

MASTER

University of Minnesota
School of Physics, Institute of Technology

Experimental and Theoretical
Studies in Solid State and Low Temperature Physics

ANNUAL PROGRESS REPORT

for

1970

Submitted

September, 1970

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

U. S. Atomic Energy Commission Contract No. AT(11-1)-1569

Reg

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	Page
I. INTRODUCTION.....	1
II. DESCRIPTION OF RESEARCH	
A. SUPERCONDUCTIVITY	
1. Thermal Fluctuations and the D.C. Josephson Current.....	2
2. The Pair Susceptibility of a Superconductor	4
3. Fluctuations in Superconductors Near the Critical Temperature.....	5
4. Lifetimes of Persistent Currents in Superconducting Loops Interrupted by Josephson Junctions.....	7
5. De-Haas Van Alphen Oscillations in the Critical Temperature of Type-II Superconductors.....	8
B. THEORETICAL WORK ON QUANTUM CRYSTALS	
1. One-Phonon Excited States of Solid H ₂ and D ₂ in the Ordered Phase.....	9
2. Elementary Excitations in Solid Orthohydrogen.....	9
3. Exchange in Solid He ³	10
4. Nonlocal Vacancies in bcc He ³	11
5. Two-Body Hartree Approximation.....	12
6. Pair-Variational Calculation of the Ground- State Properties of Quantum Crystals.....	12

	Page
C. THEORETICAL WORK ON LIQUID HELIUM	
1. Quasiparticle Hamiltonian for Liquid He ³ ..	14
2. Ground State of Liquid He ⁴	14
3. Ground State of Liquid He ⁴	15
4. Hard-Core Bose Gas.....	16
5. Theory of Dilute Solutions of He ³ in Superfluid Liquid He ⁴ : the Elementary Excitations.....	17
6. Spin Waves in He ³ -He ⁴	17
7. Evidence for the Validity of the Landau Theory of Liquid He ³	18
8. Classical Impurity-Vortex Scattering.....	19
9. A Model for the Quantum Scattering of a He ³ Impurity from a Rectilinear Vortex in Liquid He II.....	19
10. Electron Mobility in Gaseous Helium at Low Temperatures.....	20
D. EXPERIMENTS ON LIQUID HELIUM	
1. Quantum Hydrodynamics of Superfluid Helium	
a. Quantization of Circulation in Superfluid Helium.....	22
b. Search for Analogs of the Josephson Effects in the Flow of Superfluid Helium.....	25

	Page
2. Phase Transitions in Liquid He^3/He^4 Mixtures	
a. Specific Heat of Liquid He^3/He^4 Mixtures Near the Junction of the Lambda and Phase-Separation Curves...	29
b. Differential Osmotic Pressure of Superfluid He^3/He^4 Mixtures Near the Lambda Curve.....	31
 E. MAGNETISM IN METALS	
1. Nuclear Magnetic Resonance.....	33
2. Heat Capacity Measurements in the Spin Reorientation Region.....	35
3. Nuclear Orientation Measurements.....	36
4. Enhanced Nuclear Hyperfine Cooling.....	38
 F. EXPERIMENTAL STUDIES OF THE PROPERTIES OF CRYSTALLINE He^3	
1. Heat Capacity Experiments	41
 III. RECENT PUBLICATIONS.....	43
 IV. STAFF.....	46
 V. EFFORT OF PRINCIPAL INVESTIGATORS.....	48

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, L. H. Nosanow, W. V. Weyhmann, and W. Zimmermann, Jr., at the School of Physics and Astronomy in the Institute of Technology of the University of Minnesota and is supported by USAEC Contract AT(11-1)-1569.

The reader is cautioned that results presented here may be tentative and subject to modification prior to publication.

II. DESCRIPTION OF RESEARCH

A. SUPERCONDUCTIVITY

1. Thermal Fluctuations and the D. C. Josephson Current

(J. T. Anderson and A. M. Goldman)

We have continued to study the effects of fluctuations on the I-V characteristics of crossed film junctions.^{1,2,3} As fluctuations are important whenever the net coupling energy is the order of thermal energies, phenomena which were studied in the vicinity of T_c may also be found in the neighborhood of minima of the $I_1(H)$ curve⁴ at low temperatures. Results obtained are in qualitative agreement with calculations^{2,3} which apply strictly to the zero-field case. A detailed comparison of our data with the modified theory of Ivanchenko and Zil'berman⁵ which explains the effects of fluctuations in the presence of a magnetic field for junctions of finite size is in progress.

In the course of the year we have worked towards the elimination of extraneous residual electrical signals within the screened room environment. The latter were responsible for observation in our earlier studies^{1,4} of an apparent noise temperature higher than the ambient temperature of the

cryogenic environment.

There has also been some effort in improving sample preparation procedure. We have developed a simple masking technique to eliminate film edges using bismuth oxide,⁶ a material which can be evaporated from a crucible or a platinum boat. Systematic studies of the effects of oxidation time, pump down time, evaporation pressure and water vapor concentration on junction resistance have also been carried out.

1. J. T. Anderson and A. M. Goldman, Phys. Rev. Letters 23, 128 (1969).
2. Yu. M. Ivanchenko and L. A. Zil'berman, Zh. Eksper i. Teor. Fiz. 55, 2395 (1968) [English Translation: Soviet Physics JETP 28, 1272 (1969).]
3. V. Ambegaokar and B. I. Halperin, Phys. Rev. Letters 22, 1364 (1969).
4. J. T. Anderson and A. M. Goldman, Proceedings of the Conference on the Science of Superconductivity, Stanford University (1969) (to be published in Physica).
5. Yu. M. Ivanchenko and L. A. Zil'berman, Zh. Eksper. i. Teor. Fiz. 58, 211 (1970).
6. M. D. Fiske suggested this material some years ago. It can be evaporated at low temperatures and apparently does not destroy thermally-grown oxide layers.

2. The Pair Susceptibility of a Superconductor

(J. T. Anderson and A. M. Goldman)

An excess tunneling current due to order parameter fluctuations has been found in tin-tin oxide-lead junctions just above the transition temperature of tin. Ferrell,¹ Kulik² and Tsuzuki³ have each treated aspects of this current. Details of the variation of the excess current with voltage, magnetic field and temperature are in agreement with a calculation by Scalapino⁴ in which the excess current-voltage characteristic is a direct measure of the frequency and wave-number dependent pair-susceptibility characteristic of the superconducting transition. The latter is a quantity of fundamental theoretical importance which may be compared directly with the results of calculations of the fluctuations associated with the transition. Our data indicate that this technique should be a useful probe of the details of the fluctuations associated with the superconducting transition. Preliminary estimates of the pair relaxation frequency based on data are 50 percent greater than theoretical predictions.

