Realisation of lambda transition temperature of ^{4}He using sealed cells

Lin Peng, Mao Yuzhu, Hong Chaosheng
Cryogenic Laboratory, Chinese Academy of Sciences, Beijing, China

Franco Pavese, Ilaria Peroni
Istituto di Metrologia "G.Colonnetti", Torino, Italy

David Head, Richard Rusby
National Physical Laboratory, Teddington, TW11 0LW, UK

Abstract

This paper presents lambda-point measurements obtained at CL, IMGC, and NPL in the past two years using sealed cells made at CL. The cells consist of two chambers containing liquid helium, separated by a stainless steel capillary. When the HeI/HeII interface is located in the capillary, the large thermal conductivity of HeII ensures that the lambda temperature is established in the top chamber. Heat flows change the position of the interface, but have only a small effect on the temperature of the top chamber. Because of the self-adjusting effect of the HeI column within the capillary, the lambda transition temperature plateau was recorded in the top chamber for many hours with a fluctuation of 3.2 μK. The temperature of the lambda transition at zero heat flow is determined by measuring the temperature at several heat flows and extrapolating to zero. The best realisations of the T_λ were made at NPL with a standard deviation of 5.8 μK, and the effect of the finite conductivity of HeII was observed for the first time in this cell.

Introduction

The superfluid transition of ^{4}He, called the lambda transition, has been studied for a long time, particularly because there is a sharp peak in the specific heat near the transition. Furthermore the thermal conductivity of liquid helium increases by several orders of magnitude when its temperature goes below the lambda point. In 1976 Hwang and Khorana reported a typical width and reproducibility of 0.01 mK for the lambda transition by pumping on a pool of liquid helium in order to cool it down through the lambda point [1]. They suggested that the lambda transition of liquid helium would provide a superior and valuable thermometric fixed point.

Using an adiabatic calorimeter with the techniques that have been used for the realisation of triple points, one would not normally expect the existence of an equilibrium phase boundary in liquid helium, because the superfluid transition is not first order and there is no latent heat at the transition. However in 1989 a sealed cell, with a capillary, was built in the Cryogenic Laboratory (CL) to realise the transition temperature of liquid helium, using the capillary as a thermal delay-line [2]. In 1990 using the same cell, a temperature plateau was obtained at CL with a small heat flow along the capillary such that an interface of HeI/HeII was maintained within the capillary [3]. Because there is a depression of the lambda transition temperature by a heat flux [4,5], the transition temperature measured by thermometer was low. Later a platform was used to control the heat flow passing along the capillary and an extrapolation was employed to determine the transition temperature with zero heat flow [6].

In 2000, three sealed cells with the current CL design were measured at CL and a small sealed cell with a shorter capillary was measured at IMGC [7,8]. In 2001 the measurements on two sealed cells with a small difference in the capillary dimension were carried out at NPL. A rhodium-iron resistance thermometer (RIRT), serial number 229841, was used in all the measurements of the transition temperature at the three laboratories. The difference in the T_λ measurements at laboratories was not more than 0.1 mK.

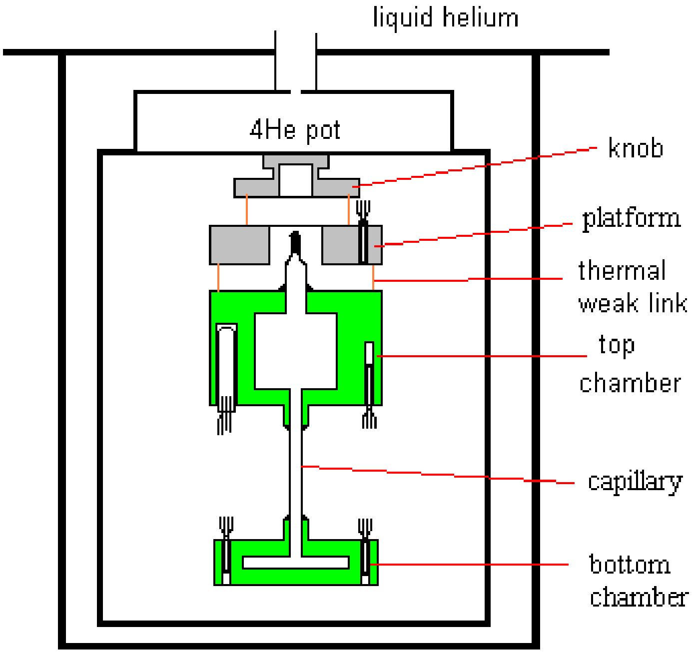

Figure 1: Diagram of the sealed cell mounted in the cryostat

The principle of operation and the sealed cells

The diagram of the sealed cell and cryostat is shown in Figure 1. The construction of the sealed cell and its operating principles have been presented elsewhere [6,7]. Briefly, the cell is composed of three parts: the top chamber is a helium reservoir and RIRTs are accommodated there, the bottom chamber is a heater block, and the two chambers are connected by a vertical stainless steel capillary. In order to control the heat flow passing through the cell, the top chamber is supported from a copper platform using three brass rods, which act as thermal weak links. On its upper side, the platform is connected through a similar rod system to a copper flange (‘knob’ in fig 1) so that the sealed cell and platform assemblage forms an easily-handled structure. Finally the device is fixed to the bottom of the ^{4}He pot of the cryostat through the threaded head of the flange.

