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EXPERIMENTAL STUDIES IN
SOLID STATE AND LOW TEMPERATURE PHYSICS

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ABSTRACT

Experimental investigations have been carried out in a broad area of low-temperature and solid-state physics which includes superconductivity, magnetism in metals, and liquid and solid helium. The pair-field susceptibility of a superconductor has been determined both above and below $T_c$ and a propagating collective mode has been identified. Anomalies in the heat capacity of superconducting films in the vicinity of $T_c$ have been studied. The sublattice magnetizations of $\text{Mn}_2\text{Sb}$ have been studied using nuclear resonance techniques. Nuclear orientation thermometry has been studied down to 4 mK and $\text{Co}^{60}$ in Ni has been found to give the most accurate indication of temperature. Nuclear demagnetizations of Pr-Cu and Pr-In alloys have been carried out. Measurements of the differential osmotic pressure of $\text{He}^3/\text{He}^4$ near the tricritical point have shown a peak in the "concentration susceptibility" at the lambda line. Additional studies of mixtures have revealed the existence of wall-film superfluidity. Studies of superfluid flow through regular pores of submicron diameter are also being carried out in pure $\text{He}^4$ and in $\text{He}^3/\text{He}^4$ mixtures. The Vinen method is being used to study superfluid circulation around fine wires. The specific heat of bcc solid $\text{He}^3$ is being studied at low temperatures.
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I. INTRODUCTION

The work described in this progress report consists of various experimental and theoretical investigations in a broad area which may be called solid-state and low-temperature physics. The research is under the direction of Professors A. M. Goldman, W. V. Weyhmann, and W. Zimmermann, Jr., at the School of Physics and Astronomy in the Institute of Technology at the University of Minnesota and is supported by USAEC Contract AT(11-1)-1569.

A brief discussion of the most important results which have been obtained during the current year is presented in the following paragraphs. All of these contributions are discussed in more detail later on in this progress report. The reader is cautioned that some of the results presented here are tentative and may be subject to modification prior to publication.

Experimental work on superconductivity, under the direction of Professor Goldman, includes studies of the generalized susceptibility or pair-field susceptibility of superconductors both above and below $T_c$ and in the critical region and the investigation of the temperature dependence of the fluctuation contribution to the heat capacity of films in the vicinity of the transition.

The major result of the continuing investigation of the pair-field susceptibility of superconductors has been the identification of a propagating order-parameter collective mode in superconducting films which may be the Goldstone boson of the superconducting phase transition. Theoretical investigations at other institutions suggest that the mode is associated with fluctuations in the phase of the order parameter and that it is analogous to fourth sound in superfluid helium.
Results of the studies of the heat capacities of thin superconducting films near $T_c$ have indicated the existence of an anomaly at the transition. A detailed analysis of the data is being carried out with the goal of ascertaining whether the results are the consequence of the granularity of the samples or are the signature of critical behavior in homogeneous systems. The experiment is also being repeated using a heat-pulse technique in a sample of finite length, in place of the ac calorimetry used previously.

Professor Weyhmann's work on the sublattice magnetizations of Mn$_2$Sb is now complete. Excellent fits have been obtained to several functional forms for the temperature dependence. Unfortunately these seem to require physically unreasonable, although possible, choices of exchange constants.

Professor Weyhmann's group has also studied nuclear-orientation thermometry at moderate applied fields using Mn$^{54}$ and Co$^{60}$ in Fe and Ni foils. At 4 mK and 4 kG, deviations among the four combinations of radioisotope and host are found to be 1 mK, with Co$^{60}$ in Ni giving the lowest and therefore presumably most accurate indication of temperature. Using this thermometry, demagnetization of Pr-Cu and Pr-In alloys was tried with results not better than those obtained with PrCu$_6$.

Professor Zimmermann has been conducting experimental work on liquid He$^3$/He$^4$ mixtures and on pure liquid He$^4$. Measurements of the differential osmotic pressure of the mixtures at two concentrations near the tricritical point have shown a distinct peak in the "concentration susceptibility" at the lambda line. This effect, which has been either very weak or absent in the work of others, appears to be consistent with the theoretical possibility that the concentration susceptibility diverges at the lambda curve. Additional work on the mixtures has included further studies of the surprising phenomenon of wall-film superfluidity, which were recently reported by this laboratory.
in Physics Letters, and a continuation of a computer analysis of specific heat data in the tricritical region.

