

# The CQ Experiment: Enhanced Heat Capacity of Superfluid Helium in a Heat Flux<sup>123</sup>

R. A. M. Lee<sup>a\*</sup>, R. V. Duncan<sup>b,a</sup>, A. W. Harter<sup>c,a</sup>, A. Chatto<sup>a</sup>, T. C. P. Chui<sup>d</sup>, P. K. Day<sup>d</sup> and D. L. Goodstein<sup>a</sup>

a) California Institute of Technology, Pasadena, CA, 91125.

b) University of New Mexico, Albuquerque, NM, 87131.

c) Georgia Tech Research Institute, Atlanta, GA 30332.

d) The Jet Propulsion Laboratory, Pasadena, CA, 91109.

**Abstract**—CQ will exploit the superfluid transition of pure liquid  $^4\text{He}$ , in a microgravity environment, in order to study a critical point phase transition under non-equilibrium conditions. It will be conducted in conjunction with the DYNAMX experiment (Critical Dynamics in Microgravity) on board the ISS, using the same hardware and electronics, and on the same mission. We call the combined mission DX/CQ.

It is expected on very general grounds that superflow will break down along a curve on the superfluid side of the  $Q$  (heat flux) -  $T$  (temperature) plane, and it has been shown that the heat capacity at constant  $Q$ ,  $C_Q$ , should diverge along that same curve, which we refer to as  $T_c(Q)$ . The fundamental purpose of the CQ experiment is to measure  $C_Q$  as close as possible to  $T_c(Q)$ . Earthbound measurements to determine  $T_c(Q)$  have given results that disagree with theory. Our own laboratory measurements of  $C_Q$  [1] yield a much larger enhancement of the heat capacity than is predicted by theory, provided that the theoretical value of  $T_c(Q)$  is used in the data analysis. However, for a variety of gravity-related reasons, these measurements could not be made close to  $T_c(Q)$ . The CQ experiment will make use of the microgravity environment on board the ISS to resolve these discrepancies, and should result in the first highly quantitative measurement of dynamical effects on a critical point phase transition.

## TABLE OF CONTENTS

1. INTRODUCTION
2. THE SUPERFLUID TRANSITION IN A HEAT FLUX
3. GROUND BASED MEASUREMENTS
4. MICROGRAVITY JUSTIFICATION
5. EXPERIMENTAL CONFIGURATION
6. ESTIMATION OF ERRORS AND LIMITATIONS
7. STRAY HEAT REQUIREMENTS
8. CONCLUSION

## 1. INTRODUCTION

The superfluid transition in pure  $^4\text{He}$  provides a model system of a critical point phase transition. Superfluid helium can be made almost perfectly chemically pure [2], and physical defects, such as vacancies and grain boundaries that are present in solid-state materials do not exist. Dislocations do not exist either, but are replaced by analogous topological defects called quantized vortex lines, which have interesting effects of their own. Since  $^4\text{He}$  is uncharged, and only very weakly diamagnetic, it is not affected appreciably by stray electromagnetic fields [3]. The equilibrium properties of the superfluid transition have been studied extensively for decades [4, 5, 6, 7], but dynamical behaviour near the transition has only recently come under study.

The full dynamics of liquid helium near the lambda point are thought to be accurately modelled theoretically by Model F of Hohenberg and Halperin [8]. Model F consists of formidable non-linear coupled partial differential equations that cannot be solved except in very special cases. Recently, renormalization group (RG) techniques have been applied to Model F (to leading order in Feynman diagrams) to predict the behaviour of liquid  $^4\text{He}$  in a heat flux near the lambda point [9, 10, 11, 12]. The study of dynamical behaviour is important because every phase transition in nature occurs at some finite rate and hence must, to some degree, be out-of-equilibrium. Thus these recent RG predictions, and other theories [13, 14], deserve close experimental attention.

## 2. THE SUPERFLUID TRANSITION IN A HEAT FLUX

Below the superfluid transition, the correlation length  $\xi$  is given by  $\xi = \xi_0 t^{-\nu}$ , where  $\nu = 0.672$  [15],  $\xi_0 = 3.4 \times 10^{-8}$  cm and  $t$  the “reduced temperature” is given by  $t = (T_\lambda - T)/T_\lambda$ . The correlation length provides a measure of the range of fluctuations of the order parameter near a critical point phase transition. Near the superfluid transition the maximum heat flux,  $Q_c$ , that can be carried by a counterflow between the normal fluid and the superfluid is given by

<sup>1</sup> 0-7803-7231-X/01/\$10.00/© 2002 IEEE

<sup>2</sup> IEEEAC paper #027, updated November 12<sup>th</sup>, 2001

<sup>3</sup> This paper was previously published, in part, in the proceedings of the Pan Pacific Basin Workshop on Microgravity Sciences.

\* corresponding author: [ralee@caltech.edu](mailto:ralee@caltech.edu), telephone: 626 395 2341.

$Q_c = -\rho_s S T_\lambda u_{s,c}$ . Here  $\rho_s$  is the superfluid density,  $S$  is the entropy, and  $u_{s,c}$  is the maximum counterflow velocity. Since  $\rho_s$  and  $u_{s,c}$  both scale as  $1/\xi$ , and since  $\xi$  scales as  $1/t^\nu$ ,  $Q_c$  goes to zero as  $t^{2\nu}$ , as the superfluid transition is approached from below. This can also be expressed as

$$t_c(Q) = \frac{T_\lambda - T_c}{T_\lambda} = \left( \frac{Q}{Q_0} \right)^x \quad (1)$$

where  $x=1/2\nu$  and  $Q_0 \approx 6600$  to  $7400$  W/cm<sup>2</sup> from RG theories [10, 12]. If  $Q$  exceeds  $Q_c$ , then the counterflow state fails catastrophically and a thermal gradient suddenly appears across the helium sample, since now the heat must be transported (at least in part) by normal diffusive means. For any given heat flux  $Q$ , there is a temperature,  $T_c(Q)$ , at which superflow breaks down. This is the same temperature at which the heat capacity is expected to diverge. Beyond that point there exists a region of temperature  $T_c(Q) < T < T_\lambda$  where the helium is resistive, but where the helium would suddenly display heat superconductivity if  $Q$  were lowered isothermally. Over this region (in fact over a region twice as wide and centred on  $T_\lambda$  [9, 16]), the response of the helium to the heat flux is strongly dependent on the heat flux itself. This region is called the nonlinear region.

