Giant Proximity Effect in Superfluid Helium

Justin K. Perron and Francis M. Gasparini

Department of Physics, University at Buffalo, the State University of New York, Buffalo, NY 14260

E-mail: jkperron@buffalo.edu

Abstract. Recently, it was shown that two confined regions of liquid ^{4}He exhibit a proximity effect over distances much larger than the correlation length ξ[1; 2]. Here we report measurements of the superfluid fraction ρ_s/ρ , and specific heat c_p of a 33.6 nm film. Comparison with previous data from a 31.7 nm film in contact with an array of 34×10^6 $(2\ \mu\text{m})^3$ boxes of ^{4}He allows us to show quantitatively the enhancement in ρ_s/ρ and c_p due to the presence of the boxes in the temperature region where the film orders. The enhancement in ρ_s/ρ is observed up to distances 650 times the bulk correlation length. This anomalously large length scale is analogous to a giant proximity effect observed in High-T_c superconductors (HTSC)[3].

1. Introduction

When two materials with different long-range order are in contact the properties of the materials near the interface are modified[4]. These effects are termed Proximity Effects (PE) and have been studied in a variety of systems, ranging from ferromagnets to superconductors. The most well understood and longest studied example of the PE is that which occurs at the interface between a superconductor and a normal metal (see for example [5]).These effects are manifest within a spatial region of the order of the correlation length ξ. Recently however, some systems have shown an anomalously large PE spanning several times ξ. Groups working with HTSC junctions have reported supercurrents through regions several times thicker than ξ[3; 6–13]. This so called "Giant Proximity Effect" (GPE) has been described as "quantitatively different"[14] from the standard PE of conventional superconductors. A similar GPE has been observed recently in confined liquid ^{4}He [1; 2]. The ^{4}He system showed effects similar to those observed in the HTSC systems, such as a shift in the critical temperature of a thin film, but also substantial effects on c_p. With the present measurement of a 33.6 nm uniform isolated film of ^{4}He we are in a position to better quantify the effects previously reported for the specific heat without making any assumptions involving correlation-length finite-size scaling[15]. In addition, these new data show an enhanced ρ_s/ρ through a decade in reduced temperature $t = |T_\lambda - T|/T_\lambda$. This enhancement is measurable up to $\sim 650 \times \xi(t)$.

2. Measurement

The measurement was performed on a confinement cell consisting of a 50 mm patterned silicon wafer directly bonded to a bare wafer. To fabricate the patterned wafer a 33.6 ± 0.93 nm thermal oxide was grown on it. The oxide was then processed in an identical manner to that of the top wafer of the confinement cell measured in [1]. The patterned wafer was then bonded directly[16] to a bare silicon wafer leaving a uniform 33.6 nm gap to be filled with ^{4}He .

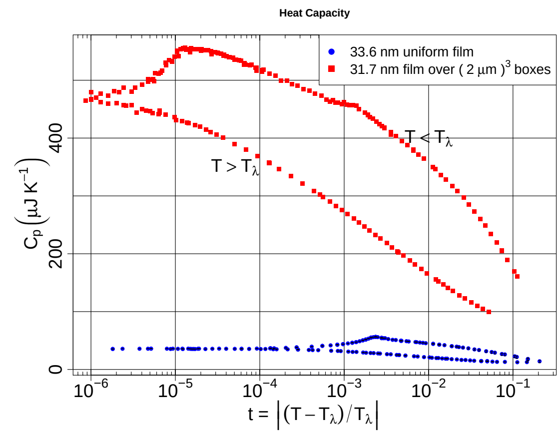

Figure 1. The heat capacity of a 33.6 nm film of ^{4}He (blue circles) and a 31.7 nm film in contact with an array of 34×10^6 (2 μm)^3 boxes (red squares).

The measurement of heat capacity (C_p) is made by AC heating the cell and measuring the resulting temperature oscillations while the average cell temperature is held constant to better than a μK[17].

The ρ_s/ρ measurement was made using Adiabatic Fountain Resonance (AFR)[18].

3. Results

The heat capacity of the 33.6 nm film is shown in Fig. 1. Also shown is the heat capacity of a 31.7 nm film on top of an array of 34×10^6 (2 μm)^3 boxes[1]. The data taken on the film with the boxes have two distinct features: a maximum associated with the ordering of the ^{4}He in the boxes at $t \sim 1.5 \times 10^{-5}$; and, a feature associated with the ordering of the ^{4}He in the film at $t \sim 2 \times 10^{-3}$. By comparing the position of the latter with the maximum of the 33.6 nm film one sees from Fig. 1 the first sign of a PE: Contact with the (2 μm)^3 boxes raises the temperature of the heat capacity maximum, essentially reducing the effect of the confinement.

