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ANNUAL PROGRESS REPORT

FOR PERIOD ENDING DECEMBER 31, 1967

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SOLID STATE DIVISION

ANNUAL PROGRESS REPORT

For Period Ending December 31, 1967

D. S. Billington, Director
M. K. Wilkinson, Associate Director

MARCH 1968

OAK RIDGE NATIONAL LABORATORY
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Preface

I thought to make, in the way of introduction, a few comments on certain aspects of solid state research as it is practiced in the Solid State Division. For example, it may not be readily apparent to all readers, particularly those not involved intimately in solid state research, that an extremely high degree of interdisciplinarity is involved. Many forms of both classical and modern chemistry, metallurgy, electronics, and physics from both a theoretical and experimental standpoint and many forms of engineering are involved. Thus, many divisions of the Laboratory participate directly or indirectly in our research. An even more essential form of cooperative research is the high degree of interplay between the various groups within the Division.

We have recognized for a long time that understanding of radiation damage in solids depends most strongly on being able to characterize accurately the solid under study. It is not a simple matter to do so, and it requires the interaction of many varied and sophisticated techniques applied to the study of solids. This problem has occupied the attention of members of the Division for a long time, and it is becoming apparent that these efforts are beginning to pay off. Several sophisticated techniques in the use of anomalous transmission, channeling, and resistivity studies at low temperatures have led to very precise characterization of crystals in both the irradiated and non-irradiated case. This precise characterization and the confidence placed in the experimental data resulting therefrom has led to a renewed excitement on the part of the theorists, who are now pursuing the consequences of new models made tenable by the new data in the areas of anomalous transmission (pp. 71,72), channeling (pp. 53-59), and low temperature annealing (pp. 42-45). An essential feature of the high-precision data that is obtained in low temperature resistivity measurements under nuclear irradiation is the dedicated helpfulness of the Operations Division, particularly in the operation of the BSR. The pool temperature of the reactor is maintained at $\pm 0.25°C$ for periods of weeks, thus providing very stable neutron flux and gamma heating conditions, which in turn permits low temperature irradiation at $3.600°K \pm .005°K$. Damage production rates to 0.5% are easily obtained,

and changes in resistivity are reproducible to 0.01%. Just as important is the ability to reproduce dosages to within 1%. This reproducible reactor control is important in all phases of our radiation damage program at the BSR (p. 89).

Other techniques used that lead to precise data are electron microscopy (pp. 60,61), x-ray diffraction (pp. 40,41), and single crystal growth and purification wherein specimens are prepared that are dislocation-free and of precise orientation (p. 79). In the important area of impurity analysis, the Analytical Chemistry Division provided an essential sophisticated service, and in the preparation of high-purity starting materials for single crystal growth work.

The above remarks apply most strongly to research in metal physics, but apply also in the area of nonmetals. Significant advances have been made in understanding the optical behavior of MgO, KCl, and ZnO (pp. 25-28, 46-50) as a result of the close interaction of the experimentalists and theorists. It now appears that radiation damage in MgO is mostly of the knock-on type, resembling damage in metals as contrasted to the ionization damage in KCl.

Other types of activities that require a great amount of cooperative effort are those that were involved in the design, construction and installation of the automatic triple-axis spectrometers that are now being used in the HFIR beam hole facilities HB-1 and HB-3 (p. 88). In this enterprise, carefully coordinated joint effort was given by the Plant and Equipment, General Engineering and Construction, and Instrumentation and Controls Divisions of the Laboratory, and in certain aspects of the fabrication it was necessary to carry out coordinated machining efforts at machine shops at ORNL, Y-12, and the Oak Ridge Gaseous Diffusion Plant. The triple-axis units are now in full use at the HFIR and have been utilized for coherent inelastic neutron scattering techniques whereby a localized vibrational mode has been measured for the first time by this method in a Cu-4% Al alloy. This technique has the unique advantage of providing information on the spatial localization of the mode, which in this alloy seems to be very strong, since the amplitude is damped almost completely within two unit cells (p. 5). Another group is studying the possibilities

of a new technique involving polarization analysis of scattered neutrons (p. 11). Studies on incoherent scattering, paramagnetic scattering, magnon scattering and magnetic structure analysis indicate that much unique information on magnetic materials can be obtained by this method. At the ORR, a neutron time-of-flight instrument which utilizes a magnetic chopper has been developed (p. 87) and placed in operation. This technique offers a combination of simplicity, precision, and flexibility that cannot be duplicated by conventional devices. It also seems probable that coded-pulse techniques will be developed which will lead to an enhancement of the neutron intensity of an order of magnitude.

I have up to this point noted just a few examples where other divisions in the Laboratory are important to our research. There is another side to cooperative research, where the emphasis is on assistance to other divisions and programs, and again I'd like to mention just a few examples. We are involved, for example, with the Reactor Division in the Heavy Section Steel Program, a vital part of the AEC's program in reactor safety (pp. 70,71). The Solid State Division's role in this and related programs of the AEC is to study the factors that are important in the nuclear radiation inducement of enhanced brittle fracture and to learn ways of suppressing this sensitivity (pp. 67-69). Research is carried on using niobium and other body-centered cubic metals that are related in behavior to the iron and steels used in pressure vessel steels, since they exhibit the brittle-ductile behavior of iron and steel. Defect clusters in irradiated niobium have been observed recently for the first time (p. 65). Recent experiments on pressure vessel steels as a function of temperature appear to indicate that the increase in brittle-ductile transition upon irradiation is a consequence of the increase in yield and flow stress and is not due to a change in fracture properties as such (p. 68).

The Pure Materials Program of the Division is involved in providing high-purity single crystals of research materials that are in great demand to members of the Division, other divisions of the Laboratory, other National Laboratories, universities, and research centers throughout the world (pp. 83,84). No attempt is made to meet all demands, since this would be an impossible task, but the Research Materials Information Center

of the Division does supply information to interested scientists on the availability of crystals and methods of single crystal growth. Aperiodic bulletins are issued to a mailing list of some 5000 scientists and engineers summarizing the latest census of supply and demand for crystals. Selected bibliographies are occasionally issued.

The last area of cooperation that I'd like to mention involves mutual cooperation with laboratories and scientists of foreign countries. This year I'd like to acknowledge our appreciation in particular to those scientists who have been directly involved with us during the past year: G. Dolling, Chalk River Nuclear Laboratories, Chalk River, Canada (pp. 1, 4,5,7,8); P. Vijayaraghavan, Bhabha Atomic Research Centre, Bombay, India (pp. 1,3,5,7); W. Reichardt, GFK, Karlsruhe, Germany (pp. 1,8); T. Riste, Institutt for Atomenergi, Kjeller, Norway (p. 11); H. H. Hahn, KFA, Jülich, Germany (p. 12); A. Bishay, The American University, Cairo, Egypt (p. 24); U. Öpik, The Queen's University, Belfast, Northern Ireland (pp. 25,28); R. Bullough, Atomic Energy Research Establishment, Harwell, England (p. 39); A. Hiraki, Osaka University, Osaka, Japan (pp. 51-53); G. Leibfried, Technical University, Aachen, Germany (p. 55); H. O. Lutz, Technical University, Munich, Germany (pp. 55,59,60); A. Merlini, CCR-Euratom, Ispra, Italy (p. 71); D. R. Harries, Atomic Energy Research Establishment, Harwell, England; P. A. Lindgaard, Research Establishment Risö, Roskilde, Denmark; S. Lovesey, University of Oxford, England; K. Yosida, University of Tokyo, Japan; and G. Gilat, Technion, Haifa, Israel.

I have not mentioned at all joint research projects with other divisions of the Laboratory or with other laboratories in the U.S., but I do hope that an appreciation of the importance of wide-ranging cooperation in solid state research has been expressed.

D. S. Billington

LATTICE DYNAMICS

LATTICE DYNAMICS OF LITHIUM FLUORIDE

G. Dolling,[1] H. G. Smith, R. M. Nicklow, P. R. Vijayaraghavan,[2] and M. K. Wilkinson

The frequency/wave-vector dispersion relation for the normal modes of vibration of ^{7}LiF at 298°K has been measured by means of slow neutron inelastic scattering techniques. Triple-axis crystal spectrometers at two reactor facilities at ORNL were employed, mostly in the "constant-Q" mode of operation. The results can be satisfactorily fitted by a seven-parameter dipole approximation model involving nearest neighbor and second nearest neighbor F^--F^- short range forces, a variable ionic charge, and the polarizability of the F^- ions only. The applicability of other force models to ^{7}LiF is also discussed. Certain inconsistencies have been found between the slopes of the acoustic branches near $\underset{\sim}{q}=0$ and the appropriate velocities of sound as measured by ultrasonic techniques; it is believed that these arise from anharmonic effects. The frequency distribution of the normal modes has been computed with high precision from the best-fit dipole approximation model, together with related quantities such as the lattice heat capacity, entropy, and Debye-Waller factors for each ion. Combined (two-phonon) density of states functions have also been calculated; comparisons are made between these one- and two-phonon distribution functions and certain features observed in optical and infrared absorption experiments on LiF. [Abstract of paper to be published in The Physical Review.]

[1]Guest scientist from Chalk River Nuclear Laboratories, Chalk River, Canada.

[2]Guest scientist from Bhabha Atomic Research Centre, Trombay, Bombay, India.

COHERENT INELASTIC NEUTRON SCATTERING IN NH_4Cl

H. G. Smith and W. Reichardt[1]

Extensive studies on the ammonium halides have been made by utilizing incoherent inelastic neutron scattering techniques. A particular

goal has been to elucidate the nature of the various order-disorder transitions as a function of temperature. A knowledge of the lattice dynamics of these compounds combined with the available infrared, Raman, NMR, neutron, and x-ray data would be most useful in understanding these transitions. However, for a complete understanding of the lattice dynamics of NH_4Cl, it is necessary to determine the phonon dispersion curves for the acoustical and optical modes as well as for the torsional modes of vibration. This can only be accomplished by coherent inelastic neutron scattering from single crystals.

It has generally been assumed that the large incoherent scattering cross section of hydrogen precluded coherent inelastic scattering studies of hydrogenous materials. However, we have demonstrated on the triple-axis spectrometer at the ORR that coherent inelastic scattering in NH_4Cl is practical. The LA(00ζ) and TA(00ζ) dispersion curves have been determined and some of the TO(00ζ) phonons have also been measured. In addition, the coherent scattering amplitude of H(-0.378×10^{12}cm) is not negligible, and for some reflections from NH_4Cl the coherent scattering by the four hydrogen atoms is comparable to or even larger than the scattering from N or Cl, which are considered to be strong scatterers. This suggests that even those modes that are predominantly due to hydrogen motion can be measured.

The measurements were carried out at room temperature and at 78°K on a single crystal with dimensions of 14 × 16 × 6 mm. The results indicate good agreement with the elastic constants determined by ultrasonic techniques and also with the reststrahlen frequency observed by infrared methods. It will be of interest to extend the present studies to the order-disorder transition at 241°K, because elastic constant measurements indicate pronounced changes in the lattice vibrations as the critical temperature is approached.

[1]Guest scientist from GFK, Karlsruhe, Germany.

LATTICE DYNAMICS OF AgCl

P. R. Vijayaraghavan, R. M. Nicklow, H. G. Smith, and M. K. Wilkinson

The dispersion relation for phonons propagating along the three principal symmetry directions for silver chloride (AgCl) has been determined at 78°K using the triple-axis facilities at the Oak Ridge Research Reactor and the High Flux Isotope Reactor. Compared to the alkali halides, AgCl has several interesting properties: the elastic constant C_{11} has a larger temperature dependence, the degree of failure of the Cauchy relation ($C_{12} - C_{44} = 0$) is higher and opposite in sign, and the substance is more covalent. The measured dispersion curves have been fitted using a shell model for the interatomic forces, and it has been found that a large number (13) of parameters is required to fit the neutron data and low temperature elastic constants.[1] A good fit is obtained with a model which includes next nearest neighbor interactions for both ions, a variable ionic charge, the electrical and mechanical polarizabilities of both ions, and core-shell interactions. The present data for the q=0 phonon wave vector are in good agreement with the transverse optic and longitudinal optic frequencies extrapolated from infrared measurements[2,3] at 300° and 93°K. However, the measured phonon frequencies are not consistent with those used by Bassani et al.[4] in their interpretation, based on phonon assisted electronic transitions, of certain features in the optical absorption data for AgCl. Frequency distribution functions, the associated thermodynamic properties and mean square vibrational amplitudes for both ions have been calculated, and a combined density of states function has been obtained for comparison with optical absorption data.

[1] W. Hidshaw, J. T. Lewis, and C. V. Briscoe, Phys. Rev. 163, 876 (1967).

[2] G. L. Bottger and A. L. Gedds, J. Chem. Phys. 46, 3000 (1966).

[3] F. C. Brown and R. Brandt (private communication).

[4] F. Bassani, R. S. Knox, and W. B. Fowler, Phys. Rev. 137, 1217 (1965).

LATTICE DYNAMICS OF MOLECULAR SOLIDS

G. Dolling

The conventional phenomenological framework, within which the dynamics of simple, highly symmetric, crystalline solids has been treated to date, is briefly outlined. The dynamics of an alkali (LiF) is described as an example. The theoretical and experimental problems encountered when this framework is utilized for somewhat more complicated solids (e.g., sodium nitrite, hexamethylenetetramine) are enumerated, and possible ways of alleviating them are considered. Finally, it becomes clear that for even more complex materials (e.g., naphthalene and anthracene), a new approach is necessary. The use of empirical interatomic potentials, specified by simple analytic expressions and involving few parameters, to calculate appropriate intermolecular force constants is described. [Abstract of an invited paper to be published in Proceedings of NBS Second Materials Research Symposium on Molecular Dynamics and Structure of Solids.]

LATTICE DYNAMICS FOR FACE-CENTERED ORTHORHOMBIC STRUCTURE WITH DUMBBELL MOLECULES

Clifton Bob Clark[1]

The molecular crystal dynamics method used by Cochran and Pawley[2] for hexamethylenetetramine has been modified to obtain the dynamical matrix for a face-centered orthorhombic structure having at each lattice point a diatomic molecule. Axes are chosen for librational modes which do not coincide with those used for translational modes. Interactions out to fifth neighbors are included. Of the 52 force constants in the model, 37 are involved in dispersion relations for normal modes corresponding to phonon momenta parallel to the orthorhombic cell edges. Dispersion curves have been computed for these directions from apocryphal force constants.

[1]Research Participant from University of North Carolina at Greensboro.

[2]W. Cochran and G. S. Pawley, Proc. Roy. Soc. (London) A280, 1 (1964).

NUMERICAL CALCULATIONS OF PHONON PEAK SHAPES OBSERVED IN TRIPLE-AXIS NEUTRON SPECTROMETRY

R. M. Nicklow

The shapes of a number of typical constant-Q phonon scans have been calculated by a numerical folding of the resolution function of a triple-axis neutron spectrometer with the one-phonon neutron scattering cross section. The resolution function derived by Cooper and Nathans[1] is used, and the sample mosaic spread, phonon lifetime, and curvature of the dispersion surface $\nu(\vec{q})$ are taken into account. Of particular interest in the present work is the fairly common experiment for which the resolution function samples a significant portion of a non-planar dispersion surface. In such cases a constant-Q scan generally yields a phonon peak, which is asymmetric, significantly broader than that calculated by various simple formulae previously published, and shifted from the true frequency of the dispersion surface at the mean $\vec{q}$ of the scan. The calculations have been compared with data obtained for ^{7}LiF and for Cu.