The heat capacity of flowing superfluid helium near the lambda point was first calculated by Haussmann and Dohm (HD) in a leading order RG solution of Model F [17]. They predicted a modest increase above the heat capacity at rest, terminating at a finite value at  $T_c(Q)$ . However, they had calculated the heat capacity at constant superfluid velocity,  $u_s$ . Chui *et al.* [14] and HD [18] then pointed out that if  $Q$  rather than  $u_s$  were held constant the heat capacity would, instead, diverge at  $T_c(Q)$ .

In general the superfluid density,  $\rho_s$ , depends both on  $T$  and  $u_s$ . If  $\rho_s$  depended only on  $T$ , the contribution of superflow to the free energy in the near-critical region we are discussing would be  $(1/2)\rho_s(T,0)u_s^2$ . However, because  $\rho_s(T, u_s)$  decreases as  $u_s$  increases, a plot of the excess free energy density,  $f$ , versus  $u_s$  at constant  $T$  has a point of inflection. At this point  $\partial Q/\partial u_s = 0$ , a condition that causes both the superflow to be unstable and  $C_Q$  to diverge: The former outcome identifies this point as the  $T_c(Q)$  discussed above, and the latter is the result of an elementary thermodynamic transformation [14].

As early as 1969 Mikeska [19] studied the stability of superfluid counterflow using a free energy analysis and predicted the existence of the nonlinear region. Mikeska argued that the increase in the free energy of the He-II phase by counterflow should decrease the superfluid order parameter, and hence  $\rho_s$ . Mikeska studied these effects systematically in 1969, although he was only able to estimate  $d\rho_s/du_s$  approximately using experimental considerations. Later, Ginzburg and Sobyenin [3] developed a field-theoretic treatment of the superfluid order parameter, which they used to refine their theoretical estimate of the variation of  $\rho_s$  with  $u_s$ . These dynamical

effects on  $\rho_s$  were observed deep within the superfluid phase, and hence well away from the critical region, in superfluid oscillator experiments [20] and in measurements of the critical counterflow velocity as a function of the container size [3]. Careful measurements of these nonlinear effects in the critical region, where fluctuation effects are important, were made only recently by the collaborators of DX/CQ [16, 21, 1]. In conclusion, note that it is the variation of  $\rho_s$  with  $u_s$  which causes the heat capacity to diverge.

### 3. GROUND BASED MEASUREMENTS

The breakdown of superflow in a heat flux near  $T_\lambda$  was measured in a thermal conductivity experiment by Duncan, Ahlers, and Steinberg [22]. They fitted their data to a power-law similar in form to Eq. (1), but with  $Q_0 \approx 600$  W/cm<sup>2</sup> and  $x = 0.81$ . This is a curve in the  $T$ - $Q$  plane that (for experimentally accessible values) always occurs before  $T_c(Q)$  can be reached. We shall call the temperature at which this phenomenon occurs  $T_{DAS}(Q)$ . This difference between the predicted  $T_c(Q)$  and the measured  $T_{DAS}(Q)$  is the first of two disagreements between theory and experiment.

Our group has measured  $C_Q$  for  $Q$  in the range 1-4  $\mu$ W/cm<sup>2</sup> [1]. We find an enhancement of the heat capacity,  $\Delta C = C_Q - C_0$ , for values of  $(Q/Q_c)^2$  from zero to 0.1, which is about ten times larger than predicted on the basis of the above simple argument provided that the theoretical value of  $Q_c$  is used to scale the data. The data are shown in Fig. 1 and compared to various theoretical predictions. The theories predict that  $\Delta C t^\alpha$ , where  $\alpha$  is the ordinary heat capacity exponent, will be a universal function of  $(Q/Q_c)^2$  and, as the figure shows, that prediction is obeyed. However, the magnitude of the enhancement is much larger than expected. This is the second disagreement.

There are three plausible explanations for these discrepancies. Each of these will be tested by the CQ experiment. They are:

1. The theorists are incorrect in their predictions of  $Q_0$  (amplitudes of this sort are notoriously difficult to predict accurately) and the experimentalists are slightly off in their measurement of the exponent  $x$  (for which the theory should be dependable). In this case  $T_{DAS}(Q)$  could be very close, or equal to,  $T_c(Q)$ . If that is true, then by the thermodynamic argument presented earlier,  $C_Q$  must diverge at  $T_{DAS}(Q)$ . Thus, both discrepancies would be accounted for. There would be no disagreement between the theoretical and experimental critical temperature, and the large heat capacity would be the result of being close to the divergence at  $T_c(Q)$ . This point is demonstrated in Fig. 1(b), where we show what Fig. 1(a) would look like if the amplitude of  $Q_0$  was taken to be 3400 W/cm<sup>2</sup> instead of 6571 W/cm<sup>2</sup>. As we explain in the next section, we could not reach  $T_{DAS}$  in the laboratory and even if we had, the supposed divergence would have been rounded by gravity.

