Experimental Observation of Thermal Energies of Helium-4 Superflows

Authors: Yu, Yongle, Luo, Hailin, Yu, Yongle

Date: 2020-12-12T12:04:35+00:00

Abstract

We observed a counter-intuitive remarkable heating phenomenon generated by helium-4 superflows. This phenomenon establishes that superflows carry thermal energies and entropies, which is in contrast to the hypothesis of the two-fluid model. Quantum many-body theory of superfluids provides a natural understanding of the phenomenon.

Full Text

Preamble

Experimental Observation of Thermal Energies of ^{4}He Superflows

Yongle Yu † and Hailin Luo ‡

† State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, West No. 30 Xiao Hong Shan, Wuchang, Wuhan, 430071, China

‡ Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, 155 Yangqiao Road West, Fuzhou, 350002, China

Abstract. We observed a remarkable and counter-intuitive heating phenomenon generated by ^{4}He superflows. This phenomenon establishes that superflows carry thermal energy and entropy, which contrasts sharply with the hypothesis of the two-fluid model. Quantum many-body theory of superfluids provides a natural understanding of this phenomenon.

PACS numbers: 05.70.-a, 67.25.dg, 67.40.Kh

Keywords: superflow, entropy, quantum many-body physics

Superfluid ^{4}He exhibits several fascinating behaviors beyond superfluidity itself, including the mechano-caloric effect, the fountain effect, and its unmatched thermal conductivity. The phenomenological two-fluid model of superfluids has played an indispensable role in textbook explanations of these phenomena. However, despite its broad descriptive power, the two-fluid model is not without fundamental flaws. It postulates a superfluid component with zero entropy; this component, being free of any thermal motion, would constitute a subsystem at absolute zero temperature. Yet it is difficult to conceive how a zero-temperature subsystem could coexist with its thermal environment. Previous experiments [1, 2] have already hinted at the model's limitations. In this work, we report a remarkable heating phenomenon caused by ^{4}He superflows that firmly establishes superflows carry thermal energy and entropy, in direct contradiction to the central hypothesis of the two-fluid model.

The experimental setup for the superflow system is shown schematically in Figure 1. Three containers—designated as pot A, pot B, and cell C—are connected by two superleaks (SAC and SBC). Cell C is thermally isolated from its surroundings except for its thermal connections to the pots through the superleaks. Initially, pot A is filled with superfluid ^{4}He. Superflows in the two superleaks can be established by creating a positive temperature difference between pot B and pot A (i.e., via the fountain effect), causing liquid helium to transport from pot A to pot B through cell C. If superflows carried zero thermal energy, the temperature of cell C (TC) would eventually settle between the temperatures of pot B (TB) and pot A (TA). However, we observe that cell C is strikingly heated by the superflows, with TC reaching a steady-state value that exceeds TB by more than one hundred millikelvins.

The experiment was conducted using a two-stage Gifford-McMahon refrigerator with 1 W cooling power at 4.2 K and a base temperature of 2.4 K. To access the superfluid temperature regime, we constructed a liquid ^{4}He cryostat based largely on the design described in reference [3]. A stainless steel capillary with an inner diameter (i.d.) of 0.18 mm, outer diameter (o.d.) of 0.4 mm, and length of 1 m serves as the Joule-Thomson impedance in the cryostat. The copper pot for collecting liquid helium, with an i.d. of 4.0 cm and volume of 78 cm^3, functions as pot A in the experiment. A second identical copper pot serves as pot B.

Cell C consists of a small copper block containing a cylindrical inner cavity 3 mm in diameter and 40 mm long. Each superleak comprises a stainless steel tube packed with jeweler's rouge powder. The SAC tube has an i.d. of 1.0 mm, o.d. of 2.0 mm, and length of 65 mm, while the SBC tube has an i.d. of 0.8 mm, o.d. of 2.0 mm, and length of 65 mm. The superleaks are soft-soldered to cell C such that each end of the cylindrical cavity is positioned near the lower end of a superleak (see Figure 2). The upper end of SAC connects to pot A, and the upper end of SBC connects to pot B.

Thermal management is achieved through several design features. A combination of copper braids and brass strips provides a thermal link between pot A and a cooling plate mounted directly on the second stage of the GM refrigerator, with a thermal conductance of approximately 2 mW/K at 2 K.

