New type liquid He free $^3$He Cryostat using Commercial GM Refrigerator

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Abstract. We have succeeded to construct a novel $^3$He cryostat by improving a low cost commercial two stage Gifford-McMahon (GM) refrigerator whose cooling power is 0.3 W at 4.2 K. This main portion of this system consists of 4 K pot, 1 K pot, heat exchanger and $^3$He pot, which are connected to the second cold stage. The main portion is covered with the 1st radiation shield attached to the 1st cold stage and the $^3$He pot is covered with the 2nd radiation shield attached to the heat exchanger, where the 1st shield must be further covered with more than five layers of super-insulation films in order to realize $^3$He temperature. The achieved temperature is 0.4 K and persists over one day. The temperature oscillation is less than 1 mK below 4 K. The required time to attain the lowest temperature is typically about 8 hours. This system allows us to deal with almost all the low temperature experiments of condensed matter physics without requiring low temperature technique.

1. Introduction
Some heavy fermion systems show superconductivity near the critical point where the magnetic order disappears. The appearance of the superconductivity is considered to be closely related to the magnetism of the $f$ electrons, and the elucidation of the mechanism is an important issue. The superconductivity, however, appears typically at temperatures less than 1 K. Since such low temperature is usually realized by using expensive liquid $^4$He, a lot of researchers without available $^4$He liquefaction facilities have great difficulties to investigate such fascinating heavy fermion systems.

One way to resolve this problem is to apply mechanical cryocoolers such as Gifford-McMahon (GM) refrigerator. Since the demand for the mechanical cryocoolers from various fields has grown rapidly in recent years, the performance has improved and the price has fallen. Nevertheless they can use only as a supplementary cooling apparatus for the above study due to the available lowest temperature of 3 K and large temperature oscillation. Although some cryocoolers which combine GM or pulse-tube refrigerator with Joule-Thomson (JT) circuit are able to attain temperature below 1 K [1, 2], they are not easy to be operated due to complex and large systems, and furthermore can be applied to limited experiments.

The purpose of this paper is to develop a compact refrigerator system less than 1 K without using neither liquid $^4$He and JT circuit. In order to achieve this, we have tried to improve a low cost two stage GM refrigerator. As a result, we have succeeded to realize $^3$He temperature in a simple way, and moreover to reduce temperature oscillation to less than 1 mK. This performance is enough for the experiments of heavy fermion systems.
2. $^3$He GM refrigerator system

Figure 1 shows a cross-cut drawing of the $^3$He GM refrigerator. The hatch indicates the GM refrigerator used in this study (RDK-205D, Sumitomo Heavy Industries, Ltd.). According to the catalog specifications, the cooling power of RDK-205D is 40 W at 50 K for the first stage and 0.5 W at 4.2 K for the second stage, but actually the cooling power for the second stage was 0.3 W at 4.2 K. The achieved lowest temperature for the GM unit only was 3.0 K. The most important portion of our system consist of 4 K pot, 1 K pot, heat exchanger and $^3$He pot. The 4 K pot made of copper, which is tightly screwed to the second cold stage through Apiezon N grease for good thermal contact, plays a role to liquefy $^4$He gas. Note that Indium sheet instead of the grease must not be used, because it becomes superconductor below $T_C = 3.4$ K and the thermal conductivity decreases rapidly below $T_C$. The 1 K pot is connected to the 4 K pot via thin CuNi pipe of 0.3 mm in thickness ($\phi 15 \times 40$ mm), and the role is to keep a steady temperature of 1.3 K by evacuating liquid $^4$He liquefied by the $^4$He pot. The volume of the 1 K pot depends on requiring time for 1.3 K, as an example, a standard volume to maintain for 6 hours is about 30 cc. Although 1 K pot is made of Cu for the present system, any materials can be used. The heat exchanger made of copper is silver soldered to the bottom of the 1 K

**Figure 1.** Cross-cut drawing of $^3$He GM refrigerator. The part shown by hatch is a two-stage GM refrigerator.

![Figure 1](image1.png)

**Figure 2.** Schematic block diagram of $^3$He GM refrigerator system. P1 ~ P4 and V1 ~ V11 denote pressure gauges and valves, respectively.