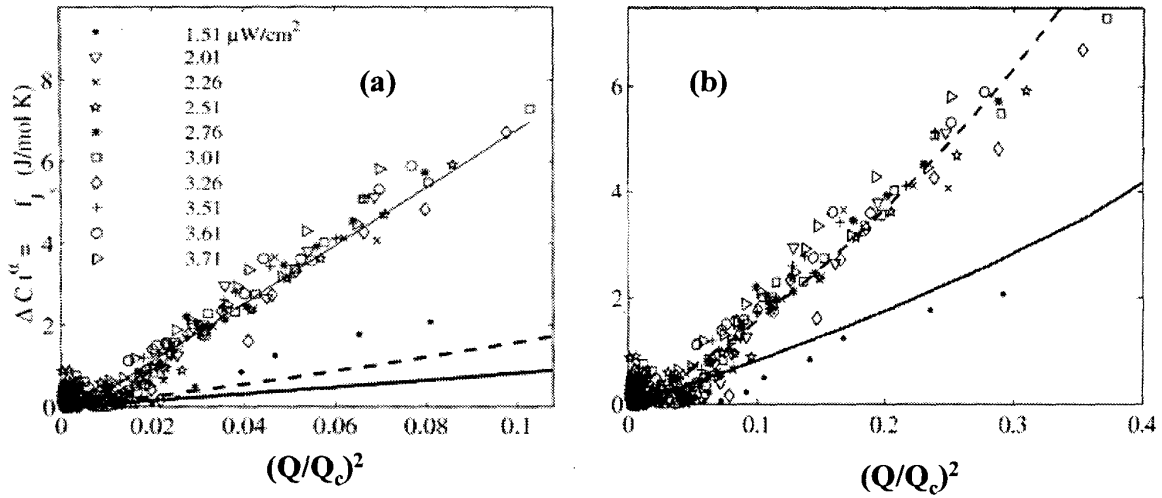


Figure 1 - Differential heat capacity measurements for various values of  $Q$ . The experimental data are scaled against the  $Q_c$  obtained by using (a)  $Q_0 = 6571 \text{ W/cm}^2$  (b)  $Q_0 = 3400 \text{ W/cm}^2$ . Thick solid line: original theoretical prediction (not rounded for gravity) [14, 18]; dashed line: Haussmann's prediction (not rounded for gravity) [12]; thin solid line in (a): fit to the  $Q \geq 2 \mu\text{W/cm}^2$  data.

However, in microgravity, it should be possible to measure  $C_Q$  right up to  $T_{DAS}(Q)$ . We'll also see that microgravity is needed to rule out a spurious apparent divergence in  $C_Q$  at  $T_{DAS}$ .

- Haussmann [23] has argued that  $T_{DAS}(Q)$  is an artefact due to the presence of gravity. If that is correct, it should prove possible to measure  $C_Q$  at  $T > T_{DAS}(Q)$ , possibly all the way up to  $T_c(Q)$ .
- We have argued [1] that  $T_{DAS}(Q)$  is an effect that takes place at the heated surface, related to the singular part of the Kapitza resistance, [24, 25] and is thus quite distinct from  $T_c(Q)$ . If this supposition is correct then, in the CQ experiment,  $C_Q$  will be found to be finite where superflow is observed to break down at  $T_{DAS}(Q) < T_c(Q)$ .

These last two scenarios account for the first discrepancy, but not the second. The CQ experiment will be very important in either of these cases, because it will be the first measurement of  $\Delta C$  free of gravitational distortion (see below), it will improve the precision of  $\Delta C$  by using the penetrating sidewall thermometers of the DX cell, and it will extend the measurements of  $\Delta C$  up to  $T_{DAS}(Q)$ . We show in the next section why all of these measurements may be done in microgravity but cannot be done on Earth. If these measurements verify the finding that  $\Delta C$  is much larger than predicted by theory, it will mean that our most fundamental theories of superflow in liquid helium will have to be revised.

*Aside: A simple derivation of  $t_c(Q)$*

The expression for  $t_c(Q)$  in Eq. (1) can also be derived using the following simple argument: In the superfluid phase there is a reduction in the free energy density by an amount,  $\Delta f$ , which is equal to zero at the lambda transition. Near, but below the transition, thermal energy can cause local regions of the superfluid phase to fluctuate into the higher energy normal phase. These fluctuations occur on all length scales up to a maximum given by the correlation length,  $\xi$ . The energy required for a fluctuation of volume  $\xi^3$  is given by

$$\Delta f \xi^3 = k_B T. \quad (2)$$

This expression is sometimes called the Josephson relation. On applying a heat flux  $\Delta f$  is reduced by an amount  $q^2/2\rho_s$ , which is the kinetic energy associated with the counterflow; where  $q \approx \rho_s u_s = -Q/ST$ . Note that fluctuations now require less energy and so can occur at a correspondingly lower temperature. Superflow is expected to break down when

$$\Delta f = \frac{q^2}{2\rho_s} = \frac{k_B T}{\xi^3}. \quad (3)$$

If one substitutes appropriate values for  $\xi = \xi_0 t^{-\nu}$  and  $\rho_s = \rho_0 t^\nu$  into Eq. (3), and solves for  $t$  in the form of Eq. (1), this gives  $x = 1/2\nu$  and  $Q_0 \approx 8200 \text{ W/cm}^2$ . This is the same exponent, and almost the same value for  $Q_0$ , obtained using complicated RG calculations [10, 12]. This elegant derivation supports the proposition that the  $Q$ -induced transition occurs at  $T_c(Q)$  and not at the lower, experimentally observed,  $T_{DAS}(Q)$ .

Note that this derivation is only approximate since we have not assumed any dependence of  $\rho_s$  on  $u_s$ , nor have we considered the case where the fluctuation volume,  $\xi^3$ , may be non-isotropic under the influence of a  $Q$ -field [26]. A