The work on pure He$^4$ concerns the quantum hydrodynamics of the superfluid. In one experiment a new ac technique has been applied to study superfluid flow through regular pores of submicron diameter where non-classical flow effects may appear. Design and construction of a new apparatus is being undertaken in order to extend this work to He$^3$/He$^4$ mixtures. In another experiment the Vinen method is being used to study the superfluid circulation around a fine wire at rest and in rotation, in an attempt to gain more clear-cut evidence concerning the quantization-of-circulation hypothesis.

Experimental work on crystalline He$^3$ is under the direction of Professor Goldman. Measurements down to 30 mK near the melting curve are being carried out. Efforts are being made to avoid difficulties associated both with temperature scales and with the use of analysis based on the Heisenberg model to account for the magnetic contribution to the specific heat below 0.1 K.
II. DESCRIPTION OF RESEARCH

A. Superconductivity

1. The Pair-Field Susceptibility of Superconductors

(R. V. Carlson and A. M. Goldman)

We have continued our measurements of the wave-vector and frequency dependent pair-field susceptibility of superconductors.\textsuperscript{1,2} Significant new data has been obtained from measurements on films both above and below their transition temperatures in magnetic fields. No studies of tricritical behavior\textsuperscript{3} which require Type I films were carried out because the apparatus was devoted entirely to measurements on disordered systems.

In the work carried out below $T_c$, raw data on the imaginary part of the pair-field susceptibility was used to calculate the structure factor using the fluctuation-dissipation theorem. The advantage of studying the structure factor rather than the susceptibility is that from the former one can more easily explore the nature of the collective mode whose existence was suggested by earlier measurements. As a consequence it was possible to identify the propagating collective mode suggested by the earlier data. A preliminary determination of the dispersion relation, which suggests that the mode is phonon-like, has been made. Theory\textsuperscript{4,5} suggests that the mode should be identified with fluctuations in the phase of the order parameter akin to fourth sound. However, the observed mode appears to be more energetic than the one which appears in the theory. The implication of the discrepancy between experiment and theory is that in a real superconductor the excitation is
coupled to charge fluctuations. The third peak in the current-voltage characteristic reported earlier may be explained as a tunneling anomaly in which the ac Josephson current breaks real pairs. 6

The development and interpretation of this experiment has been greatly aided by the three theoretical preprints 4,5,6 which attempt to explain various features of data reported in our earlier letter. At the present time there is only qualitative agreement between experiment and theory and there are many unresolved issues. An account of recent measurements in which the dispersion relation for the propagating mode is characterized has been submitted for publication in the Physical Review Letters. 7

Detailed studies were also carried out on aluminum films above $T_c$ with the goal of checking the Lee-Shenoy theory 8 of the pair-field susceptibility above $T_c$ in a magnetic field. Agreement in the low-field "linear" region was excellent and precise. In the high-field "nonlinear" region there are serious limitations on the accuracy of the experiment which have thus far prevented detailed comparison with the theory. A detailed discussion of these results will be included in the full write-up of this experiment to be included in Mr. Carlson's doctoral dissertation.

6. E. Simanek and J. C. Hayward (to be published).

2. Critical Behavior of Superconductors: The Heat Capacity of Thin Films
   (F. Aspen and A. M. Goldman)

We have observed a peak in the temperature dependence of the heat capacity of aluminum films near $T_c$. Because of the small heat capacities of thin-film samples, ac methods were employed to separate the thermal behavior of films from that of their substrates. Our results are in qualitative agreement with calculations of critical fluctuations based on the "screening" approximation, but disagree with calculations based on the "Hartree" approximation and with the results of one other experiment on films reported thus far. It is possible that the observed anomaly is a signature in the heat capacity of the low frequency collective mode discussed in section 1 of this report. A brief account of the ac heat capacity measurements was published in Physics Letters. A complete account of the work containing a detailed analysis of the data is being prepared for publication.