[1] M. J. Cooper and R. Nathans, Acta Cryst. 23, 357 (1967).

COHERENT INELASTIC SCATTERING STUDY OF LOCAL AND IN-BAND MODES IN $Cu_{1-x}Al_x$ CRYSTALS

R. M. Nicklow, P. R. Vijayaraghavan, H. G. Smith, and G. Dolling

To investigate the influence of light-mass substitutional defects on the lattice dynamics of a crystal, the normal mode frequencies in a copper crystal containing 10.0% aluminum have been measured by coherent inelastic neutron scattering experiments on a triple-axis neutron spectrometer located at the Oak Ridge High Flux Isotope Reactor. The results for this crystal differ markedly in at least two respects from the results for pure copper. The dispersion curves $\nu(\vec{q})$ for the in-band modes fall significantly below (up to 10%) those for pure copper, and an additional vibrational mode has been observed with a frequency $\nu_L(8.6 \pm .2 \times 10^{12}\text{cps})$, which is higher than the maximum frequency of pure copper. This additional mode is interpreted as a local mode that corresponds to the vibrations of

the light aluminum atom in the heavier copper matrix. To our knowledge, this is the first observation of a local mode in a coherent neutron scattering experiment. Both the value of ν_L and the measured $\vec{q}$ dependence of the neutron scattering cross section for the local mode are in good agreement with calculations based on a simple mass-defect theory which assumes a low defect concentration and no force constant changes. However, the same theory fails to predict the measured changes of the in-band modes: large decreases in $\nu(\vec{q})$ are observed rather than the small increase that is predicted. Similar measurements on a Cu-4% Al sample have recently been initiated. [Abstract of a paper to be published in the Proceedings of the IAEA Symposium on Neutron Inelastic Scattering, Copenhagen, Denmark, May 20-24, 1968.]

CALCULATIONS OF THE PHONON SPECTRUM OF DILUTE ALLOYS

R. Tseng and R. F. Wood

The presence of dilute solutions of defect atoms in an otherwise perfect crystal gives rise to observable changes (by neutron diffraction) in the phonon spectrum of the host crystal. These changes may, in the case of a light impurity in a crystal composed of heavy atoms or ions, take the form of the appearance of a local mode above the highest band modes as well as of modifications of the in-band modes. The heavy impurity atom in a crystal of light atoms, on the other hand, may produce quasi-localized modes rather than true localized modes. In either case, the problem of calculating the modifications of the pure crystal phonon spectrum and density of states can be attacked using methods which are, in principle, fairly well understood. These methods involve the calculation of the dispersion relations, the density of states and the eigenvectors of the perfect crystal. From these the real and imaginary parts of the Green's function of the perfect crystal can be calculated. The Green's function together with the defect matrix, which expresses the mass and force constant changes associated with the defect, can then be used to determine the eigenfrequencies and eigenvectors of the localized and quasi-localized modes. Computer programs have been written and

tested for most phases of the calculation and are now being assembled into a complete program which, it is hoped, can soon be applied to specific cases.

LATTICE DYNAMICS OF LITHIUM

H. G. Smith, G. Dolling, R. M. Nicklow, P. R. Vijayaraghavan, and M. K. Wilkinson

The measurement of phonon dispersion curves by the method of coherent inelastic neutron scattering is an increasingly useful tool for a possible understanding of the theory of metals. Since lithium is, in principle, the simplest of all metals, a knowledge of its lattice dynamics is of fundamental importance to any theory of metals.

Phonon dispersion curves have been determined in the [100], [110], and [111] symmetry directions in a single crystal of bcc lithium (enriched to 99.993% ^{7}Li) on the HFIR triple-axis spectrometer at a temperature of 98°K. (Lithium undergoes a martensitic transition at 78°K.) The L(00ζ) branch shows anomalous behavior in that it crosses beneath the T(00ζ) branch at $\zeta = 0.5$, indicating that the forces in lithium are long range. The data were successfully analyzed in terms of a seven-neighbor (nineteen-parameter) Born-von Kármán general force model in which the sixth-neighbor force constants are approximately 12% of the first-neighbor force constants. Frequency distributions have been calculated for several models.

Phonon dispersion curves[1] and elastic constants[2] have been calculated recently for lithium by the method of the pseudo-potential, with very poor agreement between the observed and calculated frequencies; however, the calculations[1] do predict a crossover of the L(00ζ) branch below the T(00ζ) branch, as observed experimentally. [Summary of paper to be published in Physical Review Letters.]

[1] A. O. E. Animalu, F. Bonsignori, and V. Bortolani, Nuovo Cimento 44B, 159 (1966).

[2] W. M. Shyu and G. D. Gasperi, Phys. Rev. 163, 667 (1967).

LATTICE DYNAMICS OF GALLIUM

W. Reichardt, R. M. Nicklow, G. Dolling, and H. G. Smith

The only previous information about the lattice dynamics of gallium has been obtained from measurements of the specific heat and the elastic constants. From the specific heat data at low temperatures a Debye temperature of θ_D = 325°K was determined, and this value is surprisingly high compared to the low melting point of 302°K. The Debye temperature drops rapidly with increasing temperature to a minimum value of about 180°K at 17°K, thus indicating a strong deviation from the ω^2-law in the density of states even at very low frequencies.

A more thorough insight into the lattice dynamics of gallium is possible by a direct measurement of the phonon dispersion curves using the technique of coherent inelastic neutron scattering. Solid gallium is orthorhombic with four atoms per unit cell; therefore, the dispersion relation consists of three acoustical and nine optical branches without degeneracies in the symmetry directions. Investigations of the phonon dispersion curves for gallium at 80°K have been initiated with the triple-axis spectrometer at the Oak Ridge Research Reactor. Extensive measurements have been performed on a single crystal with the [100] and [010] directions lying in the plane of scattering; preliminary results also have been obtained for the [001] direction with another crystal. Most branches were confirmed by measurements at different points of the reciprocal lattice.

For the analysis of the experimental data an axially symmetric Born-von Kármán model has been developed, and at present, interactions up to fifteen nearest neighbors can be taken into account. Calculations with a set of force constants, which were chosen to fit some of the previous experimental data, are in good qualitative agreement with the measured results, but no attempt has yet been made to determine the force constants from an analysis of the measured dispersion curves.

INTERFERENCE OF FINITE-AMPLITUDE ULTRASONIC WAVES IN SOLIDS

W. B. Gauster[1] and M. A. Breazeale[2]

A very sensitive means of observing the second harmonic generation of ultrasonic waves of finite amplitude in solids has been developed. The method depends on interference of overlapping pulses, which produces unusual interference effects. The applicability of the method to measurement of the distortion of finite-amplitude waves is discussed. [Abstract of published paper: J. Acous. Soc. Amer. 41, 860 (1967).]

[1]National Science Foundation Cooperative Graduate Fellow from the University of Tennessee. Present address: Sandia Laboratory, Albuquerque, New Mexico.

[2]Consultant, University of Tennessee.

TEMPERATURE DEPENDENCE OF ULTRASONIC HARMONIC DISTORTION IN A SOLID

R. D. Peters,[1] M. A. Breazeale, and V. K. Paré

Adaptation of the capacitive detector[2] to the measurement of the temperature dependence of the harmonics of an initially sinusoidal ultrasonic wave has continued. Apparatus is now available for controlling the temperature at any value between 77°K and 300°K. By use of a pneumatic adjustment of the detecting capacitor gap, it is now possible to maintain a constant gap spacing at any value between 3 and 10 microns over the entire temperature range. This capability greatly simplifies taking data on the temperature dependence of the harmonic components of a 30-MHz ultrasonic wave. From these data a measure of the temperature dependence of the third order elastic constants of crystalline solids may be obtained.

[1]Oak Ridge Associated Universities Graduate Fellow from the University of Tennessee.

[2]Rev. Sci. Instr. 37, 1544 (1966).

ULTRASONIC MEASUREMENT OF THE NON-LINEARITY PARAMETERS OF COPPER SINGLE CRYSTALS

W. B. Gauster and M. A. Breazeale

The non-linearity parameters, which are combinations of third order elastic constants, of neutron-irradiated copper single crystals were determined at room temperature by measuring quantitatively the harmonic distortion of pulsed MHz ultrasonic waves propagating in three crystallographic directions. For this purpose, a capacitive detector was used with which ultrasonic displacement amplitudes of the order of 10^{-10} cm can be detected and measured absolutely. Using the non-linearity parameters in combination with other data, a complete set of third order elastic constants for copper is calculated. The experiments represent a new technique for determining third order elastic constants which is of special interest for measurements on easily deformed metal crystals. [Abstract of paper accepted for publication in The Physical Review.]

THIRD HARMONIC OF AN INITIALLY SINUSOIDAL ULTRASONIC WAVE IN COPPER

R. D. Peters and M. A. Breazeale

The amplitude of the third harmonic of an initially sinusoidal ultrasonic wave is measured in the [100] direction in copper, both directly and by a pulse overlap technique. The value of the third order elastic constant $C_{111} = -16 \times 10^{12}$ dynes/cm^2 is obtained from measurements of third harmonic amplitudes of the order of 10^{-3} angstroms. The contribution of the fourth order constant C_{1111} to these amplitudes appears to be negligible. [Abstract of paper accepted for publication in Applied Physics Letters.]

MAGNETIC PROPERTIES

NEUTRON POLARIZATION ANALYSIS

R. M. Moon, W. C. Koehler, and T. Riste[1]

The triple-axis polarized-beam neutron spectrometer is now in operation at the HFIR with a beam polarization in excess of 0.98. The capabilities of this instrument (high flux, good polarization, automatic three-axis operation) have been fully exploited in a series of experiments aimed at exploring the possibilities of a new technique involving polarization analysis of scattered neutrons. When the incident neutron polarization is parallel to the scattering vector, any magnetically scattered neutrons reverse their spin. This spin reversal has been demonstrated for paramagnetic scattering, spin wave scattering, and coherent Bragg scattering. Nuclear scattering, except in the case of nuclear spin incoherent scattering, does not involve a change of the neutron polarization. Polarization analysis of the scattered neutrons thus provides a technique for separating magnetic from nuclear scattering. This technique has important applications in magnetic structural studies, in identifying magnon and phonon peaks, and in separating paramagnetic scattering from other sources of incoherent scattering.

[1]Guest scientist from Institutt for Atomenergi, Kjeller, Norway.

THERMODYNAMIC PROPERTIES OF THE BODY-CENTERED CUBIC HEISENBERG FERROMAGNET WITH SECOND-NEIGHBOR INTERACTIONS

J. F. Cooke

Experiments on the four copper salts $Cu(NH_4)_2Cl_4 \cdot 2H_2O$, $CuK_2Cl_4 \cdot 2H_2O$, $CuRb_2Cl_4 \cdot 2H_2O$, and $Cu(NH_4)Br_4 \cdot 2H_2O$ which have been reported by Miedema et al. provide data with which to test the Heisenberg model of ferromagnetism. These copper salts very closely represent body-centered cubic, spin one-half, insulating ferromagnets and therefore any theoretical calculations of the thermodynamic properties must include the second-neighbor exchange terms.

The thermodynamic properties of the Heisenberg model were obtained by the Green's function method. (The method of obtaining the Green's function was outlined in the previous progress report [ORNL-4098].) The magnetization, specific heat, spin-wave energy, and spin-wave lifetime were calculated as a function of $x = J_2/J_1$, the ratio of second-neighbor exchange, J_2, to first-neighbor exchange, J_1.

The calculated magnetization and specific heat were found to agree very well with the experimental data up to about 90% of the transition temperature. They were also found to be essentially independent of x over this temperature range when plotted as a function of T/T_c, which agrees with the experimental data.

Crude estimates of the transition temperature as a function of x were obtained from computer calculations of the magnetization and were found to obey the empirical formula $T_c(x) \simeq T_c(x = 0)(1 + .9x)$, where $T_c(x = 0)$ is the transition temperature for nearest-neighbor exchange only. This result agrees rather well with the result $T_c(x) \simeq T_c(x = 0) \times (1 + .99x)$ obtained by Dalton from high-temperature series expansions.

A METHOD OF CALCULATING THE SPIN GREEN'S FUNCTIONS FROM MANY-BODY BOSON GREEN'S FUNCTIONS

J. F. Cooke and H. H. Hahn[1]

In 1956 Dyson introduced the concept of establishing a correspondence between the Heisenberg spin system and a system of interacting bosons. The approach he used, however, cannot be directly applied to the calculation of the spin Green's function.

The method we use is to define image operators of the spin operators in an infinite dimensional boson space which satisfy the same commutation rules as the spin operators. They also satisfy the condition $(S_\ell^\pm)^n = 0$ if $n > 2S$, where S is the spin of the system and $S_\ell^\pm$ are the spin ladder operators. This condition is the source of the so-called kinematic interaction. Because of this property, these operators give non-zero results only within the "physical" subspace of the boson space.

By means of this correspondence we have derived an exact expression for the spin Green's functions in terms of the ordinary many-body Green's functions of the boson system. This identity will enable us in principle to calculate the spin Green's function by using the simpler statistics of the boson space.

This method is now being applied to certain spin systems with the hope of obtaining systematic expressions for the kinematic part of the Green's functions.

[1]Visiting scientist from KFA, Jülich, Germany.

SPIN CORRELATIONS IN PARAMAGNETIC NICKEL

J. W. Cable, R. W. Lowde,[1] C. G. Windsor,[1] and A. D. B. Woods[2]

The spin correlation function

$$\langle S^{\alpha}(-\vec{K},0)S^{\alpha}(\vec{K},\omega)\rangle = (\hbar/\pi g^2\mu^2)[1 - \exp(-\hbar\omega\beta)]^{-1}\mathrm{Im}\chi^{\alpha\alpha}(\vec{K},\omega)$$

(away from $\omega = 0$) has been determined experimentally for paramagnetic nickel at ~1.6 T_c by measurements of the inelastic scattering of neutrons. The range of energy transfer $\hbar\omega$ studied extends from 25 to 120 MeV. Features of the correlation are compared with predictions for the Hartree-Fock electron gas and for a Heisenberg paramagnet. [Abstract of published paper: J. Appl. Phys. 38, 1247 (1967).]

[1]Atomic Energy Research Establishment, Harwell, England.

[2]Atomic Energy of Canada Limited, Chalk River, Canada.

