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MASTER

Solid State Physics; Magnetic Phenomena

Progress Report

1 January 1971 - 31 December 1971

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Electron Spin Resonance

(Scope I)

Co-Investigator: R. H. Silsbee

Several projects, involving both magnetic and electric resonance in insulators and one magnetic resonance problem in metals, have been completed, including three Ph. D. theses. These, and continuing projects, are reviewed below.

Dr. Raschke has completed a first experiment determining the influence of the host lattice mass density upon the reorientation rate at liquid helium temperature of the O_2^- molecular impurity in KCl, by comparing the rates in normal KCl with those in KCl enriched with K^{41} . The results are in marked disagreement with predicted magnitudes based on current simple models for the reorientation process. The results may be interpreted in terms of a more microscopic model which then implies that there should be a very substantial effect resulting from changing the mass of the chlorine ions. Dr. Raschke is staying with the project for an additional few months in order to pursue this second aspect of the problem.

The electron spin resonance study of $KCl:NO_2$ is to be published in the Journal of Magnetic Resonance under the following abstract.

The electron spin resonance of the NO_2 molecule incorporated as an impurity in KCl is studied in the temperature range 1.6°K to 10°K and as a function of applied uniaxial stress at 1.8°K and 4.2°K . The results are interpreted in terms of a model in which the molecule is assumed to be in uniaxial hindered rotation, with the first excitation energy, or tunneling splitting, estimated to be about 3 cm^{-1} , to be compared with a free rotational excitation energy of 8 cm^{-1} . Because the hindering potential is only moderate, it is necessary to include the effect of the molecular spin rotational coupling in developing a satisfactory spin hamiltonian to describe this system.

A problem, started at about the same time, involving the low temperature reorientation of N_2^- in KI and other alkali halides, remains of considerable interest because of the observation of clear effects on the reorientation rate of the relative orientation of the nitrogen nuclear spins. Unfortunately there has been too little time available to make much progress on this problem.

Dr. Bill, of the University of Geneva, is a Visiting Fellow with the project for the current academic year. He has been active in modifying one of our spectrometers to use the ENDOR technique and, in addition, has been pursuing investigation of

the O^- center in both the alkali halides and the alkaline earth halides. A very interesting qualitative difference has been noted in the response of the defect to an applied stress. In CaF_2 the defect axis tends to align parallel to the stress, in KI, perpendicular to the applied stress. This behavior is probably a natural consequence of the difference in crystal structures and the fact that this leads to dominantly covalent bonding of the O^- with F^- neighbors in CaF_2 , and ionic bonding with K^+ neighbors in KI.

Two projects involving the paraelectric resonance (PER) of $KCl:Li$ are completed. The first involves the measurement of the stress coupling coefficient of this system and is accepted for publication in the Physical Review under the following abstract.

The paraelectric resonance of $KCl:Li$ was studied in the presence of uniaxial stress applied along the crystallographic (110) direction. The results are interpreted in terms of the simple tunneling model proposed by Gomez, Bowen and Krumhansl and yield a coupling coefficient for coupling to T_{2g} symmetry strain of $-.185 \pm .03$ Ghz/bar.

Dr. Larson has also completed his thesis project in which he was able successfully to generate and detect phonons at 55 GHz by use of the PER technique. A long thin sample was

doped at each end with lithium, and each end placed in a separate PER cavity. One cavity was pulsed with microwaves tuned to the PER resonance; the subsequent relaxation of the PER levels resulted in the emission of a pulse of phonons. These traveled to the other end of the crystal where they heated slightly the PER system being monitored by a separate PER spectrometer, the change in this signal being a measure of the transmitted phonon intensity. This work is written up and will soon be submitted for publication.

Mr. John Vitko is continuing the study of some problems suggested by Larson's thesis by extending the PER of KCl:Li to 0.3°K. The helium-3 cryostat has been constructed and is now being checked out for satisfactory operation.

In the area of resonance in metals, two experiments have been completed. The first is Dr. Huisjen's study of the spin-flip scattering of conduction electrons in aluminum to be published in the Proceedings of the 1971 Magnetism Conference, summarized as follows.

