Experimental Observation of a Self-Heating Effect of $^4$He Superflow

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Abstract. we report a counter-intuitive self-heating effect of $^4$He superflow. This fundamentally unusual heating effect bears a phenomenological resemblance to the Peltier effect of electric current across two different conductors. It reveals that $^4$He superflow carries thermal energy and entropy, which is in contrast to the two-fluid model of superfluid $^4$He. A natural understanding of this heating effect is provided by a recently developed microscopic quantum theory of superfluid $^4$He.

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As one of the most fundamental quantum systems in condensed matter physics, superfluid $^4$He [1,2] exhibits a wide variety of extraordinary behaviors. Some intriguing phenomena of superfluid $^4$He, such as the fountain effect [3] and the mechano-coloric effect [4], reveal a fundamental coupling between thermodynamic motion and the hydrodynamic motion of the system. Pursuing a quantum understanding of this unusual coupling is challenging but nevertheless important. In the past, people rely on the two-fluid model [5,6] of superfluid $^4$He to describe physics raised by this coupling. In spite of its phenomenological success and its capability to explain many interesting behaviors of superfluid $^4$He observed later (see e.g. [7,8,9,10,11,12,13,14,15]), the two-fluid model is not completely flawless by itself. It involves a hypothesis of a macroscopic sub-system (i.e. superfluid component) with zero entropy, which is highly exotic. The zero-entropy hypothesis implies unavoidably that this sub-system has a temperature of absolute zero, but it is difficult to imagine how such a sub-system can coexist with its thermal surroundings. Some experiments [16,17] questioned the validity of the two-fluid
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In this work, we report a counter-intuitive self-heating effect of $^4$He superflow. This fundamental effect reveals that $^4$He superflow carries thermal energy and entropy, which is in contrast to the hypothesis of the two-fluid model.

The main setup of the superflow system is schematically plotted in Fig. 1. Three vessels (referred to as pot A, pot B and cell C) are connected in series by two superleaks (referred to as $S_{AC}$ and $S_{BC}$). Cell C is thermally isolated from its surroundings, except its thermal links to the pots via the superleaks. In the experiment, pot A is filled with superfluid $^4$He initially, then superflows through $S_{AC}$, cell C and $S_{BC}$ can be established eventually by setting a positive temperature difference between pot B and A (i.e. fountain effect), resulting in a superfluid transport from pot A to B. If superflow carries zero thermal energy, the temperature of cell C ($T_C$) shall eventually lie between the temperature of pot B ($T_B$) and that of pot A ($T_A$). However, it is observed that cell C can be heated strikingly by the superflows; as a result, $T_C$ reaches a steady value which exceeds $T_B$ by more than one hundred millikelvins.

The experiment is carried out on a two-stage Gifford-McMahon refrigerator with a cooling power of 1 W at 4.2 K and a base temperature of 2.4 K. In order to reach the superfluid temperature regime, a liquid $^4$He cryostat is constructed by following largely the design given in Ref. [18]. A stainless steel capillary, with an inner diameter (i.d.) of 0.18 mm, an outer diameter (o.d.) of 0.4 mm and a length of 1 m, is used as the Joule-Thomson impedance in the cryostat. The copper pot for collecting liquid $^4$He, with an i.d. of 4.0 cm and a volume of 78 cm$^3$, is also served as pot A for the experiment. Another copper pot, identical to pot A, is used as pot B. Cell C is made of a small copper block, and the main part of its inner cavity is cylindrical, with a diameter of 3 mm and a length of 40 mm. Each superleak is made of a stainless steel tube packed with jeweler’s rouge powder (with an average particle size of 70 nm determined by TEM). The tube for $S_{AC}$ has an i.d. of 0.8 mm, an o.d. of 2.0 mm and a length of 65 mm, while the tube for $S_{BC}$ has an i.d. of 1.0 mm, an o.d. of 2.0 mm and a length of 65 mm. Two superleaks are soft soldered to cell C, and they are positioned in a way so that the lower end of each superleak is in proximity to one end of cell C’s cylindrical
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Figure 2. A picture of superflow system. $S_{AC}$ and $S_{BC}$ refer to the superleaks.

cavity (see Fig. 2). The upper end of $S_{AC}$ joins pot $A$ while the upper end of $S_{BC}$ joins pot $B$.