With a measurement of the isolated film's heat capacity throughout the critical region, we are now in a position to calculate the specific heat of the boxes by themselves without relying on finite-size scaling as done previously[1]. The heat capacity of the isolated film was subtracted from the measured heat capacity of the box–film system leaving, presumably, the heat capacity of only the ^{4}He in the boxes. This was then divided by the number of moles in the boxes and normalized to the bulk specific heat far from the transition, giving us with c_p of the boxes. The result is shown in Fig. 2. Also plotted here are data from (2 μm)^3 boxes connected through a 10 nm film in 1 μm wide channels. These channels did not contain enough ^{4}He for a measurable signal that would require a correction[19]. Comparison of the two sets of (2 μm)^3 data shows reasonable agreement through most of the critical region, however, there is a clear systematic separation at $t \sim 1.5 \times 10^{-3}$. Even after the expected heat capacity of the *isolated* film was subtracted, the box system's heat capacity still shows a distinct feature associated with the film (Fig. 2 inset). This implies that the heat capacity of the film measured in the absence of the boxes is less than that of the film in contact with the boxes. Or, to cast it in terms of a PE, *contact with the larger boxes of ^{4}He enhances the heat capacity of the film.* This enhancement is $\sim$ 1 J/mol K at its peak. With the isolated film having a c_p of 41.4 J/mol K this is $\sim$ 2% enhancement. We note that at this maximum $\xi(t)$ is less than 1% of the separation of the boxes.

The ρ_s/ρ data for the isolated 33.6 nm film are shown in Fig. 3 along with data for the 31.7 nm film in contact with the (2 μm)^3 boxes[1]. As reported in [1], ρ_s/ρ of the film in contact with the

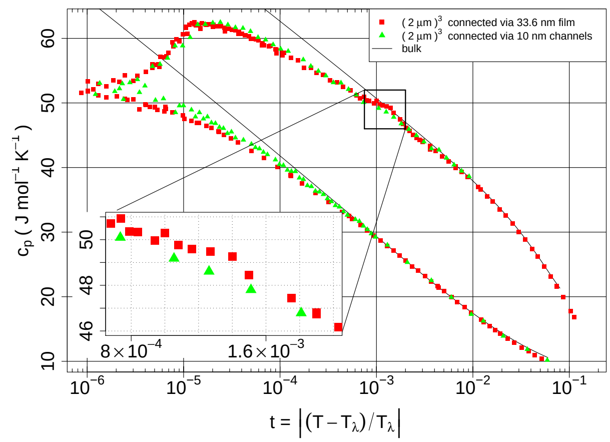

Figure 2. The specific heat of ^{4}He in a (2 μm)^3 confinement from two different measurements.

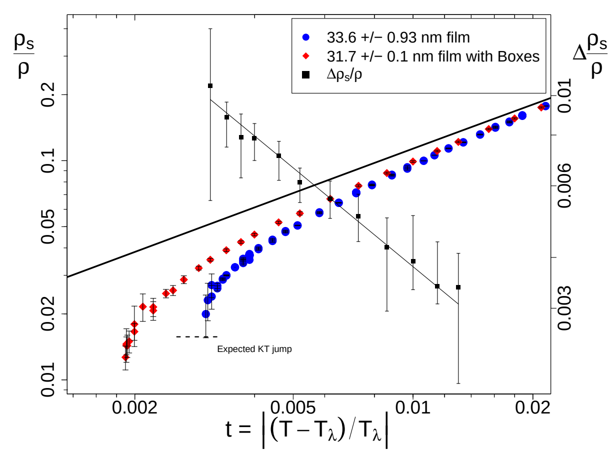

Figure 3. The measured ρ_s/ρ of a 33.6 nm isolated film and a 31.7 nm film over an array of (2 μm)^3 boxes. The presence of the boxes causes an enhancement of ρ_s/ρ over a wide range of temperatures. This enhancement is plotted on the 2nd y-axis.

boxes persists to a higher temperature than one expects from scaling. A much more significant comparison can now be made using these new data. One finds that ρ_s/ρ *not only survives to a higher temperature but proximity with the boxes enhances* ρ_s/ρ *throughout the critical region, and yields a smaller jump than expected for the Kosterlitz-Thouless transition*[20; 21].