An account of this work has been submitted to the Physical Review Letters.⁵

1. R. A. Ferrell, J. Low Temp. Phys. 1, 423 (1969).

2. I. O. Kulik, Zh. Eksper. i Teor. Fiz., Pisma Red. 10, 488 (1969) [English Translation: Soviet Physics JETP Letters 10, 313 (1969).]
3. T. Tsuzuki, Prog. Theor. Phys. (Kyoto) 41, 1600 (1969).
4. D. J. Scalapino, Phys. Rev. Letters 24, 1052 (1970).
5. J. T. Anderson and A. M. Goldman (submitted to Phys. Rev. Letters).

3. Fluctuations in Superconductors Near the Critical Temperature (F. M. Schaer and A. M. Goldman in collaboration with L. Toth of the School of Materials Science)

A detailed characterization of the resistance vs. temperature in NbN films has been carried out in the vicinity of the superconducting transition in zero field, and as a function of magnetic field. The temperature dependence of the conductivity possesses a functional form in agreement with the predictions of mean field theory.¹ A transition from 2-D to 3-D behavior has been found.² The temperature dependent coherence length has been determined within the context of mean field theory by analysis of measurements of $\frac{dH_{c2}}{dT}$ in fields up to 100 kilogauss. The latter were carried out

using a 100 kilogauss superconducting magnet.

A detailed analysis of data is currently in progress. Preliminary results indicate that the conductivity in the 3-D regime is in detailed agreement with the original Aslamazov-Larkin¹ theory as corrected by Fulde and Maki³ for strong coupling effects. The strong coupling correction has been determined from the results of tunneling measurements on bulk NbN which are assumed to apply to films. The results in the 2-D regime do not agree with the predictions of any published theory.

Precise comparison of experiment and theory is currently hindered by the absence of knowledge of the depairing parameter.⁴ We currently believe this parameter to be the order of $\frac{1}{2}$ because of an observed 6°K downward shift of the transition temperature of our films relative to the transition temperature of bulk NbN. Auger analysis of typical films indicates the presence of substantial amounts of dissolved oxygen sufficient to produce strong pair breaking and a large shift in T_c . Unfortunately a detailed theory in this pair-breaking regime does not exist although the problem is tractable.⁵

1. L. G. Aslamazov and A. I. Larkin, Fiz. Tverd. Tela 10, 1104 (1968) [English Translation: Soviet Physics Solid State 10, 875 (1968).]

2. A. M. Goldman, F. M. Schaer, L. Toth and J. T. Zbasnik, Proceedings of the Conference on the Science of Superconductivity, Stanford University (1969) (to be published in Physica).
3. P. Fulde and K. Maki, Phys. Kondens. Materie 8, 371 (1969).
4. R. S. Thompson, Phys. Rev. B1, 327 (1970).
5. P. Hohenberg, (private communication).

4. Lifetimes of Persistent Currents In Superconducting Loops Interrupted by Josephson Junctions

(A. M. Goldman)

The lifetimes of quantized persistent current states of a superconducting loop interrupted by a single Josephson junction have been estimated using the techniques of random noise theory.^{1,2} Numerical results have been presented for physically realizable examples.³ In the calculation it was assumed that

$RC \left[\frac{2eI_1}{\hbar C} \right]^{1/2} \ll 1$, a condition which can be satisfied by either a low-capacitance crossed film junction or a weak link.

1. V. Ambegaokar and B. I. Halperin, Phys. Rev. Letters 22, 1364 (1969).
2. Yu. M. Ivanchenko and L. A. Zil'berman, Zh. Eksperim. i Teor. Fiz. 55, 2395 (1968) [English Translation: Soviet Physics JETP 28, 1272 (1969).]

3. A. M. Goldman, J. Low. Temp. Phys. 3, 27 (1970).

5. De Haas-Van Alphen Oscillations in the Critical Temperature of Type-II Superconductors (A. M. Goldman and L. Abad)

The goal of this work was to study the periodic variation of the transition temperature with magnetic field of pure type-II superconductors which was predicted by Gruenberg and Gunther.^{1,2} This phenomenon is associated with the inclusion of electron orbital diamagnetism in the calculation of the transition temperature from microscopic theory. Measurements using the Little-Parks³ technique have not yet commenced, as the ultra low temperature facilities upon which this work depends have been devoted exclusively to work on solid He³ in the past year. As the He³ work is likely to continue to tie up facilities and resources, further work on this project is not planned.

1. L. Gunther and L. W. Gruenberg, Solid State Communications 4, 329 (1966).
2. A. K. Rajagopal and R. Vasudevan, Phys. Letters 20, 585 (1966) and Phys. Letters 23, 539 (1966).
3. W. A. Little and R. D. Parks, Phys. Rev. 133, A97 (1964).

B. THEORETICAL WORK ON QUANTUM CRYSTALS

1. One-Phonon Excited States of Solid H₂ and D₂ in the Ordered Phase (L. H. Nosanow in collaboration with K. N. Klump and O. Schnepf of University of Southern California)

Optical phonon frequencies of ordered solid H₂ and D₂ have been calculated using a Lennard-Jones intermolecular potential derived from measurements of gas-phase properties. Good agreement with experiment is obtained. Density of states functions and phonon dispersion curves in three directions have also been computed. This work was published in Phys. Rev. B1, 2496 (1970).

2. Elementary Excitations in Solid Orthohydrogen
(A. K. McMahan and L. H. Nosanow)

Elementary excitations in solid orthohydrogen may be put into two classes - phonons (those originating in the center-of-mass variables for each molecule) and librons (those originating in rotational degrees of freedom). These excitations have both been studied using the random-phase approximation (RPA), but only the phonons have been studied using the self-consistent

harmonic approximation (SCHA). In this work an attempt was made to find a general approach, analagous to the SCHA to treat both the phonon and libron excitations. Unfortunately, it seems to be impossible to find such a formulation, and this work has been discontinued.

3. Exchange in Solid He³ (A. K. McMahan and L. H. Nosanow)

A systematic study of exchange in solid He³ has been undertaken in order to reexamine recent work¹⁻³ from a first-principles point of view. It seems that an adaptation of the work of Herring⁴ on electronic exchange is the best way to proceed. Following Herring, a general expression for exchange is derived. This expression includes the wave function of the whole system, in contrast to previous work which has always used a two-body approximation for the short-range correlations. Furthermore, this approach has led to a better understanding of the exchange operator.¹ In particular, one proposed mechanism for spin-lattice relaxation, i.e., the phonon-modulation of exchange, has been shown not to exist by this approach. This work will be continued.