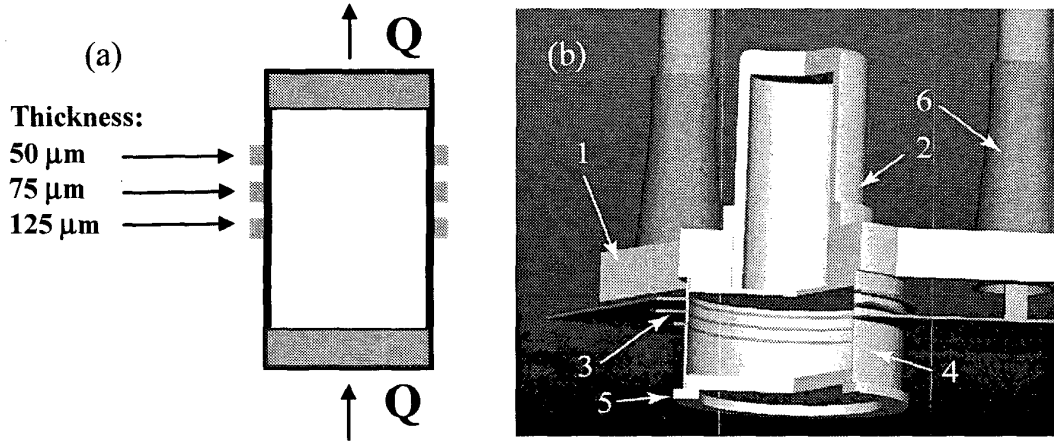


Figure 2 - (a) A conceptual depiction of the cell showing the three sidewall probes. (b) Scale drawing of the cell displayed in a cut-away view, with 1) the cool end-plate, 2) the bubble chamber, 3) the sidewall thermometry probes, 4) the insulating sidewall, 5) the warm end-plate, and 6) the mini high-resolution thermometer mounts.

further inconsistency arises over the choice of the expression for  $\xi$  below  $T_\lambda$ . Experimentalists generally use the expression quoted above, where  $\xi_o = 3.4 \times 10^{-8}$  cm [27], which results in  $Q_o \approx 8200$  W/cm<sup>2</sup>. Theorists, however, use  $\xi = \xi_o 2^{-\nu} t^{-\nu}$  where  $\xi_o = 1.43 \times 10^{-8}$  cm [10, 12]; this results in  $Q_o \approx 60,000$  W/cm<sup>2</sup> making our comparison with theory considerable less favourable.

#### 4. MICROGRAVITY JUSTIFICATION

At very small reduced temperature,  $t$ , the approach to ideal criticality can be impeded either by gravity ( $g$ ), or by a heat flux ( $Q$ ). The basic purpose of DX/CQ is to remove the effects of  $g$  in order to study in their purest form the effects of  $Q$ . In this section we consider the limitations imposed on heat capacity measurements by both  $g$  and  $Q$ , in order to understand what needs to be done on orbit and what can adequately be studied on Earth.

Above  $4 \mu\text{W}/\text{cm}^2$ , Gorter-Melink-like dissipation in the superfluid becomes substantial compared to the sub nano-kelvin resolution of the DX/CQ thermometers. In this regime, a new, dissipative phase of heat transport near the superfluid transition has been observed by Liu and Ahlers [28], and by Murphy and Meyer [29]. The interpretation of the nature of this new phase has not yet been determined, but it should be possible to study this region adequately on Earth.

Between approximately  $70 \text{ nW}/\text{cm}^2$  and  $4 \mu\text{W}/\text{cm}^2$  the super-normal counterflow created by  $Q$  is isothermal and effectively free of dissipation so long as  $T$  remains below  $T_\lambda(Q)$ . In this narrow range of temperature, however, the hydrostatic gradient in the lambda point temperature puts severe limits on laboratory experiments. The recent experiments by the CQ group explored this region as well as can be done on Earth.

The temperature of the lambda transition decreases with increasing pressure by about 0.01 K/bar. Therefore, on Earth, the hydrostatic pressure inside a column of liquid helium causes the lambda temperature to vary with height,  $h$ , as  $dT_\lambda/dh = -\alpha = -1.273 \mu\text{K}/\text{cm}$  [30]. Thus, in a cell 0.06 cm high (the height of the cell used by the CQ group on Earth), the lambda temperature is about  $10^{-7}$  K lower at the bottom of the cell than it is at the top. In the superfluid phase, where the CQ measurements will be made,  $T$  is uniform on Earth, but the distance from criticality,  $t$ , is not. Hence, if a sharp divergence is expected at some  $(Q, t)$ , the best possible measurement necessarily averages over a range of  $t$ , smearing out the divergence, unless the change in  $t$  across the cell is very small compared to  $t$  itself. However, for values of  $Q$  small enough not to cause dissipation, the  $Q$ -dependent part of the heat capacity is immeasurably small whenever that criterion is satisfied. In other words, in measurements made on Earth, not only is it impossible to see a sharp divergence, it is impossible to obtain any data at all that are not distorted by gravity.

Gravity has another, more indirect effect on the CQ measurement. The 0.06 cm cell height, chosen to minimize the effect of gravity, made it impractical to do side-wall thermometry on Earth. This required us to use thermometers located on the cell end-plates, which had a number of undesirable effects: It limited the range and precision of the measurements, because the singular Kapitza resistance had to be subtracted from the data in order to obtain the heat capacity. The range of measurements was limited further by a sudden change in Kapitza resistance that occurred when the local correlation length at the bottom (hotter) surface of the cell end-plate became comparable to the surface roughness. It also restricted the choice of measurement technique to the heat pulse method, which may or may not be optimal for CQ. Finally, there could be no independent check of whether the cell was isothermal.

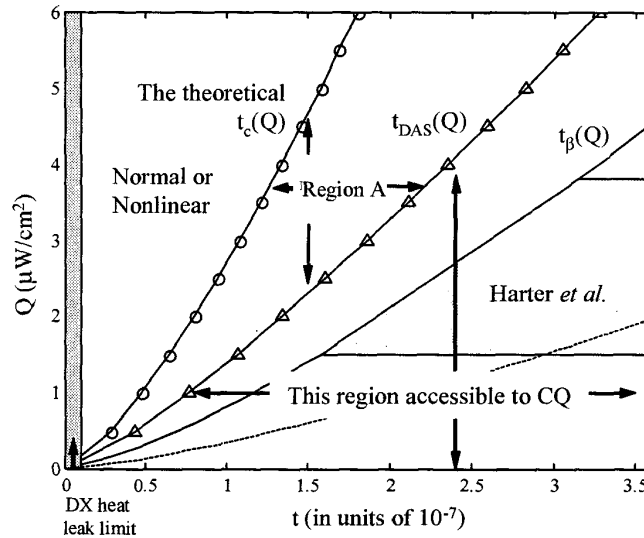


Figure 3 - The  $t$ - $Q$  plane. The CQ experiment will yield measurements unaffected by gravity in the entire region below the curve marked  $t_{DAS}(Q)$ . Region A: This region may require a more advanced experiment if the disagreement between theory and experiment, as outlined in explanation (3), is observed in microgravity. The dashed line shows where the heat capacity enhancement rises above 1% according to a fit to the data of Harter *et al* [1]. Shaded region: measurements by Harter *et al*.

