2^{nd} *Pan Pacific Basin Workshop on Microgravity Sciences, 2001*
Paper FP-1025

THE CQ EXPERIMENT: ENHANCED HEAT CAPACITY OF SUPERFLUID HELIUM IN A HEAT FLUX

D.L. Goodstein[1], R.V. Duncan[1,2], A.W. Harter[1*], R.A.M. Lee[1], A. Chatto[1], T.C.P. Chui[3], P. Day[3]

[1] California Institute of Technology, Pasadena, CA, USA
[2] University of New Mexico, Albuquerque, NM, USA
[3] The Jet Propulsion Laboratory, Pasadena, CA, USA

ABSTRACT

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 predicted by theory, provided that the theoretical value of $T_c(Q)$ is used in the analysis of data, but for a variety of gravity-related reasons, measurements could not be made close to $T_c(Q)$. The CQ experiment will make use of the microgravity environment to resolve both of these discrepancies between theory and experiment. It will be done in conjunction with the DYNAMX experiment (DX), using the same hardware and electronics, on the same mission.

INTRODUCTION

The superfluid transition in pure ^{4}He is an excellent model system of a critical point phase transition. Superfluid helium can be made almost perfectly pure chemically [2]. Physical defects, such as vacancies and grain boundaries that are present in solid-state materials do not exist in superfluid helium. Dislocations do not exist either, but they are replaced by analogous topological defects called quantized vortex lines, which have interesting effects of their own. Since ^{4}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 behavior near the transition has only recently come under study.

The full dynamics of helium near the lambda point are thought to be accurately modeled 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, RG techniques have been applied to Model F (to leading order in Feynman diagrams) to predict the behavior of liquid ^{4}He in a heat flux near the lambda point [9,10,11,12]. The study of dynamical behavior is important because every phase transition in nature occurs at some finite

---

[*] corresponding author awh@caltech.edu

rate, and hence must be out-of-equilibrium at some level. Thus these recent RG predictions, and other theories [13,14], deserve close experimental attention.

SUPERFLUID TRANSITION IN A HEAT FLUX

Below the superfluid transition, the correlation length x is given by $x = x_o t^{-n}$, where $n = 0.672$ [15] and $x_o = 3.4\times10^{-8}$ cm. The correlation length provides a measure of the range of fluctuations of the order parameter near a critical point phase transition. The maximum heat flux, Q_c, carried by counterflow is given by $Q_c = -r_s S T_l u_{s,c}$ near the superfluid transition. Here r_s is the superfluid fraction, S is the entropy, and $u_{s,c}$ is the maximum counterflow velocity. Since r_s and $u_{s,c}$ both scale as $1/x$, and since x scales as $1/t^n$, Q_c goes to zero as t^{2n} as the superfluid transition is approached from below. This can also be expressed as

$$t_c=(Q/Q_0)^x, \tag{1}$$

where $x=1/2í$. 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 a region of temperature $T_c(Q) < T < T_l$ exists 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 centered on T_l [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 diverge at $T_c(Q)$.

In general the superfluid density, r_s, depends both on T and u_s. If r_s depended only on T, the contribution of superflow to the free energy in the near-critical region we are discussing would be $(1/2)r_s(T,0)u_s^2$. However, because $r_s(T,u_s)$ 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 superflow to be unstable and C_Q to diverge. The former condition 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 r_s. Mikeska studied these effects systematically in 1969, although he was only able to estimate dr_s/du_s roughly using experimental considerations. Later, Ginzburg and Sobyanin [3] developed a field-theoretic treatment of the superfluid order parameter, which they