1. D. Thouless, Proc. Phys. Soc. 86, 893 (1965).

2. L. H. Nosanow and C. M. Varma, Phys. Rev. 187, 660 (1969).

3. R. A. Guyer and L. I. Zane, Phys. Rev. 188, 445 (1969).
4. C. Herring in Magnetism, vol. II, edited by G. Rado and H. Suhl, Academic Press, Inc., New York, (1968).
4. Nonlocalized Vacancies in bcc He³ (H-T. Tan and L. H. Nosanow)

Various questions concerning vacancies in bcc He³ have been discussed in the literature.^{1,2} The concept of a vacancy wave was introduced by Hetherington.¹ The object of the present work has been to improve upon Hetherington's formulation of the problem, his calculation of the energy gap, and also to calculate the wave-vector dependence of the vacancy-wave energy. The formalism has been developed and the calculations (using Horner's correlation function³) are in progress.

1. J. H. Hetherington, Phys. Rev. 176, 231 (1968).
2. A. F. Andreev and I. M. Lifshitz, Zh. Eksp. Teor. Fiz. 56, No. 6 (1969) [Sov. Phys. - JETP 29, No. 6 (1969)].
3. H. Horner, Phys. Rev. A1, 1712 (1970); A1, 1722 (1970).

5. Two-Body Hartree Approximation (L. H. Nosanow and P. M. Steinback)

The basic idea of this approach was to develop an approximation in which two particles could move in a self-consistent field due to all of the other particles. Approximate equations were written and numerical solutions obtained. The results did give a crystal, but they were quantitatively unsatisfactory. This work has now been superseded by the work on the pair variational calculation.

↓

6. Pair-Variational Calculation of the Ground-State Properties of Quantum Crystals (W-L.Lim, L. H. Nosanow, H-T.Tan and P. M. Steinback)

A variational calculation using a trial wave function which is a product of pair wave functions f_{ij} has been studied. When the energy is minimized with respect to f_{ij} , there results an equation involving f_{ij} and the two-, three- and four-particle distribution functions F_{ij} , F_{ijk} and F_{ijkl} . One can also write a BBGKY-like equation which involves f_{ij} , F_{ij} and F_{ijk} . On physical grounds one expects $F_{ij}(\underline{r}_{ij})$ to look like a phonon distribution function $\phi_{ij}(\underline{r}_{ij})$ when $\underline{r}_{ij} \approx \underline{R}_{ij}$ (the lattice

vector between sites i and j) and to fall off rapidly when $|\underline{r}_{ij} - \underline{R}_{ij}|$ gets large. Thus, one may define $F_{ij} \equiv \phi_{ij} G_{ij}$, where G_{ij} then takes into account the effect of short-range correlations. The parameters in ϕ_{ij} may then be obtained from the curvature of an effective potential which determines F_{ij} . The higher distribution functions may be approximated by a modified Kirkwood superposition approximation; e.g. $F_{ijk} \approx \phi_{ijk} G_{ij} G_{ik} G_{jk}$. Preliminary calculations have been performed and the results look encouraging.

C. THEORETICAL WORK ON LIQUID HELIUM

1. Quasiparticle Hamiltonian for Liquid He³ (H-T. Tan
in collaboration with C-W. Woo of Northwestern University)

A quasiparticle Hamiltonian for liquid He³ is derived from matrix elements computed in the correlated representation using realistic He-He interactions. We outline here a prescription for systematically evaluating the irreducible self-energy parts and vertex parts of Green's functions defined in this representation. These quantities lead directly to a determination of ground state and Fermi liquid properties. Earlier work¹ using the same matrix elements has led to numerical results in good quantitative agreement with experiment. The present reformulation serves to clarify its contents and indicate directions for improvement. This work has been published in J. Low. Temp. Phys. 2, 187 (1970).

1. H-T. Tan and E. Feenberg, Phys. Rev. 176, 370 (1968).
2. Ground State of Liquid He⁴ (R. D. Murphy in
collaboration with R. O. Watts of the University
of Waterloo, Canada)

A variational calculation of the ground-state energy of

liquid He^4 is performed under the assumption that the ground-state wave function is a product of pair functions and the potential is a sum of pair potentials. Results obtained from the Percus-Yevick (PY) and Hypernetted Chain (HNC) theories are compared with both Monte Carlo (MC) studies and with experiment. It is found that in the case studied the PY is not useful for this variational calculation but that the HNC is. A comparison of three model pair potentials indicates that the uncertainty in the pair potential produces an uncertainty in the ground-state energy of about 2°K . One of the pair potentials used leads to the best agreement yet obtained with experimental ground-state energies. This work has been submitted for publication in the Journal of Low Temperature Physics.

3. Ground State of Liquid He^4 (W-L. Lim, L. H. Nosanow, H-T. Tan and P. M. Steinback)

Many calculations of the ground state of liquid He^4 have been performed using a wave function that is a product of pair functions $f(r)$.¹ These calculations have all used various analytic forms for $f(r)$. However, it is possible to consider the energy as a functional of $f(r)$ and minimize with respect to $f(r)$. This produces an equation² which involves $f(r)$ and

F_2 , F_3 and F_4 — the two-, three- and four-particle distribution functions. It is also possible to write the BBGKY equation, which involves f , F_2 and F_3 . If F_3 and F_4 are approximated in terms of F_2 via the Kirkwood superposition approximation, one has two equations for the two functions f and F_2 . Because these are nonlinear integrodifferential equations, they are difficult to solve numerically. We have tried to find a solution for some time without success.

1. See e.g. Theory of Quantum Fluids by E. Feenberg, Academic Press, New York and London, 1969.
2. J. C. Lee and A. A. Broyles, Phys. Rev. Letters 17, 424 (1966).

4. Hard-Core Bose Gas (W. J. Titus)

Work has been started on an improved calculation of the properties of a hard-core Bose gas. The T-matrix equation, resulting from a sum of ladder diagrams, is solved by assuming that a finite number of poles dominates the propagator. The effects of this approximation and the corresponding results are now being investigated. X

5. Theory of Dilute Solutions of He³ in Liquid He⁴ II: The Elementary Excitations (H-T. Tan in collaboration with C-W. Woo of Northwestern University)

Applying a first-principle theory for dilute He³-He⁴ solutions developed earlier, we compute higher order contributions to He³ effective mass and the concentration dependence of the phonon spectrum. We find that the higher order contributions are small as expected. In the long wave-length limit, the leading concentration dependence of the phonon spectrum goes as

$$\omega(p;x) = \omega(p;0) [1 + \beta x + \dots]$$

where x is the concentration. Our result for β differs by a factor of two from that obtained by direct experimental measurement¹. This work is being written up for publication.

