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The boundary resistance between superfluid ^{4}He near T_λ and a solid surface

Haiying Fu, Hanan Baddar, Kerry Kuehn, and Guenter Ahlers

Department of Physics and Center for Nonlinear Science, University of California, Santa Barbara, California 93106, USA
E-mail: guenter@tweedledee.ucsb.edu

We report high-resolution measurements of the singular contribution R_b to the thermal boundary resistance between a solid surface and superfluid helium near the superfluid-transition temperature T_λ . The results confirm the observation by Murphy and Meyer that a gap between the cell end and the sidewall leads to an apparent finite-current contribution to R_b . In the absence of such a gap, overall agreement of R_b with theoretical predictions is very good. Remaining small differences require further investigations. Without a sidewall gap and within our resolution we found no finite-current effects over the range 3.9 μW/cm^2 < Q < 221 μW/cm^2.

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In bulk superfluid ^{4}He heat transport occurs through counterflow of the normalfluid (j_n) and superfluid (j_s) currents and does not produce a temperature gradient [1]. However, a heat current Q orthogonal to a solid wall will produce a boundary layer in the fluid adjacent to the wall with a temperature difference ΔT_b across it [1]. Physically there are two reasons for this. The superfluid must be converted to normal fluid near the wall in order to maintain the counterflow in the interior. In addition, the order parameter, and thus j_s and j_n , are suppressed near the wall. The boundary layer has a thickness which is proportional to the correlation length ξ. Within it, some of the heat must be carried by diffusive processes. Consequently, a thermal gradient is developed near the wall. However, the thermal resistance $R_b = \Delta T_b/Q$ is unobservably small deep in the superfluid phase where the boundary-layer thickness is of atomic dimensions. Only very close to the superfluid transition temperature T_λ , where $t \equiv 1 - T/T_\lambda$ becomes small and $\xi = = \xi_0 t^{-\nu}$ diverges, does R_b become measurable in high-precision experiments. Thus this phenomenon was discovered experimentally only about a decade ago by Duncan et al. [2,3]. Roughly speaking one can assume that the temperature gradient in the boundary layer decays exponentially from $-Q/\lambda$ at the wall (where there is no counterflow at all) to zero deep in the superfluid (where all the heat is carried by counterflow) with a characteristic length equal to ξ. Here $\lambda \simeq \lambda_0 t^{-x_\lambda}$ with $x_\lambda \simeq 0.42$ is the diffusive thermal conductivity of the fluid [4]. This leads to the crude estimate $R_b \simeq \xi/\lambda \sim t^{-x_b}$ where $x_b = \nu - x_\lambda \simeq 0.25$. A renormalization-group-theoretical calculation of R_b carried out by Frank and Dohm [5,6] agrees with this qualitative expectation and is expected to give the behavior of $R_b(t)$ quantitatively. We report new measurements of R_b which agree well with the predicted overall size of R_b in the range $3{\cdot}10^{-7} \le t \le 10^{-3}$. However, at the smallest values of t the data fall somewhat below the theory and additional work is in progress to explore the precise dependence upon t of R_b .

The apparatus was a modified version of one described previously [3,7]. A schematic diagram of the sample cell is shown in Fig. 1. It had cylindrical copper top and bottom ends and a stainless-steel sidewall. The top plate was silver soldered into the sidewall, thus leaving no gap between the copper anvil and the stainless steel. The bottom endplate has an anvil which fits snugly into the sidewall, and was sealed with an indium gasket to the bottom flange of the sidewall. The gap between the anvil and the sidewall was approximately 0.01 mm. The top surface of the cell was finely machined copper. The bottom surface was atomically smooth gold [8] epoxied onto a polished copper surface. The cell was filled from the bottom. It had an inside diameter of 1.27 cm and an interior height of 0.50 cm. The sample was high

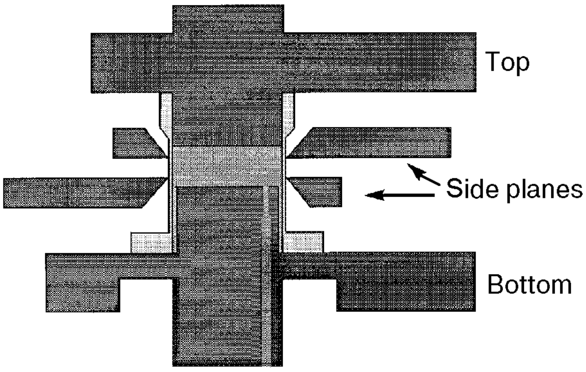

Fig. 1. Schematic diagram of the cell.

