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University of Minnesota
School of Physics, Institute of Technology

Experimental and Theoretical Studies in Solid State and Low Temperature Physics

ANNUAL PROGRESS REPORT

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DISCLAIMER

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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 was under the direction of Professors A. M. Goldman, L. H. Nosanow, W. V. Weyhmann and W. Zimmermann at the School of Physics and Astronomy in the Institute of Technology of the University of Minnesota and was supported by USAEC Contract AT(11-1)-1569.

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

II. DESCRIPTION OF RESEARCH

A. Superconductivity

1. The Josephson Effect

a. Meissner Effect and Vortex Penetration in Wide, High-Current Josephson Junctions

Investigation of the magnetic field dependence of the maximum zero-voltage current of wide, high-current Josephson Junctions has revealed behavior drastically different from the usual Fraunhofer pattern for narrow junctions.[1] The experiments are interpreted as evidence for a Meissner Effect for the insulating layer and adjacent penetration layers of wide junctions in low external fields and for an eventual transition to a mixed state[2] as the external field is increased from zero. The observed current-field curves are in reasonable agreement with detailed calculations by Owen and Scalapino[3]. This work was reported at the March meeting of the American Physical Society[4] and will be published in The Physical Review[5].

1. J. M. Rowell, Phys. Rev. Letters 11, 200 (1963).
2. B. D. Josephson, Adv. in Physics 14, 419 (1965).
3. D. J. Scalapino and C. J. Owen (to be published).
4. A. M. Goldman and P. J. Kreisman, Bull. Am. Phys. Soc. II 12, 309 (1967)
5. A. M. Goldman and P. J. Kreisman, Phys. Rev., to be published, USAEC Report C00-1569-10.

b. Stability of Current States of Superconducting Rings Interrupted by Josephson Junctions

The experiments of Goldman, Kreisman, and Scalapino[1] have been continued and extended. In this work circulating ring currents in superconducting rings containing two junctions were detected by measuring the depression of the maximum zero-voltage current through a parallel combination of the two junctions. Up to ten quantum levels have been observed in recent experiments. The various levels were randomly populated by repeatedly traversing the I-V characteristic of the ring structure. Histograms of the occurrence of the various states were recorded digitally. Measurements of the temperature dependence of the level structure were also made. Ring currents were also prepared by warming and cooling in the presence of an axial magnetic field and removing the field. A single measurement of the maximum zero-voltage current then could be used to destructively read out the ring current. Results of these experiments appear to be in good agreement with theory. A detailed description of this work will shortly be submitted to The Physical Review. A brief account will appear in the proceedings of the Tenth International Conference on Low Temperature Physics.[2]

Development of a flux-flow magnetometer[3] to be used to extend this work is well underway.

1. A. M. Goldman, P. J. Kreisman and D. J. Scalapino, Phys. Rev. Letters 15, 495 (1965).

2. A. M. Goldman and P. J. Kreisman, Proceedings of the Tenth International Conference on Low Temperature Physics, Moscow 1966 (in press), USAEC Report no. C00-1569-5.

3. J. E. Mercereau, Proceedings of the Conference on Superconducting Devices, Charlottesville 1967 (in press).

2. Quantum Effects at the Superconducting Transition Temperature (A. M. Goldman)

a. Extensions of the Little-Parks Experiment

Experiments to observe the periodicity of the transition temperature of long superconducting rings in axial applied magnetic fields were initiated during the past year. This work has two aims: the first is to check the observation of Little and Parks of an apparent hc/8e flux period for indium in addition to the usual hc/2e value. The second is to search for the predicted large depression of the transition temperature of low inductance cylinders caused by depairing due to induced ring currents. These investigations are currently being pursued using both circular and planar rings.

1. W. A. Little and R. D. Parks, Phys. Rev. 133, A97 (1964).

2. Peter Fulde and R. A. Ferrell, Phys. Rev. 131, 2457 (1963).

b. De Haas-van Alphen Oscillations in the Critical Temperature of Type-II Superconductors

It was recently predicted[1,2] that the critical temperature of a Type-II superconductor should exhibit de Haas-van Alphen like oscillations. The theory predicts the ratio of the amplitude of the temperature oscillations to the critical temperature to be 10^{-4} at $0.025^{\circ}K$ and to decrease rapidly with increasing temperature.