MAGNETIC COUPLING IN THE Ni-Pd ALLOY SYSTEM

E. O. Wollan

The magnetic coupling properties of the Ni-Pd alloy system are considered in terms of a molecular field solution based on a Heisenberg type of interaction for spin 1/2. The unpaired electrons in Ni are assumed

to be part of a band of mainly t_{2g} character in which the totality of interactions leads to an interatomic ferromagnetic coupling. The unpaired electrons in pure Pd are assumed to be part of a narrow weakly interacting band with more nearly e_g symmetry. In the alloy the Pd band structure becomes progressively more like that of Ni. The magnetic energy is then calculated in terms of the probability of finding unpaired electrons in the overlapping orbitals of the Ni and Pd atoms. The probability is determined from the average moment curve on the assumption of $3d^9$ and $3d^{10}$ states only. A fit of the Curie temperature and average magnetic moment data then gives the following relative values for the exchange constants (molecular field coefficients): A for Ni-Ni, αA for Ni-Pd, and $\alpha^2 A$ for Pd-Pd with $\alpha \simeq 0.8$. [Abstract of paper to be published in The Physical Review.]

A NEUTRON DIFFRACTION STUDY OF THE MAGNETIC BEHAVIOR OF GADOLINIUM

J. W. Cable and E. O. Wollan

Neutron diffraction measurements were made on a single crystal of gadolinium at sample temperatures from 10° to 350°K to investigate the possible occurrence of a spiral spin structure. The measurements show that Gd is a normal ferromagnet with a rather complex temperature dependence of the spontaneous moment alignment. Between T_c = 294°K and 232°K the moment is parallel to the c-axis; below 232°K it moves away from the c-axis to a maximum deviation of about 65° near 180°K and then back to within 32° of the c-axis at low temperatures. [Abstract of paper to be published in The Physical Review.]

MAGNETIC PROPERTIES OF RARE EARTH-LANTHANUM ALLOYS

W. C. Koehler, H. R. Child, E. O. Wollan, and J. W. Cable

Alloys of the heavy rare earth metals with La have been studied by neutron diffraction methods. For alloys with 15 at.% or less of La, the alloys have the simple hexagonal close-packed structure. The influence

of La on the magnetic structures of the metals is such as to enhance the stability of a ferromagnetic configuration relative to an oscillatory one. The transition temperature is lower and the initial turn angle (when it exists) smaller in a lanthanum alloy than in the corresponding yttrium alloy. In the lanthanum-rich region, the system La-Tb has been most extensively studied with five compositions ranging from $Tb_{0.10}La_{0.90}$ to $Tb_{0.75}La_{0.25}$ having been investigated. Of these, the compositions $Tb_{0.20}La_{0.80}$, $Tb_{0.40}La_{0.60}$, and $Tb_{0.50}La_{0.50}$ formed a single phase alloy with the double hexagonal lanthanum structure (dhcp). The 4.2°K diffraction patterns of these three alloys exhibited a number of broad diffraction maxima rather similar to those found for Nd in the antiferromagnetic region. Néel temperatures of approximately 50°K, 68°K, and 75°K, respectively, were estimated for the three specimens. The specimen $Tb_{0.75}La_{0.25}$ exhibited lines from the hcp and dhcp structures as well as of a third phase which is probably the δ-phase. In the $Tb_{0.10}La_{0.90}$ alloy both a dhcp and an fcc phase were observed at room temperature; the low temperature pattern exhibited magnetic reflections characteristic of the dhcp alloys. The La-rich Tb alloys thus are antiferromagnetic, rather than ferromagnetic as had been proposed previously. [Abstract of paper to be published in the Journal of Applied Physics.]

MAGNETIC PROPERTIES OF FCC RARE EARTH-THORIUM ALLOYS

H. R. Child, W. C. Koehler, and A. H. Millhouse[1]

A neutron diffraction study of rare earth-thorium alloys having the face-centered cubic (fcc) structure has been carried out at temperatures ranging from room temperature to 1.3°K. For alloys of the heavy rare earth metals Tb, Ho, and Er, the fcc field starts at approximately 50 at.% Th. In a typical case the diffraction pattern at low temperatures exhibits broad diffuse maxima, due to magnetic scattering, which are centered at scattering angles which are 0.3 and 0.8 of that of the (111) nuclear reflection. The pattern can be interpreted in terms of short range antiferromagnetic correlations. These results are to be contrasted with those previously found for the rare earth-rich hcp alloys, in which dilution by

thorium stabilizes the ferromagnetic phase. For alloys of the light metals, Pr and Nd, the fcc structure is found in alloys containing 20 at.% Th. The magnetic scattering from such an alloy with Nd is similar to that observed for a polycrystalline specimen of the pure metal in which half the atomic sites have local symmetry which is cubic. It is probable that the magnetic structure of the fcc alloy is similar to the arrangement of moments on the cubic sites in the pure metal. The corresponding Pr-based alloy showed no magnetic ordering to 1.3°K. [Abstract of paper to be published in the Journal of Applied Physics.]

[1]Oak Ridge Associated Universities Graduate Fellow from Virginia Polytechnic Institute.

SINGLE CRYSTAL NEUTRON DIFFRACTION STUDIES OF BINARY RARE EARTH ALLOYS

A. H. Millhouse, H. R. Child, and W. C. Koehler

Single-crystal specimens of intra-rare earth alloys in the Dy-Er and Dy-Ho systems have been grown by the strain-anneal method. Nuclear grade sponge from the Lunex Corporation was the starting material. The mixtures were arc-cast in an argon atmosphere several times to ensure good mixing, and on the last heating the high power density arc was shut off suddenly in order to develop thermal strain. The cast button was then suspended by a Ta wire inside a sealed Ta crucible, which was then heated in an induction furnace for several days at a temperature some fifty degrees below the melting point. Grains with linear dimensions greater than ten millimeters were nearly always developed. Specimens suitable for neutron diffraction studies were isolated, oriented, and shaped to fit one of the ORNL low-temperature goniometers.

Magnetic structure determinations of a number of compositions in these two series have now been made in order to determine how the anisotropy properties of Er and Ho are affected by alloying with Dy. The addition of Dy to Er rapidly causes the basal plane and c-axis components of the moment to order at the same temperature, in contrast to the situation in pure Er. In an alloy containing 10% Dy both components begin to

order at 93°K; just above the Curie point of 31°K, the magnetic structure appears to consist of a sinusoidally modulated moment of 8.2 μ_B/atom in the c-axis direction and a helically ordered basal plane component of 4.7 μ_B/atom. Further addition of Dy to Er reduces the c-axis component of the moment: an alloy containing 50% Dy transforms to a helical structure at 140°K with no further transitions to 4.2°K. The alloying of Ho with Dy stabilizes the helical structure and suppresses the development of a ferromagnetic phase. The conical structure, which is present in Ho below 20°K, is not present at temperatures down to 4.2°K in an alloy containing 10% Dy. The addition of 10% Ho to Dy lowers the Curie temperature from 87°K to 80°K, and an alloy containing 50% Ho has no ferromagnetic transitions at temperatures down to 4.2°K.

MAGNETIC STRUCTURES OF VF_2 AND $NiCl_2$

H. Y. Lau,[1] J. W. Stout,[1] W. C. Koehler, and H. R. Child

Neutron diffraction studies have been carried out on polycrystalline and single-crystal specimens of VF_2 and $NiCl_2$. The former is isostructural with rutile-type MnF_2, FeF_2, CoF_2, and NiF_2, which were shown by Erickson[2] to possess uniaxial antiferromagnetic structures. Magnetic susceptibility[3] and specific heat measurements[4] on VF_2 have indicated a long-range magnetic ordering transition at 7.0°K, and a gradual maximum in the magnetic susceptibility and specific heat at higher temperatures are indicative of short-range order. The neutron diffraction data confirm the existence of an antiferromagnetic structure below 7.0°K, which is, however, the screw structure in which the c-axis is the screw axis. The interlayer turn angle was found to be 96.2 ± 0.3°, and the effective magnetic moment was found to be 2.2 μ_B. $NiCl_2$, isostructural with $FeCl_2$ and $CoCl_2$, has a structure which is a particular stacking arrangement of hexagonal layers. The magnetic structure at 4.2°K is very similar to that of $CoCl_2$,[5] namely, a ferromagnetic layer structure with the moments perpendicular to the unique axis. A magnetic moment per Ni^{++} ion of about 2.0 μ_B was deduced from the data. Measurements of the intensities of selected reflections as a function of applied magnetic field were made, from which it was deduced that

the spins in the virgin state are in three equally populated domains aligned along the three equivalent [10$\bar{1}$0] directions. With increasing field the domains repopulate so that the spins are all as nearly perpendicular to the field direction as possible.

[1]University of Chicago.

[2]R. A. Erickson, Phys. Rev. 90, 779 (1953).

[3]J. W. Stout and H. Y. Lau, J. Appl. Phys. 38, 1472 (1967).

[4]J. W. Stout and W. O. J. Boo, J. Appl. Phys. 37, 966 (1966).

[5]M. K. Wilkinson, J. W. Cable, E. O. Wollan, and W. C. Koehler, Phys. Rev. 113, 497 (1959).

DIAMAGNETIC SUSCEPTIBILITY OF HIGH-PURITY ThO_2 CRYSTALS

H. M. Smith[1] and G. W. Clark[1]

A precise determination of the diamagnetic susceptibility of pure, optical quality ThO_2 crystals grown at this Laboratory has been made by the Faraday technique, and was found to be $26.3 \pm 0.3 \times 10^{-6}$ cm^3/mole. Measurements at room and liquid nitrogen temperatures were of the same value within experimental error, indicating no paramagnetic impurities. The two previous literature references were on powders and differed by a factor of two; no data on single crystals were reported. Calculations are in progress to determine a theoretical value for comparison.

[1]Metals and Ceramics Division, ORNL.

THE PROPERTIES OF MAGNETIC PEROXYBORATES: THE PSEUDO-SUPEROXIDES

J. O. Edwards,[1] D. L. Griscom,[1] R. B. Jones,[1] K. L. Watters,[1] and R. A. Weeks

Peroxyborate compounds, when heated carefully, can be modified so as to release appreciable quantities of gaseous oxygen when dissolved in water. In addition, these preparations exhibit unusually high paramagnetic

susceptibilities. Because of these properties the preparations have been given the acronym EMPB (from Effervescent Magnetic Peroxy Borates). A monotonic relation was found between the gaseous oxygen released on solution and the concentration of paramagnetic centers. Electron spin resonance measurements have resolved and tentatively identified three magnetic centers, and a fourth center was identified in irradiated specimens; all centers are due to various chemically bound forms of oxygen. A quantitative discrepancy between the number of spins contributing to the resonances and the number contributing to the susceptibility suggests the presence of O_2 molecules. Using the ^{18}O isotope, the path of oxygen atoms during preparation and aqueous decomposition was charted; only peroxide oxygen atoms end up in the evolved O_2 gas. The nature of the preparations was investigated using the techniques of x-ray, infrared spectra, reflectance spectra, NMR, and chemical analysis. A number of conclusions concerning structure and mechanism have been reached. [Abstract of paper to be published in J. Am. Chem. Soc.]

[1]Brown University.

ELECTRON SPIN RESONANCE

PARAMAGNETIC RESONANCE OF Ge^{3+} IN CeO_2 SINGLE CRYSTALS

M. M. Abraham, L. A. Boatner,[1] C. B. Finch,[2] E. J. Lee,[3] and R. A. Weeks

Ge^{3+} has been incorporated into single crystals of CeO_2 (fluorite structure) in cubic sites and the ESR spectrum observed. The temperature dependence of the cubic crystal splitting has been measured from room temperature to ~2°K and values of g, the fourth order parameter c, and the sixth order parameter d, in the spin Hamiltonian treatment for the crystal field potential have been obtained using a computer program. The parameters c and d were found to have the same sign, and intensity observations of the temperature dependence of the resonance absorption lines showed that c was negative. The temperature dependence of the total

splitting for H parallel to [100] was found to be similar to that observed in Ge^{3+}:ThO_2. Forbidden transitions with $|\Delta M_s| > 1$ were observed, as well as axial spectra in heavily doped crystals. Lines due to transitions with $\Delta M_s = \pm 4$ were identified in both ThO_2 and CeO_2. [Abstract of published paper: J. Phys. Chem. Solids 28, 81 (1967).]

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[2]Metals and Ceramics Division, ORNL.

[3]Mathematics Division, ORNL.

TEMPERATURE VARIATION OF Gd ESR SPECTRA IN CUBIC AND AXIAL CRYSTALS

M. M. Abraham, L. A. Boatner, E. J. Lee, and R. A. Weeks

The electron spin resonance of gadolinium was observed and the temperature variation of the splitting was studied in single crystals of CeO_2, ThO_2, CaF_2, and CaO, where the symmetry of the local crystalline field was cubic. Similar measurements were made on single crystals of $La(C_2H_5SO_4)_3 \cdot 9H_2O$, $LaCl_3$, and $LaBr_3$ in which the symmetry of the local field was axial. Absolute signs of "spin" Hamiltonian parameters have been determined from the relative intensity of the resonance lines at low temperature. [Abstract of paper presented at Sixth Rare Earth Conference, Gatlinburg, Tennessee, May 1967.]

ELECTRON SPIN RESONANCE OF TRIPOSITIVE CURIUM IN ThO_2 AND CeO_2

M. M. Abraham, C. B. Finch, and G. W. Clark

The ESR spectra of $^{244}Cm^{3+}$-doped ThO_2 and CeO_2 single crystals were measured at approximately 10 Gcps and liquid helium temperatures. Sites of cubic symmetry were observed in both hosts with the crystal field splitting being larger than the microwave quanta used. The ground states are Γ_6 doublets, indicating that the fourth order parameter of the cubic crystal field Hamiltonian is negative. For ThO_2 the g-value was 4.484 ± 0.002, and for CeO_2 it was 4.475 ± 0.002. [Abstract of paper to be published in The Physical Review.]

TEMPERATURE VARIATION OF Gd ESR SPECTRA IN $LaCl_3$ AND $LaBr_3$ SINGLE CRYSTALS

L. A. Boatner and M. M. Abraham

The electron spin resonance of gadolinium was observed and the temperature variation of the splitting was studied in single crystals of $LaCl_3$ and $LaBr_3$ where the symmetry of the local crystalline field was axial. Absolute signs of "spin" Hamiltonian parameters have been determined from the relative intensity of the resonance lines at low temperatures. For $LaBr_3$ the temperature variation of the second order term in the axial "spin" Hamiltonian in the presence of an appreciable fourth order term is sufficient to change the relative positions of the resonance lines between 77°K and room temperature for H parallel to the crystal axis. [Abstract of published paper: Phys. Rev. 163, 213 (1967).]

PARAMAGNETIC RESONANCE OF Gd^{3+} IONS IN $SrCl_2$ SINGLE CRYSTALS

M. M. Abraham, L. A. Boatner, and E. J. Lee

The cubic site spectrum of Gd^{3+} in $SrCl_2$ was observed and the "spin" Hamiltonian parameters determined at various temperatures. Considerable disagreement is noted between the results obtained at room temperature and those obtained previously by other workers. [Abstract of published paper: Phys. Letters 25A, 230 (1967).]