1. B. M. Abraham, Y. Eckstein and J. B. Ketterson, Phys. Rev. Letters 21, 422 (1968).

6. Spin Waves in Liquid He³-He⁴ Dilute Solutions
(H-T. Tan and J. W. Halley)

It has been shown that spin wave propagation will occur in zero external field for He³-He⁴ solutions¹ but not for pure He³. However, in a strong magnetic field, spin waves propagate

in both systems.² We have solved the Landau-Silin transport equation for a thin film of Fermi liquid in a static field H_0 perpendicular to the film and a radio-frequency field perpendicular to H_0 . There are two branches of spin waves, one going as k^2 and the other as $-k^2$ for small k . We suggest a nuclear magnetic resonance experiment to study the spin waves. Our estimate of the absorption intensities shows that these waves are observable in both systems at high fields (~ 20 kG) and low temperatures (~ 20 mK) in a film of about 10 micron thickness.

1. V. J. Emery, Phys. Rev. 161, 194 (1967).
2. V. Silin, Soviet Phys. JETP 8, 870 (1959).

7. Evidence for the Validity of the Landau Theory of Liquid He³ (H. T. Tan)

With the aid of sum rules, we show that the contribution to the static structure factor $S(k)$ of liquid He³ from the multiple quasi-particle-hole pair excitations is less than 2% of the Landau contribution calculated by Widom and Sigel¹ in the long wavelength limit. This provides additional evidence for the validity of neglecting the multipair excitations in the Landau theory of liquid He³. This work has been submitted to

the Comments and Addenda section of Phys. Rev.

1. A. Widom and J. Sigel, Phys. Rev. Letters 24, 1400 (1970).

8. Classical Impurity-Vortex Scattering (W. J. Titus)

A classical model for the scattering of a small particle by a rectilinear vortex in liquid He II was studied for the purpose of explaining the experimental results of Steyert, Taylor and Kitchens.¹ Although many of their observations are accounted for, verification of the theory would require a reanalysis of the experimental data. A classical analogue of an Iordanskii force² was also discussed. The results of the work were published in J. Low Temp. Phys. 2, 291 (1970).

1. W. A. Steyert, R. D. Taylor, and T. A. Kitchens, Phys. Rev. Letters 15, 546 (1965).
2. S. V. Iordanskii, Zh. Eksperim. i Teor. Fiz. 49, 225 (1965) [English trans.: Sov. Phys. -- JETP 22, 160 (1966)].

9. A Model for the Quantum Scattering for a He³ Impurity from a Rectilinear Vortex in Liquid He II (W. J. Titus)

A model was investigated to describe the quantum scattering of a He³ impurity from a rectilinear vortex in liquid He II. The

principal assumption was the existence of an impurity wave function satisfying a Schrodinger equation. Various possibilities for the impurity-vortex interaction were studied. For certain interactions, the theoretical results were consistent with the experimental work of Rayfield and Reif¹ provided spatial variations in the superfluid density are considered. A T-matrix formalism was also developed and applied to the vortex scattering of impurities as well as phonons and rotons. The results were compared to existing theoretical and experimental work; the main discrepancies occurred for roton scattering. A summary of the work will appear in Phys. Rev. A, July (1970).

1. G. W. Rayfield and F. Reif, Phys. Rev. 136, A1194 (1964).

10. Electron Mobility in Gaseous Helium at Low Temperatures

(W. J. Titus)

A many-body calculation of electron mobility in gaseous helium at low temperatures (around 4°K) was undertaken for the purpose of explaining and understanding the experimental work of Levine and Sanders.¹ They found that the mobility of an electron in gaseous helium decreased by four orders of magnitude as the gas density n approached 10^{21} particles per cm^3 . The sharp decrease in the mobility was thought to be due to an electron-bubble formation similar to that which occurs in liquid He II.

the
As of/present, a linear-response, many-body calculation has been pursued. The dominant interaction has been assumed to be a hard-core interaction between the electrons and the gas particles characterized by a scattering length a . Any interaction between the gas particles themselves has been neglected. The important parameter in summing diagrams is $na^2\lambda_e$, where λ_e is the thermal wave length of an electron. A sum of ladder diagrams yields the classical Langevin result for electron mobility μ ; no precipitous drop in the mobility occurs. Other diagrams of order $na\lambda_e$ are now being considered.

1. J. L. Levine and T. M. Sanders, Jr., Phys. Rev. 154, 138 (1967).

D. EXPERIMENTS ON LIQUID HELIUM

1. Quantum Hydrodynamics of Superfluid Helium

a. Quantization of Circulation in Superfluid Helium

(S. F. Kral and W. Zimmermann, Jr.)

One of the most fundamental manifestations of quantum mechanics in the hydrodynamics of helium superfluid is that of quantization of circulation.^{1,2} Perhaps the most direct method for investigating this phenomenon is the one due to Vinen, in which the circulation around a fine wire is measured by the influence it exerts on the wire's vibration.³ Because we believe this phenomenon to be of fundamental importance and because other methods to observe circulation at the quantum level around solid objects appear to be limited,⁴ we have been working to extend the earlier work of Whitmore and Zimmermann⁵ with a new apparatus.

This apparatus was designed to permit us to extend our observations in a number of directions. In the first place, the use of a pumped inner He⁴ bath in addition to an unpumped outer He⁴ bath at 4.2°K permits us to increase considerably the length of time that superfluid helium in the experimental cell can be held below the lambda temperature. In our earlier measurements

the irregularities seen in the motion of the fluid around the wire appeared to decrease slowly over a period of a number of hours, possibly representing the slow disappearance of unwanted vorticity in the fluid. Therefore, by extending the length of our runs to several days it is hoped to be able to observe a simpler and more regular behavior of the fluid.

Second, a He^3 refrigeration stage will permit measurements to be made at temperatures down to 0.5°K or so. The reduction in the amount of normal fluid present should simplify the role played by the superfluid vortices in the experiment and thus make it easier to understand and to analyze.

Third, the use of a closed cell for the helium surrounding the wire will allow a study of the effect of pressure on the circulation observed. Moreover, it will permit the superfluid to be formed in the rotating state not only by cooling the liquid through the lambda transition, but also by condensation from the vapor or by decompression from the solid. In the first method unavoidable fluctuations in the superfluid near the lambda transition may be responsible for the large amount of extraneous vorticity that appears to be generated in the superfluid.⁵ Because the latter two methods involve passage through first-order phase transitions in which fluctuations are small, they hold promise for reaching a more nearly vortex-free state of the

superfluid. Such a state should permit more ideal measurements to be made on the circulation around the wire than were possible earlier.⁵ Some recent work by Jagger and Vinen suggests that the second of the two latter methods is the most promising.⁶

Finally, a magnet rotating with the apparatus, provision for the He³ and He⁴ baths to be pumped in rotation, and rotating electrical connections to the apparatus will permit measurements of the circulation to be made with the apparatus in rotation at speeds up to a few radians per second. Whereas our previous measurements were all made with the apparatus at rest, so that our observations were restricted to the metastable circulation persisting after rotation of the apparatus had stopped, we expect now to be able to observe the equilibrium circulation in rotation.