A dilution refrigerator, which will be used to reach the required temperature range is being assembled. A sensitive quantum voltmeter which employs a solder bead on a niobium wire[3] has already been con-

structed. The latter device is capable of resolving 10^{-14} volts. Samples of high purity niobium with a resistivity ratio in excess of 10,000 have been made available to us by the Union Carbide Corporation for this experiment.

1. Leon Gunther and Leonard W. Gruenberg, Solid State Communications 4, 329 (1966).

2. A. K. Rajagopal and R. Vasudevan, Physics Letters 23, 539 (1966).

3. J. Clarke, Phil. Mag. 13, 115 (1966).

B. Theory of Quantum Crystals

1. Improved Correlation Functions for Quantum Crystals (W. J. Mullin, L. H. Nosanow and P. M. Steinback)

In recent work[1], it has been shown that the cluster expansion approach leads to a reasonable approximation scheme for calculating the properties of quantum crystals, at least for a restricted class of correlation functions. An obvious question which has been opened by this work is whether it is possible to improve the theory by the use of better correlation functions. This problem has been studied by using the cluster expansion approximation for the ground-state energy and writing a differential equation for correlation function. It has been found necessary to include the 3-body terms in the differential equation and to impose a constraint on the long-range behavior of the correlation function, since this behavior is not determined by the leading terms of the cluster expansion. The computer program to solve this differential equation has been written and is currently being debugged.

1. J. H. Hetherington, W. J. Mullin and L. H. Nosanow, Phys. Rev. 154, 175 (1967).

2. Calculation of Phonon Frequencies and Thermodynamic Properties of Crystalline BCC He (F. W. de Wette (University of Texas), L. H. Nosanow and N. R. Werthamer (Bell Telephone Laboratories)).

In this paper the lattice dynamics of crystalline bcc helium is treated by using the time-dependent Hartree approximation together with the results of variational calculations of the ground-state energy using correlated trial wave functions. The phonon spectrum has been calculated for various densities of bcc He^3 and He^4. We present dispersion curves, density of state histograms and sound velocities for selected densities. In addition we have calculated (with these densities) the mean displacement and a specific heat. This paper has been submitted for publication in The Physical Review.

3. A Critique of The Saunders Theory of Solid He^3 at $0^\circ K$ (W. J. Mullin)

An examination is made of the theory of the ground-state of solid ^3He proposed by Saunders[1] and modified by Garwin and Landesman.[2] We find the theory is inconsistent or wrong in the following respects: unphysical, single-particle functions result from a misapplication of the Pluvinage[3] method of generating a wave function; the derivation of an expression for the exchange integral J is inconsistent with this wave function; a correct solution for the integral equation for the single-particle probability density has not been given; the heuristic expression used for the cohesive energy is inconsistent with the Pluvinage method. This paper has been submitted for publication in The Physical Review.

1. E. M. Saunders, Phys. Rev. 126, 1724 (1962).

2. R. L. Garwin and A. Landesman, Physics 2, 107 (1965).

3. P. Pluvinage, Ann. Phys. 5, 145 (1950).

4. Simple Approach to the Self-Consistent Phonon Theory (L. H. Nosanow)

In the last year the use of self-consistent phonons has been shown to be important not only for quantum crystals, but also for other noble gas crystals. The existing derivations of this approach by Koehler[1] or Horner[2] are rather complicated. It is possible to give a simpler derivation of this approach by studying the equation of motion. One finds that these equations can be recast in a form such that the leading term is the self-consistent harmonic approximation and that successive terms yield corrections which may be identified as interactions between these self-consistent phonons. A paper on this work is in preparation.

