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THE LAMBDA POINT EXPERIMENT IN MICROGRAVITY

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INTRODUCTION

The remarkable phenomena which occur when a system undergoes a cooperative phase transition have claimed the attention of scientists for many years. It was recognised that the unusual behavior was a result of the interactions between the constituents of the system, but a realistic treatment of the problem, either microscopic or phenomenological, appeared prohibitively difficult. In the early 70's Wilson[1] developed a new model of these transitions based on the application of the Renormalization Group (RG) technique. In general, the predictions of this theory were found to be in reasonable agreement with experiment, but in at least some of the highest resolution experiments discrepancies have been reported.[2,3] This situation has led us to develop new, advanced experimental tests which can be performed deep in the asymptotic region, close to a transition, where the theoretical predictions are most firmly established. Careful evaluation of candidate systems exhibiting cooperative transitions has led us to choose the lambda point of helium as the system with the most potential for improved measurements. In this paper we briefly outline the factors that limit the resolution of the lambda transition in space, and describe the status of a flight program to perform heat capacity measurements to the limit of resolution possible on the Shuttle.

All experimental tests of theoretical predictions for cooperative phenomena to date have encountered severe difficulties due to the need to avoid both intrinsic broadening close to the transition and non-asymptotic behavior far from the transition. These effects limit the dynamic range of the measurements and hence the accuracy of the parameters to be compared with theory. To obtain significantly better tests of the RG theory it is not enough to simply increase the accuracy of the measurements. The existence of the non-asymptotic corrections makes this approach unattractive by dictating further reductions of the range of the measurements. Only by obtaining data extending deeper into the asymptotic region near the transition is there hope of a significant gain. Fortunately in this region the cooperative effects are strong and the limitations are primarily of a technical nature.

Two major classes of systems exhibiting cooperative transitions can be studied expeimentally: solids and fluids. In the former case, impurity gradients and crystal imperfections generally cause uncontrolled distortion of the idealised singularity at a

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resolution $t \sim 10^{-4}$ or 10^{-5} at best. Here $t = |1-T/T_c|$ is a dimensionless temperature parameter, where T_c is the transition temperature. These difficulties are avoided in fluid systems, but instead gravitational compression causes distortion. For example at the critical point of a single component fluid the compressibility diverges, causing unacceptably large density gradients in samples with vertical heights as small as a few microns. In practice this limits the experimental resolution to $t \sim 10^{-5}$. In the case of the lambda transition of helium this problem is minimised, since the compressibility is only weakly divergent. Here the major effect of gravity is due to the pressure dependence of the transition temperature, T_λ. On earth a resolution of about 5×10^{-8} is possible, making this transition the primary testing ground for the RG theory. Unfortunately it is here that the strongest case can be made for potential departures from the predictions.[3] In the case of solid systems with sample defects the main source of rounding, improved materials processing is dictated. However, major improvements in the quality of these materials are needed before they will become competitive with fluid systems. In this case the effect of gravity can relatively easily be reduced by performing the experiments in space. Here, the lambda transition again provides the maximum potential resolution, perhaps to $t \sim 10^{-12}$ in ideal circumstances. For reasons discussed elsewhere, a measurement of the heat capacity singularity at the transition currently appears to be the most useful for advancing our knowledge of cooperative phenomena.

TRANSITION BROADENING

In a spacecraft with no external forces and far from all sources of gravitational fields, the broadening of the heat capacity singularity at the lambda point is governed by two effects. First, a finite size effect occurs due to the divergence of the correlation length at the transition, dictating a large sample size for small rounding. It is easy to show that for a spherical sample a nominal 1% correction to the heat capacity occurs when

$$t = 4.6 \times 10^{-10} r_s^{-3/2} \qquad (1)$$

where r_s is the radius of the sample in cm. In addition, the transition will be completely smeared out when r_s equals the correlation length, giving a second relation

$$t = 2.8 \times 10^{-12} r_s^{-3/2} \qquad (2)$$

Competing with the finite size effect is the self-gravitation of the helium, generally negligible, but nevertheless setting an ultimate limit on the sharpness of the transition. For a self-gravitating sphere of helium in hydrostatic equilibrium it is easy to show that the pressure difference ΔP between the surface and the center is given by