The spin-flip scattering cross sections for V, Cr, Mn and Fe impurities in aluminum are measured and compared with predictions of Yafet based on the Friedel-Anderson model. The data confirm the predicted dependence upon both the spin orbit coupling constant and the density of

states associated with the d resonance. The level breadth, $\Delta > .8\text{eV}$, deduced from the fit is significantly larger than that derived from other experiments, indicating that the Hartree-Fock treatment of this model is not entirely adequate to describe these non-magnetic alloy systems.

In a second experiment, Dr. Siebert has doped aluminum foils with several rare earth impurities, Gd, Er and Lu, using a novel doping technique involving sputtering deposition of the rare earth onto a host foil with subsequent thermal diffusion of the impurity into the foil. This technique has provided very well controlled specimens at impurity levels of 100 ppm and less and has successfully avoided problems of oxidation of the impurities. These samples have been characterized by resistivity measurements by Mr. Dodds and he and Siebert have measured both the transmission and reflection ESR signals from these samples, observing both the conduction spin resonance and the rare earth resonance (for the two magnetic rare earths Gd and Er). Siebert is currently analyzing the results of these experiments.

Magnetic Phenomena and Electronic Structure

Scope II

Co-Investigator: R. Bowers

Much of our work during the past year has related to understanding the electrical and thermal transport properties of potassium and tungsten. Direct generation of acoustic waves in aluminum and potassium has continued with major emphasis being placed on the zero and low magnetic field behavior.

The present phase of our extensive investigation of the magnetoresistance and Hall effect of potassium is nearly complete. These studies, which were begun about three years ago, have involved dc electrical measurements on both single and polycrystals between 1.5 and 4.2°K in magnetic fields up to 100 kG. One very important result of this work was to demonstrate the extremely important role of annealing in the magnetoresistance behavior of extruded specimens of potassium. It appears that annealing near the melting point for times on the order of one or two weeks are required to produce specimens having a reproducible magnetoresistance behavior. For the first time a systematic trend has been observed in the high field linear magnetoresistance. There is a well-defined purity dependence in specimens having a residual resistance ratio (RRR) below about 3000. For $RRR > 3000$, the high field magnetoresistance is nearly purity independent. In both regimes, the magnetoresistance depends

upon the state of anneal; only in well annealed specimens are the results reproducible.

We were not as successful with our measurements of the Hall effect in ribbon-like, single crystal specimens of potassium. In most specimens, there was an apparent field dependence to the Hall coefficient and most specimens exhibited some anisotropy to the Hall coefficient. However, specimens prepared in an identical manner gave quite different results; no consistent trends could be determined. Because of the experimental problems associated with this work, no further measurements are planned.

In an attempt to obtain more information about the intrinsic behavior of potassium, we have begun radio frequency size effect (RFSE) and thermal transport measurements in potassium.

The RFSE line shape (both width and amplitude) is related in a moderately complicated way to the carrier scattering rate. In the case of limiting point RFSE resonances, the line shape is determined by a group of carriers lying within a small cone about the magnetic field direction. Altering the field direction changes the group of carriers that contribute to the limiting point resonance. Hence a determination in a single specimen of changes in the line shape for resonances associated with different magnetic field directions allows one to make a qualitative estimate of the scattering rate anisotropy. Quantitative estimates of scattering rate anisotropy must rely upon some knowledge

of scattering processes and the nature of the specimen surfaces and are therefore subject to considerable uncertainty. Of course, scattering rate anisotropy measurements must be done on single crystal specimens.

So far, we have succeeded in demonstrating that useful signals can be obtained from polycrystalline specimens having surfaces that are not extremely difficult to prepare. It is now necessary to produce thin, single crystal specimens with smooth flat surfaces so that we can attempt to determine the scattering rate anisotropy.