STRESS DEPENDENCE OF THE g-FACTORS OF Yb^{3+} IN ThO_2 AND Ho^{2+} IN CaF_2

M. Tachiki,[1] Z. Sroubek,[1] P. Zimmermann,[1] and M. M. Abraham

The change of the spin Hamiltonian parameters g and A has been measured for Yb^{3+} in ThO_2 and Ho^{2+} in CaF_2 (both in cubic sites) as a function of uniaxial stress. The experimental Δg is compared with the values of Δg calculated in point charge approximation. The comparison leads to the following conclusions. (1) In the case of $CaF_2:Ho^{2+}$ stressed along [001] and $ThO_2:Yb^{3+}$ stressed along [111], the second order term (A_2^0) of crystalline field is dominant. Without any shielding a very good agreement

with experiment is achieved. (2) In the case of Ho^{2+} stressed along [111], the fourth order terms of crystalline field are important. To get an agreement with experiment, these terms should be multiplied by three. (3) The dipolar contribution to the second order term in the case of $ThO_2:Yb^{3+}$ is six times larger than the point charge contribution. Then the calculated Δg is seven times larger than the observed Δg. The reason for this discrepancy is discussed. [Abstract of paper presented at International Congress on Magnetism, Boston, September 10-16, 1967.]

[1]University of California, Los Angeles.

PARAMAGNETIC RESONANCE OF STRUCTURAL DEFECTS IN IRRADIATED RUTILE

R. A. Weeks and T. Purcell[1]

Electron spin resonance spectra have been observed in single crystals of TiO_2 which had been neutron irradiated at 300°K or 140°K or gamma irradiated at 78°K. The observations were made at 10 GHz and at 78°K prior to warm-up. A crystal, exposed to 5.4×10^{16} fast neutrons cm^{-2} at 330°K, displayed the same spectrum as observed before irradiation. This spectrum is attributed to a transition ion impurity. After an irradiation with gamma rays (1.2×10^7R at 78°K), the intensity of this spectrum increased by two orders of magnitude. In addition, a center whose spectrum was previously reported by Young[2] was observed. A specimen irradiated with 3×10^{17} fast neutrons cm^{-2} displayed four distinct paramagnetic centers. Line widths ranged from 2 to 10 gauss. After warming the crystal to room temperature, the signals were not observed. The most intense center, $\sim 10^{18}$ spins cm^{-3}, had an orientation dependence attributable to a substitutional site with $g_x = 1.983$, $g_y = 1.969$, $g_z = 1.988$. The other three centers, for H parallel to [001], had g-values of 1.972, 1.965, and 1.953. One of these, g = 1.972, split into four lines for rotation about the [110] axis. Extremals in g-value occurred at ±10° from the [100] axis. The concentration of spins in this center was $\sim 10^{17}$ cm^{-3}. The g = 1.953 line had an angular dependence

attributable to a substitutional site and a spin concentration of ~10^{16} cm^{-3}. The g = 1.965 center had the largest line width, ~10 gauss, and a spin concentration of ~10^{18} cm^{-3}. The data are consistent with the hypothesis that these paramagnetic states are due to defects of the rutile structure and not to impurity-type defects.

[1]HEW Radiological Physics Fellow from the University of Tennessee.

[2]C. G. Young, A. J. Shuskus, and O. R. Gilliam, Bull. Am. Phys. Soc. 6, 248 (1961).

ELECTRON SPIN RESONANCE OF INTRINSIC DEFECTS IN IRRADIATED POLYCRYSTALLINE AND AMORPHOUS GeO_2[1]

T. Purcell and R. A. Weeks

Radiation-induced paramagnetic centers have been studied in pure hexagonal and tetragonal polycrystalline GeO_2, pure GeO_2 glasses, and in glasses with added alkali oxide of molar ratio, GeO_2/M_2O, of 0.003, 0.03, and 0.3. The samples, irradiated with electrons, neutrons, and gamma rays at ~330°K and 78°K, were observed at 10 GHz and at 78°K. One resonance with $g_1 \simeq 2.002$, $g_2 \simeq g_3 \simeq 1.955$, observed in hexagonal polycrystalline powder and pure GeO_2 glass, was present in all the alkali-doped glasses after irradiation. The intensity of this resonance, attributed to a singly charged oxygen vacancy, increased monotonically with increasing irradiation in all the glasses. The intensity, for constant gamma-ray dose, decreased with increasing alkali or oxidation and increased with degree of reduction. These results are further confirmation of the proposed model. With electron or neutron irradiation followed by thermal treatment a second resonance was detected with $g_1 \simeq 2.003$, $g_2 \simeq 2.008$, and $g_3 \simeq 2.051$ in all the glasses. Under other conditions of irradiation at least one other resonance was observed with one principal value of the g-tensor being 2.006. The spectrum of neutron irradiated tetragonal polycrystalline powder was composed of three resonances attributable to sites with approximately cubic (g = 1.998), axial ($g_{||} = 2.0047$, $g_{\perp} = 2.0035$), and rhombic ($g_1 = 2.002$, $g_2 = 2.006$,

g_3 = 2.030) symmetry. On the basis of g-values, intensities, growth with irradiation, and known impurities, tentative models for these centers have been proposed.

[1]Research sponsored in part by the U. S. National Aeronautics and Space Administration.

OPTICAL ABSORPTION AND ELECTRON SPIN RESONANCE SPECTRA OF LIBYAN DESERT GLASS[1]

R. A. Weeks and A. Bishay[2]

The electron spin resonance spectra of Libyan Desert glass (LDG) is characterized by absorption in the region of three g-values, $g \sim 2$, $g \approx 4.3$, and $g \geq 6$. The absorption in the region of $g \approx 2$ measured at 10 GHz is similar, with respect to line shapes and g-values, to the absorption observed in pure silica glass irradiated with energetic particles or photons. One of the absorption lines in this region has parameters which are the same, within experimental error, as those of the E_1' center (an oxygen vacancy which has trapped one electron). The absorption in the region of $g \approx 4.3$ to ≥ 6 is similar to that observed in silicate glasses doped with iron. Part of this resonance absorption has been attributed to Fe^{3+} in a crystalline field of rhombic symmetry. In our LDG specimens the intensity of the absorption in this region is approximately independent of the total iron content. By comparing the absorption intensity in this region in LDG with the absorption intensity in a glass of similar composition made in the laboratory, we would estimate that only a small fraction of the Fe ions in LDG glass contribute to the absorption intensity in this region.

One interpretation of this difference in relative intensities of absorption due to Fe^{3+} ions is that in the LDG a large fraction of Fe ions are present as Fe^{2+}, because the resonance absorption of Fe^{2+} is expected to be very difficult to detect in glasses. This interpretation is in agreement with the results of chemical analysis in which most of the Fe ions were found to be present as FeO. Similar results have been reported for tektites.

Irradiation with energetic photons (^{60}Co gamma rays) increased the intensity of absorption in the region of g ~ 2 approximately proportionally to integrated dose, with the magnitude of the increase after a given dose being approximately inversely proportional to the weight per cent of Fe present in the sample. No change, outside of experimental error, in the intensity of the g = 4.5 absorption in the LDG was observed after the largest integrated dose to which the samples were exposed (2×10^8R).

The optical absorption spectra of the sample used for ESR measurements were measured in the wavelength range of 2,000 to 22,000 Å as a function of gamma-ray dose. Optical bands observed in the unirradiated samples were attributed primarily to Fe^{2+} and Fe^{3+}. One of the bands, attributed to Fe^{2+}, increased and one of the bands, attributed to Fe^{3+}, did not change with increasing dose. Because of some uncertainty in relating these optical bands to specific valence states and to site symmetry, only a tentative hypothesis can be suggested: the electrons excited by gamma-rays are trapped at Fe^{3+} ions converting them to Fe^{2+} ions with the trapping occurring at those sites at which the Fe ion is four-fold coordinated.

[1]Research sponsored in part by the U. S. National Aeronautics and Space Administration.

[2]Guest scientist from American University, Cairo, Egypt.

ELECTRONIC AND OPTICAL PROPERTIES

ELECTRONIC STRUCTURE OF THE U CENTER. I. OPTICAL ABSORPTION AND LATTICE RELAXATION

R. F. Wood and U. Öpik[1]

The electronic structure of the U center in KCl, KBr, and KI is calculated for the ground and first excited states using a model in which the interactions with the first-nearest-neighbor ions are taken into account in detail and all other ions are treated as point charges. A

second, more refined model, which involves the electronic structure of all ions and polarization effects, is briefly described. It is used for calculations of the electronic structure, optical absorption, and lattice relaxation of the U center in KCl. [Abstract of published paper: Phys. Rev. 162, 736 (1967).]

[1]Guest scientist from The Queen's University, Belfast, Northern Ireland.

ELECTRONIC STRUCTURE OF THE U CENTER. II. FORCE-CONSTANT CHANGES AND LOCAL MODES

R. F. Wood and R. L. Gilbert

The force constants and local-mode frequencies of the U center in KCl, KBr, and KI have been obtained from a detailed quantum-mechanical calculation. The model which has been used corresponds to the "static-well" approximation. It takes into account both the electronic structure of the first-nearest-neighbor ions and the polarization of the H^- ion during the local-mode oscillations. The agreement of the calculated local-mode frequencies with the experimental values is greatly enhanced when the polarization of the H^- ion is included. [Abstract of published paper: Phys. Rev. 162, 746 (1967).]

STUDIES OF THE EFFECTS OF PRESSURE AND TEMPERATURE ON THE POSITION AND LINE SHAPE OF THE F BAND IN THE POTASSIUM HALIDES

R. L. Gilbert and R. F. Wood

Preliminary calculations on the pressure- and temperature-induced changes in the absorption energy and line shape of the F center in KI have been completed. The results are in reasonably good agreement with observation. The work will be extended to KCl and KBr. It is hoped that the corresponding calculations on the emission energy can be carried through.

EMPIRICAL RELATIONSHIPS FOR THE EMISSION ENERGIES AND LIFETIMES OF THE F CENTER

R. L. Gilbert

Empirical relations for the emission energies, ε, and the lifetimes, τ, of the F center in the Na, K, Rb, and Cs halides have been established with the following forms:

$$\varepsilon = AK_o^n \quad \text{and} \quad \tau = A'K_o^{n'}$$

where K_o is the optical dielectric constant. The existence of two classes of radiative lifetimes is suggested. Those τ observed at liquid helium temperatures (fluorescence measurements) and those measured above liquid nitrogen temperatures (photoconductivity measurements) yield separate straight lines on log-log plots of τ vs K_o. Implications of the existence of these correlations are discussed. [Abstract of report, ORNL-TM-2054.]

THEORY OF THE ELECTRONIC STRUCTURE OF DEFECTS IN INSULATORS

R. Tseng and R. F. Wood

Some purely formal work on the relationships between the various formulations of the defect problem in insulators has been carried out. In particular, attempts have been made to trace the connection between models frequently used in calculations, such as the semi-continuum, point ion, etc., models, and the Green's function formulation given by Koster and Slater which is frequently used in general discussions. Also, attempts have been made to formulate a method of calculating resonance states associated with defects and excitons which does not involve a complete knowledge of the band structure, as is required in a Green's function approach.

CALCULATIONS ON THE ELECTRONIC STRUCTURE OF THE F AND F' CENTERS IN MgO AND CaO

A. Meyer,[1] U. Öpik, and R. F. Wood

Preliminary calculations on the one- and two-electron point defects in MgO have been completed using the model mentioned under "Theory and Calculations of the Electronic Structure of Defects in Ionic Crystals." These calculations indicate that the one- and two-electron centers absorb at approximately the same energy (~5 eV) and that only the one-electron center should have a readily observable emission energy at ~3.4 eV. After further checking of the MgO work, the calculations will be extended to CaO. Both the singlet and triplet states will be calculated for the two-electron center. This work is being done in close conjunction with the experimental work of W. A. Sibley and coworkers.

[1]Present address: Northern Illinois University, DeKalb, Illinois.

THEORY AND CALCULATIONS OF THE ELECTRONIC STRUCTURE OF DEFECTS IN IONIC CRYSTALS

U. Öpik and R. F. Wood

A general model for the electronic structure of electron excess point defects in ionic crystals has been developed and computer programs have been written. The model allows for the detailed treatment of the interactions of the defect electrons with the ions of the crystal within a certain radius, R_a, and an approximate treatment of these interactions in terms of effective mass theory outside of R_a. R_a can be given any value less than the fourth nearest neighbor distance. Dielectric polarization effects are included in the model, as are lattice relaxation effects. Thus, the absorption and emission energies, oscillator strengths, and lifetimes of the excited states can be calculated. Applications of the model have been made to the F center in KCl, KBr, KI, and NaCl. The results show that after lattice relaxation the 2s state is lower than the 2p state, a fact which is of importance in explaining the long lifetime of the excited state. Two papers covering this work are being prepared for publication.

LUMINESCENCE IN MgO

W. A. Sibley, C. M. Nelson,[1] and Y. Chen

The phosphorescence and x-ray stimulated luminescence of a series of nominally pure MgO crystals has been investigated. We suggest that the series of emission peaks around 1.4 eV is due to $Mg(OH)_2$ impurity, and have presented evidence which substantiates the assignment of the 1.7 eV and 2.5 eV luminescence with Cr^{3+} and Ni^{2+}, respectively. The effect of electron and neutron irradiation on the samples is generally to suppress the total luminescence. We are initiating a search for the luminescence from F (a negative ion vacancy with one trapped electron) and/or F' (a negative ion vacancy with two trapped electrons) centers in irradiated crystals. [Abstract of paper to be published in the Journal of Chemical Physics.]

[1]Consultant, Emory and Henry University.

THERMOLUMINESCENCE OF DOPED THORIUM DIOXIDE

C. B. Finch,[1] L. J. Nugent,[2] and M. M. Abraham

Intense thermoluminescence in the optical region on heating between 150° and 200°C has been observed from ThO_2 crystals doped with an estimated 100 to 1000 ppm of Eu^{3+}, Dy^{3+}, Er^{3+}, Tm^{3+}, or $^{244}Cm^{3+}$ and grown at the Laboratory. After thermalizing, the crystals are reactivated to near full intensity within three weeks, probably by the internal alpha bombardment of ^{232}Th. They are also reactivated within 10 min by 2600 Å uv light. The thermoluminescent emission spectrum is identical to the uv fluorescent emission spectrum, and is characteristic of the lanthanide or actinide dopant. Contrary to a model proposed for $Ln^{2+,3+}$-doped CaF_2, the mechanism of thermoluminescence does not appear to involve reoxidation of Ln^{2+} to Ln^{3+} (as judged by the absence of Tm^{2+} in the ESR spectrum of thulium-doped ThO_2 crystals both before and after thermoluminescence).

[1]Metals and Ceramics Division, ORNL.

[2]Chemistry Division, ORNL.

RESISTIVITIES AND THERMOPOWERS OF THE ALKALIS UNDER PRESSURE

J. M. Dickey,[1] A. Meyer, and W. H. Young[1]

Calculations of the pressure dependence of the resistivities and thermopowers of the alkalis, both in the liquid and solid states, are made covering volume changes approaching 50%. Good qualitative agreement with experiment is obtained. The method depends basically on the Ziman pseudo-atom concept, the scattering from such pseudo-atoms being calculated as a function of Fermi level. A spherical Fermi surface is assumed throughout. [Abstract of published paper: Proc. Phys. Soc. (London) 92, 460 (1967).]

[1]University of Sheffield, England.