$$\Delta P = \frac{2}{3} \pi \rho^2 G r_s^2 \qquad (3)$$

where G is the gravitational constant and ρ is the density of the fluid. Since the transition broadening due to any source of pressure gradient is just

$$\Delta t = \frac{\Delta P}{T_\lambda} \left(\frac{dP}{dT} \right)_\lambda \qquad (4)$$

where $(dP/dT)_\lambda$ is the slope of the lambda line separating the normal and superfluid sections of the phase diagram, we obtain the result

$$\Delta t = 2.6 \times 10^{-16}\ r_s^2 \qquad (5)$$

In figure 1 we show the various resolution limits set by (1), (2) and (5). It can be seen that the maximum possible resolution is $t \sim 10^{-12}$ with the application of minor corrections to the data, and $t \sim 10^{-13}$ if extensive corrections are used, with corresponding optimum sample sizes in the 10-100 cm range. These levels of resolution represent the best that can be achieved in any presently envisaged situation, extending four to five orders of magnitude beyond that possible on earth.

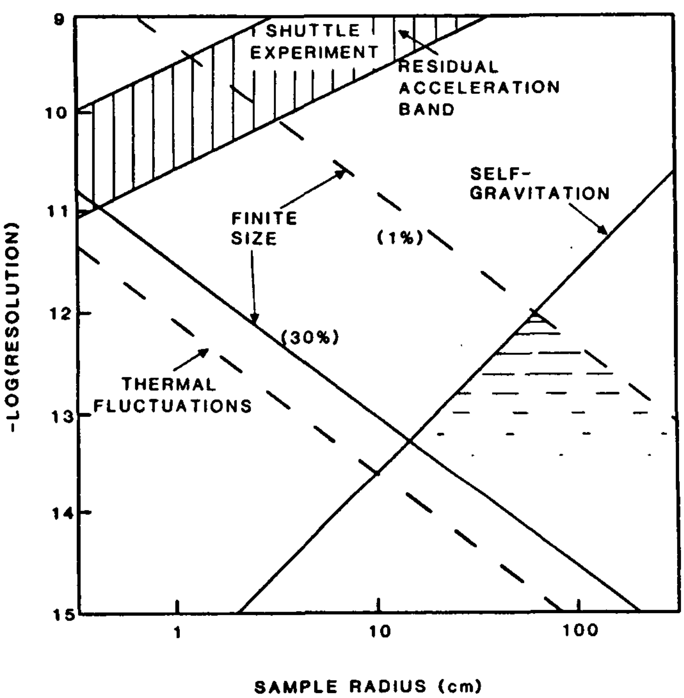

Figure 1 Comparison of the factors limiting the ultimate resolution of the lambda transition in space

In more practical situations, effects other than self-gravitation often compete with finite size rounding to limit the resolution attainable. On board the Shuttle, residual acceleration in the range 10^{-3} to 10^{-4} g is the dominant factor competing with the finite size effect. In this case transition broadening is given by substituting $\Delta P = a\rho r_s$ in (4), where a is the acceleration. We obtain

$$\Delta t = 1.8 \times 10^{-9} a\rho r_s \qquad (6)$$

Between the lambda point and the temperature given by (6) the helium is in a two-phase region with co-existing superfluid and normal fluid, and the heat capacity curve is highly distorted. It can be seen from (6) that the width of the perturbed region is proportional to both the size of the sample and the acceleration level. In figure 1 we have plotted (6) as a band covering the range of acceleration between 10^{-3} and 10^{-4} g expected on the Shuttle. This pressure broadening again competes with the finite size effect described by (1) or (2) to give an optimum resolution in the range 5×10^{-10} to 10^{-11}, depending on the details of the situation.

TABLE 1

g/g_o	Δt	r_0 (cm)
1	5.0×10^{-8}	.088
10^{-1}	1.3×10^{-8}	.22
10^{-2}	3.2×10^{-9}	.56
10^{-3}	7.9×10^{-10}	1.40
10^{-4}	2.0×10^{-10}	3.5
10^{-5}	5.0×10^{-11}	8.8
10^{-6}	1.3×10^{-11}	22.2
10^{-9}	2.0×10^{-13}	351.