Some previous measurements of the zero-field thermal conductivity of potassium showed an anomalous decrease in the thermal resistance near 6°K. Although tentatively attributed to a change in the lattice thermal conductivity, no theory has been able to produce this anomalous change. Isolating the source of this anomalous thermal behavior in potassium might help in understanding the origin of the linear magnetoresistance. For this reason we undertook to measure the thermal conductivity of potassium in zero field. Preliminary measurements on polycrystalline specimens show no anomalous behavior. Measurements are currently underway in single crystal specimens and thermal resistance measurements in a magnetic field are planned.

Direct electromagnetic generation studies looking for anomalous coupling between helicon and acoustic modes in single

crystal aluminum and potassium have so far failed to produce positive results. This means that we are still without a good understanding of direct generation in pure metals at low temperatures. A recent simple model calculation that we have done indicates that the surface is not adequately taken into account in existing calculational methods; this problem is being investigated further. We have succeeded in observing transverse acoustic wave excitation which results when currents associated with the Gantmakher radio frequency size effect transfer momentum to the lattice. This method may be useful in our studies of scattering rate anisotropy in potassium. Based upon a model that we developed, direct generation in the mixed state of Nb, $\text{Nb}_{87}\text{Mo}_{13}$ and $\text{Pb}_{85}\text{In}_{15}$ type II superconductors has been interpreted in terms of the mixed state surface impedance.

Measurements of the lattice thermal conductivity in very pure tungsten single crystals have been made by suppressing the electronic conductivity with a large magnetic field transverse to the heat current. The lattice thermal conductivity is difficult to determine in materials that do not go superconducting so relatively few measurements have been made. Calculations of the lattice thermal conductivity of metals are quite difficult. Our measurements have the expected temperature dependence and the magnitude is consistent with other experimental work and theoretical estimates.

High-field Lorenz number measurements have also been made in tungsten to help elucidate the scattering mechanisms present at low temperatures. Extensive use of high-field semiclassical magnetoresistance theory was made to interpret these measurements. We have extended the theory to describe situations in which a relaxation-time does not exist. The results of these measurements were compared with our previous zero-field measurements in tungsten. It was found that there are clear difficulties in attempting to identify the low-temperature scattering mechanism with electron-electron scattering as the zero-field results had suggested.

A preliminary investigation of size effects in tungsten was done in an attempt to understand the anomalous behavior of the Lorenz number in small diameter single crystals. This work has been extended to cover specimens having diameters ranging from 0.13 mm to 3 mm; the mean free path of most specimens is about 3 mm. Newly available zone refined specimens having smooth electropolished surfaces seem to cause an effect similar to specular scattering. Our electrical and thermal resistivity measurements cannot be explained by a simple theory which includes specular scattering. The Lorenz number as a function of temperature, the extrapolated zero-temperature resistivities, and the longitudinal magnetoresistance have all been measured and the results indicate that the condition of the surface plays

an important role in determining each of these quantities.

The electrical and thermal resistance in size-effect conduction limited specimens shows a greater temperature dependence than observed in bulk specimens. In general, small diameter specimens give a zero-temperature Lorenz number about 20% below the bulk value. The field dependence of the longitudinal magnetoresistance is not that expected from the classical size-effect limited electrical conduction processes. We plan to change the surface character in a controlled manner and determine the effect of these controlled surfaces on the Lorenz number and longitudinal magnetoresistance.

Personnel

Dr. J. F. Siebert is teaching on a part time basis at College of the Holy Names in Oakland, California, and is associated part time with a resonance group at the University of California at Berkeley.

Dr. T. R. Larson is now a staff member of the Naval Research Laboratory in Washington.

Dr. M. A. Huisjen has a postdoctoral appointment in the Analytical Instruments Division of Varian Associates.

Dr. Haskell Taub now has a position of Research Associate with the Physics Department at New York University.

Dr. Martin Gaerttner now has a position of Research Associate with the Department of Applied Physics, Cornell.

Dr. G. A. Stringer now has a position of Assistant Professor at Southern Oregon College.

