Operation of a dilution refrigerator in a micro mode.

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Abstract

It is shown that a dilution refrigerator in which ^{3}He circulates due to condensation of He evaporating in the still on a cold wall at T = 0.4-0.5 K and condensate drains down to the mixing chamber can operate at ^{3}He circulation rate down to 1 μmol/s. On the base of this result we designed and tested experimental DR with sorption pumping of ^{3}He bath and 1 K pot which can be inserted in a helium transport Dewar with a 24 mm hole in the neck.

Key words: dilution refrigerator ; condensation pumping

1. Introduction

Due to their unique properties (high sensitivity, excellent energy resolution), radiation and particle detectors cooled to temperatures of several hundredth of Kelvin find various application. Applications, such as X-ray microanalysis [1,2] and experiments on particle Dark Matter search [3], can be mentioned. Requirements for the refrigerator designed for cooling existing detectors are rather modest. A temperature of 0.05-0.1 K is sufficient for their operation, and the energy flux by the measured signal is negligibly small compared to the parasitic heat flux of the order of 0.1 μW to the low temperature stage. Two types of instruments can be used to get temperatures in this region: an adiabatic demagnetisation refrigerator (ADR) or dilution refrigerator (DR). The latter has in principle some evident advantages but commercially available DR's do not suited for detector application.

The operation of DR in a continuous mode, when ^{3}He pumped out from the still liquefies and returns trough a heat exchanger to the mixing chamber, is described by the formula [4]

$$\dot{Q}/\dot{n} + 12.5T_c^2 = 94.5T^4 \qquad (1)$$

where $\dot{Q}$, W, is the heat delivered to the mixer, T and T_c, K, are the temperatures of the mixer and incoming concentrated ^{3}He at the inlet to the mixer, and $\dot{n}$, mol/s, is the ^{3}He circulation rate. This formula shows that the larger is ^{3}He circulation rates, the lower the mixer temperature. Therefore, the designers of DR's strive to provide a high circulation rate reaching 0.1 - 1 mol/s. As a result, such DR becomes rather complex, requires the use of high-capacity evacuation equipment, and setup becomes bulky and expensive. But in the case of detectors cooling according to formula (1) a circulation rate of the order of 1 μmol/s is sufficient. Taking this into account, we investigated the possibility for DR to operate in such a micro mode [5]. On the base of this research we designed and tested experimental DR with sorption pumping of ^{3}He bath and 1 K pot which can be inserted in a helium transport Dewar with a 24 mm hole in the neck.

2. Experimental setup

Investigations were performed with a dilution refrigerator in which ^{3}He circulates due to condensation of He evaporating in the still on a cold wall at T = 0.4-0.5 K and condensate drains down to the mixing chamber [6]. The wall is cooled by pure liquid ^{3}He, whose

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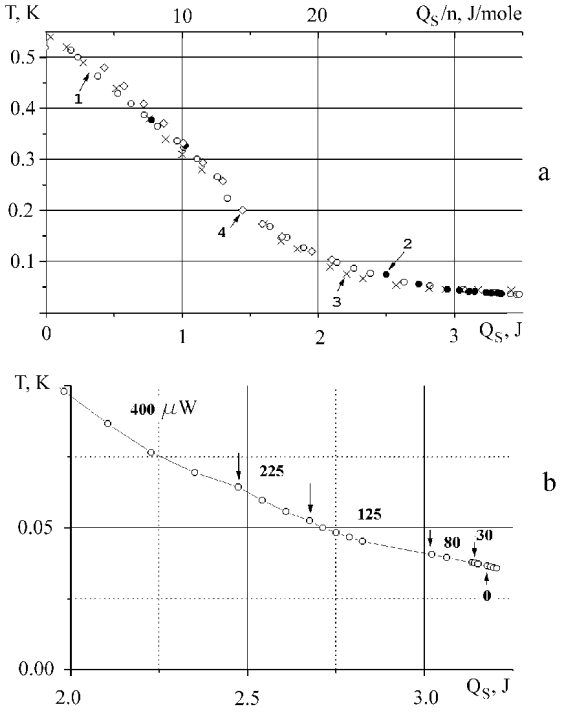

Fig. 1. The temperature of the mixer versus heat Q_S fed to the still (for points 1,2) and Q_S normalized to molar amount n of ^{3}He in the mixer (for all points). Different points correspond to different runs. A mixture contained 0.1 (points 1, 2) and 0.17 mol (points 3, 4) of ^{3}He. On fig.(b) the values of the electric power fed to the still and arrows indicating the moments of power switching are denoted.

vapours are evacuated by a sorption pump. We used the same installation as in [6] with moderate changes in a low-temperature cell described in [5].

Precooling of DR cell filled with mixture to about 0.5K was made by pumping out liquid ^{3}He condensed into the bath . After that the heater of the still was switched on. The temperature change rate at T>0.1 K was nearly proportional to the power $\dot{Q}_S$ fed to the still, amounting to 0.01 K/min at $\dot{Q}_S$=400 μW. At lower temperatures the cooling rate becomes slower.