THERMOELECTRIC POWERS OF ALLOYS OF ALKALIS IN ALKALIS

D. Thornton,[1] W. H. Young,[1] and Axel Meyer

The thermoelectric powers of alloys of alkalis in alkalis are calculated at very low temperatures and satisfactory agreement with experiment is obtained. In particular, the correct sign is found for the first time. The Faber-Ziman theory is found to be semi-quantitatively applicable in the corresponding liquids. [Abstract of paper to be published in The Physical Review.]

[1]University of Sheffield, England.

LOW TEMPERATURE PROPERTIES

STUDY OF THE RESONANT PHONON SCATTERING IN KCl:Li USING THE SPIN-PHONON INTERACTION

D. Walton

In a magnetic field, a crystal which contains magnetic ions will exhibit a field-dependent decrease in the thermal conductivity. This effect may be described as an effective removal of heat carriers from a narrow band in the phonon spectrum which is centered about the Larmor frequency for the spins. The spectrum of heat carriers and hence the frequency dependence of the total phonon scattering cross section for the crystal can be determined from the field dependence of the thermal conductivity.

Using this technique with Li-doped KCl, we have been able to identify the resonant scattering of phonons due to transitions between tunneling states of the Li ion. Three resonances at 0.7 cm^{-1}, 1.4 cm^{-1}, and 2.3 cm^{-1} have been observed.

Theory predicts that the tunneling states for the Li^+ ion in an isotropic well should consist of four equally spaced levels, and previous investigations indicate that the separation of the levels in KCl should be 0.75 cm^{-1}. Our observations are consistent with this picture, because our experimental error is about ± 0.1 cm^{-1}. [Summary of paper published in Phys. Rev. Letters; a more detailed paper is to be published in the Proceedings of the International Conference on Localized Excitations in Solids, University of California at Irvine, September 18-22, 1967.]

PHONON SCATTERING BY RADIATION-PRODUCED F-COMPLEMENT-CENTERS

E. Sonder and D. Walton

It is inferred from thermal conductivity measurements between 0.2° and 2°K on irradiated samples of KCl that large clusters of interstitial Cl atoms are formed, the sizes of which depend upon the radiation temperature. The results suggest that clusters of around 1000 Cl atoms are

formed during irradiations at 300°K, whereas much smaller clusters are formed when samples are irradiated at 77°K. These data are in agreement with other data taken at this Laboratory which indicate that the size of the F center complement depends upon the radiation temperature. [Summary of published paper: Phys. Letters 25A, 222 (1967).]

THERMAL TRANSPORT BY SPIN WAVES IN $MnCl_2$-$4H_2O$

J. E. Rives[1] and D. Walton

The thermal conductivity of $MnCl_2$-$4H_2O$ has been measured as a function of temperature between 0.25°K and 3°K. Below the Néel temperature, 1.6°K, the conductivity is higher than would be expected from the phonon contribution alone, which suggests that the magnon contribution is important. This conclusion is reinforced by the change in thermal conductivity in a magnetic field at 0.336°K: there is a sharp decrease in conductivity at the critical field for the spin-flop transition. At higher fields the conductivity recovers towards a value somewhat higher than its zero field value, the recovery becoming complete at the critical field for the spin-flop to paramagnetic transition.

A crude calculation of the thermal conductivity shows that it is possible to account for the gross features of the experimental data by taking into account the differences in the magnon dispersion relations for the three phases alone.

[1]University of Georgia.

THE EFFECT OF SPIN-PHONON COUPLING ON THE THERMAL CONDUCTIVITY

D. Walton and J. E. Rives

An experimental study has been completed of the magnetic field dependence of the thermal conductivity of insulating crystals containing Kramers ions. The specimens used were MgO crystals which were doped with concentrations of Co^{++} of 0.01% and 0.3%, and ruby. From the data on the

MgO a quantitative comparison can be made with existing theories. It is possible to make a comparison, with no adjustable parameters, with the theory of Elliott and Parkinson,[1] and the agreement appears to be good. Comparison of the data on MgO-Co^{++} and ruby also indicates the correct dependence on the magnitude of the spin-phonon coupling constants.

[1]R. J. Elliott and J. B. Parkinson, Proc. Phys. Soc. 92, 1024 (1967).

NEW INTERPOLATION FORMULA FOR SPEER CARBON RESISTORS

M. C. Hetzler[1] and D. Walton

The resistance vs temperature data for three different Speer resistors[2] were studied in the temperature range of 0.2°K to 2.3°K for the purpose of obtaining and evaluating an analytical expression for T as a function of R. Since 1/T varies almost linearly with R, the expression

$$\frac{1}{T} = A + BR + CR^n$$

was tried with several values for n. The value of n giving the best fit was n = 1/4.

The three expressions

$$\frac{1}{T} = A + BR + CR^{1/4} \qquad (1)$$

$$T = \theta\left(\frac{R + R_1}{R - R_o}\right) \qquad (2) \quad \text{(Lounasmaa, 1958)}^3$$

$$\frac{C}{T} = \log R + \frac{A}{\log R} - B \qquad (3) \quad \text{(Clement and Quinnell, 1953)}^4$$

were compared with each other for their ability to fit the R vs T data for each of the three different resistors. The rms value of the deviations in the temperature region from 0.2°K to 2°K ranges between 0.3% and 0.7% for Eq. (1), between 0.5% and 1.04% for Eq. (2) and between 4.5% and 6.1% for Eq. (3). It is interesting that the data for resistor A were

taken during two runs six months apart and no sign of a calibration shift as great as 0.5% was seen.

[1]Oak Ridge Associated Universities Graduate Fellow from Vanderbilt University.

[2]Data on two of the resistors were kindly supplied to us by W. Seward, Cornell University, and J. E. Rives, University of Georgia.

[3]O. V. Lounasmaa, Phil. Mag. 3, 658 (1958).

[4]J. R. Clement and E. H. Quinnell, Rev. Sci. Instr. 23, 213 (1952).

NEUTRON IRRADIATION EFFECTS IN SUPERCONDUCTING NIOBIUM

R. H. Kernohan and S. T. Sekula

The superconducting magnetization behavior and transition temperatures of single crystals of Nb were investigated prior to and after a series of fast neutron irradiations (E > 1 MeV) in the Oak Ridge Research Reactor at a temperature of approximately 40°C. The experimental results indicate that the point defects and defect aggregates which are created lead to increases in the upper critical field H_{c_2} and small changes in the superconducting transition temperature. In addition, the increase in non-equilibrium behavior of the magnetization with integrated fast neutron flux establishes that defects are present with the ability to pin magnetic flux. For fast neutron doses of approximately 2×10^{19} neutrons/cm^2, the magnetization approaches in behavior that of a completely irreversible type-II superconductor. Successive reductions in cross-sectional area of this sample by chemical etching and subsequent measurements of the magnetization indicate only a small size dependence of the hysteresis, indicating essentially complete flux pinning in a macroscopic sheath approximately 0.1 mm thick. The flux-pinning defects are considered to be dislocation loops as evidenced by other work, and the present experimental results are discussed in terms of these loops. [Abstract of published paper: J. Appl. Phys. 38, 4904 (1967).]

SUPERCONDUCTIVITY IN THE TECHNETIUM-VANADIUM ALLOY SYSTEM

C. C. Koch,[1] R. H. Kernohan, and S. T. Sekula

The superconducting properties of Tc-V alloys with compositions ranging from 0 to 100 at.% V have been investigated in fields up to 15 koe by measurements of the bulk magnetization determined ballistically. A phase diagram of the Tc-V system has been determined by several metallurgical techniques. The sequence of crystal structures at 1500°C with increasing vanadium content is hcp → bcc → CsCl → bcc. The technetium-rich bcc phase, when quickly cooled to room temperature, exhibits superlattice x-ray diffraction lines of the CsCl structure. The superconducting transition temperature of the technetium-rich hcp alloys increases with vanadium concentration from 7.73°K to a maximum for the system of 11.3°K at the limit of vanadium solubility (~6.5 at.% V). This transition temperature remains constant for the two-phase alloys. The transition temperature decreases progressively with increasing vanadium content in the CsCl structure, and at compositions in the 50 to 80 at.% V interval no evidence of superconductivity is observed for temperatures as low as 1.4°K. Alloys containing the hcp phase show reversible behavior in the tails of their magnetization curves, while those with the CsCl structure exhibit a high degree of hysteresis in the tails. Estimates of the upper critical field at 0°K, $H_{c_2}(0)$, using the experimental data and theoretical calculations, yield values of $H_{c_2}(0)$ of approximately 45 koe for the samples with high transition temperatures. Results of heat treatment at 1100°C on the superconducting parameters of alloys near the 30 at.% V composition are presented. [Abstract of published paper: J. Appl. Phys. 38, 4359 (1967).]

[1]Metals and Ceramics Division, ORNL.

SUPERCONDUCTING STUDIES OF DEFECTS IN NIOBIUM

R. H. Kernohan, R. E. Reed, and S. T. Sekula

The isothermal magnetization behavior of type-II superconductors, such as niobium, is sensitive to the presence of defects in the sample.

Measurements of the superconducting parameters of certain metals and alloys then afford a somewhat novel approach to studies of defects in these materials.

Thus, the annealing of defects in niobium that had been irradiated at 40°C in the Oak Ridge Research Reactor is currently being studied by measurements of the superconducting magnetization at 4.2°K. It is found that the remanent moment (a measure of the degree of magnetic flux pinning by the defects present) decreases rapidly when isochronally annealed (2 hrs) at temperatures in the interval from 400°C to 700°C. The preliminary evidence also indicates that 4 hrs at 1000°C is sufficient to almost restore the sample to its pre-irradiated condition.

Also under study are the effects of the chemical etching of niobium single crystals employing a standard etchant composed of 60% HNO_3-40% HF. It is believed that hydrogen charging by this etching procedure leads to the increases in hysteresis and remanent moment observed in the isothermal magnetization curves. Initial annealing studies of these samples under a vacuum of 5×10^{-8} Torr indicate that the hydrogen is retained in the sample when heat treated at temperatures of less than 200°C.

ELECTRONIC INTEGRATOR FOR SUPERCONDUCTIVITY MEASUREMENTS

R. H. Kernohan and S. T. Sekula

Measurements of the bulk magnetization properties of superconductors are of value in the study of the role of defects on superconducting behavior. While the classical technique of sample extraction from a sensing coil in a uniform field with subsequent integration of induced voltage pulse using a ballistic galvanometer has been successfully used in the past, the method has a disadvantage in that the time required to obtain a complete set of point by point magnetization data can be considerable. In order to facilitate the procurement of magnetization data, a system incorporating commercially available electronic equipment has been constructed. Using a swept field technique, magnetization data are recorded as a function of the applied magnetic field on an X-Y recorder. Data obtained in this

manner agree very well with data obtained by the classical technique with the time required to obtain an equivalent set of data reduced by approximately a factor of ten.

THE HEAT CAPACITY OF ALUMINUM BETWEEN 2.7° and 20°K

W. T. Berg and L. C. Templeton

The heat capacity of aluminum has been measured between 2.7° and 20°K, and the results are in quantitative agreement with results derived from inelastic neutron scattering experiments. There is an initial increase of θ_D at low temperatures which cannot be accounted for in terms of the elastic constants. [Abstract of paper to be published in The Physical Review.]

THE SPECIFIC HEAT OF CORNING 7560 GLASS BETWEEN 4.5° AND 20°K

W. T. Berg and L. C. Templeton

The specific heat of Corning 7560 glass has been measured so that small corrections could be made accurately for changes in the amount of glass on the calorimeter seal. Below 3°K the time for thermal equilibrium was excessive, which indicated that the small amount of helium used for heat conduction inside the vessel had been adsorbed. The effect of desorption of the helium on the specific heat results is negligible above 4°K. A plot of the results in the form C/T^3 vs T^2 is similar to that for vitreous silica and cristobalite. [Summary of a Communication to the Editor, Journal of Applied Physics.]

THE LOW TEMPERATURE HEAT CAPACITY OF PLATINUM

W. T. Berg and L. C. Templeton

The heat capacity of platinum has been measured between 2.6° and 20°K. Previously published values of γ were found to be incompatible with

the present measurements. Analysis of the results gave $\gamma = 6.59 \times 10^{-3}$ j/g atom deg^2 and 240.1°K for the Debye temperature at 0°K. [Abstract of paper submitted to The Journal of Physics and Chemistry of Solids.]

RADIATION DAMAGE

DIRECT OBSERVATION OF NEUTRON IRRADIATION DAMAGE IN NIOBIUM

R. P. Tucker[1] and S. M. Ohr

Polycrystalline sheets of pure niobium were irradiated to a fluence of 2×10^{18} neutrons/cm^2 (E > 1 MeV). Defects appearing as black spots, as well as black-white contrasts, were observed by transmission electron microscopy. The density of the black spots was estimated as $5 \times 10^{15}/cm^3$. The defects were identified as small dislocation loops. Slip traces free of black spots were observed after plastic deformation. This is believed to be the first report of direct observation of neutron damage in niobium. Attempts are now being made to determine the nature of the loops. [Abstract of published paper: Phil. Mag. 16, 643 (1967).]

[1]Oak Ridge Associated Universities Graduate Fellow from the University of Tennessee.

THE EFFECT OF OXYGEN ON STAGE III ANNEALING IN NEUTRON-IRRADIATED NIOBIUM

J. M. Williams, W. E. Brundage, and J. T. Stanley

The effect of oxygen on "Stage III" annealing in neutron-irradiated niobium was investigated using internal friction and electrical resistivity techniques. It was found that the oxygen Snoek peak decreased during isothermal annealing at 150°C and the kinetics of this process were similar to the kinetics of the electrical resistivity decrease at the same temperature. Oxygen-free samples exhibited no annealing effects in Stage III. It was concluded that Stage III is caused by migration of oxygen to radiation-produced defects. The oxygen trapped at the radiation-produced defects returned to solution after annealing in the temperature

range from 300° to 500°C. The return of the oxygen to solution was indicated by an increase of electrical resistivity and an increase of the oxygen internal friction peak.

THE KINETICS OF MIGRATION OF IMPURITIES TO SMALL DISLOCATION LOOPS

R. Bullough,[1] J. T. Stanley, and J. M. Williams

The initial kinetics for the migration of interstitial impurity atoms to a distribution of small dislocation loops has been evaluated and compared with the measured kinetics of Stage III recovery in neutron-irradiated niobium containing oxygen impurity. Both the theoretical calculation and the relevant electrical resistivity measurements are presented. The agreement between them is very good, and provides strong support for the assumption that the Stage III recovery is due to the migration of oxygen to the dislocation loops introduced by the irradiation. [Abstract of paper to be published in Metal Science Journal.]

[1]Guest scientist from Atomic Energy Research Establishment, Harwell, England.

TRAPPING OF INTERSTITIAL IMPURITIES IN NEUTRON-IRRADIATED VANADIUM

J. M. Williams, W. E. Brundage, and J. T. Stanley

The trapping of interstitial impurities at radiation-produced defects in vanadium was investigated using techniques similar to those employed for niobium. As for niobium, it was found that oxygen became trapped at radiation-produced defects upon annealing at the oxygen peak temperature (185°C). The vanadium samples used for this investigation contained both oxygen and nitrogen, and the nitrogen also became trapped at the radiation-produced defects upon annealing at the nitrogen peak temperature (275°C).