When the temperature of the cell cools below T_λ, 2.1768 K, the capillary is fully filled with superfluid helium, HeII. The temperature of the bottom chamber, T_B, is then set to a value higher than T_λ, say T_λ+15mK, and the temperature of the platform, T_P, is regulated to a value below T_λ. The normal fluid helium, HeI, appears at the bottom of capillary and superfluid helium exists in the upper part of the capillary and the top chamber. Because of the great change in thermal conductivity of liquid helium at the lambda transition, the column of HeI within the capillary provides a self-adjusting heat-link. Under steady conditions, the heat flowing along the capillary to the top chamber will equal the heat leak from the top chamber to the platform, which is governed by the temperature difference between them. The HeI/HeII interface within the capillary is located so as to maintain the same heat flow, and a stable temperature "plateau" is obtained in the top chamber. On increasing the set point for T_P stepwise, the heat flow progressively decreases and a series of new plateaus are reached at slightly different temperatures. These generate a staircase pattern on a chart recorder, each plateau corresponding to a different heat flow. Plotting the readings of the rhodium-iron resistance thermometer (RIRT) against the heating power dissipated at the bottom chamber, P_B, and extrapolating to zero heat flow, the temperature with no heat flow depression is obtained.

Five sealed cells were employed in the realisations. The basic data are listed at Table 1. The cell C-3, D-1, and D-2 were made under the current CL design. The cell E-1 is smaller and designed with a short capillary with a length of 20 mm. The cell D-3 was based on the current CL design, but an expansion section was constructed part way along the capillary. All of the sealed cells were filled with pure helium with about 10 MPa.

Table 1 Basic data of the measured sealed cells

Cell number	C-3	D-1	D-2	D-3	E-1
Outer diameter of the top chamber (mm)	42	42	42	42	30
Total length of the sealed cell (mm)	150	150	150	160	100
od of the capillary (mm)	3.0	3.0	3.0	3.0	3.0
id of the capillary (mm)	2.0	2.0	2.0	2.0	2.0
Length of the capillary (mm)	40	47	47	55	20
Cavity volume of the cell (cm^3)	9.75	9.75	9.75	10.03	4.88
Sealed date	31/3/2000	8/6/2000	8/6/2000	1/9/2000	13/10/2000
Fill pressure (MPa)	10.5	10.0	10.0	10.0	10.5

Experiments

The cryostats used in the measurements are liquid helium evaporation cryostats with an inner ^{4}He pot. The sealed cell is connected to the bottom of the ^{4}He pot. There are some slight differences in the experiments at the three laboratories. In the realisation at CL, there was no thermal shield connected to the 1 K pot and the sealed cell can "see" the vacuum can with a temperature of 4.2 K. In the realisation at IMGC, a thermal shield connected to the ^{4}He pot was used around the sealed cell. The temperature of the pumped ^{4}He pot was normally below 1.5 K in the realisations at CL and IMGC. The temperature of the platform was controlled to adjust the heat flowing along the capillary. In realisations at NPL, a thermal shield extending from the ^{4}He pot surrounded the cell and the temperature of the ^{4}He pot was controlled rather than the platform.

The resistance of the RIRTs was measured using Guildline 9975 dc bridge at CL and IMGC. The output of the bridge was connected to a chart recorder to record the temperature plateau. There was always electrical noise equivalent to some tens of microkelvin at the lambda transition plateau when the temperature was recorded using this dc bridge. An ASL F18 ac bridge was employed at NPL to measure the RIRT's resistance with a resolution of 1 μΩ, which is equivalent to a temperature resolution of 3.2 μK at 2.17 K.

T_B was regulated using a temperature controller and a germanium thermometer (GRT) was used as sensor. At CL and IMGC, T_P was controlled with a fixed current because the temperature of the ^{4}He pot was very stable. At NPL, the temperature of the ^{4}He pot was controlled by balancing an electric temperature controller against a partially open needle valve connecting to the pumping system. The voltage drop across the bottom heater was measured using a multimeter and the power P_B was measured.