During the past year the apparatus has been thoroughly tested at low temperature, and a number of difficulties have been corrected. We hope to be able to begin systematic measurements of the superfluid circulation in the near future.

1. L. Onsager, *Nuovo Cimento* 6, Suppl. 2, 249 (1949).
2. R. P. Feynman, in Progress in Low Temperature Physics, Vol. I, ed. by C. J. Gorter (North-Holland Publishing Co., Amsterdam, 1955), Chap. II.

3. W. F. Vinen, Proc. Roy. Soc. (London) A260, 218 (1961).
4. Some promise lies in the method of heat-current-induced torques. However, quantum-level resolution is yet to be achieved. T. K. Hunt, Phys. Rev. 170, 245 (1968).
5. S. C. Whitmore and W. Zimmermann, Jr., Phys. Rev. 166, 181 (1968).
6. M. Jagger and W. F. Vinen, in Proceedings of the Eleventh International Conference on Low Temperature Physics, ed. by J. F. Allen, D. M. Finlayson, and D. M. McCall, (University of Saint Andrews, 1968), page 146.

b. Search for Analogs of the Josephson Effects in the Flow of Superfluid Helium (B. B. Sabo and W. Zimmermann, Jr.)

Ever since the discovery of the Josephson effects in superconductors, the extremely interesting question has arisen whether analogous effects exist in superfluid helium. Although it appears to be quite difficult to construct a true tunnel junction between two reservoirs of superfluid helium, a small orifice or the fine channels of a porous membrane connecting two reservoirs might well provide a suitable weak link with which to observe Josephson-like behavior. Indeed, recent experiments

with a small orifice have shown the existence of an effect analogous to the a.c. Josephson effect.^{1,2,3} However, the effect discovered so far can be explained in terms of conventional two-fluid hydrodynamics, supposing the existence of quantized vortices in the superfluid, as well as by more general arguments in terms of the phase of the order parameter.^{4,5,6} It is of considerable interest to investigate whether superfluid helium under the proper circumstances can exhibit Josephson-like behavior which lies outside of the usual two-fluid hydrodynamics.

One of the basic and most useful techniques for gaining information about superconducting Josephson junctions and weak links has been the study of the voltage-versus-current characteristics of the junction or weak link. It seems likely that the analog experiment in helium, a study of the pressure-difference versus volume-rate-of-flow characteristic of an orifice or permeable membrane, holds considerable promise for revealing interesting effects.

An apparatus for such studies has recently been completed, and preliminary tests at low temperature have been carried out.

The heart of the apparatus consists of a cell containing two chambers separated by the orifice or membrane under study. The two chambers will each be completely filled with superfluid

helium. One flexible diaphragm located in the wall common to both chambers will be used to drive the fluid in an oscillatory way from one chamber to the other at approximately 10 Hz, while another flexible diaphragm in the same wall will be used as part of a capacitance manometer to detect any pressure differences developing between the chambers. It is expected that it will be possible to make pressure-difference measurements with a sensitivity of 10^{-2} dyne cm^{-2} . The repetitive nature of the process will permit a direct display of the pressure-drop against flow-rate on the face of an oscilloscope and will allow more sophisticated signal-averaging techniques to be used if necessary.

The parameters of the apparatus have been chosen so that any pressure difference developing across the orifice will not significantly alter the flow through the orifice. In terms of its electrical analog the orifice will be driven from a high-impedance source, a state of affairs which should be particularly suited for observing the region in which flow occurs with very little or no dissipation.⁷

In addition to the mechanical drive and pressure-sensing system each cell has been provided with electrical heaters and sensitive resistance thermometers so that the superfluid motion can also be driven thermally and that any thermal contributions to the total difference in chemical potential between the two

chambers can be detected.

By use of an apparatus in which the measurement cell is only weakly coupled thermally to an internal pumped He^4 bath, which in turn is surrounded by an unpumped He^4 bath at 4.2°K , we expect to achieve a high degree of thermal stability and uniformity in the cell. The importance of thermal uniformity arises from the interdependence of temperature and pressure differences in relation to the motion of the superfluid. Because of the interdependence, any stray temperature differences would introduce spurious effects into the experiment.

Although our preliminary experiments will be conducted above 1.0°K , provision has been made for later installation of a He^3 refrigeration stage for work below 1.0°K .

1. P. L. Richards and P. W. Anderson, Phys. Rev. Letters 14, 540 (1965).
2. B. M. Khorana, Phys. Rev. 185, 299 (1969).
3. B. M. Khorana and D. H. Douglass, Jr. in Proceedings of the Eleventh International Conference on Low Temperature Physics, ed. by J. F. Allen, D. M. Finlayson, and D. M. McCall (University of Saint Andrews, 1968), page 169.
4. P. W. Anderson, in Quantum Fluids, ed. by D. F. Brewer (North-Holland Publishing Co., Amsterdam, 1966), page 146.

5. W. Zimmermann, Jr., Phys. Rev. Letters 14, 976 (1965).
6. E. R. Huggins, Phys. Rev. A 1, 332 (1970).
7. For an example of a recent "low-impedance-source" experiment see H. A. Notarys, Phys. Rev. Letters 22, 1240 (1969).
8. For example porous mica.

2. Phase Transitions in Liquid He³/He⁴ Mixtures

a. Specific Heat of Liquid He³/He⁴ Mixtures Near the Junction of the Lambda and Phase-Separation Curves

(W. Zimmermann, Jr.)

In liquid He³/He⁴ mixtures at saturated vapor pressure, the lambda curve meets the phase separation curve at a temperature T of 0.87°K and a He³ mole fraction x of 0.67.¹ This unusual intersection of phase boundaries represents the transformation of a second-order phase transition into a first-order transition with decreasing temperature.² In order to investigate further the thermodynamics of this unusual transformation, measurements of the specific heat of the liquid in the region of the junction were begun by the investigator and his colleagues during a year's visit in the laboratory of Professor O. V. Lounasmaa in Finland.³ The results obtained in that laboratory for values of x in the

range $0.53 \leq x \leq 0.73$ indicate that the lambda peak in the specific heat $c_{P,x}$ at constant pressure P and mole fraction x is finite, continuous, and cusped, in agreement with recent findings at lower values of x .⁴ The results also show that as the junction of phase boundaries is approached both the lambda peak and the discontinuity in specific heat as the system passes from the two-liquid-phase region to the one-liquid-phase region tend to disappear. The disappearance of the latter indicates that despite the finiteness of $c_{P,x}$, the complementary specific heat $c_{P,\phi}$ at constant pressure and relative molar chemical potential $\phi = \mu_3 - \mu_4$ diverges at the junction. A thermodynamic model accounting at least qualitatively for these features of the junction region has recently been discussed by Griffiths.⁵

The correction of the measured specific heat to $c_{P,x}$, the specific heat at constant pressure P and mole fraction x has recently been completed and partial analysis of the significance of the results has been carried out by the investigator at the University of Minnesota. The preparation of a full report of this work is currently in progress.