THE EFFECT OF NEUTRON IRRADIATION ON COPPER CRYSTALS AT HIGH TEMPERATURES

L. D. Hulett, Jr., T. O. Baldwin, J. C. Crump, III, and
F. W. Young, Jr.

Etching, x-ray topography, and electron microscopy studies have shown that neutron irradiation at about 400°C produces a defect structure different from that produced by irradiation at ambient temperatures. On a macroscopic scale the damage was non-homogeneous; there were regions containing high concentrations of defects separated by apparently perfect crystal. The size of the defect regions ranged from 1-50 microns, and the distance between regions was ~100 microns. Borrmann topographs showed long-range order among the defect regions in that they tended to be aligned in habit planes parallel to (111) planes. Measurements of the absolute integrated intensities of Borrmann diffracted beams indicated that there must have been a large degree of elastic strain between defect regions. It has been shown that the defect regions were aggregates of large dislocation loops 1000-2000 Å in diameter, dislocation tangles of roughly the same dimension, smaller loops 50-150 Å in diameter, and three-dimensional point defect clusters 200 Å or less in dimension. The larger loops were principally interstitial; the smaller loops were principally vacancy type. The concentration of vacancies and interstitials within defect regions, as estimated from the loops and clusters, was $1.6 \times 10^{18}/cm^3$ and $2 \times 10^{18}/cm^3$, respectively, which averaged to about $3 \times 10^{16}/cm^3$ for the entire crystal. These high-temperature irradiation effects were somewhat independent of the state of perfection of the specimens; defect regions were observed in polycrystal as well as single-crystal specimens. Annealing of the high-temperature damage occurred non-homogeneously between 500° and 800°C, a higher range than that for annealing damage produced at ambient temperatures. Defect regions remote from as-grown dislocations were annealed at the lower temperatures, while those near dislocations required anneals at 800°C. [Abstract of paper submitted to the Journal of Applied Physics.]

AN INVESTIGATION OF FAST NEUTRON RADIATION DAMAGE IN NEARLY PERFECT COPPER CRYSTALS BY X-RAY DIFFRACTION TECHNIQUES

T. O. Baldwin, F. A. Sherrill, and F. W. Young, Jr.

The effects of fast neutron irradiation at about 40°C in nearly perfect copper crystals have been examined by x-ray diffraction techniques. Anomalous x-ray transmission (Borrmann) and Bragg reflection geometries were used to investigate the changes in diffracted intensities caused by defects produced by the neutron irradiation. Both Borrmann and Bragg peak intensities were reduced to values significantly below those for perfect crystals, and the reduction in the Bragg intensities was accompanied by a large increase in the diffuse scattering in the wings of the peak. It is shown that isolated point defects and the distortion associated with them would not account for the changes in x-ray intensities. Annealing studies indicated that both vacancies and interstitials were present in these crystals after irradiation, and all of the damage was removed by annealing at 500°C. [Abstract of paper to be published in the Journal of Applied Physics.]

THE USE OF ANOMALOUS X-RAY TRANSMISSION FOR THE DETECTION OF DEFECTS PRODUCED IN SILICON AND GERMANIUM BY FAST NEUTRON IRRADIATION

T. O. Baldwin and J. E. Thomas[1]

Absolute x-ray intensities anomalously transmitted through fast neutron irradiated silicon and germanium crystals have been measured and compared with those transmitted through nearly perfect (unirradiated) crystals. The results indicate that the Borrmann intensities in both silicon and germanium irradiated with 4×10^{19} fast neutrons/cm^2 ($E > 0.6$ MeV) were reduced by nearly a factor of 2 for $\mu t \approx 30$. In contrast, very small (<5%) decreases in the Bragg intensities diffracted from the surfaces were observed. The observed decreases in intensity have been attributed to the strains in the vicinity of "disordered regions," previously observed in electron microscopy studies of irradiated germanium. Isochronal annealing studies have demonstrated that the crystals could be restored to near their original state of perfection by heating to $\simeq$700°C

for 30 minutes. Two well defined annealing peaks were found in both kinds of crystals, silicon annealing at about 190°C and 630°C, and germanium at about 150°C and 400°C. These studies suggest that fast neutron doses at ambient temperature in the range of 10^{19}-10^{20}/cm^2 (E > 0.6 MeV) are necessary for observations of appreciable effects on the x-ray intensities diffracted from silicon and germanium. [Abstract of paper submitted to the Journal of Applied Physics.]

[1]Research Participant from Kansas State College, Pittsburg, Kansas.

DISLOCATION DAMPING IN COPPER AFTER LOW-TEMPERATURE IRRADIATION

V. K. Paré and P. B. DeNee

The semiautomatic anelasticity apparatus and continuous-flow liquid helium cryostat were placed in operation at an ORR beam hole irradiation facility and studies were begun on the effects of low-temperature irradiation of a copper crystal. The measurement sequence is all done with the sample mounted in the cryostat and starts with a 500°C anneal to remove effects of the previous irradiation. After the anneal the temperature dependence of damping and resonant frequency is measured from 12°K to 350°K. The sample is then cooled again to 23°K and irradiated at that temperature. During the subsequent warm-up, reductions in damping and modulus defect from the values in the annealed condition are looked for as evidence of long-range migration of radiation defects to dislocations. To date, low-temperature irradiations of 2, 20, and 85 hours have been made. The last is the longest attainable with the 50-liter liquid helium storage dewar now used and corresponds to a dose of approximately 6×10^{13} neutrons/cm^2/sec above 0.6 MeV. After the 2- and 20-hour irradiations dislocation pinning was observed in the temperature ranges of Stages III and IV of radiation damage annealing in copper; after the 85-hour irradiation pinning was also observed at the temperature of Stage I_E. More detailed analysis will be required to establish whether the latter observation represents true long-range migration of defects.

DEFECTS IN NEUTRON-IRRADIATED COPPER

J. C. Crump, III

Recent studies by Ruhle and Wilkens[1] and by McIntyre[2] on small dark spots observed in neutron-irradiated copper have led to conflicting conclusions regarding the nature of these defects. The former concluded that the defects they observed were vacancy in nature, whereas the latter concluded that those they observed were interstitial in nature. Similar studies have been made on copper samples irradiated at ≈40°C in the core of the LITR at Oak Ridge with a flux of 1.67×10^{13} fast neutrons/cm^2/sec (E > 0.6 MeV). Electron micrographs of defects produced in samples irradiated to doses of 1.2×10^{17}, 5.8×10^{17}, 1.4×10^{18}, and 4.2×10^{19} neutrons/cm^2 have been analyzed using stereo techniques, and >90% of the visible defects were found to be vacancy in character. The density of visible defects was found to vary from ~9×10^{14}/cm^3 to ~1.4×10^{16}/cm^3 with increasing dose, and although the size of the largest defects observed also increased with dose, the peak in the distribution remained essentially constant at ~60 Å diameter.

[1] M. Ruhle and M. Wilkens, Phil. Mag. 15, 1075 (1967).

[2] K. G. McIntyre, Phil. Mag. 15, 205 (1967).

THERMAL NEUTRON DAMAGE IN CADMIUM

R. R. Coltman, Jr., C. E. Klabunde, J. K. Redman, and A. L. Southern

The study of (n,γ) recoil damage in cadmium has been resumed using .0015-in.-thick single-crystal ribbons of different orientations. The specimens, which have resistance ratios around 3000, exhibit various electrical size effects. By measuring damage production rates during small thermal neutron doses at constant flux intensity, empirical corrections for the size effect in each specimen were derived. The application of these corrections to isochronal recovery data combined with improved thermometry enables an accurate comparison to be made between recovery studies of doses which differ by a factor of 1000. Using isochronal annealing programs of greater resolution than in the past, a

partial completion of the present effort has revealed a previously unobserved recovery process, which occurs at about 230°K. The fraction of damage associated with this process is seen to decrease with increasing initial irradiation dose obtained at 3.6°K. From earlier data a recovery process occurring in the range of 70-90°K was thought to be non-first order in character and to represent some type of long-range defect migration. Recent data obtained with greater resolution, however, suggest that the 70-90°K range involves two processes which may be first order in nature; the fraction of damage associated with each changes with increasing dose. This result can have a substantial effect upon the interpretation of the recovery mechanisms. Damage rate measurements have been made at 3.6°K for doses up to 3.6×10^{-4} atomic concentration of capture events. After correction for the electrical size effects all samples show about the same decrease in production rate with increasing dose. This decrease, which is attributed to irradiation annealing, indicates that the interaction volume associated with annihilation of existing damage by the occurrence of a new capture event is 200 atomic volumes.

DISPLACEMENT CROSS SECTIONS BY FAST ELECTRONS

O. S. Oen

Some of the details and assumptions involved in the calculation of defect production in solids by the recoil mechanism have been reviewed. It is found that an improved account of the increased path length of the fast electron due to small angle multiple scattering may be made by incorporating the multiple scattering theory of Molière into the increased path length formalism of Yang. The average increase in path length found in this way should be considerably better than using one-half the Yang prediction as conventionally done in the past.

A simple method has been found to extract the atomic displacement cross section for a linear displacement probability function of arbitrary slope from the calculated primary and total displacement cross sections based on a sharp displacement threshold. The procedure is very direct

and should enhance the usefulness of the rather extensive tables which have been calculated using the sharp threshold assumption.

The most favorable channeling directions for heavy particles in single crystals are the same as those used for fast electron bombardment when determining threshold displacements and defect yields as a function of crystal direction. Evidence for electron channeling has been observed recently, but what effect this may have on displacement cross sections is not yet known. Conventional channeling theories cannot provide a direct answer, since the charge of the electron causes it to be pulled into the atomic row where it will undergo additional scattering. Further work is necessary to assess the role electron channeling may have in displacement cross sections. [Summary of paper to be published in Radiation Effects in Semiconductors, edited by F. L. Vook, Plenum Press.]

THEORY OF THE ANNEALING OF RADIATION DAMAGE

W. E. Atkinson

The annealing theory of T. R. Waite,[1] with extensions, has been programmed for the IBM 360 computer. The program provides great flexibility in treating annealing data. Using this program, the model of Corbett, Smith and Walker[2] has been reapplied to Stages I_D and I_E in copper, using the recent data of Coltman, Klabunde and Redman. The model entails correlated migration of interstitials to their original sites, together with free migration of interstitials, leading to both annealing and interstitial clustering. No treatment of the competition between these processes has been given before. The model has been shown to give qualitative agreement with the slight, but significant, dose dependence of Stage I_D. Investigation is under way to consider the effects of impurities and of the initial probability distribution of an interstitial atom about its original site, in order to improve the quantitative agreement with the dose dependence of the amount annealing in I_D and the peak shift with dose of I_E.

[1] T. R. Waite, Phys. Rev. 107, 463 (1957).

[2] J. W. Corbett, R. B. Smith, and R. M. Walker, Phys. Rev. 114, 1460 (1959).

RADIATION DAMAGE IN ZnO SINGLE CRYSTALS

W. E. Vehse,[1] W. A. Sibley, F. J. Keller,[2] and Y. Chen

The radiation and additive coloration of Li-doped and "pure" ZnO crystals have been investigated. The radiation coloration is enhanced by the presence of Li impurity when the radiation temperature is in the range 80-330°K, but the additive coloration is suppressed in Li-doped specimens. The defect production rate, as measured by the increased optical absorption of the samples, is a linear function of electron irradiation intensity and decreases with irradiation energy. The energy dependence of the electron coloration suggests that the defect giving rise to the coloration is produced by the displacement of zinc ions. For a given dose of radiation, fast neutrons (>1 MeV) produce about 30 times as many defects as do energetic electrons. In irradiated crystals the coloration anneals out around 250°C, whereas in additively colored samples the annealing out temperature is about 900°C. Gamma irradiation during and after annealing indicates that in both cases annealing is complete and not due only to the loss of electrons or holes from the defect center. It is concluded from the study that radiation damage in ZnO occurs primarily as a result of elastic collisions, and that the photochemical processes prevalent in alkali halides contribute very little, if any, to the damage. [Abstract of paper to be published in The Physical Review.]

[1]Research Participant from West Virginia University, Morgantown.

[2]Consultant, Clemson University.

NEGATIVE-ION VACANCIES IN IRRADIATED MgO

Y. Chen, W. A. Sibley, F. D. Srygley,[1] R. A. Weeks, E. B. Hensley,[2] and R. L. Kroes[2]

An ESR signal occurring in neutron-irradiated MgO crystals has been identified as being due to F centers (negative-ion vacancies with each vacancy possessing <u>one</u> trapped electron), and the results of recent ENDOR measurements are consistent with this identification. Recently several

researchers have claimed, on the basis of optical and ESR data obtained on neutron-irradiated specimens, that the large absorption band at about 5.0 eV is due to F centers. Our results, which combine optical and ESR measurements on neutron-irradiated, electron-irradiated, and additively colored samples, indicate that for our crystal purity and irradiation conditions this is not the case. In fact, we would tentatively identify the optical absorption at 4.96 eV in our specimens as due to F' centers (negative-ion vacancies which have trapped two electrons). [Summary of paper to be published in J. Phys. Chem. Solids.]

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[2]University of Missouri, Columbia.

ON THE NEGATIVE-ION VACANCY IN IRRADIATED MgO

J. L. Kolopus and Y. Chen

Optical and electron spin resonance (ESR) studies are being made on single crystals of MgO to establish whether or not there is a correlation between the optical absorption band at 250 nm and the ESR F-center signal in irradiated samples. Previously the optical absorption band at 250 nm has been correlated with the F-center resonance in neutron-irradiated single crystals, and the oscillator strength as calculated from Smakula's formula was 0.8.[1] Our studies with nominally pure crystals irradiated from 1 minute to 60 hours in the ORR at the ambient temperature of 50°C indicate that the growth rates of the ESR F-center signal and the 250-nm band are not the same. Moreover, the "apparent oscillator strength" far exceeds unity. Preliminary studies also indicate that there is a dependence of the defect production on irradiation temperature and that at low doses this dependence is stronger in the optical measurement than that of the ESR. Samples which have been encapsulated in quartz (to give higher irradiation temperatures) show a decrease in the production of optical centers and F centers compared with samples irradiated at the pool temperature.

Thermal annealing studies of the 250-nm band and the F centers in neutron-irradiated samples both show the maximum rate of decay to be near 400°C. After heating to 600°C, virtually all of the centers have decayed and they cannot be recovered by subsequent gamma irradiation. In samples which have been additively colored, no ESR F-center signal exists and the 250-nm absorption band anneals at about 1150°C. During the annealing process, several neutron-irradiated samples have been optically bleached using light in the 250-nm wavelength region from high pressure Hg arc lamp, in an attempt to determine whether at a given temperature the optical bleaching could increase the rate of annealing. Both the ESR and the optical measurements indicate that, if there is an effect, it is not much larger than the experimental error. Further attempts to repeat these measurements with greater precision and with a stronger illuminating source will be made.

[1]R. D. King, Ph.D. thesis, University of Reading, England, 1967.