Because of the controversial nature of the results and their importance for the understanding of critical phenomena in superconductors, we have been building an apparatus to repeat the experiment using an entirely different technique. It is possible to measure the heat capacity of films using a heat pulse technique in a sample of finite length. A pulse is produced at one end of a sample and the temperature is measured as a function
of time at a different location. The analysis of data involves the calculation of several moments of the temperature rise in the thermometer as a function of time. This method should be as sensitive as the ac technique and yields the thermal conductivity of the sample as well as the heat capacity. The technique can also be easily implemented with our current technology.


B. Experiments on Magnetism in Metals

1. Nuclear Magnetic Resonance Studies

(Chi-Ping Hu and W. Weyhmann)

We have previously reported our nmr measurements of the temperature dependencies of the two sublattice magnetizations of Mn₂Sb, a ferrimagnet. The most striking feature of these observations is the approximately $T^{5/2}$ behavior of one of these magnetizations while the other is normal ($T^{3/2}$). The anomalous behavior is already clear below 30 K, over an order-of-magnitude below the Curie temperature. Ferrimagnets previously investigated have shown $T^{3/2}$ behavior up to $T_c/3$. Mr. Hu has completed a computer analysis of the data and is presently writing his thesis.
Two models have been shown to give reasonably satisfactory fits to the data in a mathematical sense, but neither is completely satisfying physically. The standard spin wave approach applied to a three dimensional ferrimagnet gives a satisfactory set of parameters indicating a low-lying optical branch in the spin wave spectrum. The excitations in this branch give rise to deviations from $T^{3/2}$ behavior at temperatures as low as 20 K. We have not, however, been successful in finding a set of spins and exchange constants which generate these parameters and are either physically reasonable or internally consistent. A second phenomenological model results from the simple observation that the anomalous site behaves almost like a two dimensional ferromagnet with anisotropy, namely, $T^2 e^{-\Delta/T}$. By admixing $T^{3/2}$ with this behavior and visa versa for the normal site, an excellent fit for the two can be obtained. While Mn$_2$Sb is a layered compound, we find it difficult to imagine a two dimensional magnet spatially imbedded in and almost independent of a three dimensional magnetic structure.

2. Nuclear Orientation Studies

(D. Bakalyar, R. Swinehart, and W. Weyhmann)

Nuclear orientation of $^{54}$Mn and $^{60}$Co in Fe and $^{60}$Co in Co has been frequently used for thermometry below 30 mK. Since a knowledge of all pertinent parameters needed to calculate the gamma ray anisotropy was thought to exist, these measurements were considered to indicate absolute temperature without calibration at reference temperatures. Below 10 mK we have observed significant differences in indicated temperature between $^{54}$Mn and $^{60}$Co in Fe foils. We have therefore initiated a program to calibrate several orientation thermometers for use in our work.
As a first step we have studied the temperatures indicated by $^{60}\text{Co}$ and $^{54}\text{Mn}$ dissolved in Fe and Ni foils in the 3 to 10 mK range with applied magnetic fields of 1 to 5 kG. The lowest temperature is always indicated by $^{60}\text{Co}$ in Ni and the next lowest by $^{54}\text{Mn}$ in Ni. Even between these, differences as large as 5 mK exist between 3 and 4 mK at fields less than 4 kG. Both isotopes in iron foils give somewhat higher temperature indications. We have also observed, as have Krane et al.,\textsuperscript{1} that increasing the magnetic field to 10 kG and above reduces the differences to acceptable levels. It remains to be established exactly how these temperature scales relate to the absolute temperature, but it is clear that serious errors can be made when these thermometers are used in low polarizing fields.

We have further improved our facilities for preparing dilute alloys and rare earth intermetallics by the addition of significantly better vacuum systems to our melting and annealing furnaces. We should now be able to prepare samples with minimal oxidation. By backfilling the melting system with ultrahigh-purity argon, we have been able to make PrIn$_3$ with little evaporation of the indium. Unfortunately, a failure of our first dilution refrigerator, after successful operation for about two years, has precluded any experiments on local moment alloys thus far this year.