1. E. H. Graf, D. M. Lee, and J. D. Reppy, Phys. Rev. Letters 19, 417 (1967).
2. O. K. Rice, Phys. Rev. Letters 19, 295 (1967).

3. T. Alvesalo, P. Berglund, S. Islander, G. R. Pickett and W. Zimmermann, Jr., Phys. Rev. Letters 22, 1281 (1969).
4. F. Gasparini and M. R. Moldover, Phys. Rev. Letters 23, 749 (1969).
5. R. B. Griffiths, Phys. Rev. Letters 24, 715 (1970).

b. Osmotic Pressure of Superfluid He³/He⁴ Mixtures Curve Near The Lambda (C. A. Gearhart, Jr. and W. Zimmermann, Jr.)

As discussed above, recent experiments^{1,2} and theoretical discussions^{3,4} have indicated that the junction of the lambda and phase-separation curves in He³/He⁴ mixtures is an interesting topic of study. However, it has also become clear from this and other work^{5,6} that the nature of the lambda transition in the mixtures itself is a topic of considerable interest. At present much less is known about the critical behavior of various thermodynamic quantities near the transition in the mixtures than is known for the lambda transition in pure He⁴. In particular, as mentioned above, recent measurements at saturated vapor pressure of the specific heat $c_{p,x}$ at constant pressure P and He³ mole fraction x indicate that while this specific heat appears to diverge logarithmically at $x = 0$ (pure He⁴) it remains finite at values of $x > 0$.^{5,2} The interesting

question then arises whether the complementary but experimentally less accessible specific heat $c_{p,\phi}$ at constant pressure and relative molar chemical potential $\phi = \mu_3 - \mu_4$ diverges all along the transition curve despite the finiteness of $c_{p,x}$. Evidence derived somewhat indirectly from measurements of $c_{p,x}$ suggests that $c_{p,\phi}$ does diverge all along the curve.^{5,2}

Another way of answering this question would be to determine how the important derivative $(\partial\phi/\partial x)_{p,T}$ behaves near the transition, since it can be shown to vanish if and only if $c_{p,\phi}$ diverges. One way to measure $(\partial\phi/\partial x)_{p,T}$ on the superfluid side of the transition rather directly would be to measure the differential osmotic pressure of the mixture, using a cell with two chambers containing mixtures of slightly different concentration connected by a superleak permeable only to He^4 . On the superfluid side of the transition the derivative $(\partial\phi/\partial x)_{p,T}$ is then given in terms of the pressure and concentration differences ΔP and Δx by the expression $(\partial\phi/\partial x)_{p,T} \cong (v_4/x) (\Delta P/\Delta x)$, where v_4 is the partial molar volume of the He^4 component. It seems likely that estimates of v_4 can be made on the basis of existing molar volume data,⁷ although more extensive molar volume data would be of help here.

The apparatus for this experiment has been designed and is currently under construction. The osmotic pressure cell will

differentiable vector connection. The osmotic pressure set with

the expression for this experiment has been obtained and to
attempts more extensive work would be of great value.
can be made on the basis of existing work would be of great

of the h^d component. It seems likely that estimates of λ^d
 $(\partial\phi/\partial x)_{B^d} = (\lambda^d/x)(\nabla B/\nabla x)$ where λ^d is the binary work volume
concentration differences ∇B and ∇x by the expression

$(\partial\phi/\partial x)_{B^d}$ is then given in terms of the pressure and
on the arbitrary side of the transition the relative
concentration connected by a arbitrary reference only to h^d .

two separate computing schemes of arbitrary different
differentiable osmotic pressure of the mixture, and a set with
side of the transition rather directly would be to measure the

the c^{B^d} values. One may to measure $(\partial\phi/\partial x)_{B^d}$ on the arbitrary
the transition, since it can be shown to enter it and only
reference from the arbitrary relative $(\partial\phi/\partial x)_{B^d}$ reference used.

another way of measuring this direction would be to
 c^{B^d} and also that c^{B^d} does value all around the circle 2π .

Evidence relative somewhat indirectly from measurements of
around the transition circle relative the differences of c^{B^d} .

relative work current potential $\phi = h^d - h^d$ values all
these successive effects near c^{B^d} of constant pressure and
direction then states whether the combination of the experimentally

make use of a diaphragm capacitance-manometer for making pressure-difference measurements. Provision for He^3 refrigeration has been included in the design to permit measurements to be carried out along the entire length of the lambda-curve at low pressure. A system for preparing and handling He^3/He^4 gas mixtures is near completion.

1. E. H. Graf, D. M. Lee, and J. D. Reppy, Phys. Rev. Letters 19, 417 (1967).
2. T. Alvesalo, P. Berglund, S. Islander, G. R. Pickett, and W. Zimmermann, Jr., Phys. Rev. Letters 22, 1281 (1969).
3. O. K. Rice, Phys. Rev. Letters 19, 295 (1967).
4. R. B. Griffiths, Phys. Rev. Letters 24, 715 (1970).
5. F. Gasparini and M. R. Moldover, Phys. Rev. Letters 23, 749 (1969).
6. M. E. Fisher, Phys. Rev. 176, 257 (1968).
7. E. C. Kerr, Phys. Rev. Letters 12, 185 (1964).

E. MAGNETISM IN METALS

1. Nuclear Magnetic Resonance (J. Aslam and W. Weyhmann)

We have been studying the structure of the satellite lines on the nmr line of cobalt caused by the introduction of dilute

impurities, particularly vanadium and chromium. In spite of intensive study in the past, the assignments of the various satellites to particular neighbors (1st, 2nd, etc.) or combinations of neighbors has never been unambiguous. Integration of the intensity of the various lines and the large error associated with it has made this task difficult. Our own attention has been focused on the observation that the time decay of the spin echos of some of the satellite lines is modulated whereas the main line is not. This is a result of the impurity causing an electric gradient which does not otherwise exist at the host site. Thus the resonance of the host with nearby impurity shows a quadrupole splitting. It appears on theoretical grounds that the exchange contributions to this modulation are negligible. If this is so, then we have here a powerful tool for the study of electric field gradients in metals, as the different types of neighbors give rise to distinguishable resonances and the assignment of neighbor to resonance may ultimately be feasible. (In fact, this method may have the solution to that problem built in, as the farther the impurity from the host atom, the lower the electric field gradient.)