-purity ^{4}He containing less than 1 ppb ^{3}He. Both the top and bottom of the cell had copper platforms on which high-resolution copper-ammonium-bromide (CAB) susceptibility thermometers [9] with a resolution of 3 nK were mounted. Two sideplanes similar in construction to the midplane of [2,3] were attached to the cell wall. Each sideplane carried a CAB thermometer, thus permitting a determination of the helium temperature adjacent to it.

The top temperature was held constant and the desired current Q was passed through the cell. The resulting ΔT between the cell top or bottom and the nearest sideplane gave the total thermal resistance R. The result includes the boundary-layer resistance R_b of interest as well as the Kapitza resistance R_K due to the temperature jump at the wall and the resistance R_{Cu} of the copper between the cell surface and the relevant thermometer. At large currents there also was a contribution R_{He} due to mutual friction in the helium layer between the sideplane and the cell end. The contribution from R_{He} was measured separately using the two sideplanes and subtracted when necessary. It was less than our resolution for $Q < 7$ μW/cm^2.

Figure 2 gives results for the cell top on linear s

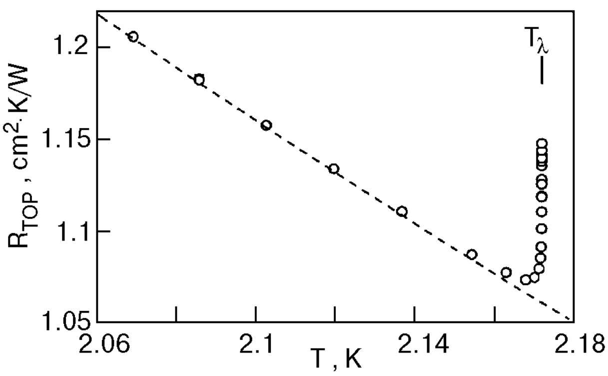

Fig. 2. The total resistance R of the top cell surface as a function of temperature on linear scales.

range of T. It shows t

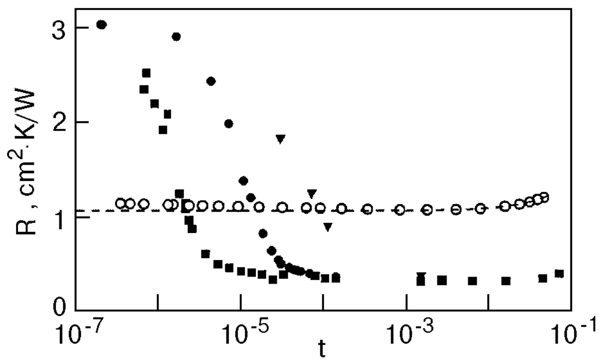

Fig. 3. The total resistance R of the top (open circles) and bottom (solid symbols) cell surface. The solid squares, circles, and triangles are for Q = 1, 10, and 100 μW/cm^2, respectively. The open circles are for the same three currents; for clarity we show them all by the same symbol.

he regular contribution from R_K and R_{Cu} , as well as the singular contribution very near T_λ from R_b . Some of the same data are plotted in Fig. 3 (open symbols) on a linear scale as a function of t on a logarithmic scale. Also shown there are the results for the bottom end (solid symbols). The data for the bottom surface show a strong anomalous current-dependent contribution. This phenomenon was observed previously in a number of investigations [10]. Recently it was suggested by Murphy and Meyer [11] that such an effect can arise from a small gap between the copper anvil and the cell wall (see Fig. 1). From the data in Fig. 3 one sees that the top surface of our cell, which does not have such a gap, does not have an anomalous current-dependent contribution. Thus our data confirm the observation of Murphy and Meyer [11], and provide conclusive evidence that the previously observed current dependence is unrelated to the theoretically calculated [5,6,12] boundary resistance.