Two analog-to-digital converters for the two Ge(Li) gamma ray detectors have been interfaced to the NOVA 1220 minicomputer and are now being checked out. This completes the essential data acquisition system for the nuclear orientation experiments.

3. **Enhanced Hyperfine Nuclear Cooling**

We have continued our program of study of rare earth alloys useful for enhanced hyperfine nuclear cooling. In these materials much if not most of the magnetic entropy can be removed at temperatures easily achieved with dilution refrigerators and at fields produced by modest superconducting solenoids.

Before a failure of our dilution refrigerator this winter we had tried experiments on two new alloys. We tried to enhance the thermal conductivity of PrCu$_6$ by melting the alloy with a small excess (a few percent) of copper. The alloy phase separated as expected into compound rich and copper rich portions, the copper forming a fine mesh between the crystallites of PrCu$_6$. This sample showed large irreversible heating and was not useful for cooling. We then prepared an ingot of PrIn$_3$ for study. With only 20 kG available and a starting temperature of 25 mK, we could not remove enough entropy to cool the sample and thermometers and compensate for eddy current heating. We must therefore wait to retry this when our new refrigerator and magnet are in operation.

We have also unsuccessfully tried two samples prepared at Los Alamos under the direction of Dr. Steyert: TmCO$\varepsilon$ and Pr$_2$(SO$_4$)$_3$-8H$_2$O, both pressed in gold powder for thermal contact.

A new set of heat exchangers and mixing chamber are now in place and being tested. We now have five (instead of three) heat exchangers similar to those of Niinikoski$^1$ with the hope of improving cooling efficiency.
in the 20 to 50 mK region where most of the entropy of our nuclear coolants must be removed and of lowering the no heat load temperature to below 15 mK. The mixing chamber is considerably larger than before to improve thermal contact to the samples by the use of more surface area of sintered powder and to allow longer "single shot" cooling with the refrigerator. In order to reduce the eddy current heating of the mixing chamber in the fringing field of the nuclear cooling magnet without excessive reduction of the thermal conductivity, we vacuum cast an alloy of copper – 2% gold in order to obtain the optimum conductivity. The sintered powder is a similar alloy.

We were previously limited to demagnetizing fields of 20 kG by our 2¼" bore superconducting solenoids. We have constructed a new magnet with twisted multifilament wire which is calculated from the short sample performance of the wire to produce over 55 kG. The high current power supply required for this magnet has not yet been delivered, so it has not been tested. Use of the multifilament wire as well as a thick OFHC copper form should result in still smaller eddy current heating due to a virtual elimination of flux jumping.

Finally, a large metal dewar to replace the old glass set is near completion in our shop. This will give a much longer hold time for the liquid helium, probably eliminating the need for refilling except between demagnetizations. A quiet electrical environment should also be much easier to maintain in the cryostat.

With a reasonable amount of good luck we expect to be in operation again in September or October.

C. Experiments on Liquid Helium

1. The Lambda Transition and the Tricritical Point in Liquid He\textsuperscript{3}/He\textsuperscript{4} Mixtures

   a. The Osmotic Pressure of He\textsuperscript{3}/He\textsuperscript{4} Mixtures Near the Lambda Curve and Tricritical Point

   (C. A. Gearhart, Jr. and W. Zimmermann, Jr.)

Over the past several years there has been a growing interest in critical behavior near tricritical points.\textsuperscript{1} For a number of reasons, including purity and homogeneity of sample, liquid He\textsuperscript{3}/He\textsuperscript{4} mixtures have provided an excellent system for the study of tricritical behavior. At saturated vapor pressure, the tricritical point in these mixtures occurs at a temperature $T$ of 0.87 K and a He\textsuperscript{3} mole fraction $x$ of 0.67.

During the past year we have continued our experiment to measure the osmotic pressure difference between two He\textsuperscript{3}/He\textsuperscript{4} mixtures of slightly different concentration at the same temperature in the tricritical region. The purpose of this experiment is to determine the critical behavior of the concentration susceptibility $(\partial x/\partial \phi)_{T,P}$, where $\phi$ is the difference $\mu_3 - \mu_4$ between chemical potentials and $P$ is the pressure.