A simplified view of the experimental cell used in DX/CQ is displayed in Fig. 2. An all-metal-cylindrical liquid helium cell, of diameter 2.3 cm, contains three sidewall thermometer probes of different thickness along its 0.9 cm height. A heat flux  $Q$  passes in the bottom and out of the top of the cell. When the cell is entirely in the He-II phase the helium is isothermal, and the probes all read the same temperature. All CQ measurements will be made in this condition. Departure from this condition signals that a normal-superfluid interface is present within the cell and the CQ run has finished producing useful data. The three sidewall thermometers in the DX cell will avoid all of the problems described in the previous paragraph. The range of space in the  $Q$ - $t$  plane made accessible by doing the CQ experiment on orbit in the DX cell is shown quantitatively in Fig. 3.

## 5. EXPERIMENTAL CONFIGURATION

The hardware for the prototype flight Instrument Sensor Package (ISP) assembly consists of two coaxial radiation and residual gas shields surrounding an experimental cell assembly. The cell assembly, which includes the cell, thermometers, heaters, and a bubble chamber to maintain saturated vapour pressure (SVP) conditions, has been built using the minimum possible mass (30 g) in order to avoid systematic errors associated with variations in charged particle heating. The cell fill line is closed using a miniature, hydraulically operated, cryogenic valve situated on top of the bubble chamber.

The cell consists of a 75μm thick stainless steel sidewall that is brazed to ≈ 75μm thick copper probes which extend around the full circumference of the cell. The temperature of each of the sidewall probes is measured using a new design of miniature high-resolution thermometer (mini-HRTs). Each HRT uses a thermometric element of  $Pd_{1-x}Mn_x$  where  $x$ , the atomic concentration of Mn, is 0.7% in order to achieve a Curie temperature of 2.1 K, as described in a recent DX publication [31]. The flux tubes of these magnetic susceptibility thermometers are charged with a magnetic field between 50-200 gauss using a superconducting magnet. During the ground-based measurements, this magnet is located in the liquid helium surrounding the vacuum can, while in the flight experiment it will be located on the outer radiation shield. The magnet will only be used to charge the flux tubes of the mini-HRTs during cool-down, and will not be energized during the measurements. Each sidewall thermometer has a mass of 2.7 g which also includes the mass of the flux tube.

## 6. ESTIMATION OF ERRORS AND LIMITATIONS

The DX cell was not designed for taking precise heat-capacity measurements, but it is almost perfectly suited for that purpose. One reason is that the DX control of the super-normal interface position is extremely sensitive to parasitic heat-leaks. Thus, it was designed to limit uncontrolled heating from all sources to less than 20 pW over a 10 minute period, and this performance has been verified in ground testing and modelling of the cosmic ray environment. This feature, combined with the established performance of the HRTs should make it possible to obtain

heat capacity measurements with a resolution better than 1% at all temperatures more than  $10^{-8}$  K below  $T_\lambda$  (i.e. the entire parameter space shown in Fig. 3, where this limit is also indicated).

The upper limit of the heat flux is governed by the total thermal resistance between the sample stage and the bath, which is maintained at approximately 1.6 K. This thermal resistance will be less than  $10^5$  K/W, guaranteeing a range of at least zero to  $6 \mu\text{W}/\text{cm}^2$ . This range has been verified experimentally in the DX prototype, and it overlaps the range of heat flux used in the CQ ground based experiments [1].

The Kapitza resistance at the small contact area between the copper sidewall probes and the liquid helium limits the temperature resolution of the HRTs. This area is small because DX requires narrow probes in order to achieve high spatial resolution. Laboratory measurements together with modelling of the charged particle heating environment lead us to expect a resolution of  $0.15 \text{ nK}/\sqrt{\text{Hz}}$ . It may be possible to improve on this resolution, or to reduce the integration time necessary for measurements of 1% or better, by observing all three sidewall HRTs simultaneously.

To summarize: The DX cell comes as close as one could hope to be ideally suited to make precise heat capacity measurements over the range of parameter space shown in Fig. 3.

#### *Thermal Counterflow and Mutual Friction*

In the thermal counterflow of the CQ experiment, the viscous flow of the normal fluid results in a small contribution to the temperature gradient that is linear in the heat flux. More importantly, the interaction of the normal fluid component with vortices, entrained in the counterflowing superfluid, also results in dissipation. This latter effect is called vortex mutual friction and produces a temperature gradient that varies approximately as  $Q^3$ .

Recently, Baddar *et al* [32] measured the superfluid thermal resistance very close to the transition. They demonstrated that their results can be described by a simple expression consistent with earlier measurements made by Leiderer and Pobel [33], much farther from the transition and at higher  $Q$ . These results were also verified in DX measurements [34] at temperatures very near the transition, using an engineering model of the DX instrument. Because the observed temperature gradients vary with  $Q^3$ , they vanish rapidly with decreasing  $Q$  and were not resolvable in the ground based measurements made with the DX instrument for  $Q$  below  $1 \mu\text{W}/\text{cm}^2$ . In the large diameter cells used by both DX and Baddar *et al*, the linear behaviour was too small to be observed.

These measurements allow us to estimate with confidence the limits that these effects place on the CQ experiment. Figure 4(a) shows an estimate of the temperature profiles

through the cell, for various values of  $Q$ , once the warm end of the cell has reached the breakdown temperature, assumed here to be  $T_{DAS}$ . These temperature profiles are approximately linear because the divergence of the superfluid resistivity at  $T_\lambda$  is cut off when one end of the cell breaks down at  $T_{DAS}$ . The estimated gradients are larger than the actual observed gradients in the laboratory at the same  $Q$ , because gravity makes it impossible to approach closer to  $T_{DAS}$ . Figure 4(a) makes it clear that the superfluid's resistivity is only significant for  $Q$  greater than about  $400 \text{ nW}/\text{cm}^2$ . Above that value of  $Q$ , the effect of the temperature gradient is analogous to that of gravity on ground based experiments.