1. T. M. Koehler, Phys. Rev. Letters 18, 654 (1967).

2. H. Horner, Z. Physik, to be published.

5. Exchange in Crystalline Helium Three (L. H. Nosanow and C. M. Varma)

A derivation of the appropriate spin Hamiltonian for the nuclear spin system of crystalline helium three has been given. It is found that the exchange integral must be replaced by an appropriately defined exchange operator. Expressions for matrix elements of this exchange operator have been given within the context of the cluster

expansion. The temperature dependence of the exchange frequency is studied within the context of this approach. A report of this work will be submitted to Physical Review Letters.

6. Study of the Nuclear Relaxation of the Spin System of Crystalline ^{3}He (L. H. Nosanow and C. M. Varma)

The various mechanisms for the relaxation of the nuclear spin system of crystalline helium three are extremely complicated. This work is part of a systematic study of all of the nuclear relaxation mechanisms of this system. The main progress so far has been made with respect to the relaxation of the system from the exchange bath to the lattice which can be caused by the lattice modulation of the dipole interaction. The equations for the relaxation rate due to this process have been derived using the results of the theory of quantum crystals and include the effects of self-consistent phonons. The numerical calculation of this relaxation rate is in progress. An interesting physical feature is that there is a lower bound to this rate which is determined by the very large zero-point motion in crystalline helium. Thus there is an intrinsic upper limit to the relaxation time which is set by the zero-point motion. Consequently crystalline ^{3}He might be the best substance to use for cooling by nuclear demagnetization.

C. Mixtures of Helium Isotopes

1. Phase Separation in Liquid ^{3}He-^{4}He Mixtures

(R. D. Murphy and L. H. Nosanow)

The ground state properties of liquid ^{3}He-^{4}He mixtures have been studied. The approach is to introduce the experimental information on the pure isotopes and thereby obtain information about the mixtures of the isotopes, i.e. we are trying to find an interpolation procedure which will give the concentration dependence of various properties of the mixture. It is hoped that this work will yield accurate caculations of quantities like the partial molar volume of ^{3}He and ^{4}He which are very important from a theoretical point of view. Calculations using this approach are currently in progress.

2. Phase Separation in ^{3}He-^{4}He Crystals (W. J. Mullin)

The calculations which have been used to study the properties of crystals of pure ^{3}He and ^{4}He have been extended to treat crystalline mixtures of these isotopes. It has been assumed that the different isotopes are distributed randomly. With this assumption, it is possible to calculate the ground-state energy in a straightforward manner. The effects of finite temperatures have also been included in a simple way. With this theory it is possible to calculate the phase separation curve for ^{3}He-^{4}He crystal mixture. Preliminary results indicate qualitative agreement with experiment, although the phase separation temperature is off by a factor of two. A particularly encouraging feature of the calculation is that the phase separation curve has the correct form at very low concentra-

D. Magnetism in Metals

1. Nuclear Resonance in Magnetic Materials (R. Houghton, J. Aslam, J. Yanez, W. Weyhmann)

Our studies of $Mn_{2-x}Cr_xSb$ have been considerably aided by our completed development of a reliable and versatile spin-echo spectrometer which is simple to use and free of long-line problems. A single set of instruments is used from 50 to 1000 MHz. This range can easily be extended if necessary. Work from liquid helium temperatures to well above room temperature is feasible, though we have only used the instrument from 55 to 300°K.

Most of our resonance work on the Mn-Sb systems has been centered on pure Mn_2Sb in the vicinity of the spin-flip temperature (240°K). Spin echoes from both of the manganese sites and the antimony site have been observed throughout this region. For the manganese resonances, the quadrupole interaction is washed out in the spin flip region but is observable some 20°K on either side of 240°K. The nuclear spin relaxation times, T_1 and T_2, have been measured within the range of temperatures from 77°K to 300°K which includes the spin flip region as expected, T_1 decreases montonically with increasing temperature and T_2 also decreases montonically with increasing temperature except in the spin flip region. There it exhibits a minimum and then a maximum at the spin flip temperature; above 240°K it resumes its monotonic decrease with increasing temperature.