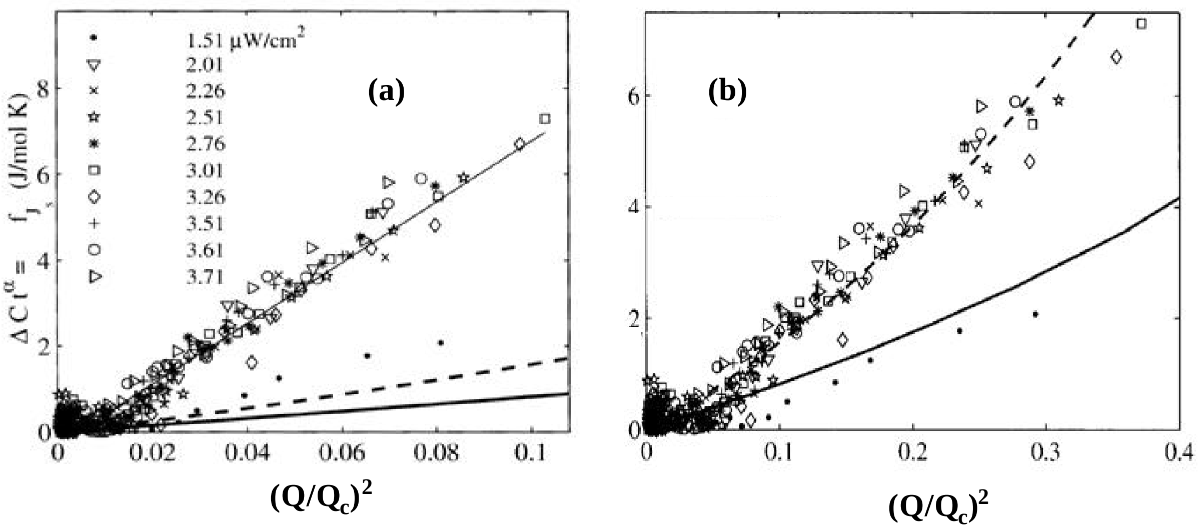

Figure 1 Differential heat capacity measurements for various values of Q. The experimental data are scaled against the Q_c obtained by using (a) $Q_0 = 6571$ W/cm^2 (b) $Q_0 = 3400$ W/cm^2. Thick solid line: original theoretical prediction (not rounded for gravity) [18,14]; dashed line: Haussmann's prediction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

used to refine their theoretical estimate of the variation of r_s with u_s. These dynamical effects on r_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]. It is the variation of r_s with u_s that causes the heat capacity to diverge.

GROUND-BASED MEASUREMENTS

The breakdown of superflow was measured in a thermal conductivity experiment by Duncan, Ahlers, and Steinberg [22]. They fit their data to a power-law similar in form to Eq. (1), but with $Q_0 \approx 600$ W/cm^2 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 μW/cm^2. We find an enhancement of the heat capacity, $DC = C_Q - C_0$, for values of $(Q/Q_c)^2$ from zero to 0.1, that is about ten times larger than predicted on the basis of the above simple argument. The data are shown in Fig. 1, compared to various theoretical predictions. The theories predict that $DCt^{á}$, where $á$ 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 of 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 were taken to be 3400 W/cm^2 instead of 6571 W/cm^2. As we explain in the next section, we could not reach T_{DAS} in the laboratory and even if we could have reached it, the supposed divergence would have been rounded by gravity. 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}.

2. Haussmann [23] has argued that $T_{DAS}(Q)$ is an artifact 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 $T_c(Q)$.

3. 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, 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 $T_{DAS}(Q) < T_c(Q)$. In this case, the CQ experiment will be very important because it will be the first measurement of DC free of gravitational distortion (see below), it will improve the precision of DC by using the penetrating sidewall thermometers of the DX cell, and it will extend the measurements of DC 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 ΔC is much larger than predicted by theory, it will mean that our most fundamental theories of superflow in helium will have to be replaced.

