is less than 100 ms. Isotopically pure helium of which $^3\text{He}$ abundance below $10^{-12}$ can increase the absorption lifetime to several thousand seconds. The up-scattering which is the inverse reaction of the UCN production strongly depends on the temperature of $T$ of the superfluid helium and roughly follows

$$\tau_{\text{He}}^{-1} \sim B \left( \frac{T}{1\text{ K}} \right)^7, \quad (3)$$

where $B$ between 0.008 s$^{-1}$ and 0.016 s$^{-1}$ [5]. In order to suppress the up-scattering to a similar level as the wall loss, the superfluid helium to be cooled down to a temperature around 1 K.

3. TUCAN source

The TUCAN (TRIUMF Ultra-Cold Advanced Neutron) collaboration has been developing a high-intensity UCN source on a dedicated proton beam line at TRIUMF, Canada. The UCN source is composed of a spallation neutron source and a superfluid helium UCN converter. Since this combination allows us to place the converter close to the spallation target, the high cold neutron flux is available at the UCN converter. In order to realize it, a cooling scheme to keep the superfluid helium UCN converter temperature around 1.0 K under the high radiation heat load needs to be developed.

The demonstration of UCN production was succeeded by using a prototype UCN source, which was developed at the Research Center for Nuclear Physics, Osaka, Japan [6]. The source was operated 0.8 K for the proton beam power of 0.4 kW. A $^3\text{He}$ cryostat is used to cool down the converter.

The prototype source was moved to and installed on a dedicated proton beamline in the meson hall at TRIUMF [7]. Commissioning of this source commenced at TRIUMF in November 2017 [8]. Following the first successful UCN production, a significant upgrade is planned with the goal to obtain the highest UCN intensity in the world. The key component of the improved apparatus is a new $^3\text{He}$ cryostat to remove high radiation heat from the superfluid helium UCN converter and thus allow for higher proton beam currents on the spallation target.

Figure 1 shows schematic diagram how to produce UCNs. The proton beamline can supply a 480 MeV $\times$ 40 $\mu$A = 40 kW proton beam on a tungsten target. High-energy neutrons are produced by spallation reaction and cycled down to cold-neutron energy range by neutron moderator consist of heavy water and liquid deuterium. The cold neutrons excite a single phonon or multiple phonons in the superfluid helium converter whereby they lose almost all kinetic energy and thus become UCNs.

The superfluid helium converter of 21 liters is used for the TUCAN source. The superfluid is surrounding by 125 litters of liquid deuterium. A study using the particle simulation tool...
MCNP6 [9] has been conducted to optimize UCN production. This study estimated the heat load on the superfluid helium and its vessel to be 5-10 W. This heat is transported to the helium cryostat by a 2 m long UCN guide filled with superfluid helium in order to place radiation shield in between.

3.1. Flow diagram of $^3$He cryostat

Figure 2 shows a flow diagram of the new $^3$He cryostat. $^3$He is circulated in a closed-loop. The $^3$He introduced from room temperature is cooled down by heat exchangers then condensed at the 1 K pot which filled decompressed liquid of natural helium. The liquid $^3$He is lead to a Joule-Thomson valve at which isenthalpic expansion occurs. After the expansion $^3$He becomes 0.8 K.

The cryostat is designed to have static heat load less than 1 W. The maximum heat load to deal with is 11 W. Necessary $^3$He mass flow for the heat load is 1.14 g/sec. In order to keep $^3$He saturated at the temperature of 0.8 K, necessary pumping speed is calculated as 8,800 m$^3$/hour.

Table 1 shows the design value of the temperature of each point. $^3$He from room temperature is cooled down to 10 K by a counter flow type heat exchanger called HEX7. After the HEX7, $^3$He gas is cooled by a coil heat exchanger in a 4.2 K natural helium bath. Before the 1 K pot, $^3$He temperature cool down to 2.8 K by another counter flow type heat exchanger is placed in the $^3$He pumping duct. Heat deposit on 1 K pot by cooling and condensation of $^3$He is 21.4 W for the $^3$He mass flow. In order to achieve 1 K pot temperature of 1.6 K, the necessary pumping power is 3,600 m$^3$/hour.