Results and discussion

When T_B was set slightly higher than T_λ, say T_λ+15 mK, and T_P was regulated below T_λ, a very stable temperature plateau was obtained at the top chamber. There was no determinable temperature drift in the plateau lasting more than ten hours. A typical fluctuation in the plateau was 1 μΩ, about 3.2 μK at T_λ, when an F18 bridge was used to measure the resistance of RIRT. The longest plateau of the lambda transition lasted over 14.5 hours and the plateau duration was limited only by the working time of the ^{4}He pot.

As the set point of T_P was increased by a step (typically 20-30 μK), the heat flow passing through the capillary decreased and the temperature of the top chamber, T_T, rose to a new plateau. Figure 2 shows a typical plot of T_T against P_B for the cell D-2. By linear fitting of the data, T_T versus P_B and extrapolating to zero heating power, the value of T_λ(229841) with no heat flow depression is obtained.

The T_λ realizations obtained at NPL, CL, and IMGC are listed in Table 2. The values of T_λ as measured using RIRT 229841 are corrected for the self-heating effect. These results have been carried out using five sealed cells as shown in Table 2. The results all lie within a range of 0.1 mK, and are all close to the expected value, 2.1768 K (the difference being the error in the thermometer calibration in terms of the ITS-90). Table 2 indicates the reproducibility of cells, the thermometer and the resistance measurements, although the intrinsic reproducibility of the cells alone is expected to be much better than this.

Table 2 The T_λ realisation results obtained at CL, IMGC, and NPL recorded by RIRT 229841

Laboratory	CL	IMGC	NPL	**Difference between measurements at NPL and CL**	**Difference between measurements at NPL and IMGC**
Cells used	C-3, D-1, D-2	E-1	D-2, D-3		
Number of realisation	7	3	8		
Resistance (Ω)	2.978361	2.978329	2.9783511	**10 μΩ**	**22 μΩ**
Temperature (K)	2.177088	2.176985	2.1770573	**31 μK**	**72 μK**
Bridge used	9975, dc	9975, dc	F18, ac		
Standard deviation	**44 μK**	**18 μK**	**5.8 μK**		

A typical plot T_T versus P_B is shown as Figure 2. From this plot, the heat flow depression was determined to be equal to the slope of T_T/P_B with a value of 2.55 mK/mW. This heat flow effect caused the T_λ depression, the temperature drop along the HeI column and the boundary resistance.

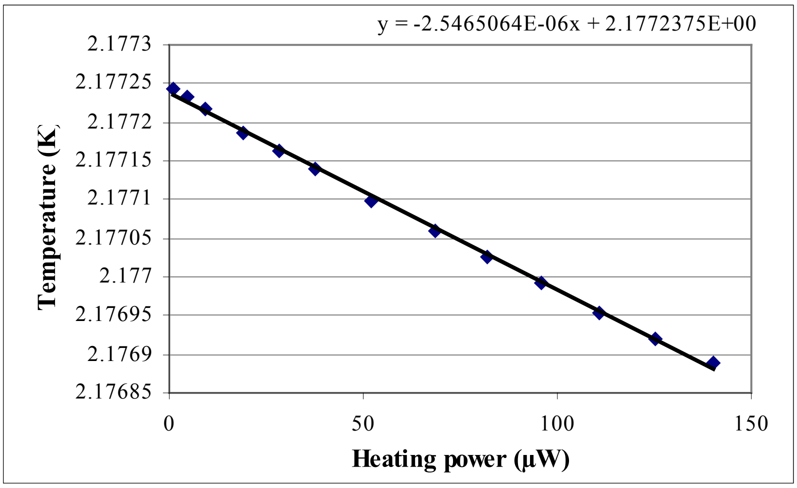

Figure 2 A typical plot of the temperature of the top chamber versus the heating power dissipated at the bottom chamber for cell D-2, measured at NPL on 2 May 2001

A typical plot of P_B versus T_P is shown as Figure 3 and it can also be fitted linearly. The thermal conductance between the top chamber and the ^{4}He pot is equal to the slope of P_B/T_P. By extrapolating to $T_P = 2.1768$ K, a value of P_B is obtained and this P_B would be equal to the residual heat leak from the cell to the environment. Multiplying the slopes of T_T/P_B and P_B/T_P, the dependence of T_T on T_P can be calculated, as the 'thermal attenuation' of the lambda cell. For cell D-2, ΔT_T is equal to $1.1\times10^{-3}\ \Delta T_P$.