To date, detailed sets of data have been obtained as a function of temperature at two concentrations, $x = 0.59$ and $x = 0.64$, and are currently being analyzed. Although there are experimental effects which appear to be associated with our fill capillaries and which we do not yet understand, the qualitative features of the data give every indication that our method is successful. Our ultimate resolution appears to be limited by gravitational
inhomogeneities in a sample only 4 mm high. Of particular interest is our observation of a pronounced, cusped peak in \( \frac{\partial x}{\partial T} \) at the lambda curve.

If \( c_p \), the specific heat at constant pressure for pure He\(^4\), diverges at the lambda point and if the concept of universality applies, then the specific heat \( c_{p,\phi} \) for the mixtures and \( \frac{\partial x}{\partial \phi} \) at the lambda curve. The peak in \( \frac{\partial x}{\partial \phi} \) that we have observed may be consistent with such a divergence. However, the divergence of \( c_p \) for pure He\(^4\) has recently been called into question.\(^2\) Further, other recent experimental determinations of \( \frac{\partial x}{\partial \phi} \) have either failed to show any peak at the lambda curve near the tricritical point,\(^3\) or have shown only a much less pronounced effect.\(^4\) Hence we believe that the question under investigation is of considerable interest. A report of our preliminary results at \( x = 0.64 \) was given to the Conference on Critical Phenomena in Multicomponent Systems, Athens, Georgia, April 1974.

During the course of this work we have developed a resistance-thermometry bridge circuit which combines a high degree of reproducibility and sensitivity with great simplicity and ease of checking performance. A manuscript describing this bridge for publication is in preparation.

b. Wall-Film Superfluidity in the Normal-Fluid Region of He³/He⁴ Mixtures
(C. A. Gearhart, Jr. and W. Zimmermann, Jr.)

The differential osmotic pressure experiment described above in Subsection a) depends upon the free flow of He⁴ through a Vycor glass superleak connecting mixtures of different concentration. In extension of the earlier results of Keyston and Laheurte¹ and of Laheurte² we have found that superfluidity through our superleak occurs in a certain region of the normal-fluid part of the phase diagram for the bulk liquid mixtures down to mole fractions of He³ as low as 0.55. This remarkable result, which permits osmotic pressure measurements to be made throughout the tricritical region, appears to be due to the formation of a He⁴-rich film at the surface of the container in which the mixture is located. This film forms as a result of the van der Waals interaction between liquid and wall. Our results were recently published in Physics Letters.³ It seems likely that this effect, which has already been used to purify He³ of He⁴ to a mole fraction of 0.9999995 and which is of enormous value to us in our osmotic pressure measurements, will find other, ingenious uses.⁴

c. Analysis of the Specific Heat of Liquid $\text{He}^3/\text{He}^4$ Mixtures Near the Lambda Curve and Tricritical Point

(L. D. Dockendorf and W. Zimmermann, Jr.)

Measurements at saturated vapor pressure of the specific heat $C_p(x)$ of liquid $\text{He}^3/\text{He}^4$ mixtures at constant pressure and mole fraction have yielded important thermodynamic information about the tricritical region which complements that from measurements of $(\partial x/\partial p)_T$. In order to utilize the specific heat data to best advantage, we have used a digital computer to fit an algebraic form to the data by the method of least squares. This work is currently being written up as Mr. Dockendorf's M.S. degree thesis.

The work supplements the numerical analysis of the same data by Islander and Zimmermann, and it has been possible to use the work to calculate, among other quantities, the concentration susceptibility $(\partial x/\partial p)_T$ from the specific heat data. The results are at least in good qualitative agreement with our preliminary results from the osmotic pressure experiment and show the same pronounced peak at the lambda curve. There do remain some unresolved imperfections in the fit which may reflect either thermodynamic inconsistencies in the original data or a less than optimal choice of fitting function. Nevertheless, we believe that the results of the fit will be of considerable use in further work characterizing the thermodynamics of the tricritical region.

2. Dynamics of Superfluid Flow Through Fine Pores in He\textsuperscript{4} and He\textsuperscript{3}/He\textsuperscript{4} Mixtures

(J. S. Brooks, P. Schubert, and W. Zimmermann, Jr.)