Publications

1. "Hindered Rotation at 2°K of the NO₂ Impurity in KCl,"
I. Bojko and R. H. Silsbee, NYO-2150-74, Jour. Mag. Res.,
December 1971.
2. "Stress Effects in the Paraelectric Resonance of KCl: Li,"
T. R. Larson and R. H. Silsbee, NYO-2150-76, Phys. Rev. B,
January 1972.
3. "Spin-Flip Scattering of Aluminum Conduction Electrons From

- Transition Element Impurities," M. A. Huisjen, J. F. Siebert and R. H. Silsbee, NYO-2150-81, Proceedings of the 17th Conference on Magnetism and Magnetic Materials, 1972.
4. "Generation and Detection of 55-GHz Phonons Using Paraelectric Resonance of KCl: Li," T. R. Larson, NYO-2150-80, Thesis, Cornell University, December 1971.
 5. "Reorientation of O_2^- in Isotopically Enriched KCl," C. R. Raschke, NYO-2150-79, Thesis, Cornell University, December 1971.
 6. "Spin-Flip Scattering of Aluminum Conduction Electrons from Transition Metal Impurities," M. A. Huisjen, NYO-2150-78, Thesis, Cornell University, December 1971.
 7. "Direct Generation of Acoustic Waves in Conducting Materials," M. R. Gaerttner, NYO-2150-70, Thesis, Cornell University, June 1971.
 8. "Low Temperature Electromagnetic Generation of Ultrasound in Potassium," W. D. Wallace, M. R. Gaerttner and B. W. Maxfield, NYO-2150-72 and Phys. Rev. Letters 27, 995 (1971).
 9. "Electromagnetic Generation and Detection of Acoustic Waves," B. W. Maxfield, NYO-2150-73. Talk presented to the Acoustic Emission Working Group, May 20, 21, 1971 in Atlanta, Georgia.
 10. "Study of the Transverse Magnetoresistance of Polycrystalline Potassium," H. Taub, R. L. Schmidt, B. W. Maxfield and R. Bowers, NYO-2150-68 and Phys. Rev. B4, 1134 (1971).
 11. "Low-Temperature Electrical and Thermal Resistivities of

Tungsten," D. K. Wagner, J. C. Garland, and R. Bowers,
NYO-2150-67 and Phys. Rev. B3, 3141 (1971).

12. "Lattice Thermal Conductivity and High-Field Electrical and Thermal Magnetoconductivities of Tungsten," D. K. Wagner, NYO-2150-75, to be published in Phys. Rev. B, January 1972.
13. Record of Invention: "Two Dimensional Coils for Electromagnetic Generation and Detection of Acoustic Waves," Martin R. Gaerttner and B. W. Maxfield, AEC Docket No. S-40, 719.

Talks

"Reorientation of O_2^- in Isotopically Enriched KCl," C. R. Raschke, Bull. Am. Phys. Soc. II 16, 378 (1971).

"Generation and Detection of 55 GHz Phonons in KCl: Li," T. R. Larson, Bull. Amer. Phys. Soc. II 16, 385 (1971).

"Spin-Flip Scattering of Aluminum Conduction Electrons from Transition Metal Impurities," M. A. Huisjen, Bull. Amer. Phys. Soc. II 16, 412 (1971). See also Publication #3.

"Study of the Transverse Magnetoresistance of Polycrystalline Potassium," H. Taub, R. L. Schmidt, B. W. Maxfield and R. Bowers, Bull. Am. Phys. Soc. Series II, 16, 143 (1971). See also Pub. #10.

"Field Dependence of the Hall Coefficient in Potassium," G. A. Stringer and H. Taub, Bull. Am. Phys. Soc. Series II, 16, 343 (1971).

"The Low Temperature Electrical and Thermal Resistivities

of Tungsten," J. C. Garland, D. K. Wagner and R. Bowers, Bull. Am. Phys. Soc. Series 11, 16, 344 (1971). See also Pub. #11.

"High Field Electrical and Thermal Magnetoconductivities of Tungsten," D. K. Wagner, Bull. Am. Phys. Soc. Series II, 16, 344 (1971). See also Pub. #11.