Pot B's primary thermal connection to its surroundings is a copper braid joining the two pots at their ends. Resistance heaters wrapped around the pots enable temperature control, and both pots are equipped with pumping lines and valves to manipulate pumping rates for additional temperature control. Calibrated carbon ceramic resistors [4] serve as temperature sensors (accuracy $±5mK)formeasuringTA,TB,andTC.ThedissipationpowerofthetemperaturesensoroncellCismaintainedu
7}$ W to minimize heating effects.

For initial accumulation of liquid helium in pot A, its temperature is intentionally raised above the λ-point to effectively block flow through superleak SAC. The heat capacity of pot A can be roughly measured using its heater to estimate the amount of liquid helium present (the copper contribution can be neglected due to the large heat capacity of liquid helium). During the experiment, superflows in SBC and SAC are driven by a relatively large temperature difference between TA and TB.

For given values of TA and TB, the superflows were allowed to run undisturbed for sufficient time to reach steady-state TC values (no appreciable changes in TC were observed with further extension of running time). Representative steady-state values of TC are listed in Table 1 .

The heat received by cell C originates from the superflows themselves. Since the center-of-mass kinetic energy of the superflows is negligible, this heat must derive from their thermal energy. Phenomenologically, this heating is analogous to the Peltier effect: the superflow entering cell C carries a greater thermal energy density than the superflow exiting cell C, resulting in net heat deposition into cell C.

The quantum many-body physics underlying superfluid ^{4}He provides a natural explanation for this heating phenomenon [5, 6, 7]. In the superfluid temperature regime, the relevant low-lying many-body energy levels of liquid helium in porous media (or very narrow capillaries) organize into distinct groups in a rather subtle manner. Different level groups are separated by energy barriers that prevent inter-group transitions from being induced by atomic-molecular interactions between liquid ^{4}He and its surroundings. However, these same interactions cause frequent intra-group level transitions within an occupied group, leading to a thermal distribution of level occupations and establishing a group-specific thermal equilibrium between the liquid ^{4}He and its environment. At a given temperature, the microscopic thermal distribution of level occupations within a group determines all group-specific macroscopic properties of the system, including its thermal energy density and flow velocity. Since different groups exhibit different flow velocities, one can use velocity to distinguish between groups and treat other group-specific properties as flow-velocity-dependent.

It can be argued that the thermal energy density of superfluid helium has a negative dependence on flow velocity (in certain temperature regimes): the greater the flow velocity, the smaller the thermal energy density. This velocity dependence naturally explains the mechano-caloric effect in superfluid ^{4}He [5].

In the experiment, the superflow velocities in the two superleaks exhibit rather subtle behavior. Since superflow is frictionless, its velocity cannot be stabilized by friction as in ordinary flow. The superflow in superleak SAC continuously accelerates or decelerates in response to the pressure difference between the liquid in pot A and that in cell C (the fountain pressure generated by the temperature difference across SAC constitutes a significant portion of the total pressure difference). The pressure in cell C rises rapidly as it transitions from a near-full to a completely filled state, which substantially regulates the inlet superflow (from cell C's perspective) and prevents it from achieving high velocity. Conversely, the outlet superflow in SBC is accelerated by the rising pressure in cell C and can approach the critical velocity regime.

Furthermore, when TC > TB, the superflow in SBC can reverse direction and flow into cell C as it deviates from the fully filled state. Consequently, the actual flow duration of the outlet superflow is shorter than that of the inlet superflow. This creates an asymmetry between the velocity distributions of the inlet and outlet superflows, leading to a difference in the thermal energies they carry and resulting in the heating of cell C.

In conclusion, we have reported a remarkable heating phenomenon generated by ^{4}He superflows. This experimental work, partially guided by theoretical studies of the quantum many-body physics of superfluids [5], may open pathways to fundamentally novel quantum physics scenarios.

References

[1] D.V. Osborne, Proc. Phys. Soc. A, 63, 909 (1950). [2] E. L. Andronikashvili and I. P. Kaverlin, J. Exp. Theor. Phys. U.S.S.R., 28, 126 (1955). [3] A. DeMann, S. Muller and S. B. Field, Cryogenics, 73, 60 (2016). [4] https://www.temati-uk.com/ [5] Y. Yu, Ann. Phys. 323, 2367 (2008), and references therein; Y. Yu, Mod. Phys. Lett. B 29, 1550068-1 (2015), Y. Yu, Mod. Phys. Lett. B 30, 1630008-1 (2016). [6] F. Bloch, Phys. Rev. A 7, 2187 (1973). [7] A. G. Leggett, Rev. Mod. Phys. 73, 307 (2001).