During the past several years a new ac technique has been developed in this laboratory to study superfluid flow through fine orifices and pores of well defined geometry in the range of size where non-classical effects may come into play.\textsuperscript{1} The technique involves a cell with two completely filled chambers separated by the porous membrane under consideration. Oscillatory flow between the two chambers at a frequency of from a few to a few hundred hertz is excited by small piezoelectric drivers in the chambers, and the pressure difference between chambers is monitored by means of a capacitive transducer located in the wall separating the chambers. The apparatus was conceived in close analogy to an experimental arrangement commonly used to study the Josephson effects in superconductors.

Up to the present we have worked exclusively with superfluid He\textsuperscript{4} and have studied flow through a single 10 \textmu m diameter pore and through highly regular Nuclepore membranes with pore diameters from 0.03 to 0.5 \textmu m. The first and most basic property which has been studied is the effective superfluid density in the pore, which can be derived with a minimum of correction from the frequency of Helmholtz oscillations in the system. Although we have observed the bulk behavior to be accurately obeyed over a wide range of temperatures below the lambda temperature \(T_{\lambda}\), we have been unable to observe the anticipated quantum length effects at temperatures near \(T_{\lambda}\).\textsuperscript{2} The reason for this failure is that the resonance becomes very difficult to observe.
near $T^*_\lambda$. The explanation for the increased dissipation which appears to set in is under study and is not understood. Great care has been taken to eliminate extraneous sources of acoustic noise which may be exciting the resonance beyond threshold for non-linear effects.

The second property studied is the critical velocity of flow. We have observed both intrinsic and extrinsic regions of critical velocity, and the results are in rather good agreement with theory and certain other measurements. However, for the membranes with finest pore size we see quite unexpected behavior which may reflect the appearance of non-classical flow effects that have not yet been correctly interpreted. One such effect is an apparent dependence of critical velocity on frequency near the resonance frequency, an effect which is extremely hard to justify on physical grounds. Another is an apparent closure of the pores at frequencies well below the resonance, even though they are open at the resonance frequency. We believe that these strange effects deserve careful investigation. Because of the simplicity of the experiment in concept, the situation appears to be an ideal one for investigation of new effects. A progress report on these experiments was given recently to the Conference on Quasiparticle Interactions in Liquid Helium, Eugene, Oregon, July 1974.

We are currently beginning the design and construction of a new cell and an associated He$^3$ refrigeration stage which will not only enable us to gain a better understanding of the flow of pure He$^4$ but will be designed for measurements on He$^3$/He$^4$ mixtures. The He$^3$ pot and external gas handling system for the He$^3$ refrigeration stage have recently been completed.

3. Quantization of Circulation in Superfluid Liquid He$^4$

(D. R. Starks and W. Zimmermann, Jr.)

Studies of the superfluid circulation around a fine wire in liquid helium using the Vinen method have provided important support for the fundamental hypothesis that the superfluid circulation in He II is quantized.\textsuperscript{1,2} Recent studies in this laboratory by Kral and Zimmermann have shown that, as a function of angular velocity of rotation $\omega_x$, the circulation $\kappa$ has on the average a form which is in excellent agreement with the theoretical expectation based on the quantization of circulation hypothesis and on the existence of quantum vortices in the liquid. However, a large degree of metastability in the relation between $\kappa$ and $\omega_x$ appears to be present which prevents the appearance of the expected discrete quantum steps in $\omega$.\textsuperscript{3} A complete report of this work for submission to Physical Review B is in the final stages of completion.

In the earlier work of Whitmore and Zimmermann it was observed that with the finest wires the range of metastable circulations observed at $\omega_x = 0$ was the least. Hence it appears that a series of measurements in rotation with finer wires than those used by Kral and Zimmermann hold some promise for showing less metastability and thus for showing the expected quantum steps.