Hence, the effects on the CQ experiment suggested by these measurements are, firstly, that the superfluidity in the cell will break down when the average cell temperature is still below the breakdown temperature. This limitation turns out to be insignificant, because the temperature difference between the average cell temperature at breakdown and  $T_{DAS}$  is much smaller than the difference between  $T_{DAS}$  and  $T_\lambda$ .

The second effect on CQ is the heat capacity error that results from the variation of the reduced temperature across the cell, and is similar to (but much smaller than) the gravitational smearing observed in ground measurements. In Fig. 4(b), we plot the average cell temperature at which superfluidity breaks down at one end of the cell due to the gradient shown in the previous figure (diamonds). On the scale of this graph, that line would be virtually indistinguishable from  $T_{DAS}$ . For small gradients in the reduced temperature, the corresponding error in the heat capacity can be corrected for by a curvature correction, just as one does in gravity. The temperature at which the curvature correction reaches 0.1% of the measured heat capacity is also plotted in the figure (triangles). Except for the very highest values of  $Q$  in the measurement range, that temperature is higher than the breakdown temperature and therefore will never be reached. For reference, we also plot the temperatures at which we expect the  $Q$ -induced heat capacity enhancement to reach 0.1% (squares) and 1% (circles) of the zero- $Q$  heat capacity. We conclude that dissipation should not affect the CQ measurements significantly anywhere in the planned range of the experiment, based on extensive earth bound measurements. If dissipation is different in space than on Earth, that phenomenon will constitute an important discovery and bear careful measurement by the CQ experiment.

## 7. STRAY HEAT REQUIREMENTS

There are two major environmental sources of stray heating, charged particle heating and stray heating induced by vibrations.

#### *Charged Particle Heating*

The accuracy of the CQ measurements could be affected by charged-particle heating from the space radiation environment. Because of its random nature, charged

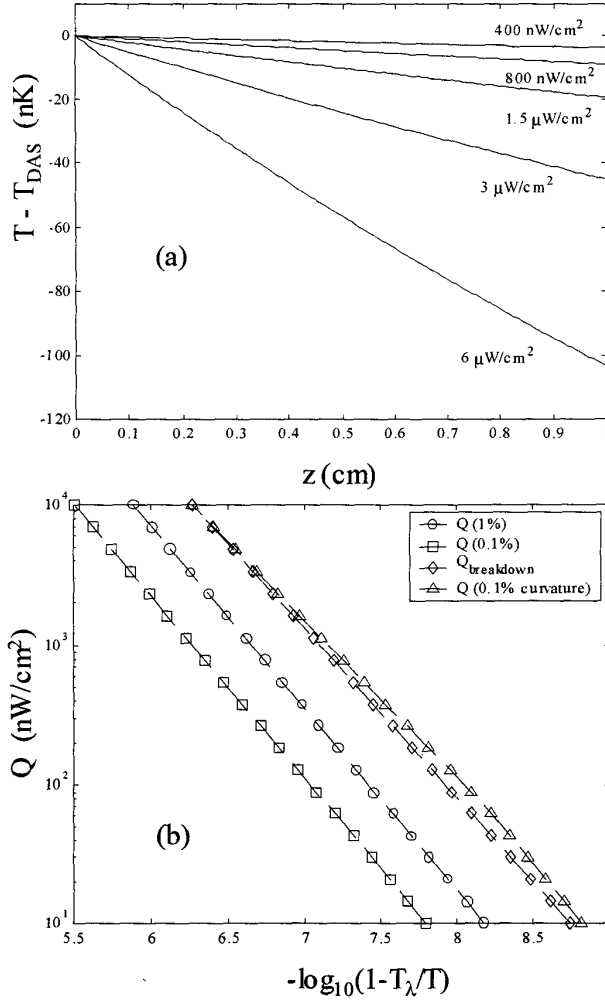


Figure 4 - (a) Expected temperature profiles across the cell for various values of  $Q$ . (b) Reduced temperature for 1% (circles) and 0.1% (squares) heat capacity enhancement. Breakdown temperature (diamonds) and temperature at which the curvature correction is 0.1% of the signal (triangles).

particle heating increases the noise and hence decreases the resolution of the thermometers, and it adds a fluctuating component both to the heat flux in the cell and to the extra heat used to measure the heat capacity.

The large peak in the heating over the South Atlantic Ocean is called the “South Atlantic Anomaly” (SAA). This heating peak arises because the geomagnetic dipole of the earth is displaced from its gravitational centre by some hundreds of kilometres toward the north Pacific. Away from the SAA and over the rest of the ISS orbit the trapped particle heating is negligible, except at the highest latitudes, where it is thought that a level of heating smaller than that of the SAA is contributed by the “horns” of the electron distribution. A further, much smaller, variation in heating is observed away from the SAA and the horns, caused by “galactic cosmic rays” which are bare atomic nuclei of

extra-solar origin. In interplanetary space the flux of galactic cosmic rays is nearly isotropic, but in low-earth orbit the geomagnetic field filters the fluxes according to the ratio of particle momentum to charge.

DX requires that the variation in charged particle heating be stable to within 10 pW over a ten-minute scan at its lowest value of  $Q$  (10 nW/cm<sup>2</sup>). This requirement relaxes as  $Q$  and  $t$  increases and is far beyond CQ’s needs even at the lowest value of  $Q = 100$  nW/cm<sup>2</sup> and  $t = 10^{-8}$ . Therefore, about 18 hours of each 24 hour day should be available for CQ data-taking. However, the precision thermometry required for CQ will require much longer integration times than are needed by DX.