A COMPARISON OF ELECTRON-INDUCED RADIATION DAMAGE IN KCl AND MgO SINGLE CRYSTALS

W. A. Sibley and Y. Chen

The radiation production of F centers in "pure" and doped KCl and MgO crystals has been investigated. The coloration of KCl depends sensitively on radiation temperature, radiation intensity, and sample purity but is rather insensitive to the energy of the incident radiation. For example, at radiation temperatures above 200°K color center production is proportional to a higher power of the radiation intensity and trace amounts of impurity (6 ppm Pb) are sufficient to almost completely suppress the coloration. When the radiation temperature is below 200°K, F-center production is a linear function of the radiation intensity and the addition of impurities to the specimens enhances the coloration rate rather than decreasing it. These characteristics argue strongly for a photochemical-type defect production mechanism in KCl. In MgO, unlike KCl, the F-center production rate is a linear function of electron irradiation intensity over the entire radiation temperature range 80-330°K

and decreases with irradiation energy. Moreover, impurities have not been observed to decrease the colorability of these samples. It is concluded from the study that radiation damage in MgO occurs primarily as a result of elastic collisions and the photochemical processes prevalent in the alkali halides contribute very little to the damage.

RADIATION DEFECT PRODUCTION AND ANNIHILATION IN KCl NEAR ROOM TEMPERATURE

E. Sonder and L. C. Templeton

Extended gamma irradiation of KCl near room temperature causes the F-center concentration to saturate between 10^{18} and 10^{19} cm^{-3}. The saturation concentration is a function of the dose rate and the temperature, and is the same whether approached by production of defects in a fresh sample or by destruction of an excess number of defects in a sample that has been pre-irradiated under different conditions of temperature or dose rate. The temperature dependence of the saturation level can be described by an empirical activation energy of 0.4 eV between 10° and 50°C. The approach to saturation is approximately 50 times slower than the approach to the aggregation steady state, suggesting that mobile vacancies must travel much farther to annihilate than to form F-aggregate centers. Observations that the approach to saturation cannot be described by simple kinetics and that the shape of decay curves depends upon previous irradiation conditions support the suggestion that the size of the centers with which vacancies annihilate depends upon previous irradiation conditions. [Abstract of published paper: Phys. Rev. 164, 1106 (1967).]

THE INFLUENCE OF ELECTRON-TRAPPING IMPURITY ON DEFECT CREATION AND BLEACHING IN KCl IRRADIATED AT 78°K

J. H. Crawford, Jr.,[1] W. A. Sibley, and E. Sonder

The excitonic mechanism for creation of halogen Frenkel-type defects in alkali halides predicts an early positive curvature in the defect growth

curve. The model also predicts that annihilation of V_K centers by the optical release of electrons from traps would produce Frenkel pairs in the halide sublattice. The first prediction has been checked in $KCl:Tl^+$ and $KCl:Pb^{++}$ irradiated at 78°K with 1.7-MeV Van de Graaff electrons, and the second upon IR bleaching of an irradiated Tl^+-doped crystal at 78°K. If one takes the F-center concentration as a measure of the Frenkel defect density, both tests were positive. A careful monitoring of the α-band region before and after bleaching, however, indicates that the F-center concentration is not a valid measure of the vacancy density. In a crystal containing 48 ppm Tl^0, the α-center concentration after irradiation at 80°K was 2.5 times that for F centers. Moreover, IR bleaching of Tl^0 and V_K, while enhancing the F band ≈30%, destroyed nearly all of the α centers. The last observation reveals that more empty halide vacancies are destroyed than F centers are produced by the bleaching light. [Abstract of published paper: Phys. Stat. Sol. 23, 301 (1967).]

[1]Consultant, University of North Carolina.

RADIATION-PRODUCED ULTRAVIOLET ABSORPTION IN KCl

J. C. Garth[1] and E. Sonder

Ultraviolet absorption bands produced in KCl by electron irradiation at 80°K were studied as a function of trace impurity content and annealing temperature. A single absorption band peaked at 240 nm, reported by Faraday and Compton, was found in samples from three undoped ingots and one lightly lead-doped ingot at the irradiation temperature. After step annealing to higher temperatures new bands of variable width, height, and position were formed which were strongly ingot dependent. In addition, the temperature at which the 240-nm band first showed changes was sample dependent. For a more heavily calcium-doped sample, a different initial ultraviolet band was found peaked at 230 nm. These bands are attributed to interstitial halide centers which cluster at, and are stabilized by, trace amounts of impurity. [Abstract of paper to be published in The Physical Review.]

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EXPERIMENTAL EVIDENCE FOR PRODUCTION AND ANNIHILATION OF INTERSTITIAL IMPURITIES IN ELECTRON-IRRADIATED n-TYPE GERMANIUM

A. Hiraki,[1] J. W. Cleland, and J. H. Crawford, Jr.

Although the presence of interstitial impurity as an irradiation defect has been well established in Si through electron paramagnetic resonance studies,[2] such direct evidence has not been available for Ge. In a recent study[3] indirect evidence from electrical property behavior of Cu-doped specimens was interpreted as indicating that Cu acceptors are ejected into interstitial sites with large (>50%) yield during irradiation at 77°K. Also, the recombination of migrating vacancies ($\bar{V}$) and interstitial Cu was assumed to explain the reverse annealing observed upon subsequent warming. In this paper we report the results of a study of Sb-doped Ge which also strongly suggest that interstitial impurity is an indirect product of electron irradiation at 77°K. In contrast to Cu, Sb is expected to be a shallow donor whether located in a substitutional or an interstitial site. Hence, the method for detecting interstitial Sb atoms (Sb_I) must be different from that utilized in the experiments on Cu-doped material. [Abstract of paper presented at Conference on Radiation Effects in Semiconductors, Santa Fe, New Mexico, October 3, 1967; to be published in the Proceedings.]

[1]Guest scientist from Osaka University, Osaka, Japan.

[2]G. D. Watkins, Proceedings of Seventh International Conference on the Physics of Semiconductors (Dunod Cie, Paris, 1965), Vol. 3, p. 97.

[3]A. Hiraki, J. W. Cleland, and J. H. Crawford, Jr., J. Appl. Phys. 38, 3519 (1967).

OBSERVATION OF IRRADIATION-INDUCED INTERSTITIAL COPPER IMPURITY IN GERMANIUM

A. Hiraki, J. W. Cleland, and J. H. Crawford, Jr.

The possibility that substitutional impurities can be displaced into interstitial sites in germanium by electron irradiation was investigated by electrical property measurements. The impurity chosen was copper since

it is a triple acceptor in a lattice site but is a donor when interstitial; hence, ejection of a single copper atom adds four electrons to the conduction band. Specimens of n-type germanium doped with both copper and antimony (the ratio of Cu to Sb was ~1:4) were irradiated with 1.6-MeV electrons at 77°K along with control specimens that contained no copper. The decrease in electron concentration n was appreciably less in the copper-doped specimen than in the control specimen, as would be anticipated if copper impurities were displaced into interstitial sites. Isochronal annealing at several temperatures between 70° and 260°K after irradiation produced a further decrease in n (reverse annealing) in the copper-doped specimens, whereas the control specimens showed a normal recovery of n. A likely explanation of the reverse annealing is that of restoration of irradiation-produced interstitial copper into substitutional sites through interaction with migrating vacancies. A type of negative photoconductivity was also observed in the temperature range in which reverse annealing occurred. [Abstract of published paper: J. Appl. Phys. 38, 3519 (1967).]

NEW ANNEALING STAGE OF DEFECTS IN n-TYPE GERMANIUM PRODUCED BY ELECTRON IRRADIATION AT 30°K

A. Hiraki, J. W. Cleland, and J. H. Crawford, Jr.

Electrical property measurements of 10°K electron-irradiated n-type Ge have indicated defect states (electron traps) that anneal near 65°K and a "permanent defect" that is stable at 80°K. Similar experiments involving electron or gamma irradiation at 77°K have indicated defect states that are stable nearly to room temperature. To ascertain if the "permanent defect" is similar to that introduced at 77°K, we irradiated Sb- or As-doped Ge with 1.5-MeV electrons at 30°K, annealed at 77°K to remove the 65°K defect state, and conducted isochronal anneals from 77° to 375°K in the dark or under illumination from a tungsten lamp. Dark-room annealing near 150°K removed 30% of the defects, whereas with illumination annealing of the same defects commenced at 77°K. This behavior was independent of doping type. These experiments suggest that ionization accompanying the 77°K irradiation renders the defects unstable. For this reason

no extensive annealing at 150°K is observed after 77°K irradiation with electrons or gamma rays.

IMPURITY-INDEPENDENT DEFECTS IN p-TYPE GERMANIUM PRODUCED BY ELECTRON IRRADIATION AT 77°K

A. Hiraki, J. W. Cleland, and J. H. Crawford, Jr.

Electrical property and electron paramagnetic resonance (EPR) measurements have indicated that one of the predominant effects of electron irradiation of p-type Ge at low temperatures is creation of electron traps that can be converted to donor-type defects by an appropriate optical or annealing treatment. A definite model of the type of defect was not established; hence, we used electron irradiation at low temperature of various types of p-type Ge containing different amounts of Ga, Cu, quenched-in vacancies, or fast-neutron-induced defects to study the nature of these defects. The rate of introduction and annealing behavior (at 195° and 230°K) was almost identical in all specimens, which would suggest that the defects were impurity independent. The annealing behavior from various types of specimens can be interpreted as suggesting that the defects are closely separated interstitial Ge and vacancy pairs. Some evidence for a saturation of annealing was observed for specimens containing a considerable quantity of chemical acceptor impurities.

CHANNELING

CALCULATION OF ENERGY LOSS SPECTRA IN PLANAR CHANNELING

M. T. Robinson

A machine calculation is being used to study in some detail a model proposed to account for the channeled ion energy loss spectra observed when high energy heavy ions, typically 60-MeV I, are passed through thin (0.1 to 1.0 μm) monocrystalline gold targets. The transverse oscillations of the ions in the planar channels are governed by the interaction

potential $V(x) = V_o \cosh bx$, obtained by averaging Molière's approximate Thomas-Fermi potential over the crystal planes bordering the channel and retaining only the most slowly varying term in the result. The stopping power of the medium is represented by $(-dE/dZ) = s(x)E^{1/2}$, where the dependence of the stopping power on the transverse coordinate of the ion is assumed to be

$$s(x) = \sum_{k=0}^{4} s_k \cosh (kbx/2),$$

where the s_k are parameters to be adjusted. Assuming that the transverse and longitudinal motions of the particle may be treated separately, the classical equations of motion may be solved in terms of Jacobian elliptic functions. The machine program uses these analytical solutions to produce histograms of the angles and energies with which the incident ions emerge from the target crystal. The emphasis of the calculations so far has been to obtain qualitative agreement between model and experiment and to determine the effects of mosaic misorientation in the target on the results.

The experimental energy loss spectra are characterized by a number of maxima, of approximately constant separation, commencing at a value about half that for "random" orientations. These features may be roughly reproduced by setting $s_2 = s_3 = s_4 = 0$; $s_o = 0.5$ (random value); and normalizing $s(x)$ to the random value for large angle trajectories (the normalizing fixes s_1). The group separation calculated agrees reasonably well with that observed for {111} Au channeling.

COMPARISON OF CHANNELING THEORY WITH COMPUTER RESULTS

O. S. Oen

A few results from a comparison of Lindhard's theory with the Monte Carlo computer results of Robinson and Oen were reported in last year's progress report (ORNL-4098). A further comparison has shown that for projectiles having initial energies from 2.5 to 10 keV the fraction not channeled from an external beam incident along a crystallographic direction is proportional to the square of the distance between atoms along the row

for each of the three major crystallographic directions in fcc and bcc lattices, which is close to the three-halves power predicted by theory. A square dependence is also found for the <100> and <110> directions in a diamond lattice; however, for <111> it is more complex than simply squaring the average of the unequal atomic spacing. The energy dependence of the fraction not channeled follows fairly close to the $E^{-1/4}$ dependence predicted by theory. The fraction channeled is found to have only a weak dependence on the target-to-projectile mass ratio as it is varied from 1/3 to 3, in agreement with theory, which predicts no dependence. For the Born-Mayer potential the critical channeling angles deduced from the computer results ranged from somewhat higher to somewhat lower than the predicted values, depending on the individual cases examined and which of the two channeling criteria was used in the theory. For the Bohr potential, theory predicts too large a critical angle, as reported in last year's progress report.

MOTION OF ENERGETIC PARTICLES IN CRYSTALS

S. Datz,[1] C. Erginsoy,[2] G. Leibfried,[3] and H. O. Lutz[4]

During the past five years, studies of directional effects on the trajectories, ranges, and energy losses of energetic particles in solids have done much to elucidate the nature of the processes involved in stopping. The information gained from these studies has also pointed to new methods which can be used to study a variety of crystal properties. These include the determination of stopping-power distributions and interatomic potentials in crystals, and the direct demonstration of certain crystallographic features such as lattice defects and impurities. In this article we are concerned only with effects of the crystalline structure which influence particle trajectories close to the symmetry directions of the crystal. After a review of theoretical considerations in Section 2, the ranges of heavy ions will be discussed in Section 3. Section 4 contains the results of transmission through thin crystals. Section 5 reviews investigations on nuclear reactions, x-ray yields, and radiation damage. Section 6 covers Rutherford scattering and emission from lattice sites. Section 7

describes methods for obtaining spatial distributions of emergent ions. [Abstract of published paper: Annual Review of Nuclear Science 17, 129 (1967).]

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LOCATION OF SHOULDERS IN CHANNELING PHENOMENA

J. H. Barrett

Several phenomena produced by bombarding a solid with a beam of particles show a minimum yield when the beam impinges along the directions of major rows or planes of atoms in the solid; these are the channel directions. As the direction of the beam is moved away from the precise channeling direction, the observed yield passes through a maximum called the "shoulder" of the distribution. Attention in this work is concentrated on the lattice directions at which shoulders are found. A Monte Carlo computer program for use in calculating such effects has been written. It incorporates a model of lattice vibrations in which the lattice atoms vibrate independently of each other. The position of the shoulder for a planar channel is predicted quite well as the angle at which ions injected near the center of the channel have enough kinetic energy transverse to the planes of atoms bounding the channel to break through these planes. The position of the shoulder of a row channel is found to be determined by the shoulders of the several planar channels intersecting at the row channel. The breakthrough angle for rows appears to mark a rather sharp boundary between orientations in which row or planar effects predominate. [Abstract of paper to be published in The Physical Review.]

RADIATION DAMAGE AND COLLISION SPECTRA ASSOCIATED WITH CHANNELING OF IODINE IONS IN GOLD

T. S. Noggle and J. H. Barrett

Electron microscope studies of the channeling of 51-MeV iodine ions in gold single-crystal films have shown that the damage rate for incidence in a [110] direction is more than an order of magnitude less than for incidence several degrees away from [110]. This reduction in damage rate is associated with the reduced elastic energy loss when channeling occurs. To aid in interpreting the results of such experiments, a Monte Carlo computer program incorporating thermal vibrations has been written which calculates the collision spectra of the lattice atoms. The moving ions are assumed to interact with one lattice atom at a time, and deflections are computed using the impulse approximation and the Thomas-Fermi potential. Near [110] the angular range of reduced damage rate is very nearly the same for calculation and experiment; however, the calculated minimum damage rate is approximately 1/3 the experimental value (reduction of 14 times). Planar channeling may be present in the experimental work and could account for this difference. Calculations for (111) planar channeling indicate approximately 1/10 the change in damage rate calculated for [110] channeling. Preliminary experimental studies support this much smaller change in the damage rate, and experiments in progress will further test the theory for both planar (111) and directional [110] channeling. [Abstract of paper presented at International Conference on Solid State Physics Research with Accelerators, Brookhaven National Laboratory, September 25-28, 1967.]