![Figure 2](image2.png)
pot, is cylindrical shape with 50 mm in diameter and 6 mm in height, and the hole of $\phi 3 \times 40$ mm is drilled in the side. The $^3$He pot is connected to the heat exchanger via thin CuNi pipe of 0.2 mm in thickness ($\phi 5 \times 35$ mm). We use thin bellow tubes (swagelok 321-4-X-4, 1/3 inch) as parts of $^3$He and $^4$He line in order to reduce thermal conductivity from room temperature and to increase tube conductance of the lines. The 1st radiation shield made of Cu of 0.5 mm in thickness and 70 mm in diameter is connected to the 1st stage, and is covered with five layers of super-insulations made of evaporated Al film on thin Mylar sheet. The employment of super-insulations is absolutely necessary to realize $^3$He temperature, for the bottom temperature of the radiation shield without super-insulations is above 150 K, while the temperature with it is less than 50 K. The 2nd radiation shield attached to the heat exchanger is necessary for better performance.

Figure 2 shows a schematic block diagram of $^3$He GM refrigerator system. A $^3$He gas handling system ($^3$He GHS) with $^3$He of 3 ℓ at STPD is connected to the $^3$He line. A rotary pump with a pumping speed of 500 ℓ/min (1 K rotary pump) and $^4$He container of 45 ℓ are connected to the $^4$He line. In order to supply $^4$He gas, a $^4$He cylinder is connected to the $^4$He container. A rotary pump with a pumping speed of 150 ℓ/min is used for evacuating the vacuum space, the $^4$He-line and the $^3$He-line.

A typical operation is as follows. Before the power supply of the GM refrigerator is turned on, $^4$He gas and $^3$He gas are introduced into 1 K pot and $^3$He pot, respectively, by opening valves V1, V6 and V9. Figure 3 shows a cooling process of the $^3$He refrigerator shown in Fig. 1. Required time to cool below 10 K are 1.6, 4.5 and 5.5 hours for the 4 K pot, 1 K pot and $^3$He pot, respectively, where the $^4$He pot temperature is almost the same as the 2nd cold stage. It is about eight hours to attain the lowest temperature for the present system. This time depends on heat capacities of the pots, and the pipes between the pots. Figure 4 shows the temperature variation of $^4$He pot, 1 K pot and $^3$He pot in steady state. $^3$He gas is almost condensed 15 minutes after pumping 1 K pot, and for another 15 minutes $^3$He pot temperature decreases to the same temperature as 1 K pot. Then, $^3$He GHS is operated, followed by valve V8 is closed and 1 K rotary pump is stopped. The reason why 1 K pump is stopped is that the evaporation of liquid $^4$He is much faster than liquid $^3$He due to film-flow in $^4$He superfluid. If 1 K pot is continued to be pumped and empties, 1 K pot temperature rises up to about 10 K due to

![Figure 3](image3.png)  
**Figure 3.** Cooling process from room temperature to liquid $^4$He temperature of $^3$He pot, 1 K pot and 4 K pot. The horizontal axis is an elapsed time from when the power supply of the GM refrigerator was turned on.

![Figure 4](image4.png)  
**Figure 4.** Time dependence of temperature of $^3$He pot, 1 K pot and 4 K pot in steady state. The horizontal axis is an elapsed time from when the 1 K pot was begun to be evacuated by 1 K rotary pump.
thermal radiation from the 1st radiation shield. On the other hand, if the evacuation of 1 K pot is stopped, 1 K pot temperature approaches gradually up to the 4 K pot temperature of 3.0 K, because liquid 4He remains in 1 K pot and plays a role as heat exchange gas. As shown in Fig. 4, 3He temperature persists over 1 day, which is enough time for normal physical property measurements. We enhance that the temperature oscillation is strongly reduced to less than 1 mK below 4 K due to large heat capacity of 3He, compared to 0.3 K at 4.2 K for GM unit only.

As an example of measurement, we show a result of ac susceptibility of some superconducting elements and the transitions can be clearly seen. The measurement was done by a standard Hartshorn bridge circuit, and both small coils and samples were set inside 3He pot and immersed into liquid 3He. The development of magnetization (VSM) and heat capacity measurement system are now in progress.

3. summary
We have succeeded to construct a novel type of 3He GM refrigerator, which employs Cascade method, i.e., the main portion consists of 4 K pot, 1 K pot, heat exchanger and 3He pot. This system can generate temperatures down to 0.4 K in about 8 hours after switched on, and persists over 1 day by one shot operation, and furthermore the temperature oscillation is less than 1 mK. Since this system does not adopt JT circuit, it is quite compact and easy to operate. In addition, samples as well as measurement sensors can be set to whether outside or inside 3He pot, and therefore it can be applied to almost all the condensed matter physics experiments. We hope that this system is widely utilized by researchers with difficulties to use liquid 4He.

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References
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