MICROGRAVITY JUSTIFICATION

At very small reduced temperature, t, the approach to ideal criticality can be impeded either by gravity (g), or by 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 μW/cm^2, Gorter-Melink-like dissipation in the superfluid becomes substantial compared to the sub-nanokelvin 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 [24], and by Murphy and Meyer [25]. 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 roughly 70 nW/cm^2 and 4 µW/cm^2 the super-normal counterflow created by Q is isothermal and effectively free of dissipation so long as T remains below $T_c(Q)$. 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 .01 K/bar. As a result, the hydrostatic pressure inside a liquid Helium column on earth causes the lambda temperature inside the column to vary with height, h, as $dT_\lambda/dh = -\alpha = -1.273$ µK/cm [26]. Thus, in a cell .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 unmeasurably 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 .06 cm cell height, chosen to minimize the effect of gravity, made it impractical to do side-wall thermometry on Earth. End-wall thermometry 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 became comparable to the surface roughness. It also restricted the choice of measurement technique to the pulse method, which may or may not be optimal for CQ. Finally, there could be no independent check of whether the cell was isothermal.

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 thermometry 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 side-wall 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.

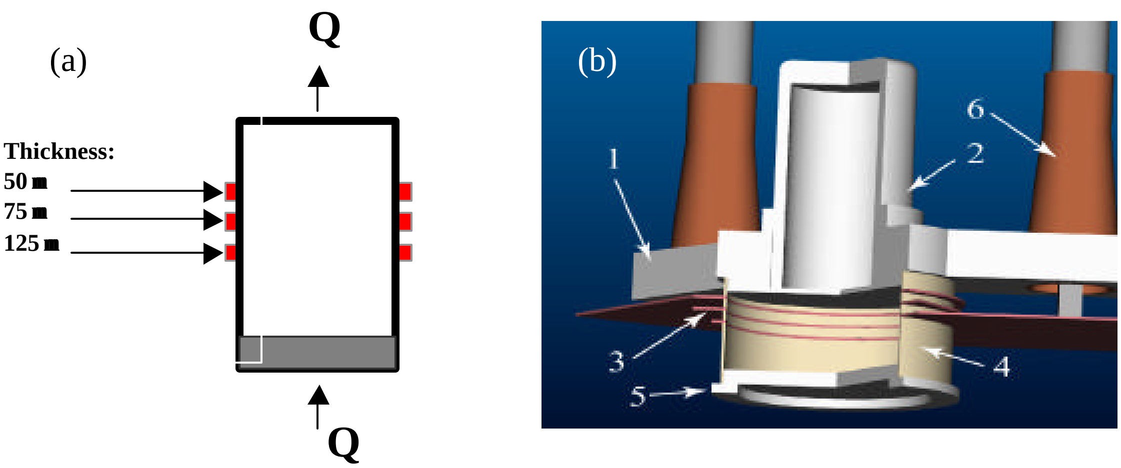

Figure 2: (a) A conceptual depiction of the cell showing the three sidewall probes. (b) Scale drawing of the cell displayed in a cut-away view, with 1) the cool end-plate, 2) the bubble chamber, 3) the sidewall thermometry probes, 4) the insulating sidewall, 5) the warm end-plate, and 6) the mini high-resolution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

FLIGHT EXPERIMENT CONFIGURATION AND CONTROL

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 vapor pressure (SVP) conditions, has been built using the minimum possible mass (30 g) to avoid systematic errors associated with variations in charged particle heating. The miniature high-resolution thermometers (mini-HRTs) use a thermometric element of $Pd_{1-x}Mn_x$, where x, the atomic concentration of Mn, is 0.7% to achieve a Curie temperature of 2.1 K, as described in a recent DX publication [27]. The cell fill line is closed using a cryogenic valve.

The cell consists of a 75-micron thick stainless steel sidewall that is brazed to 75-micron thick copper probes that extend around the full circumference. The temperature of each of the sidewall probes is measured using a mini-HRT of a new design and a new thermometric element [27]. 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, the 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 be used only to charge the flux tubes of the mini-HRTs during cool-down, and is not energized during the measurements. Each sidewall thermometer has a mass of 2.7 g that also includes the mass of the flux tube.