3.2. Heat exchanger for the UCN converter cooling

A cylindrical heat exchanger, manufactured from oxygen-free copper, is used to remove the heat produced in the converter. This heat exchanger is called HEX1 in figure 2. As shown in the figure 3, the interior of the heat exchanger is filled with the superfluid helium for neutron conversion, while its external surface is in contact with liquid $^3$He. Fins on the outer surface increase the contact area with the $^3$He. On the other hand, the inner surface of the heat exchanger is kept flat...
Figure 2. Flow diagram of the $^3$He cryostat

Table 1. Temperature assumption

| Component                        | Temperature (K) |
|----------------------------------|-----------------|
| $^3$He pot                       | 0.8 K           |
| 1 K pot                          | 1.6 K           |
| $^3$He before 1K pot             | 2.8 K           |
| 4 K reservoir                    | 4.2 K           |
| $^3$He before 4K reservoir       | 10 K            |
Table 2. Heat exchanger parameters

| Material                  | oxygen-free copper (RRR > 100) |
|---------------------------|---------------------------------|
| Length                    | 600 mm                          |
| Diameter                  | 150 mm                          |
| Fin length                | 2 mm                            |
| Fin pitch                 | 1 mm                            |
| Surface area: inside      | 0.28 m²                         |
| Surface area: outside     | 0.89 m²                         |

To avoid excessive UCN wall losses that would be associated with a fin structure. In addition, it is plated with nickel-phosphorus (NiP) for a good UCN storage.

The Kapitza conductance $h_K$, as discussed in several text books (see, e.g., Ref. [10]), is the conductance at the thermal boundary between a solid and liquid helium. The value of the Kapitza conductance is described using a correction factor $K_G$:

$$h_K = K_G \times 20 \frac{W}{m^2K^4} \times T^3.$$  \hspace{1cm} (4)

Empirically, a $K_G$ value between 6.5 and 65 is obtained by various experiments. The surface cleanliness of the copper affects the Kapitza conductance, which can be increased by mechanical and chemical treatments. Our recent measurement shows the $K_G$ value between 45 and 48. For the conservative estimation, $K_G$ of 20 or 40 is used for the design of the heat exchanger.

The outer surface of the heat exchanger is filled with the liquid $^3$He. According to [11] and [12], the relation of the Kapitza conductance between copper and $^3$He and that between copper and superfluid helium:

$$h_{K(He-II)} = a \times h_{K(3He)} \hspace{1cm} a = 1.2 - 2.6$$  \hspace{1cm} (5)

The Kapitza conductance between nickel and superfluid helium is estimated by phonon radiation limit discussed in [10]. Comparing the Debye temperatures (Cu: 343.5 K and Ni: 910 K):
450 K) and atom number densities of copper and nickel, the ratio of the Kapitza conductance of these materials is

$$h_{K(Ni)} = 0.61 \times h_{K(Cu)}.$$  \hfill (6)

Using the surface areas of the heat exchanger provided in Table 2, its Kapitza conductance can be calculated with Eqs. (4), (5) and (6). In case of the heat load of 11 W, $^3$He bath temperature of 0.8 K, and the case of $a = 2.6$ which are conservative estimation, the temperature $T_{HEX}$ at the outer surface of the heat exchanger is 0.956 K and 0.878 K and the temperature $T_{He-II}$ of the superfluid helium close to the inner surface is 1.14 K and 0.996 K for $K_G$ value of 20 and 40 respectively. The temperature difference along the fins and in the bulk of the heat exchanger can be neglected because heat conductance in the bulk is much larger than the Kapitza conductance.