A tunnel diode oscillator operable at cryogenic temperatures has been developed. Its sensitivity is hard to control, but the device is still

valuable for wide-frequency-range searches and for measuring the temperature dependence of the resonance frequency of observed lines. It is being used to search for the resonance of various impurities in iron, cobalt, and nickel.

We have also constructed a radio-frequency induction furnace for preparing high purity samples under vacuum. This apparatus was essential for the preparation of the iron alloys.

2. Nuclear Orientation Experiments (C. Smith and W. Weyhmann)

Construction of the basic components of the adiabatic demagnetization cryostat was completed in January and assembly of the apparatus was completed about two months later. The basic refrigeration stages to $0.3^{\circ}K$ now operate adequately. The demagnetization magnet (obtained from Westinghouse) has been tested. A lead heat switch driven by the magnet is being optimized. Installation of a salt pill and sample should be completed by the end of Semptember.

The associated nuclear counting equipment is ready and the analyzer is operative. An incremental magnetic tape recorder will be used to read out the information. This tape can be directly put on the computer and is an infinite improvement over the punched tape originally proposed in speed, reliability and ultimate cost.

E. Superfluidity in Liquid Helium

1. Experiments on Ion Trapping in Rotating Helium II (W. Zimmermann, Jr. and W. Pratt)

The lifetime for the escape of negative ions from quantum vortices in rotating superfluid helium has been measured as a function of temperature both at saturated vapor pressure and at elevated pressures up to the solidfication pressure. The method used was suitable for measuring lifetimes in the range from about 10 sec to 1000 sec, and measurements were made within the range of temperatures from 1.09°K to 1.67°K. These measurements represent an extension to elevated pressures of the experiments of R. L. Douglass at saturated vapor pressure, and the results at saturated vapor pressure are in good agreement with his findings.[1] Our work complements the recent experiments of B. E. Springett and R. J. Donnelly on the capture cross section for negative ions in the rotating liquid under pressure.[2] We have analyzed our results in terms of the bubble model of the negative ion and have found a bubble radius of about 19 or 20 Å at saturated vapor pressure decreasing to 12 or 13 Å at the solidification pressure. Although somewhat larger than previous estimates, our values for the radius are in reasonably good agreement with the predictions of an extremely simple model for the bubble and are somewhat smaller than a recent experimental determination of the radius at saturated vapor pressure by J. A. Northby and T. M. Sanders.[3]

A report on this work was given at the Washington meeting of the A.P.S., April 24-27, 1967.[4] A detailed report of this work has been prepared by W. P. Pratt as his Ph.D. Thesis[5], and it is planned to

submit an article on this work for publication in The Physical Review in the near future.

1. R. L. Douglass, Phys. Rev. Letters 13, 791 (1964).

2. B. E. Springett, Phys. Rev. 155, 139 (1967).

3. J. A. Northby and T. M. Sanders Jr., Phys. Rev. Letters 18, 1184.

4. W. P. Pratt and W. Zimmermann, Jr., Bull. Am. Phys. Soc. 12, 551 (1967), AEC Report C00-1569-9.

5. W. P. Pratt, Ph. D. Thesis, University of Minnesota (1967), AEC Report C00-1569-14)

2. Experiments on Quantization of Superfluid Circulation

Our experiments making use of the Vinen method to study quantization of superfluid circulation around a fine wire at saturated vapor pressure between 1.2°K and 1.9°K have been completed.[1] The experiments represent an extension of Vinen's original work[2] in several ways, and have revealed stable superfluid circulations at the levels of 1, 2, and 3 quantum units. A detailed report of these experiments has been prepared by S. C. Whitmore as his Ph.D. thesis,[3] and an article to be submitted to The Physical Review on this work has just been completed.[4]

An effort to extend our work along these lines is currently underway. The design of a new apparatus has almost been completed. This apparatus will permit the sample cell to be cooled to 0.4°K or below in order to avoid more completely the effects of the normal component of helium II. Provision has been made for pressurizing the sample, in particular, to permit the rotating state of helium II to be reached from the solid state. In addition, the apparatus has been designed to allow measurements to be made in rotation at higher speeds than was possible with the present apparatus.