In order to extract R_b from the measurements of R for the top surface, we fit the data well below T_λ to a polynomial in $T_\lambda - T$. This fit is the back-g

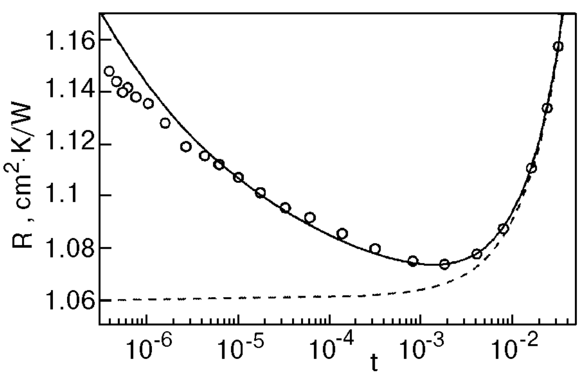

Fig. 4. The total resistance R of the top cell surface on an expanded linear scale as a function of t on a logarithmic scale.

u t i o n f r o m *R*

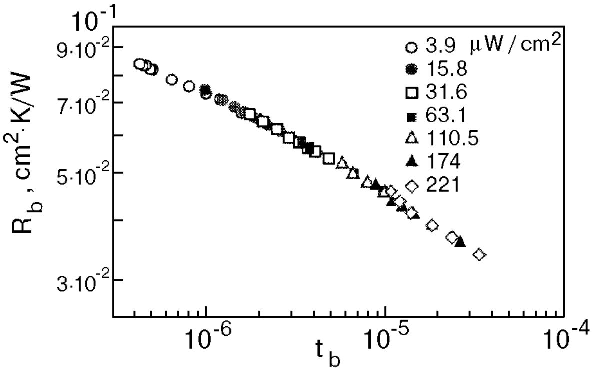

Fig. 5. The contribution R_b from the fluid boundary layer to the resistance R as a function of the mean reduced temperature t_b of the boundary layer on logarithmic scales for different heat currents.

$R_{\rm Cu}$, and is shown as the dashed lines in Figs. 2 and 3. The contribution R_b to R which is of interest to us is the small difference between the open circles and the dashed lines in the figures. In order to see the contribution from R_b more clearly, we show the data for the cell top on an expanded linear vertical scale as a function of t on a logarithmic scale in Fig. 4. The fit to the background is still shown as a dashed line. The *solid* line is the sum of the background and of the theoretical prediction [5,6] for R_b . We see that the overall agreement between the data and the theory is very good. This is in contrast to recent measurements by Murphy aud Meyer [11] which yield an R_b about a factor of two larger than the theory. At small t, our results fall slightly below the predicted curve. This small difference requires further investigation.

We searched with high resolution for any remaining current dependence of R_b at the top surface of our cell, and found none. The results are shown in Fig. 5 as a function of the average reduced temperature t_b (relative to T_λ $(Q = 0)$) of the boundary layer. In principle, a small current dependence would be expected theoretically, but only very close to T_λ [12,13]. Apparently our measurements were not sufficiently close to reveal this effect within our resolution.

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1. L. D. Landau, *J. Phys. USSR* **5**, 71 (1941) [English translation: *Collected Papers of L. D. Landau*, D. ter Haar (ed.) Gordon and Breach, New York (1965), p. 301].
2. R. V. Duncan, G. Ahlers, and V. Steinberg, *Bull. Am. Phys. Soc.* **31**, 281 (1986); *Phys. Rev. Lett.* **58**, 377 (1987).
3. R. V. Duncan and G. Ahlers, *Phys. Rev.* **B43**, 7707 (1991).
4. G. Ahlers, *Phys. Rev. Lett.* **21**, 1159 (1968).
5. D. Frank and V. Dohm, *Phys. Rev. Lett.* **62**, 1864 (1989).
6. D. Frank and V. Dohm, *Z. Phys.* **B84**, 443 (1991).
7. A. Singsaas and G. Ahlers, *Phys. Rev.* **B29**, 4951 (1984).
8. N. G. Woodard and G. P. Lafyatis, *J. Vac. Sci. Technol.* **A14**, 332 (1996).
9. H. Baddar, H. Fu, M. Larson, N. Mulders, and G. Ahlers, *Czech. J. Phys.* **46**-Suppl, 2859 (1996).
10. For a summary of early work, see Ref. 3. For a more recent summary, see Ref. 11.
11. D. Murphy and H. Meyer, *J. Low Temp. Phys.* **105**, 185 (1996).
12. R. Haussmann, *Ph. D. Thesis, Technische Hochschule Aachen*, Aachen, Germany (1991) (unpublished).
13. V. Dohm and R. Haussmann, *Physica* **B197**, 215 (1994); and references therein.
14. G. Ahlers, *Phys. Rev.* **171**, 275 (1968); *J. Low Temp. Phys.* **84**, 173 (1991).