Table 1: Optimum sample size, r_0, and corresponding temperature resolution, Δt, as a function of residual acceleration, g/g_o.

Starting from a slightly different perspective, we can ask how the maximum resolution varies as a function of acceleration if the sample size is always optimised. The results of approximate calculations for this case are summarized in table 1. For a Shuttle environment of 10^{-4} g we obtain a resolution of about 2×10^{-10}, two orders of magnitude better than on earth. For comparison, at the critical point of a typical fluid, the maximum resolution on the Shuttle is expected[4] to be of the order 10^{-8}, comparable to the lambda-point resolution on the ground. If we optimise the lambda transition experiment for the Space Station or a free-flying spacecraft in low earth orbit, we must also consider tidal forces due to the earth's field, the self-gravitation of the vehicle, and other effects. If the environment is carefully stabilized to the nano-g acceleration level, it appears possible to approach the self-gravitation limit, at a resolution of about 10^{-12}.

THERMAL FLUCTUATIONS

Goldstein[5] has pointed out that temperature fluctuations ultimately will wash out any cooperative transition. For the lambda transition this effect occurs at

$$t = 8.7 \times 10^{-13}\, r_s^{-3/2} \qquad (7)$$

which is somewhat less than the limit set by (2). More important, thermal fluctuations have the practical effect of directly limiting the resolution of the thermometers used in an experiment. It can be shown that the mean squared noise due to thermal fluctuations in a thermometer is given by

$$\langle \Delta T^2 \rangle = 2kT^2\, \tau_0 / c_e \tau \qquad (8)$$

where k is Boltzmann's constant, c_e is the heat capacity of the sensing element, τ_0 is the thermometer relaxation time and τ is the integration time. With the best available devices, this limit at present corresponds to a resolution $\delta t_{rms} = \langle \Delta T^2 \rangle^{1/2}/T_\lambda$ of about 8×10^{-11}. In principle significantly higher resolution can be obtained by increasing the heat capacity of the thermometer until it is comparable to that of the helium sample, and by reducing the detector bandwidth significantly below 1Hz.

FLIGHT EXPERIMENT

For some years we have been developing the technology to perform a high resolution heat capacity experiment near the lambda point on the Shuttle. Since the low frequency acceleration environment of the Shuttle is quite variable, the experiment was conservatively optimised for a level of 3×10^{-4} g, and a corresponding resolution of 4×10^{-10}. This will allow about two orders of magnitude higher resolution than is possible on earth, resulting in a much improved estimate of the asymptotic exponent describing the heat capacity singularity. This measurement will lead to a much stronger confrontation between theory and experiment than previously has been possible, and perhaps as severe a test as is presently feasible with current technology. Also, the data will allow exponent estimates deep in the asymptotic region which are of comparable accuracy to existing results further from the transition. These estimates will be extremely useful in testing the validity of the asymptotic representation assumed in all theoretical models to date. The ground-based results obtained so far indicate some possibility of a breakdown of this assumption.[3]

In figure 2 we show the historical development of the resolution of cooperative transitions. The data shown in this figure are not intended to be all-inclusive, but are representative of the progress in a given era. The points connected by the solid line represent the resolution at which data was available to allow some type of theoretical test; the resolution quoted by some authors is a little higher. It is clear that there is a large unexplored region, at least on a logarithmic scale, beyond the gravity cut-off on earth, where measurements near the lambda point could add substantially to our knowledge of cooperative transitions.