ESTIMATES OF ERRORS AND LIMITATIONS

The DX cell was not designed for precision heat-capacity measurements, but it is nevertheless almost perfectly suited for that purpose. One reason is that 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 modeling 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_λ (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 μW/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. The area is small because DX requires narrow probes to achieve high spatial resolution. Laboratory measurements together with modeling of the charged particle heating environment lead us to expect a resolution of 0.15 nK/√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 precision 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 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 counter-flowing superfluid results in dissipation. The latter effect is called vortex mutual friction and produces a temperature gradient that varies approximately as Q^3.

Recently Baddar *et. al.* [28] have measured the superfluid thermal resistance very close to the transition and have demonstrated that their results can be described by a simple expression that is consistent with earlier measurements, made by Leiderer and Pobel [29], much farther from the transition and at higher Q. These results have also been verified in DX measurements [30] at temperatures very near the transition using an engineering model of the DX instrument. In the large diameter cells used by DX and Baddar *et al.*, the linear behavior is too small to be observed. 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 μW/cm^2.

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, at the temperature at which 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_l 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 nW/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_l.

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 of 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 error in the heat capacity introduced by the gradient can be corrected 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

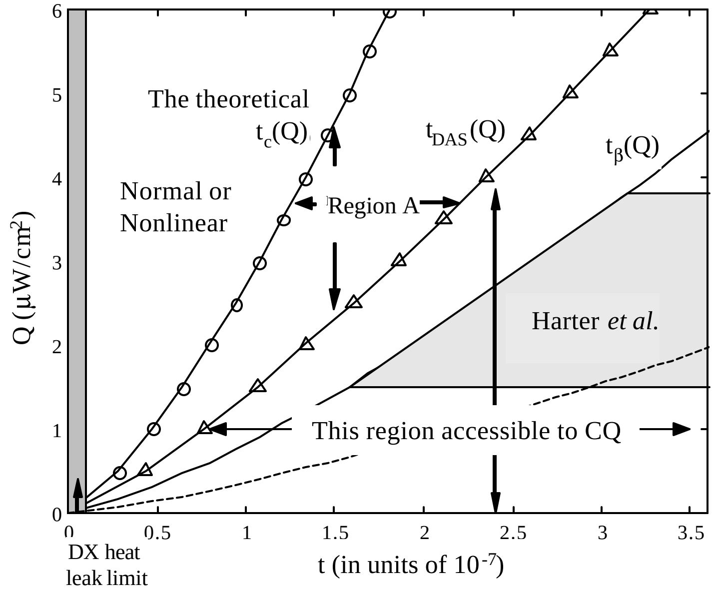

Figure 3 The t-Q plane. The CQ experiment will yield measurements unaffected by gravity in the entire region below the curve marked $t_{DAS}(Q)$. Region A: This region may require a more advanced experiment if the disagreement between theory and experiment is observed in microgravity. The dashed line 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.*