A combination of copper braids and brass strips is used as a thermal link between pot $A$ and a cooling plate directly mounted to the second stage of the refrigerator, with a thermal conductance of around $2 \, mW/K$ at $2 \, K$. Pot $B$’s major thermal link with its surroundings is a copper braid joining two pots at ends. Resistance wires wrapped around pots are used as heaters. Pot $B$ as well as pot $A$ is equipped with a pumping line. Valves are used in the lines so that the pumping rate can be manipulated to provide further means for the temperature controls of the pots. Calibrated carbon ceramic resistances [19] are used as temperature sensors to measure $T_A$, $T_B$ and $T_C$, with an accuracy of $5 \, mK$. The dissipation power of temperature sensor on cell $C$ is kept well below $10^{-7} \, W$, so that its heating effect is very limited.

Two radiation shields made of copper coated with nickel thin layer are amounted to two stages of the refrigerator, with one at a temperature around $45K$ and the other at a temperature below $2.8K$. Great care is made to prevent cell $C$ from exposing to the thermal radiations from sources at temperature above $3K$. Comparative experiments were conducted to rule out that background thermal radiation is responsible for the heating phenomenon observed.

For the initial accumulation of liquid $^4$He (with a purity of $99.999\%$) in pot $A$, $T_A$ is raised above $\lambda$ point to prevent superflow through $S_{AC}$. After decreasing $T_A$ below $\lambda$ point, superflows through superleaks and cell $C$ can be established by setting a large temperature difference between $T_B$ and $T_A$. At given $T_A$ and $T_B$, superflows are let to flow for long enough without disruption so that $T_C$ can reach its steady value .Some steady values of $T_C$ are listed in Tab. 1.

A heating process of cell $C$ is plotted in Fig. 3. At the initial moment represented in the figure, pot $A$ is filled with liquid $^4$He at a temperature above $\lambda$ point while both pot $B$ and cell $C$ are empty. Pumping pot $A$ leads to dropping of $T_A$. $T_B$ drops in pace with $T_A$ due to relatively large thermal link between two pots. At some point, electric
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| $T_A$ (K) | $T_B$ (K) | $T_C$ (K) |
|---------|---------|---------|
| 1.500(4) | 1.700(4) | 1.847 (1) |
| 1.600(4) | 1.800(4) | 1.927 (1) |
| 1.600(4) | 1.900(4) | 2.014 (1) |

Table 1. Steady values of $T_C$ at given $T_A$ and $T_B$.

current of the resistance wire around pot $B$ is activated to stabilize $T_B$ at the set value of $1.85K$. $T_C$ decreases with $T_A$. When both of them are getting below the $\lambda$ point, superfluid transport between pot $A$ and cell $C$ is initiated and consequently plays a major role in determining the value of $T_C$ relative to $T_A$. $T_C$ remains a few millikelvins below $T_A$ for superfluid filling duration of cell $C$. If $T_C$ is further below, fountain pressure of the superfluid, caused by the difference between $T_A$ and $T_C$, overcomes the gravitational pull and directs superfluid back from cell $C$ to pot $A$, leading to increase of $T_C$. On the other hand, if $T_C$ is getting closer to or further above $T_A$, the overall force (fountain pressure plus the gravitational pull) conducts superflow from pot $A$ to cell $C$, resulting in decrease of $T_C$. This negative feedback mechanism of temperature locks roughly the value of $T_C$ relative to $T_A$.