### Vibration Requirement

Vibration-induced heating must be maintained at a very low level during the measurements scans. Fortunately, the negative thermal expansion coefficient provides a cooling effect during adiabatic compression, which is in the same direction as the pressure shift in  $T_\lambda$ , substantially reducing the effect of vibrations on the distance of the helium from criticality. Direct measurements of vibration-induced heating indicate that there will be no substantial concern, provided that there are no low-frequency resonances of the DX ISP structure. An aerospace contractor (SWALES) has recently completed a modal analysis of the DX ISP, and they estimate that the first structural resonance will occur at 173 Hz. This first resonance frequency has been measured at 134 Hz in preliminary results from a recent launch-load shake test of the DX prototype flight hardware. Hence the vibration environment on the ISS, while greater than that experienced on Earth, is not expected to be a major concern.

### 8. CONCLUSION

The CQ experiment will explore a range of the  $t$ - $Q$  plane that is not accessible in Earth-bound experiments. Measurements taken by CQ will not be influenced by the singular Kapitza resistance or gravitational rounding, and should elucidate the current discrepancies between theory and experiment. We will be able to test for the following possibilities:

1.  $T_{DAS}(Q) \approx T_c(Q)$ . If so,  $C_Q$  will diverge along this curve in the  $t$ - $Q$  plane. (To determine this requires a microgravity environment in order to eliminate gravitational rounding, and to permit multiple sidewall thermometry) If this is the case, CQ will be able to reach all of the important parameter space in the  $t$ - $Q$  plane shown in Fig. 3, and reveal the physics of the predicted divergence in  $C_Q$ .
2. Haussmann's suggestion that  $T_{DAS}(Q)$  is a gravity artefact [11]. If that is so the CQ experiment will confirm this, and it should be possible to examine the predicted singular behaviour of  $C_Q$  as  $Q_c$  is approached.
3. Neither of the above, in which case  $T_{DAS}(Q)$  might be due to a wall effect as we have discussed [1]. In this case, all of the parameter space to the right of the curve  $t_{DAS}(Q)$  in Fig. 3 will be available for measurement, unaffected by gravity rounding. It should then be possible to analyze the behaviour of  $C_Q$  for small  $(Q/Q_c)^2$  for clues as to how our current theories of superfluidity will have to be modified. The region between  $t_{DAS}(Q)$  and  $t_c(Q)$  in Fig. 3 would then be the subject of a future experiment with a cell designed to overcome the influences of the singular Kapitza resistance.

In conclusion, the DX/CQ experiment will result in the first highly quantitative measurement of dynamical effects on a critical point phase transition in the limit where present theory is no longer a dependable guide. DX/CQ will provide new information on how macroscopic quantum order emerges and how it is destroyed in a system driven away from equilibrium in a highly controlled manner. Such data, taken free of hydrostatic gradients inevitable on Earth, should prove to be of broad scientific interest.

### REFERENCES

- [1] A.W. Harter, R. A. M. Lee, A. Chatto, X. Wu, T. C. P. Chui, and D. L. Goodstein, *Phys. Rev. Lett.* **84**, 2195 (2000).
- [2] The only impurity in  $^4\text{He}$  that remains liquid is the isotope  $^3\text{He}$ , which may be reduced in concentration to less than  $10^{-12}$  [P.C. Hendry and P.V.E. McClintock, *Cryogenics* **25**, 526 (1985)]. We use isotopically purified  $^4\text{He}$  with a residual atomic concentration of  $^3\text{He}$  of less than  $8 \times 10^{-10}$ . During our measurements, even our lowest value of  $Q$  will heat-flush [R.P. Behringer, *J. Low Temp. Phys.* **62**, 15 (1986)] this residual  $^3\text{He}$  to the cold endplate of the cell, and hence out of the measurement region between the sidewall probes. This low  $^3\text{He}$  concentration is far too sparse to form a monolayer on the cold endplate.
- [3] V. L. Ginzburg and A. A. Sobyenin, *Phys. Lett.* **69A**, 417 (1979); *J. Low Temp. Phys.* **49**, 507 (1982).
- [4] J. A. Lipa, D. R. Swanson, J.A. Nissen, T. C. P. Chui, and U. E. Israelsson, *Phys. Rev. Lett.* **76**, 944 (1996).
- [5] J. A. Lipa, D. R. Swanson, J. A. Nissen, P. R. Williamson, K. Geng, D. A. Stricker, T.C.P. Chui, U.E. Israelsson, and M. Larson, *J. Low Temp. Phys.* **113**, 849 (1998).
- [6] W. Y. Tam and G. Ahlers, *Phys. Rev. B* **32**, 5932 (1985); **33**, 193 (1986).
- [7] M. Dingus, F. Zhong, and H. Meyer, *J. Low Temp. Phys.* **65**, 185 (1986); M. Dingus, F. Zhong, J. Tuttle, and H. Meyer, *J. Low Temp. Phys.* **65**, 213 (1986).
- [8] P. C. Hohenberg and B. I. Halperin, *Rev. Mod. Phys.* **49**, 435 (1977).
- [9] R. Haussmann and V. Dohm, *Phys. Rev. Lett.* **67**, 3404 (1991), *Z. Phys. B* **87**, 229 (1992).
- [10] R. Haussmann and V. Dohm, *J. Low Temp. Phys.* **89**, 429 (1992), *Phys. Rev. B* **46**, 6361 (1992).
- [11] R. Haussmann, *J. Low Temp. Phys.* **114**, 1 (1999).
- [12] R. Haussmann, *Phys. Rev. B* **60**, 12349 (1999).



[13] P. Weichman, A. Prasad, R. Mukhopadhyay, and J. Miller, *Phys. Rev. Lett.*, **80**, 22 (1997); P. Weichman and J. Miller, preprint.

[14] T. C. P. Chui, D. L. Goodstein, A. W. Harter, and R. Mukhopadhyay, *Phys. Rev. Lett.*, **77**, 1793 (1996).

[15] A. Singaas and G. Ahlers, *Phys. Rev. B* **30**, 5103 (1984). In the nonlinear region we do not distinguish between the correlation length above and below the transition.

[16] P. Day, W. Moeur, S. McCready, D. Sergatskov, and R. Duncan, *Phys. Rev. Lett.*, **81**, 2471 (1998).