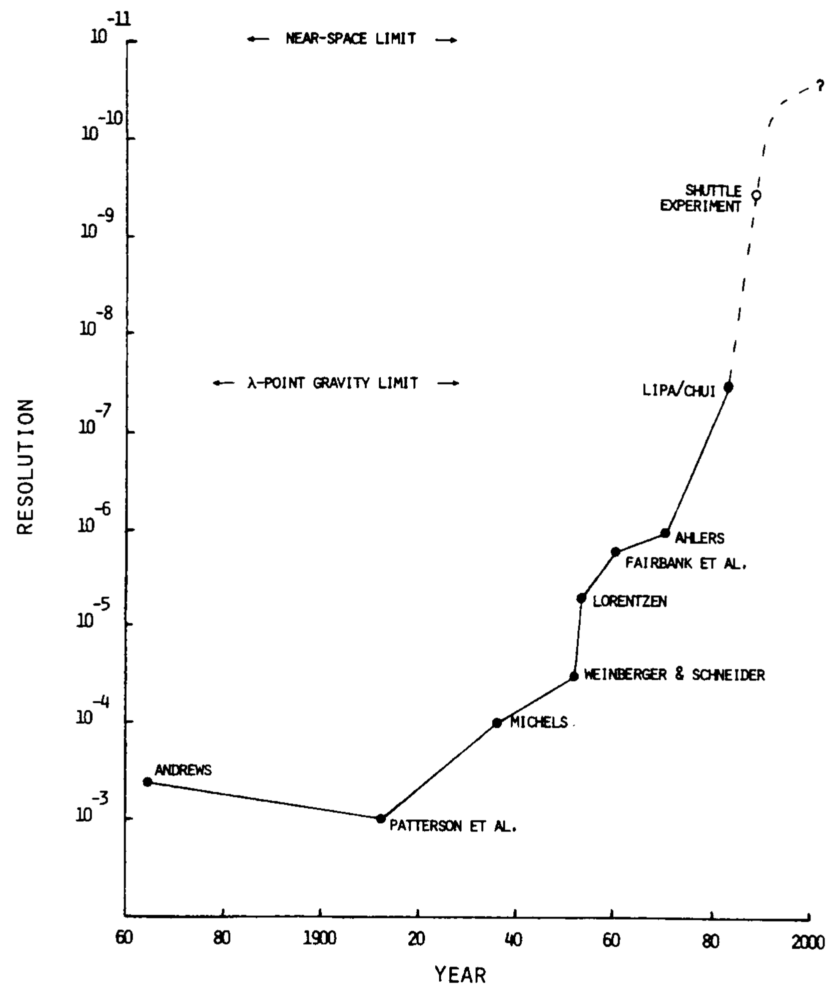

Figure 2: Historical development of resolution of cooperative transitions.

TECHNOLOGY DEVELOPMENT

The lambda point flight experiment requires a number of technology developments that go significantly beyond the level usually encountered in the laboratory. To make use of the potential resolution available in space, significant advances in thermometry and thermal control are required. Also a zero-g superfliud helium facility is needed, and the experiment must be designed to function correctly after being subjected to launch loads. The status of our work in these areas is described briefly below.

High Resolution Thermometers

Of utmost importance in any high resolution experiment near a phase transition is the temperature sensor. For the flight experiment it is necessary to resolve to t $\sim 10^{-11}$ in an integration time of a few minutes in order to make individual heat capacity measurements of sufficient accuracy. In addition, extremely low dissipation is needed, since the uncertainty in the power input to the sample must be held below $\sim 10^{-11}$ W. These requirements ruled out conventional low temperature thermometers and forced us to construct a special sensor optimized for the present application.

The new thermometer we developed is based on measuring the temperature dependent magnetization of a paramagnetic salt in a constant applied magnetic field. The device has an exceptionally low intrinsic dissipation level ($<10^{-17}$ W), and a very high sensitivity due to the use of a superconducting SQUID magnetometer as the detector. Similar devices have been built[6] for use below 1°K, but their noise characteristics were not reported. We constructed a device[7] optimized for use near the lambda point and provided it with a high degree of shielding to minimize the effect of external magnetic fields. A schematic view of the thermometer is shown in figure 3. Table 2 lists some of its operating characteristics obtained with two different salt materials. To date we have achieved a resolution of about 5×10^{-11} in a 1Hz bandwidth, which is adequate for the Shuttle experiment. This resolution compares well with the intrinsic thermodynamic limit for such a device given by (8).