Hence we have embarked on a program to make measurements with finer wires. During the past year a new mounting scheme for the wire has been successfully developed so as to ensure more stable measurement conditions. We have also extended the temperature range of our measurements down to 0.5 K. The levels of circulation seen at such low temperatures with an intermediate-
size wire are qualitatively similar to earlier results with larger wires at 1.3 K. However, the reduction in the normal-fluid damping of the wire's vibration at low temperature brings about a considerable reduction in noise and promises to enable more accurate measurements of circulation.


D. Experimental Studies of the Properties of Crystalline He

1. Heat Capacity Measurements
   (N. McNeal, N. Rao, and A. M. Goldman)

There is substantial evidence for the existence of an anomalous lattice contribution to the heat capacity at low temperatures in solid He. The anomaly takes the form of an excess specific heat which has been characterized within the context of the Debye model by a temperature dependent Debye theta. In the recent work of Castles and Adams the excess heat capacity could be represented by a term linear in temperature. At the present time there is no consistent theoretical explanation for either a temperature dependent Debye theta or a term in the heat capacity varying linearly with temperature.

It is possible that a linear term in the temperature dependence of the heat capacity in solid He is an artifact of the temperature scale rather than an inherent property of the material. It may also be a consequence of
the dependence of the analysis$^5$ on the Heisenberg model to account for the magnetic contribution to the specific heat below 0.1 K.

We have continued our work on the heat capacity over the past year. We use an all-copper calorimeter which can be cooled to 30 mK and is linked to our dilution refrigerator by a tin heat switch. In the calorimeter, the large surface for thermal contact is provided by a number of copper plates machined into the lower half of the chamber. The primary thermometer is a powdered CMN sample which is calibrated in the range from 1.5 K to 2.5 K against a germanium thermometer which is itself calibrated against T$_\text{cm}$. An additional check on the thermometer is the minimum in the melting curve. The thermometer is linked directly to our minicomputer with the heater power for the measurements set by the software. The residual heat leak in the apparatus is now of the order of a few ergs/minute.

Several difficulties with the apparatus in the course of the past year have prevented the completion of the measurements at this time. In an attempt to reduce the heat leak even further a set of superconducting coils were substituted for the copper coils in the thermometer. It then became impossible to calibrate the thermometer. The problem turned out to be the failure of some integrated circuits in the electronics package of the Robinson oscillator circuit which occurred simultaneously with the change in the coils. There were subsequent difficulties with the heat switch and with an anomalous heat leak, both of which have also been solved at this point. It is hoped that the series of runs planned for September will produce reliable data for the lattice heat capacity over the temperature range in which anomalous behavior has been observed.
5. H. Horner (private communication).
6. L. H. Nosanow (private communication).
III. RECENT REPORTS


IV. STAFF

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J. S. Brooks Research Associate
R. Swinshart Research Associate
F. Aspen Research Assistant
J. Babcock Research Assistant
D. Bakalyar NSF Trainee
R. V. Carlson Research Assistant
L. D. Dockendorf Research Assistant
C. A. Gearhart, Jr. Research Assistant
C. -P. Hu Research Assistant
P. J. Kreisman Graduate Student
J. Lewis Research Assistant
J. A. McLim Graduate Student
N. McNeal Research Assistant
N. Rao Graduate Student
P. Schubert Research Assistant
D. Starks Research Assistant

1. Supported on University funds through 9/74.

2. Summer 1974 only.

3. Terminated 9/74.

4. Terminated 6/73.

5. Summer 1974 only.

6. Summer 1974 only.
V. EFFORT OF PRINCIPAL INVESTIGATORS

(Percentage of time during calendar year 1974)

<table>
<thead>
<tr>
<th></th>
<th>January 1 to June 15</th>
<th>June 16 to September 15</th>
<th>September 16 to December 31</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. M. Goldman¹</td>
<td>25%</td>
<td>66.7%</td>
<td>50%</td>
</tr>
<tr>
<td>W. Weyhmann</td>
<td>50%</td>
<td>66.7%</td>
<td>50%</td>
</tr>
<tr>
<td>W. Zimmermann, Jr.</td>
<td>50%</td>
<td>66.7%</td>
<td>50%</td>
</tr>
</tbody>
</table>

¹On leave: March 15, 1974 - June 15, 1974 at the Department of Physics, Technion-Israel Institute of Technology, Haifa, Israel.