In order to estimate the efficiency of DR, we should plot the function T(Q_S), where Q_S is the heat energy fed to the still (or T(Q_S/n) to account for mixture specific heat, nearly proportional to the molar amount n of ^{3}He in a mixture). Such a plot (Figs.1 a,b) is convenient, because, within rather wide ranges of still and mixer temperatures almost pure ^{3}He evaporates from the still and the heat of evaporation is 23 J/mol [7]. Thus, the power fed to the still unambiguously determines the ^{3}He circulation rate. It can be seen that points for different experiments in Fig.1a lie close to each other.

The experiment has demonstrated that the mixer temperature continued lowering even after the heater was switched off. This indicates that the still obtains heat from another source, probably, due to superfluid film flow on the wall of the filling capillary, attached to the bottom of the still. From the known critical velocity [8] we can evaluate the heat flux to the still as about 20-30 μW. When plotting the curves in Fig.1, we used an additional heat flux of 30 μW, which is a reasonable value corresponding to a fairly smooth curves T(Q_S).

Fig.1b allows us to estimate the DR efficiency: when the heating power is switched at T=0.065 K kink is observed and the $|dT/dQ_S|$ rises from 0.042 to 0.067 K/J as the power decreases. There are two reasons for this effect. First, the lowering of the still temperature (from 0.9K at Q_S=400 μW to 0.75 K at 225 μW), and, as a result, the heat of evaporation decreases and the content of ^{3}He in the vapour rises. According to [7, Fig.20], for 0.1mol of ^{3}He with specific heat 25T J/mol, the values of $|dT/dQ_S|$ must be 0.052 and 0.08 K/J correspondingly.

The small differences between experimental and calculated figures my be due to the second reason: the heat flux to the mixer caused by incoming concentrated ^{3}He decreases with decreasing circulation rate. A 1 μW of a heat flux at S=400 μW (and T_c=0.1K) is sufficient to account for difference. As was shown in [4] for tubular heat exchanger,

$$T_c^2 = 50R \times \dot{n} \qquad (2)$$

Here R is Kapitza resistance ((6-10)$\times 10^{-3}$ K^{4}m^2/W for cupronickel). This formula for $\dot{n}$=10 μmol/s ($\dot{Q}_S$=400 μW) yields T_c = 0.08 - 0.1 K for our heat exchanger in good agreement with the value presented above. According to formula (2), if the heat flux to the mixer from other sources is sufficiently small, then a temperature of 10 mK can be expected at a circulation rate of 1 μmol/s.

Thus we get very important results that DR with condensation pumping can operate at temperatures 0.035 - 0.05 K or even lower at circulation rate of about 1 μmol/sec.

3. Construction and operation of micro DR

Small heat flux to the still at which DR can operate is crucial for design of a compact refrigerator with all components - including 1K pot with sorption pumping - contained inside the stainless steel tube inserted in a helium transport Dewar with a Ø=24 mm hole in the neck. Micro DR (MDR) includes two sorption pumps filled with activated charcoal. Its volumes are about 20 and 6 cm^3 and they can absorb 0.07 and 0.02 moles of ^{4}He and ^{3}He respectively.

The sorption pumps are thermally connected with a 4.2 K flange via heat switches. Each heat switch consist from to coaxial copper elements placed inside vacuum tight stainless steel tube. In "off" position heat transfer between copper elements is determined by conductivity along stainless steel tube with high thermal resistance. In "on" position a helium gas desorbed from small piece of charcoal while heating by power of 0.5 mW produces thermal contact between copper elements with resistance of about 0.05 K/mW. It is known that heat of sorption for helium is an order of magnitude greater than heat of evaporation. So, at $\dot{Q}_S$ = 30 -100 μW, sorption pumps are cooled down practically to the temperature of helium in transport Dewar, i.e., to 4.2 K.

During the operation initially ^{4}He is released by heating its sorber to 30-40 K and under the pressure slightly higher than 1 atmosphere it condenses in "1K pot". Then by heat switch on due to cooling of sorption pump the pressure drops and "1 K pot" cools down till 0.9 K. After that ^{3}He sorption pump is heated till 30 K and ^{3}He condenses in corresponding bath. Due to pumping out of its vapours (with corresponding heat switch on) the temperature of ^{3}He in some minutes reaches 0.35 K and temperature of mixture in mixer and still reaches about 0.6 - 0.4 K. In our previous experiments after about 30 min at $\dot{Q}_S$ = 60 -100 μW the mixer temperature lowered till 0.13 K.

Finally we should to point out that (i) due to small amounts of ^{3}He and ^{4}He inside of micro refrigerator and small heat fluxes it is possible to place the different parts on different position. For instance, the mixing cell can be placed above sorption pumps and 1 K pot. Than it becomes rather easy to get access to millikelwin region from the top of refrigerator. (ii) It is possible to get continuous operation of DR by using two or more 3He pumps [9] or by inclusion additional pair condenser - ^{3}He bath for the temperature stabilization of condensation pump in the course of sorption pump regeneration due to sufficiently high heat capacity of liquid ^{3}He. (iii) Due to absence of moving parts and due to small power required for operation (<0.2 W for heating of sorption pumps, 0.5 mW for heat switches, <0.1 mW for still heating) it is rather easy to operate the refrigerator under computer control.

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