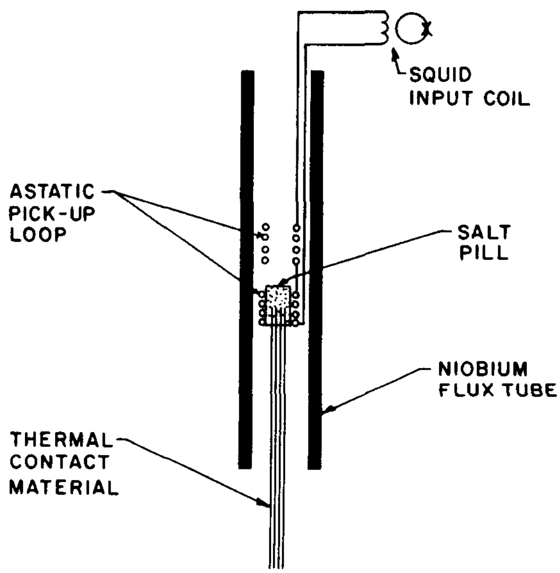

Figure 3: Schematic view of paramagnetic salt thermometer.

TABLE 2

SALT MATERIAL:	$Cu(NH_4)_2Br_4 \cdot 2\ H_2O$	$Mn(NH_4)_2 (SO_4)_2 \cdot 6\ H_2O$
Curie Temperature; ^oK	1.8	0.150
Sensitivity at 2.17 K; $\phi_o/\mu K$	3.86	1.08
RMS Noise Level at 1 Hz, ΔT_{RMS}; ^oK	1.04×10^{-10}	6.48×10^{-10}
Resolution at 1 Hz; $\Delta T_{RMS}/T_\lambda$	4.8×10^{-11}	3.0×10^{-10}
Thermodynamic Resolution Limit	8.7×10^{-11}	2.1×10^{-10}
Heat Capacity; 10^{-3} J/K	1.82	0.31
Response Time; sec.	2	0.7
Drift; K/sec.	$\sim 10^{-14}$	5×10^{-14}

Table 2: Operating parameters for paramagnetic salt thermometers

Thermal Control System

A second factor limiting the accuracy of high resolution heat capacity measurements is stray heat leak control. An advanced thermal control system designed to minimise this problem is shown in figure 4. It contains three stages of thermal isolation controlled with conventional germanium resistance thermometers. Within this system is located a thermal shield which can be controlled to level of a few nano-kelvins using a paramagnetic salt thermometer of the type described above. This shield isolates the experiment module from ambient and stray room temperature radiation, and from gas transfer effects associated with temperature changes elsewhere in the apparatus. The experiment module consists of a sample container and a pair of high resolution thermometers, and is attached to the inside of the thermal shield using low conductivity supports. A prototype version of this system has been operated in the laboratory for a number of months and shown to provide adequate control for the Shuttle experiment. It has also passed launch level shake qualification tests.