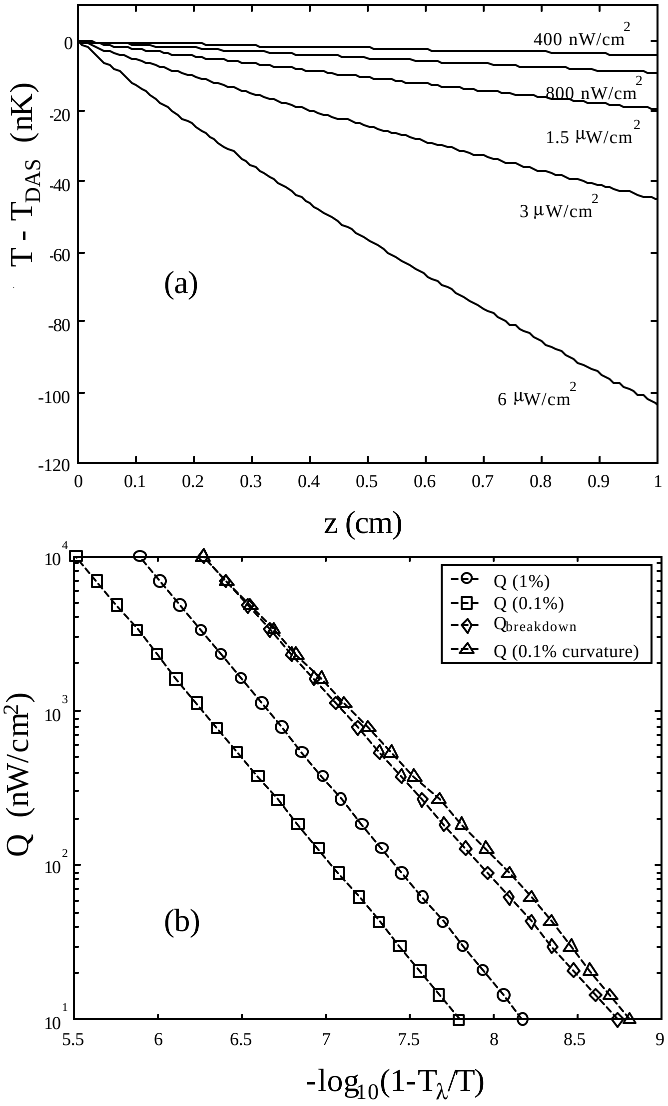

Figure 4 (a) Expected temperature profiles across the cell for various values of Q. (b) Reduced temperature for 1% (circles) and 0.1% (squares) heat capacity enhancement. Breakdown temperature (diamonds) and temperature at which the curvature correction is 0.1% of the signal (triangles).

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.

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 CQ measurements can be affected by charged-particle heating from the space radiation environment. Because of its random nature, charged 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 the gravitational center of the earth by some hundreds of kilometers toward the north Pacific. Away from the SAA the trapped particle heating is negligible over the rest of the ISS orbit, 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. The much smaller variation in heating seen away from the SAA and the horns is caused by "galactic cosmic rays", which are bare atomic nuclei of extrasolar 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^2). This requirement relaxes in proportion to Q. This is far beyond CQ's needs at the lowest value of t (10^{-8}), and relaxes as t increases. 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. Fortuitously, the negative thermal expansion coefficient provides a cooling effect during adiabatic compression, which is in the same direction as the pressure shift in T_l, 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 the 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.

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 shed light on 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 microgravity to eliminate gravitational rounding, and to permit multiple sidewall thermometers. If this is the case, CQ will be able to reach all of the important parameter space in the t-Q plane of Fig. 3, and reveal the physics of the predicted divergence in C_Q.

2. Haussmann's suggestion that $T_{DAS}(Q)$ is a gravity artifact [11]. If that is so the CQ experiment will confirm this, and it should be possible to examine the predicted singular behavior 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 supposed [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 be possible then to analyze the behavior 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 DAS mechanism.

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.

---

[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}He that remains liquid is the isotope ^{3}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 typically use isotopic purified ^{4}He with a residual atomic concentration of ^{3}He of less than 8×10^{-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}He to the cold endplate of the cell, and hence out of the measurement region between the sidewall probes. This low ^{3}He concentration is far too sparse to form a monolayer on the cold endplate.

[3] V. L. Ginzburg and A.A. Sobyanin, *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. Singsaas 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] Duncan, R. V., G. Ahlers and V. Steinberg, Phys. Rev. Lett. **60**, 1522, (1988).

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

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

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

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

[27] 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).

[28] H. Baddar, G. Ahlers, K. Kuehn, and H. Fu, to be published in the Journal of Low Temperature Physics (update before submitting.)

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

[30] P. Day, unpublished