1. S. C. Whitmore and W. Zimmermann, Jr., Phys. Rev. Letters 15, 389 (1965).

2. W. F. Vinen, Proc. Roy. Soc. (London) A260, 218 (1961).

3. S. C. Whitmore, Ph.D. Thesis, University of Minnesota (1966).

4. S. C. Whitmore and W. Zimmermann, Jr., AEC Report C00-1569-13.

3. Studies of Superfluid Flow in a Porous Medium

Our experiments studying the flow of the superfluid in powder-filled glass spheres has been completed. In these experiments studies were made both of the torsional oscillation of the spheres and also of the behavior of persistent circulating superfluid flow in the spheres using a gyroscopic technique.[1] A detailed report of this work was prepared by J. B. Mehl as his Ph.D. thesis,[2] and an article on this work has been submitted to The Physical Review for publication.[3]

New experiments have been undertaken to study superfluid flow in very fine channels. A superfluid gyro has been constructed for this purpose in the form of a powder-filled torus, with the flow circuit around the torus interrupted by a number of barriers of Millipore filter having pores on the order of 100 Å in size. It is expected that the lowering of the λ-transition temperature in the barrier will reflect inself in the dependence of the angular momentum of a persistent current on temperature, and that this experiment will provide a way for studying the variation in λ-point depression as the pore size is varied.

In preliminary runs it has been found that the critical flow velocities in the filter appear to be surprisingly low and temperature-dependent. As a result we have considered it advisable to improve the sensitivity of our measuring scheme before making further measurments and a servo system for controlling the gyro torsion suspension has been developed.

1. J. B. Mehl and W. Zimmermann, Jr., Phys. Rev. Letters 14, 815 (1965).

2. J. B. Mehl, Ph.D. Thesis, University of Minnesota (1966), AEC Report C00-1569-4.

3. J. B. Mehl and W. Zimmermann, Jr., AEC Report C00-1569-12.

4. Other Work

a. Studies have been undertaken to explore the feasibility of using tunnel cathodes to inject negative ions into liquid helium. A high-speed vacuum system has been assembled in which to carry out the evaporations needed to produce the cathodes.

b. Design studies have been carried out for an apparatus to study possible Josephson effect analogs in the flow of superfluid helium through a small orifice. Attention has been focused on the use of small capacitor microphones for both setting the fluid into motion and detecting the small pressure differences that are expected to be of interest. For the latter an fm detection scheme is being considered.

F. Millidegree Facility (A. M. Goldman, W. Weyhmann and W. Zimmermann, Jr.)

Significant strides towards the development of a coherent millidegree program have been made in the past year. The first stage of this program involves development of apparatus for reaching temperatures in the 0.100°K to 0.010°K range. To this end both an adiabatic demagnetization apparatus and a ^{3}He-^{4}He dilution refrigerator are being constructed. The former is the customary means of cooling systems into the 0.100°K-0.010°K temperature range and the latter an extremely promising new technique. The adiabatic demagnetization apparatus under construction will be employed in nuclear orientation studies (see Section D).

1. Adabatic Demagnetization Cryostat (W. Weyhmann)

This apparatus is described in the section on nuclear orientation experiments.

2. ^{3}He-^{4}He Dilution Refrigerator (A. M. Goldman and A. Menard)

All of the equipment for the refrigerator has been purchased. The low temperature apparatus has been assembled and leak checked. A Stokes 4" ring-jet booster pump and a sealed Edwards 17 cfm mechanical pump have been obtained for circulating ^{3}He. Sintered copper blocks have been fabricated for use in the heat exchanger. The apparatus that has been constructed will be mounted in the bottom access dewar which was obtained from Sulfrian Cryogenics Corp. Trials should commence in late summer, 1967, upon completion of the gas handling system.

G. Theoretical Properties of Liquid Helium Near the Lambda Transition

1. Critical Indices of the Lambda Transition

The Widom-Kadanoff Scaling Laws are derived assuming that the free energy is an analytic function of the temperature and the order parameter except at the transition point. Using this formulation and microscopic theory we argue for an additional relation for the critical indices of the liquid helium λ-transition.