![Figure 3. A heating process of cell C.](image)

When cell $C$ is approximately fully filled and superfluid transport between cell $C$ and pot $B$ is initiated, $T_B$ goes through some fluctuations. This is mainly due to the fact that heat capacitance of the empty pot $B$ (made of copper) is relatively small. Even a small amount of cold superfluid $^4$He entering pot $B$ can cause a large variation of $T_B$ and the temperature stabilization system is not capable to respond in a timely manner. After a certain amount of superfluid $^4$He is accumulated in pot $B$, further injection of cold superfluid is no longer capable to change $T_B$ dramatically and the stabilization of $T_B$ is well restored.

Once the transport of superfluid $^4$He through superleak $S_{AC}$, cell $C$ and superleak
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$S_{BC}$ is fully established, $T_C$ rises steadily and reaches a value 120 mK above $T_B$. The heat received by cell $C$ comes from superflows. Since the kinetic energies of superflows are negligible [20], the heat must originate from the thermal energies of superflows. This heating phenomenon is some way analogous to the Peltier effect of an electric current flowing across two conductors: the superflow entering cell $C$ carries a thermal energy (density) larger than that of the superflow leaving from cell $C$, leading to the heating of cell $C$.

A natural understanding of this heating phenomenon can be provided by a recently developed quantum theory of superfluid $^4$He [21, 22, 23, 24, 25]. In quantum mechanics, microscopic processes of a liquid $^4$He system are governed by the many-body Hamiltonian operator of the system and by the atomic-molecular interactions between the system and its surroundings. One can use the many-body eigen-states/levels of the Hamiltonian operator and quantum jumps among these eigen-states/levels (caused by the interactions between the system and its surroundings) to give a full microscopic description of the system. When the temperature is below the transition point, one can consider only the low-lying levels since the high-lying levels become irrelevant due to the Boltzmann exponential factor. It is found that all the low-lying levels fall into a large number of groups in a hidden way, with each level belonging to one group only. There exist high energy barriers which separate different groups (of levels) and prevent inter-group quantum level transitions. On the other hand, the atomic-molecular interactions between the system and its surroundings cause frequent intra-group level jumps in an occupied group, which leads to a thermal distribution in the group and to a group-specific thermal equilibrium between the system and its surroundings. At a given temperature, the thermal distribution of levels in a group determines all (group-specific) macroscopic properties of the system, such as its thermal energy (density) and its flow velocity. Different groups have different flow velocities, thus one can use the flow velocities to distinguish groups and can further regard other group-specific properties as being flow-velocity-dependent. It can be argued that the thermal energy density has a negative dependence on flow velocity: the larger the flow velocity is, the smaller the thermal energy density. This unusual velocity dependence of thermal energy density is responsible for the fundamental coupling between the thermodynamic motion and the hydrodynamic motion of superfluid $^4$He, and it can be used to explain naturally the mechano-caloric effect of the system.

In this experiment, the superflow velocities in superleaks behave in a rather subtle way. Note that a superflow is frictionless and its velocity can not be stabilized by friction, which is in contrast to the case of an ordinary flow. The superflow in superleak $S_{AC}$ keeps accelerating or decelerating, subject to pressure difference between superfluid in pot $A$ and that in cell $C$ (the fountain pressure, caused by the temperature difference across $S_{AC}$, consists of a significant part of the overall pressure difference). The pressure in cell $C$ rises rapidly when it changes from a nearly-fully-filled state to a fully-filled state, which regulates the inlet superflow (from the viewpoint of cell $C$) in a great deal and prevents it from getting a rather large velocity. On the other hand, the outlet superflow
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can be accelerated by the pressure rising in cell $C$ and can reach rather large velocity regime. Moreover, with $T_C > T_B$, the superflow in $S_{BC}$ can reverse flow direction when cell $C$ deviates from a fully-filled state, thus the actual flow time of outlet superflow is shorter than the flow time of inlet superflow. From these analyses it is clear that there is an asymmetry between the velocity distribution of the inlet superflow and that of the outlet superflow, which in turn leads to a difference between their thermal energies and to the heating of cell $C$.

In conclusion, we observed an intriguing heating effect of $^4\text{He}$ superflows. This fundamental phenomenon can be explained naturally by a microscopic quantum theory of superfluid $^4\text{He}$.

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