The data for the two films allowed us to calculate the enhancement $\Delta(\rho_s/\rho\ )$ caused by the contact with the boxes. This is plotted on the right y-axis in Fig. 3, and is measurable out to $t \sim 1.3 \times 10^{-2}$ where ξ is only 62 $\mathring{A}$. Since the boxes are spaced 4 μm edge-to-edge, this PE is still evident at distances over $640 \times \xi$, a truly "giant" effect.

To explain the GPE observed in HTSC junctions Marchand *et al.*[14] used a model involving vortex-antivortex pairs within a junction of width L. When the separation between the pair reaches a certain distance the phase gradient between them spills into the outer HTSCs (the leads). This causes the energy of the pair to be greatly affected. They predict a logarithmic dependence of the vortex unbinding temperature T_{eff} on $x = \ln d/\ln L$ where d is the film thickness. This argument could be applicable to the GPE we observe in our ^{4}He system, where the energy of vortex-antivortex pairs in the film may be altered when the phase gradients spill into the (2 μm)^3 boxes where ^{4}He is more strongly ordered. Clearly, the geometry of our system is different from that considered theoretically and more measurements need to be made before any quantitative comparisons can be made. However, for the time being, at least qualitatively, the model used by Marchand *et al.* is a possible explanation for the large length scales involved in the GPE we observe.

Acknowledgments
Work was supported by the NSF DMR-0605716; The Cornell Nanoscale Science and Technology Facility 526-94; The Mark Diamond research Fund of the Graduate Student Association at the University at Buffalo, and internal funding from the University at Buffalo.

References

[1] Perron J K, Kimball M O, Mooney K P and Gasparini F M 2010 *Nat. Phys.* **6** 499–502
[2] Perron J and Gasparini F M 2011 *Journal of Low Temperature Physics* **162**(3) 136–145
[3] Bozovic I, Logvenov G, Verhoeven M A, Caputo P, Goldobin E and Beasley M R 2004 *Phys. Rev. Lett.* **93** 157002
[4] Buzdin A I 2005 *Rev. Mod. Phys.* **77** 935–976
[5] Tinkham M 1996 *Introduction to Superconductivity* (New York: McGraw-Hill)
[6] Kabasawa U, Tarutani Y, Fukazawa T, Tsukamoto A, Hiratani M and Takagi K 1991 *Jpn. J. Appl. Phys* **30** 1670–1675
[7] Tarutani Y, Fukazawa T, Kabasawa U, Tsukamoto A, Hiratani M and Takagi K 1991 *Appl. Phys. Lett* **58** 2707–2709
[8] Kasai M, Ohno T, Kanke Y, Kozono Y, Hanazono M and Sugita Y 1990 *Jpn. J. Appl. Phys.* **29** L2219–L2222
[9] Kasai M, Kanke Y, Ohno T and Kozono Y 1992 *J. Appl. Phs.* **72** 5344–5349
[10] Yausa R, Nemoto M, Fujiwara S, Furukawa H, Mukaida H, Tokunaga S and Nakao M 1991 *Physica C* **185-189** 2587–2588
[11] Barner J B, Rogers C T, Inam A, Ramesh R and Bersy S 1991 *Appl. Phys. Lett* **59** 742–745
[12] Meltzow A, Hu S, Hollkott J, Auge J, Spangenberg B, Kurz H, Zakharov N and Hesse D 1997 *Applied Superconductivity, IEEE Transactions on* **7** 2852 –2855 ISSN 1051-8223
[13] Decca R S, Drew H D, Osquiguil E, Maiorov B and Guimpel J 2000 *Phys. Rev. Lett.* **85** 3708–3711
[14] Marchand D, Covaci L, Berciu M and Franz M 2008 *Phys. Rev. Lett.* **101** 097004
[15] Gasparini F M, Kimball M O, Mooney K P and Diaz-Avila M 2008 *Rev. Mod. Phys.* **80** 1009–1059
[16] Rhee I, Bishop D J, Petrou A and Gasparini F M 1990 *Rev. Sci. Instrum.* **61** 1528–1536
[17] Mehta S, Kimball M O and Gasparini F M 1999 *J. Low Temp. Phys.* **114**(5) 467–521
[18] Gasparini F M, Kimball M O and Mehta S 2001 *J. Low Temp. Phys.* **125** 215–238
[19] Perron J K, Kimball M O, Mooney K P and Gasparini F M 2009 *J. Phys.: Conf. Ser.* **150** 032082–032086
[20] Kosterlitz J M and Thouless D J 1973 *J. Phys. C* **6** 1181–1203
[21] Nelson D R and Kosterlitz J M 1977 *Phys. Rev. Lett.* **39** 1201–1205