This work has been submitted to Physics Letters,

2. Liquid Helium Green Functions near the Lambda Transition

The renormalized expressions for the thermodynamic potentials and the Green functions of an interacting Bose system have been studied in the region of small condensate density.

An account of this work has been submitted to The Physical Review.[2]

1. Eero Byckling, USAEC Report C00-1569-8.

2. Eero Byckling, USAEC Report C00-1569-11.

STAFF

[1] L. H. Nosanow	Associate Professor
[2] W. Zimmermann, Jr.	Associate Professor
[3] A. M. Goldman	Assistant Professor
W. V. Weyhmann	Assistant Professor
[4] W. Mullin	Research Associate
[5] E. Byckling	Research Associate
[7] H. Horner	Research Associate
[8] C. M. Varma	Research Associate

GRADUATE STUDENTS

L. Abad	Research Assistant
J. Aslam	Research Assistant
W. Gutheil	Research Assistant
R. Houghton	Research Assistant
S. Kral	Research Assistant and NSF Fellow
P, Kreisman	NASA Trainee
A. Menard	Research Assistant
R. Murphy	Research Assistant
W. Pratt	NASA Trainee
B. Sabo	Research Assistant
F. Schaer	NSF Trainee
C. Smith	Research Assistant
[9] C. Varma	Research Assistant
J. Yanez	Ford Foundation Fellow, Univ. of Concepción

1. John Simon Guggenheim Fellow 1966-1967, on leave academic year 1966-1967 at University of Utrecht, the Netherlands.
2. NSF Senior Postdoctoral Fellow 1967-1968, will be on leave academic year 1967-1968 at The Technical University of Helsinki.
3. Alfred P. Sloan Fellow.
4. Present address: University of Massachusetts, Amherst, Mass.
5. Present address: University of Oulu, Oulu, Finland.
6. Requirements for Ph.D. completed in August, 1966, present address: Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
7. Started 16 September 1967.
8. Started 16 September 1967.
9. Terminated 15 September 1967.

IV. BIBLIOGRAPHY

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6. C00-1569-6 "Observation of Quantized Circulation in Superfluid Helium" (S. C. Whitmore, doctoral dissertation).

7. C00-1569-7 "Meissner Effect and Vortex Penetration in Wide, High-Current Josephson Junctions" (A. M. Goldman and P. J. Kreisman). Abstract of paper presented at the Chicago Meeting of the APS, 1967.

8. C00-1569-8 "Critical Indices of the Lambda Transition" (E. Byckling). Submitted to Physics Letters.

9. C00-1569-9 "The Effect of Pressure on the Lifetime of Negative Ions Trapped in Rotating Liquid Helium II" (W. P. Pratt and W. Zimmermann, Jr.). Abstract presented at the APS Society, April 1967.

10. C00-1569-10 "Meissner Effect and Vortex Penetration in Josephson Junctions" (A. M. Goldman and P. J. Kreisman). Physical Review, to be published.

11. C00-1569-11 "Liquid Helium Green Functions near the Lambda Transition" (E. Byckling). Submitted to The Physical Review.

12. C00-1569-12 "Flow of Superfluid Helium in a Porpus Medium" (J. B. Mehl and W. Zimmermann, Jr.) Submitted to The Physical Review.

13. C00-1569-13 "Observation of Quantized Circulation in Superfluid Helium" (S. C. Whitmore and W. Zimmermann, Jr.) Submitted to The Physical Review.

14. C00-1569-14 "Ion Trapping in Rotating Superfluid Liquid Helium Under Pressure" (W. P. Pratt) Doctoral Dissertation.

15. C00-1569-15 "Progress Report (1967).

16. C00-1569-16 "A Critique of the Saunders Theory of Solid ^{3}He at $0^{\circ}K^{+}$" (W. J. Mullin) Submitted to Physics.

17. C00-1569-17 "Theory of Quantum Crystals" (L. H. Nosanow, W. J. Mullin and J. H. Hetherington) Presented at the 10th International Conference on Low Temperature Physics.