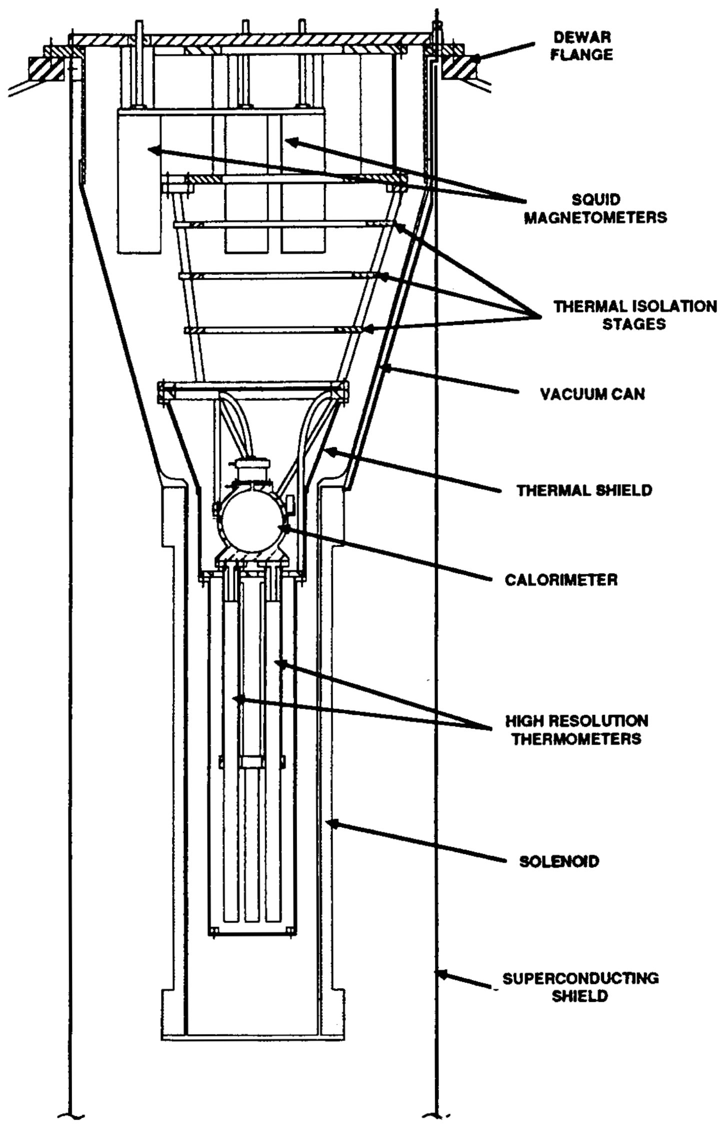

Figure 4: Thermal control system for flight experiment

Helium Facility

In order to reduce the cost and effort of cryogenic experiments in space the Jet Propulsion Laboratory has constructed a re-usable, flight qualified superfluid helium dewar. This facility was flown with the first set of experiments in July 1985 as part of the Spacelab-2 program, when it was located on a pallet in the Shuttle bay. A schematic view of the system is shown in figure 5. Experiments can be attached to the cover plate sealing the helium tank, and can interface with external electronics via an evacuated feedthrough area. Liquid helium is placed in the dewar several days before launch, and is maintained in the superfluid state with a small vacuum pump. On orbit, the system is vented to space through a throttling orifice designed to maintain the operating temperature in a range from 1.5 to 2.1 Kelvins. After equilibrium is established, the dewar temperature is stable to within 100 millikelvins for an 8-day flight.

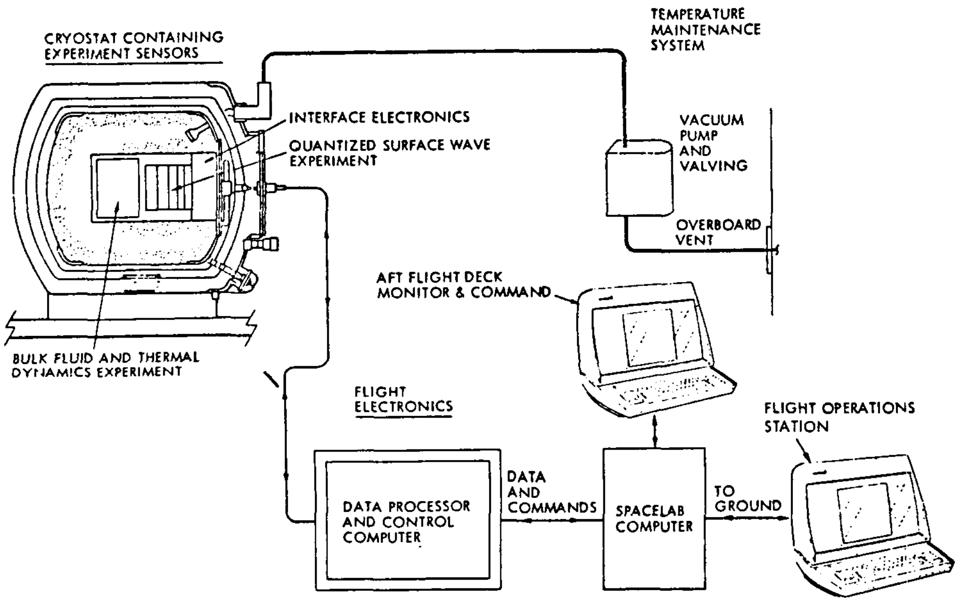

Figure 5: Schematic view of JPL superfluid helium facility as configured for the SL-2 flight