[17] R. Haussmann and V. Dohm, *Phys. Rev. Lett.*, **72**, 3060, (1994).

[18] R. Haussman and V. Dohm, *Czech. J. Phys.*, **46-S1**, 171, (1996).

[19] H.J. Mikeska, *Phys. Rev.* **179**, 166 (1969)

[20] G. B. Hess, *Phys. Rev. Lett.* **40**, 1191 (1978).

[21] W. A. Moeur, P.K. Day, F-C. Liu, S. T. P. Boyd, M. J. Adriaans, and R. V. Duncan, *Phys. Rev. Lett.* **78**, 2421 (1997).

[22] R. V. Duncan, G. Ahlers and V. Steinberg, *Phys. Rev. Lett.* **60**, 1522 (1988).

[23] R. Haussmann, *J. Low Temp. Phys.* **114**, 1 (1999).

[24] R. V. Duncan and G. Ahlers, *Phys. Rev. Lett B* **43**, 7707 (1991).

[25] H. Fu, H. Baddar, K. Kuehn, and G. Ahlers, *Low Temp. Phys.* **24**, 69 (1998).

[26] R. Mehrotra, G. Ahlers, *Phys. Rev. Lett.* **51**, 2116 (1983).

[27] A. Singaas and G. Ahlers, *Phys. Rev. B*, **30**, 5103 (1984).

[28] F-C. Liu and G. Ahlers, *Phys. Rev. Lett.* **76**, 1300 (1996).

[29] D. Murphy and H. Meyer, *Phys. Rev. B* **57**, 536 (1998).

[30] G. Ahlers, *Phys. Rev.* **171**, 275 (1968).

[31] B. J. Klemme, M. J. Adriaans, P. K. Day, D. A. Sergatskov, T. L. Aselage, and R. V. Duncan, *J. Low Temp. Phys.* **116**, 133 (1999).

[32] H. Baddar, G. Ahlers, K. Kuehn, and H. Fu, *J. Low. Temp. Phys* **119**, Nos.1/2, 1 (2000).

[33] P. Leiderer and F. Pobell, *J. Low Temp. Phys.* **3**, 577 (1970).

[34] P. K. Day, unpublished.

**Richard A. M. Lee** is a Senior Scientist at the California Institute of Technology. His current research interests include liquid  $^4\text{He}$ , in particular the lambda transition, superfluidity and applications in microgravity. He recently served as a Senior Research Scientist at the National Physical Laboratory in the United Kingdom, where he worked on high temperature superconducting (HTS) SQUIDS and their applications in primary noise thermometry. Prior to this he served as a postdoctoral scholar at Caltech and the Jet Propulsion Laboratory where he worked on the ground based CQ experiment. He received his B.Sc. (Hons) and Ph.D. in physics from the University of Lancaster in the UK.



**Robert Duncan, Ph.D.**, is a professor of physics at UNM, and a visiting associate in physics on the Caltech faculty. He is the principal investigator on Critical Dynamics in Microgravity, which is scheduled as part of the first fundamental physics microgravity mission to the International Space Station in the year 2005. Duncan serves as Chair of the Instrumentation and Measurement Topical Group of the American Physical Society. He is an ultra-marathon runner, with two official finishes in the gruelling Leadville 100-Mile Mountain Run.



**Alexa W. Harter** is a Research Scientist II at the Georgia Tech Research Institute. Her current research interests include the electromagnetic and mechanical properties of meta-materials. As a graduate student at Caltech, she observed the first experimental evidence that the heat capacity of superfluid  $^4\text{He}$  is enhanced by a heat flux. She received a Sc.B. in physics and mathematics from Brown University and a Ph.D. in physics from Caltech.

**Andrew Chatto** is a graduate student at the California Institute of Technology working towards his doctorate in physics. He received his BS in Mathematics and Physics from Yale University in 1995. His current research interest is the helium superfluid phase transition under a heat flow.

**Talso C. P. Chui** is a Principal Technical Staff member at the Jet Propulsion Laboratory. He began his career at Stanford University co-developing the high-resolution thermometer, which, he later showed, to have reached the limited imposed by thermodynamic fluctuations. He participated in two successful flight experiments, the

*Lambda Point Experiment and the Confined Helium Experiment, to study the properties of helium very near the superfluid transition of  $^4\text{He}$ . After joining JPL he has continued his research on the dynamic properties of superfluid helium and participated, in various roles, in the development of the Low Temperature Microgravity Physics Experiment Facility. His achievements at JPL include, the theoretical prediction that the heat capacity of superfluid helium diverges under a heat flux, and the first observation of the Josephson effect in superfluid  $^4\text{He}$ . He graduated from Caltech with a B.S. degree and from Rutgers University with a Ph. D. degree in physics.*

**Peter K. Day** is a Staff Scientist at the Jet Propulsion Laboratory in Pasadena, CA. His research interests include phase transitions in thin films, superfluid helium, applications of SQUIDS and superconducting detectors for use in astrophysics. He received a bachelors degree in physics from the University of California, Berkeley in 1988 and a PhD from Caltech in 1993.

**David L. Goodstein** is vice provost and professor of physics and applied physics at the California Institute of Technology. In 1995 he was named the Frank J. Gilloon Distinguished Teaching and Service Professor. His books include *States of Matter* and *Feynman's Lost Lecture*, co-authored with his wife Dr Judith R. Goodstein. His research interests include phases



and phase transitions in adsorbed, two-dimensional matter, ballistic phonons in solids, superfluidity in liquid helium, and critical point phenomena, resulting in nearly 200 scientific publications. He has served on numerous scientific and academic panels, including the National Advisory Committee to the Mathematical and Physical Sciences Directorate of the National Science Foundation, which he currently chairs. He is a founding member of the Board of Directors of the California Council on Science and Technology. Dr Goodstein was the host and project director of "The Mechanical Universe", a 52-part college physics telecourse, which has garnered more than a dozen prestigious awards including the 1987 Japan Prize for television. He has also been awarded the 1999 Oersted Medal of the American Association of Physics Teachers. He attended Brooklyn College and received his Ph.D. in physics from the University of Washington.