A variable temperature nmr probe has been completed mechanically and is now being wired up. This device is simply

a shorted 50 Ω transmission line with the shorted end thermally isolated and temperature controlled. (The School of Physics contributed the labor required for building this device.) A germanium resistance thermometer and thermocouples will provide precision temperature measurements from 1.5 to 300 K. Since it is a precise 50 Ω line of low attenuation, measurements can be performed over a very wide frequency range. The first experiment with this will be a precise sublattice magnetization measurement on the anomalous site of Mn_2Sb .¹

2. Heat Capacity Measurements in the Spin Reorientation Region (R. Sundararajan and W. Weyhmann in collaboration with M. Moldover and G. Sjolander)

Preliminary measurements were made on a single crystal of $YbFeO_3$ by the ac heat capacity technique.² (The single crystal was provided by Prof. Robert L. White of Stanford University.)

An AuFe-chromel thermocouple was used as the sensor but provided too low a sensitivity. Nevertheless, an anomaly was detected in the expected region. The magnetic field dependence of the anomaly was not clear.

New measurements have been made in zero applied field with a

germanium resistance thermometer and the standard dc method. This measurement shows a well-defined heat capacity anomaly which does not resemble a lambda shape and does not have a latent heat. The system may prove to be close to Landau type behaviour. We have also noticed that by measuring the heat capacity away from the anomaly and combining these results with the magnetization measurements of Beaulieu³, we can measure the effective field on the rare earth moment:

$$C \sim H \frac{dM}{dT}$$

In this way we can directly check their assignments made mainly from magnetization measurements.

3. Nuclear Orientation Experiments (R. J. Holliday, C. Smith, R. Swinehart, and W. Weyhmann)

We are just completing an extensive series of measurements of the internal field of ⁶⁰Co in Au, Cu, and AuCu alloys in magnetic fields up to 40 kOe. Cobalt is thought to be nonmagnetic in these hosts and so should show a very small Knight shift. In gold, however, our measurements show the internal field to be 1.29 ± 0.11 of the applied field whereas in copper it equals the applied field within statistical error. Three explanations have occurred to us:

1. The hyperfine field is negative, as expected, but exceptionally large.
2. The hyperfine field is positive, which is not expected, and only slightly larger than normal.
3. The Kondo temperature, instead of being very high as present measurements at high concentration imply, is low for very dilute concentrations of cobalt in gold. It is known that the Kondo temperature is considerably lower in gold than in copper for the same magnetic impurity.⁴

Since cobalt lies between elements that show clear magnetic (iron) and nonmagnetic (nickel) behaviour in these hosts, these results may have an important bearing on the occurrence of Kondo behaviour.

The Kondo system Mn in Cu has been very well investigated with nuclear orientation,⁵ however, the measurements have not been carried well into the saturation region with applied magnetic field. The Oxford data was carried to 15 kOe and, judging from the very slight increase over lower field data, implied that saturation had been essentially achieved. However, their point in the vicinity of 5 kOe does not agree with that of the Los Alamos group, the Oxford point lying considerably

higher. We have measured this curve with very high precision to 40 kOe and find that the Mn is not yet saturated at 15 kOe and that the Los Alamos data at lower fields is correct. Furthermore, an older sample shows the same qualitative dependence of internal field on applied field but lies lower everywhere. Thus manganese in copper may be subject to oxidation⁶ and so may not be stable with time at room temperature. These measurements carry important implications for the use of this material as an ultralow-temperature thermometer as is now being contemplated by a number of workers. These measurements may well be the most precise ever made by nuclear orientation.

An analysis of the results on orientation of ^{142}Pr in Pr metal is continuing. Two solutions exist for the beta-decay matrix elements of this isotope,⁷ and this leads to an ambiguity in the interpretation of the magnetic structure of Pr metal. We have some data taken with scintillation counters which might be unraveled enough to pick one of the two solutions, and this work is now in progress.

4. Enhanced Nuclear Hyperfine Cooling (W. Weyhmann and C. Smith)

We have continued trying to demagnetize Pr metal, which shows a large nuclear orientation at moderate fields and temperatures.

So far temperatures in the 5-10 mK region have been obtained starting from 20 to 40 kOe and 15 to 25 mK. Very pure ingots about one gram in size have been used. We have observed irreversible heating effects at the low field end of the demagnetization but have not yet ascertained the cause of these. They may be experimental artifacts such as superconductor "switching" in the solders used or magnetic field jumps, or they may be inherent magnetic effects in Pr such as ordering or heating from the demagnetization of the antiferromagnetic site. Some heat capacity data exist on the Pr from these measurements in the 8-35 mK region and will join onto the results of Holmstrom et al.⁸ Because of the several magnetic fields that must be applied (to paramagnetic salt for initial cooling, to Pr for the nuclear cooling, and to the nuclear orientation sample for thermometry) and because of the limitation on the initial temperature of the nuclear stage (due to the high heat capacity of the Pr), a dilution refrigerator of 10 mK ultimate temperature would greatly aid this work.

1. R. W. Houghton, Ph.D. thesis, University of Minnesota, 1968.
2. Y. A. Kraftmakher, Zhur. Priklad. Mekh. i Tekh. Fiz 5, 176 (1962). P. F. Sullivan and G. Seidel, Phys. Rev. 173, 679 (1968), and P. Handler et al., Phys. Rev. Letters 19, 356 (1967).

3. T. J. Beaulieu, Ph.D. Thesis, Stanford University, 1967
(Microwave Laboratory Report No. 1530).
4. E. Lagendijk et al., Phys. Rev. Letters 19, 1319 (1967), and
J. W. Loram et al., Phys. Rev. B, to be published.
5. I. A. Campbell et. al., *ibid.*, and W. P. Pratt, Jr., et al.,
J. Low Temp. Phys. 1, 469 (1969).
6. D. H. Howling, Phys. Rev. 155, 642 (1967).
7. R. Hess et al., Nucl. Phys. 54, 573 (1964).
8. B. Holmstrom et al., Phys. Rev. 188, 888 (1969).

F. EXPERIMENTAL STUDIES OF THE PROPERTIES OF CRYSTALLINE HE³

1. Heat Capacity Measurements (L. Abad, A. M. Goldman
and P. J. Kreisman)

During the past year groups at Brookhaven¹ and Cornell² successfully measured the sign and the magnitude of the exchange constant in solid He³ thus forcing us to alter the direction of our research. We chose to carry out specific heat measurements of bcc and hcp solid He³ down to 20 mK. in our dilution refrigerator. We have thus set up to study in a systematic way dependence of the specific heat on molar volume, He⁴ concentration, and temperature. These measurements should provide a more detailed characterization of the specific heat anomaly in solid He³ than was previously available. This anomaly has been the subject of recent experimental and theoretical interest. Our studies may provide sufficient experimental information to permit an understanding of the role of exchange in the specific heat.