PROGRAMMATICS

The possibility of measuring the heat capacity singularity at the lambda point in space was first considered seriously at the Quantum Fluids in Space Conference held in 1975. It was determined that the major obstacle preventing improved experiments in space was temperature resolution since at that time no devices existed to resolve below $t \sim 10^{-7}$. Over the following seven years the paramagnetic salt thermometer described above was developed at Stanford using funds from the NASA PACE program. By 1982 the capability of resolving to $t \sim 5 \times 10^{-11}$ was demonstrated, which is of the order of the fundamental limit set by thermodynamic fluctuations. This technological development set the stage for proceeding with the flight experiment. In Jan. 1984 a Science Review was held and the project was recommended to proceed with planning for a flight. Work was intensified after

CoDR in Sept. 1984 and, shortly after PRR in Oct. 1985, approval was obtained to proceed with flight hardware development.

A prototype of the instrument shown in figure 4 has been fabricated by Ball Aerospace and has passed shake qualification tests. Thermal and functional tests are now in progress at Stanford. So far no major difficulties have been encountered and development is proceeding on schedule. Almost all operating modes of the prototype have been demonstrated to the level of performance needed for the flight. Detailed design of the flight electronics is now underway, with completion of the whole system scheduled for Nov. 1988. After testing at Stanford, the instrument will be integrated with the dewar system at JPL for final functional and environmental check-out. The experiment is expected to be available for flight by the second half of 1990. The major programmatic milestones of the experiment are shown in table 3.

1975:	Proposed at Quantum Fluids in Space Conference
1977:	Proposed to PACE
1979:	Phase I Study Completed
Jan. '84:	Science Review, Phase III
Sept. '84:	Conceptual Design Review, recommended for transfer from PACE to Microgravity
May '85:	Subcontractor for Hardware Development selected
Oct. '85:	Preliminary Requirements Review
Mar. '87:	Preliminary Design Review
Oct. '87:	Critical Design Review
Aug. '90:	Experiment available for Launch

Table 3: Lambda point experiment milestones

CONCLUSION

We have briefly discussed the motivation and potential for performing very high resolution measurements of the heat capacity singularity at the lambda point of helium in micro-gravity conditions. It is clear that tests extending deep into the asymptotic region can be performed, where the theoretical predictions take on their simplest form. This advantageous situation should lead to a major improvement in our understanding of the range of applicability of current theoretical ideas in this field. The lambda transition holds out the prospect of giving the maximum advance of any system, and with the application of cryogenic techniques, the potential of this system can be realised. The technology for the initial experiments is already well developed, and results could be obtained in 1990.

TABLE 4

Static scaling at the lambda point:

1) Temperature dependence of the order parameter

2) Test of universality along the lambda lines

Dynamic scaling at the lambda point:

1) Thermal conductivity of ^4He and ^3He-^4He mixtures above T_λ

2) Second sound damping coefficient below T_λ

Critical point measurements:

1) Heat capacity of ^3He and ^4He

2) Order parameter measurements below T_c

3) Thermal conductivity and viscosity of ^3He and ^4He above T_c

Tri-critical point measurements:

1) Heat capacity singularity

2) Concentration susceptibility

Observation of new phenomena:

1) Cross-over to 2-dimensional behavior

2) Finite size effects in controlled geometries

3) Proximity effect near the He-I/He-II interface

4) Josephson effects in helium

Table 4: Possible follow-on experiments which could take advantage of the technology developed for the heat capacity experiment described here

It is easy to imagine a number of follow-on experiments which could be performed near the lambda point, significantly extending the range of existing ground-based measurements. Some of these are listed in Table 4. Also listed are some other experiments on helium that can take advantage of the technology advances being developed for the lambda point work. In the ^3He-^4He system there are two pure fluid critical points, two phase separation lines and a tri-critical point. All these systems involve cooperative transitions and can benefit from being studied in space. Both static and dynamic properties can be studied, allowing a wide range of potential tests for the continually developing RG theory. Some of the experiments are already under development, and ultimately additional work may be conducted on the Space Station. The advantages of this environment will be extended observation times and the availability of sub-microgravity conditions. Hopefully the possibilities described in this paper will also stimulate additional theoretical effort in this exciting area of physics.

ACKNOWLEDGEMENT

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