### 3.3. Heat transport in superfluid helium

Here we discuss the heat transport through the superfluid-helium filled UCN guide between the UCN production chamber and the heat exchanger. The two-fluid model is often used to describe the thermo-fluid behavior of superfluid helium. The ratio of the superfluid to the normal fluid components depends on the temperature. At the temperature below 1.0 K the superfluid component is dominant. Since the superfluid component has no entropy and viscosity, the normal component plays a role in energy transport. Heat transfer in a superfluid occurs via a counter flow between the superfluid and normal fluid components. If the relative velocity between these two components exceeds a critical value, mutual friction occurs between them. This is regarded as a superfluid turbulent state. The Reynolds number of the normal fluid component is described as

$$Re_n = \frac{u_n D_{UCN}}{\nu_n}, \quad \nu_n = \eta_n/\rho,$$

where $u_n$ is the velocity of the normal fluid, $\eta_n$ is its viscosity, $\rho$ is the total helium density [10], and $D_{UCN}$ is the UCN guide diameter. For a heat load of 11 W and $D_{UCN} = 150$ mm, the Reynolds number is calculated to be $Re_n \sim 10^6$, using data from the HEPAK dataset [13]. This is much larger than the critical value $Re_{nc} = 1200$. Therefore, the flow can be regarded as a turbulent superfluid.

The temperature gradient during turbulent heat transport in steady-state can be described with

$$\frac{dT}{dx} = -f(T)q^3,$$

where $f(T) = A_{GM}p_n/(\rho^3 s^4 T^3)$ is a heat conductivity function. $A_{GM}$ is the Gorter-Mellink mutual friction parameter, $s$ is the entropy, and $p_n$ and $\rho_n$ are the normal and superfluid densities. The values of $A_{GM}$ are also available from HEPAK [13]. Based on an empirical fit by Van Sciver [10] to the Gorter-Mellink parameter, it is possible to parametrize this heat conductivity function:

$$f^{-1}(T) = g(T_\lambda) \left[ t^{5.7} (1 - t^{5.7}) \right]^\lambda,$$

where $g(T_\lambda) = \rho^3 s^4 T_\lambda^3 / A_\lambda$, $t = T/T_\lambda$, $s_\lambda = 1.559$ J/(kg·K), $A_\lambda = 1450$ m/s/kg, $\rho = 145.2$ kg/m$^3$, and $T_\lambda = 2.172$ K [10]. The heat transport efficiency has been determined with high accuracy by many experiments at temperatures around 1.4 K or more. However, it has a large discrepancy in the vicinity of 1.0 K, at which the Van Sciver parametrization obtains larger heat conductivities.

In a straight channel with a length $L$ and a cross section $A$, the total heat transport $Q$ is given by

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

where $T_L$ and $T_H$ are the temperatures at the start and end of the channel, respectively.
where $T_L$ and $T_H$ are low-temperature and high-temperature end of the superfluid-helium. In our system, $T_L$ and $T_H$ mean temperature at the $^3$He cryostat and the production volume, respectively. Fig. 4 shows the temperature at both ends, calculated for $A = D_{UCN} = 150$ mm and $L = 2.0$ m, and for heat loads of 5 W and 10 W in the UCN production chamber.

Table 3 lists the temperatures at the heat exchanger and in the UCN production volume, for values of the function $f(T)^{-1}$ derived from the HEPAK and Van Sciver equations. The correction factor $K_G$ of the Kapitza conductance (see Eq. (4)) typically exceeds 20. For $K_G > 40$, as indicated by our latest measurements, we can thus achieve a UCN source temperature below 1.14 K.

**Table 3.** Important temperatures of the UCN source cryostat. The conversion factor $a$ (see Eq. (5) is assumed to be 2.6, the maximum value.

| heat load | $^3$He | $T_{\text{He,HEX}}$ | $T_{\text{prod}}$ | $f(T)^{-1}$ | Van Sciver | HEPAK |
|-----------|--------|------------------|------------------|--------------|------------|-------|
|           |        | $K_G$ = 20 40    |                  |              |             |       |
| 10 W      | 0.8    | 1.14            | 0.996            | 1.16 1.18    | 1.10 1.14  |       |

**4. Summary**

UCNs are used for various physics experiments. The TUCAN collaboration has been developing a high-intensity UCN source at TRIUMF. This source combines a spallation neutron source and a superfluid helium UCN converter. Effective UCN production requires the superfluid temperature to be maintained at approximately 1.0 K. The heat load from the spallation target is estimated to be 5 - 10 W. The development of the helium cryostat to remove this amount of heat is ongoing. In this article, we have analyzed in some detail the heat exchanger and the heat transfer in superfluid helium, which are key parameters for achieving the target temperature.

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