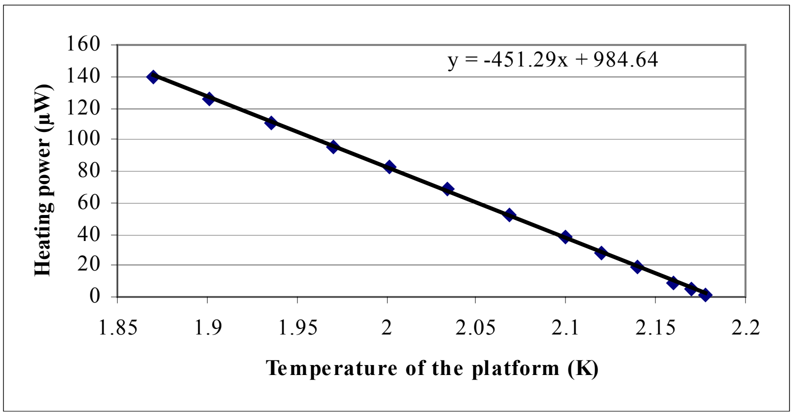

Figure 3 A typical plot of the heating power dissipated at the bottom chamber versus the temperature of the platform, measured at NPL on 2 May 2001

If T_B is increased while T_P remains constant, the temperature difference across the capillary, $\Delta T_C = T_B - T_T$, rises. Under these conditions, in the experiments at NPL, a slight increase of T_T was observed for the first time. Figure 4 shows the data obtained for several values of ΔT_C and heat flow. At constant T_P, the heat flow passing through the capillary does not change, and the depression of T_λ by the heat flux and the temperature drop across the HeII/copper boundary will remain the same. Only the HeI/HeII interface rises in the capillary and the length of the HeII column decreases as ΔT_C rises. The change in the temperature T_T is the result of the finite conductivity of HeII, and is similar for all values of T_P (ie heat flow). The small magnitude of the effect shows the insensitivity of T_T to ΔT_C and indicates the success of the lambda point experimental design.

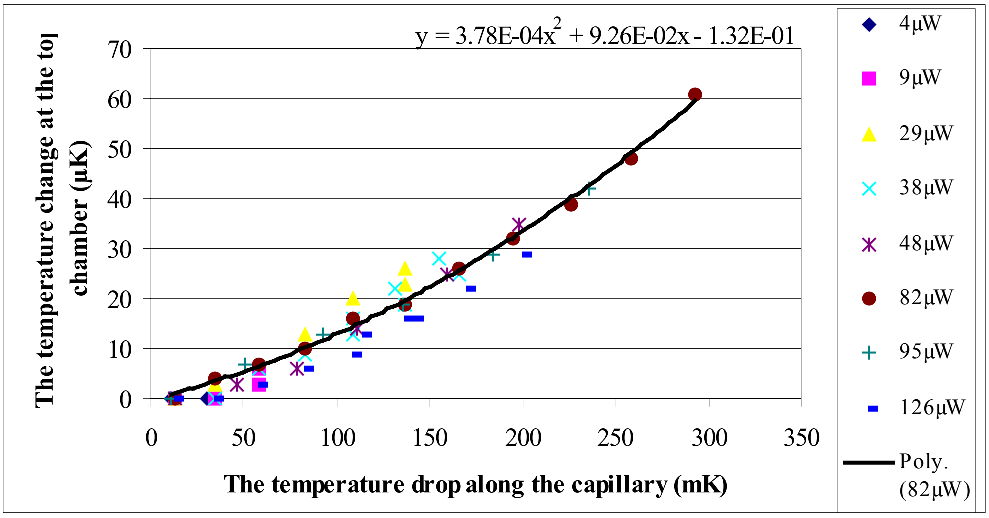

Figure 4. Dependence of the temperature change of the top chamber on ΔT_C

Conclusion

Measurements on five Chinese lambda-point sealed cells have been made at CL, IMGC, and NPL. The results show excellent reproducibility of T_λ and good agreement between the measurements at the three laboratories. The results also show that the reproducibility of T_λ has improved with improvements in bridge performance. However, this still limits the resolution of the lambda-point realization. For the first time a change in T_T has been detected with an increase of ΔT_C, due to the finite thermal conductivity of HeII.

The measurements at these three laboratories supply messages for the improvement in the design of sealed cell. The current sealed cell design gives plateaus with good reproducibility of T_λ. T_B has little effect on the reading of T_T and T_λ. The uncertainty in the measurement of T_P restricts the accuracy in the measurement of the heat flow as the heat flow is reduced to zero. The heat flow depression may vary between cells as a function of capillary diameter, but the T_λ realisation remains the same. Therefore the dimensions of the capillary can be chosen for convenience e.g. the capillary could be fatter thereby a reducing the heat flux. The results will bring forward the time that a sealed lambda cell can be recognized as a fixed point device of the first quality.

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