All of the facilities for these experiments have been assembled. Tests have indicated that we can prepare He³ with less than one part per million He⁴ impurity in our still. We are able to accurately and quickly characterize samples of both high and low He⁴ impurity concentration with an on-line mass spectrometer system based on an Utek residual gas analyzer.

The pressurization system for producing solid He^3 has been assembled and tested. A specific heat cell has also been assembled and tested at low temperatures and high pressures.

In our present apparatus low temperature thermometry is carried out by measuring the susceptibility of CMN using the method of Casimir and Dupre¹⁰ at a frequency of 1.5 MHz. Later efforts will employ the nuclear susceptibility of He^3 as a thermometer.

~~Experiments are under way and results will be reported when they are available.~~

1. W. P. Kirk, E. B. Osgood and M. Garber, Phys. Rev. Letters 23, 833 (1969).
2. J. R. Sites, D. D. Osheroff, R. C. Richardson and D. M. Lee, Phys. Rev. Letters 23, 835 (1969).
3. H. H. Sample and C. A. Swenson, Phys. Rev. 158, 188 (1967).
4. R. C. Pandorf and D. O. Edwards, Phys. Rev. 169, 222 (1968).
5. P. N. Henricksen, M. F. Panczyk, S. B. Trickey and E. D. Adams, Phys. Rev. Letters 23, 518 (1969).
6. W. C. Thomlinson, Phys. Rev. Letters 23, 1330 (1969).
7. C. M. Varma, Phys. Rev. Letters 24, 203 (1970).
8. R. A. Guyer, Phys. Rev. Letters 24, 810 (1970).
9. H. Horner, Phys. Rev. Letters 25, 147 (1970).
10. H. B. G. Casimir and F. K. Dupre, Physica 5, 507 (1938).

III. RECENT PUBLICATIONS

52. COO-1569-52 "Classical Scattering of a Sphere by a Vortex--
A Possible Explanation of the Steyert, Taylor,
Kitchens Experiment" (W. J. Titus) submitted
to Phys. Rev.
53. COO-1569-53 "Fluctuation Effects in Nb_{.88}Ti_{.12}N Films"
(F. M. Schaer, A. M. Goldman, J. Zbasnik,
L. E. Toth) Bull. Am. Phys. Soc. II 15, 40
(1970).
54. COO-1569-54 "One-Phonon Excited States of Solid H₂ and D₂
in the Ordered Phase" (K. N. Klump, O. Schnepf
and L. Nosanow) Phys. Rev. B1, 2496 (1970).
55. COO-1569-55 "Magnetic Behaviour of Very Dilute Co in Au"
(R. J. Holliday and W. Weyhmann) Phys. Rev.
Letters 25, 243 (1970).
56. COO-1569-56 "Experimental Determination of the Pair
Susceptibility of a Superconductor" (J. T.
Anderson and A. M. Goldman) submitted to Phys.
Rev. Letters.
57. COO-1569-57 "Specific Heat of Liquid He³/He⁴ Mixtures
Near the Junction of the Lambda and Phase-
Separation Curves" (T. Alvesalo, P. Berglund,
S. Islander, G. R. Pickett, and W. Zimmer-
mann, Jr.) Bull. Am. Phys. Soc. II 15, 58
(1970).

58. COO-1569-58 "Specific Heat of Liquid He^3/He^4 Mixtures Near the Junction of the Lambda and Phase-Separation Curves" (T. Alvesalo, P. Berglund, S. Islander, G. R. Pickett, and W. Zimmermann, Jr.) submitted for publication in the Proceedings of LT-12.
59. COO-1569-59 "Annual Progress Report" (1970).
60. COO-1569-60 "Ground State of Liquid He^4 " (R. D. Murphy and R. O. Watts) Bull. Am. Phys. Soc. 12, 1175 (1969).
61. COO-1569-61 "Ground State of Liquid He^4 " (R. D. Murphy and R. O. Watts) submitted to J. Low Temp. Phys.
62. COO-1569-62 "Quasiparticle Hamiltonian for Liquid He^3 " (H-T. Tan and C-W. Woo) J. Low Temp. Phys. 2, 187 (1970).
63. COO-1569-63 "A Model for the Quantum Scattering of a He^3 Impurity from a Rectilinear Vortex in Liquid He II" (W. J. Titus) Phys. Rev. (In Press).
64. COO-1569-64 "Spin Waves in Liquid He^3 - He^4 Dilute Solutions" (H-T. Tan and J. W. Halley) submitted to Phys. Rev. Letters.
65. COO-1569-65 "Evidence for the Validity of the Landau Theory of Liquid He^3 " (H-T. Tan) submitted to Phys. Rev.

66. COO-1569-66 "Theory of Dilute Solutions of He³ in Liquid He⁴ II" (H-T. Tan and Chia-Wei Woo) submitted to Phys. Rev.
67. COO-1569-67 "Nuclear Orientation Studies of Local Moments in Noble Metal Hosts" (R. J. Holliday and W. Weyhmann) Doctoral Dissertation, University of Minnesota (unpublished).
68. COO-1569-68 "A Filing Machine for Preparation of Metallic NMR Samples" (J. Aslam and W. Weyhmann) submitted to Rev. Sci. Instruments.
69. COO-1569-69 "Operation of GaAs LED's and Si Detectors at 4.2°K" (J. C. Solinsky) submitted to Rev. Sci. Instruments.

IV. STAFF

L. H. Nosanow	Professor
W. Zimmermann, Jr.	Associate Professor
A. M. Goldman	Associate Professor
W. V. Weyhmann	Associate Professor
H. T. Tan	Research Associate
W. Titus ¹	Research Associate
P. M. Steinback	Research Fellow

GRADUATE STUDENTS

L. Abad	Research Assistant
J. Anderson	Research Assistant
J. Aslam	Research Assistant
D. Bakalyan ²	Research Assistant
R. Carlson	NSF Trainee
C. A. Gearhart, Jr.	Research Assistant
J. Holliday ³	Research Assistant
S. Kral	Research Assistant
P. Kreisman	NSF Trainee
W. L. Lim	Research Assistant
A. K. McMahan	NSF Fellow
B. Sabo	Research Assistant
F. Schaer ⁴	NSF Trainee

C. Smith ^{2,5}	Research Assistant
J. C. Solinsky ²	Research Assistant
R. Swinehart ²	Research Assistant

1. Present Address: Carleton College
2. Summer 1970
3. Present Address: John Brown University
4. Present Address: Drury College
5. Present Address: Macalester College

V. EFFORT OF PRINCIPAL INVESTIGATORS (percentage of time,
calendar year, 1970)

Investigator \ Period	January 1 to June 15	June 16 to September 15	September 16 to December 31
A. Goldman	50%	100%	50%
L. Nosanow	50%	100%	50%
W. Weyhmann	50%	100%	50%
W. Zimmermann, Jr.	50%	66.6%	50%