EFFECT OF CHANNELING ON DAMAGE RATES ASSOCIATED WITH HEAVY ION IRRADIATION OF GOLD

J. H. Barrett and T. S. Noggle

Electron microscope studies of radiation damage associated with channeling of 60-MeV iodine ions in gold have been compared with the collision spectra obtained from Monte Carlo calculations of successive two-body interactions occurring as an ion moves through the crystal. This calculation uses the Thomas-Fermi potential with Firsov's screening radius

and takes into account parameters such as thermal vibrations, mosaic spread and beam divergence. Change in the calculated frequency of energetic collisions with orientation correlates very closely with the experimental variation in damage rate with incident beam direction. The scan of (111) shows a minimum damage rate about 0.2 that for a random direction with a half-width of 0.23°. The scan of [110] shows a minimum about 0.08 that for a random direction and an apparent half-width of 0.8°. The calculations have shown that the concept of a simple acceptance angle relative to [110] has little meaning, since the variation in damage rate is a sensitive function of the detailed beam direction, due to the contribution to channeling of low index planes which dominate for angles more than about 0.5° from [110].

The calculations predict oscillations in the damage density with depth in the crystal. These oscillations are a maximum near the entrance surface and are damped in about two periods corresponding to a path length of ~700 Å. Stereo studies of the damage have failed to identify depth variations of the damage density which correlate with the calculations.

INTERACTION OF MONOENERGETIC ARGON IONS (0-8 keV) WITH COPPER TARGETS: SPUTTERING AND ION SCATTERING

J. R. Woodyard[1]

A summary is given of studies of particles emitted from a Cu (100) target when bombarded by 0.5 to 8 keV Ar^+ ions.[2] The target was rotated about a <100> axis and the particles emitted at a 90° angle with respect to the incoming beam were analyzed with a mass spectrometer.[3] [Abstract of paper to be published in Proceedings of the 15th Annual Conference on Mass Spectrometry and Allied Topics, Denver, Colorado, May 14-19, 1967.]

[1]U. S. Atomic Energy Commission Postdoctoral Fellow under appointment from Oak Ridge Associated Universities.

[2]A detailed report of these investigations will be submitted to J. Appl. Phys. for publication.

[3]A. J. Smith, D. J. Marshall, L. A. Cambey, and J. Michael, Vacuum 14, 263 (1964); A. J. Smith, L. A. Cambey, and D. J. Marshall, J. Appl. Phys. 34, 2489 (1963); A. L. Southern, Twelfth Annual Conference on Mass Spectrometry, Montreal, 1964.

ELECTRON CAPTURE AND LOSS PROCESSES FOR FAST (20-150 MeV) BROMINE AND IODINE IONS IN GASES

S. Datz, C. D. Moak,[1] H. O. Lutz, L. C. Northcliffe,[2] and L. B. Bridwell[3]

Monoenergetic bromine and iodine ion beams of high charge purity from the Oak Ridge tandem accelerator and an MP tandem accelerator[4] have been used to investigate the variation of ion-charge state with increasing gas-target thickness. From the single-collision data, it was apparent that multiple-charge loss processes are significant. For example, when 110-MeV ^{127}I ions with an initial charge of +12 collided with Ar, as many as 9 electrons were lost in a single collision, and the sum of the multiple-loss cross sections was comparable in magnitude with the single-loss cross section ($0.4 \times 10^{-16} cm^2$). The relative multiple-loss cross sections are not as large with lighter target gases such as hydrogen or helium. These effects are also observable in the variation of charge state population with increasing pressure and cause strongly non-gaussian distributions at equilibrium. [Abstract of paper to be published in Proceedings of Fifth International Conference on Physics of Electronic and Atomic Collisions, Leningrad, July 1967.]

[1]Physics Division, ORNL.

[2]Texas A & M University.

[3]Research Participant from Murray State University, Murray, Kentucky.

[4]We are indebted to High Voltage Engineering Corporation, Burlington, Massachusetts, for the use of the MP tandem accelerator facility.

STOPPING POWERS FOR IODINE IONS AT ENERGIES UP TO 200 MeV

L. B. Bridwell, L. C. Northcliffe, S. Datz, C. D. Moak, and H. O. Lutz

Multicomponent beams of ^{127}I ions from an MP tandem accelerator have been used to extend some earlier stopping-power measurements for C, Al, Ni, Ag, Au, and UF_4 to energies up to 200 MeV. The expected maximum values of stopping powers have been reached in some cases. [Abstract of published paper: Phys. Rev. 159, 276 (1967).]

EVIDENCE OF SHELL EFFECTS AND THE APPROACH TO EQUILIBRIUM IN THE CHARGE-STATE DISTRIBUTIONS FOR 15-160 MeV ^{79}Br AND ^{127}I IONS IN CARBON

C. D. Moak, H. O. Lutz, L. B. Bridwell, L. C. Northcliffe, and S. Datz

Equilibrium charge distributions of ^{79}Br and ^{127}I ions have been obtained with an electrostatic analyzer. Influences of ionic shell structure upon the charge distributions have been found. Thin carbon foils (8-78 $\mu g/cm^2$) have been used to observe the approach to charge-state equilibrium. [Abstract of published paper: Phys. Rev. Letters 18, 41 (1967).]

DISLOCATIONS, RADIATION EFFECTS ON PLASTIC DEFORMATION AND FRACTURE

DISLOCATION CONFIGURATIONS IN COPPER IN THE FIRST STAGES OF PLASTIC FLOW

F. W. Young, Jr.

The experimental evidence concerning the motion and multiplication of dislocations at very low stresses in copper crystals of low dislocation density is reviewed, particularly in the terms of dislocation dynamics. Yet to be determined experimentally are the sources of new dislocations and the mechanism of multiplication. The results of new experiments on crystals deformed by compression, bending and tension, in which the dislocation configurations were determined by x-ray topography, have established that edge dislocations move more easily through the crystal and leave long screw dislocations for all types of deformation at the initial stages of motion and multiplication. In some cases the new dislocations may arise from as-grown ones in the crystal, but the mechanism has not been established. [Summary of paper to be published in proceedings of Battelle-Seattle-Harrison Colloquium on Dislocation Dynamics, Seattle, Washington, May 1-6, 1967.]

ELECTRON MICROSCOPE OBSERVATIONS ON THE DISLOCATION ARRANGEMENT IN COPPER SINGLE CRYSTALS IN THE STRESSED CONDITION

J. C. Crump, III, and F. W. Young, Jr.

Copper crystals were compressed with resolved stresses of 40, 100, and 500 g/mm^2, then irradiated with fast neutrons while under compression to pin the dislocations in their stress-applied positions, and examined by electron microscopy. Although the dislocation arrangements found in the sample compressed to 500 g/mm^2 were very similar to those which have been reported previously, the dislocation configurations found in samples after applying the lower stresses were significantly different from those reported previously in stress-relaxed crystals. [Abstract of paper to be published in Philosophical Magazine.]

EQUILIBRIUM SHAPE OF DISLOCATIONS UNDER STRESS: COMPARISON OF EXPERIMENTAL OBSERVATIONS WITH THEORY

V. K. Paré and J. C. Crump, III

Single crystals of copper were compressed and irradiated with fast neutrons while under load to pin dislocations in their stress-applied positions. Thin electron microscope samples were prepared with surfaces parallel to the primary slip plane and micrographs were taken of dislocations lying in this plane. The equilibrium shapes of these dislocations were compared with those predicted by the theory of DeWit and Koehler.[1] A computer and digitally controlled plotter were used to generate curves representing the theoretical dislocation shapes, and these curves were plotted on transparent film for superposition onto micrographs of dislocations. The stresses thus measured on dislocations observed in samples compressed to 40, 100, and 500 g/mm^2 resolved shear stress were found to agree closely with the applied stress even though a majority of the dislocations studied were in the vicinity of other dislocations whose presence might be expected to modify the stress acting on the dislocations studied.

[1] A. DeWit and J. S. Koehler, Phys. Rev. 116, 1113 (1959).

DEFORMATION BANDS AND THE FORMATION OF <111>-<001> FIBER TEXTURES IN ALUMINUM

R. E. Reed and C. J. McHargue[1]

Single crystals of aluminum were reduced 90% in diameter by extrusion at 296° and 77°K. The resultant double fiber texture had a strong <111> component with a weak <001> component. The relative amounts of these components varied with starting orientation. Decreasing the temperature of deformation increased the amount of <001> texture component in crystals with initial orientations near <111>. The starting orientation and temperature of deformation strongly affected the morphology of the <001> component. The effects of orientation and temperature upon the distribution of the <001> texture component in extruded aluminum single crystals were rationalized on the basis of deformation band formation and interaction. [Abstract of published paper: Trans. AIME 239, 1604 (1967).]

[1]Metals and Ceramics Division, ORNL.

STRESS DEPENDENCE OF DISLOCATION VELOCITY IN SINGLE-CRYSTAL NIOBIUM

H. D. Guberman

The stress dependence of dislocation velocity was measured by etching in niobium single crystals grown by an electron-beam floating-zone technique. The velocity-stress relation was determined with temperature, purity, and low neutron dose levels as variables. The data can be expressed by an equation of the form $\bar{v} = (\tau^*/\tau_o)^{m^*}$ in all cases. The exponent m* was found to increase slightly with decreasing temperature, increase strongly with greater impurity content, and decrease with neutron irradiation up to 8.3×10^{17} n/cm^2 (E > 1 MeV).

Measurements of the strain-rate sensitivity and the stress relaxation indicated that these techniques were unsatisfactory in determining the exponent m* in the velocity equation.

Correlations could be made between the data from etching and mechanical measurements in irradiated samples which suggest that the increase

in the upper yield stress upon neutron irradiation is associated with a dynamic resistance to dislocation motion. [Abstract of paper to be published in Acta Metallurgica.]

CHARACTERIZATION OF THE STRAIN RATE DEPENDENCE OF THE SHEAR STRESS FOR NIOBIUM SINGLE CRYSTALS

R. E. Reed, H. D. Guberman, and R. W. Armstrong[1]

There are two alternative descriptions which are widely used for characterizing the temperature and strain-rate dependence of the resolved shear stress for single crystals. One involves the relation

$$m' = \left(\frac{d \ln \dot{\gamma}}{d \ln \tau}\right)_T \tag{1}$$

and the other

$$\frac{v^*}{kT} = \left(\frac{d \ln \dot{\gamma}}{d \tau_{th}}\right)_T \tag{2}$$

where $\dot{\gamma}$ is the shear strain rate, τ is the applied shear stress, τ_{th} is the thermal component of the applied shear stress, v^* is an activation "volume", and the other symbols have their usual meaning. Normally τ and τ_{th} are related by

$$\tau = \tau_{th} + \tau_G \tag{3}$$

where τ_G is the athermal component of the applied stress, and for a strain rate change test

$$\left(\frac{d \ln \dot{\gamma}}{d\tau}\right)_T = \left(\frac{d \ln \dot{\gamma}}{d \tau_{th}}\right)_T. \tag{4}$$

Our purpose is to compare the two parameters defined by Eqs. (1) and (2) for strain rate change tests performed on niobium single crystals produced under various growth conditions. [Abstract of published paper: Scripta Met. 1, 83 (1967).]

[1]Consultant, Brown University.

DEFORMATION OF IRRADIATED AND UNIRRADIATED Nb SINGLE CRYSTALS IN COMPRESSION

H. D. Guberman and R. E. Reed

The deformation of niobium is being investigated in single crystals which are of relatively high purity (resistivity ratio approximately 500 to 4.2°K). They were grown by the electron-beam floating-zone method from CIBA stock containing about 20 ppm Ta and 3 ppm W, which is significantly lower than that in material used before. The samples were further subjected to three zone passes. The flow stresses and parameters related to the thermal activation theory of deformation were determined at 194°K, 298°K, and 525°K in samples irradiated to 1.1×10^{17} n/cm^2 and 8.3×10^{17} n/cm^2 (E > 1 MeV) in the ORR, and nonirradiated material.

The flow stresses were markedly temperature dependent. In addition, the temperature dependence in this high-purity material appeared to be altered by the neutron irradiation to a greater extent than in less pure material. Measurements indicate that both the thermal and the athermal components of stress were affected by irradiation.

At the highest temperature at which measurements were made, all the samples showed strain-rate dependence which was reduced by about an order of magnitude from that at the lower temperatures. However, the flow stress was found to be independent of temperature in this range. Thus, it was concluded that this strain rate dependence was evidence of the fact that the mobile dislocation density did not remain constant during the strain-rate change test as is usually assumed.

RADIATION HARDENING IN BCC METALS NIOBIUM AND IRON

S. M. Ohr, R. P. Tucker, and M. S. Wechsler

The paper discusses some recent work on the effect of neutron irradiation on plastic deformation in single crystal niobium and polycrystalline iron. In particular the following experimental results are presented: (1) the temperature and strain rate dependencies of the yield stress, (2) direct observations in niobium of radiation damage and slip bands by

transmission electron microscopy, and (3) the size distribution of the defects following fluences of 5×10^{17} and 2×10^{18} n/cm^2 (E > 1 MeV). The hardening is found to be due primarily to an increase in the athermal component of stress. From thermal activation analysis there is an indication of slight increase in the activation energy while the activation volume hardly changes following irradiation. Thus irradiation does not appear to alter effectively the thermally activated motion of dislocations. Consequently, the observation of defects identified as dislocation loops and "channels" swept clean of defects led to an analysis of radiation hardening by contact elastic interaction between dislocations and the loops. It is found that a strong barrier model is in good agreement with the experimentally observed increase in yield stress. Thus it is suggested that the major factor contributing to radiation hardening in the bcc metals is the short-range elastic interaction between radiation-induced dislocation loops (diameters >50 Å) and dislocations set in motion during deformation. [Abstract of paper to be published in Proceedings of the International Conference on the Strength of Metals and Alloys, Transactions of the Japan Institute of Metals, Tokyo.]

THE ANNEALING CHARACTERISTICS OF NEUTRON-IRRADIATED NIOBIUM

S. M. Ohr, R. P. Tucker, E. D. Bolling, and M. S. Wechsler[1]

The annealing characteristics of neutron-irradiated niobium have been investigated in terms of tensile properties and transmission electron microscopy. In niobium single crystals as well as polycrystals relatively free of oxygen, in addition to an increase in the yield stress upon irradiation, there is a further marked increase in the yield stress following two-hour post-irradiation anneals in the temperature range 200° to 400°C. This is the temperature range where interstitial carbon atoms are found to migrate in niobium. An 800°C-anneal results in complete recovery of the yield stress to the unirradiated value. Observations by transmission electron microscopy indicate that the radiation-induced defects grow in size during anneals between 200° and 400°C. However, changes in the defect size distribution cannot account for the observed radiation-anneal hardening

based on an elastic contact interaction model. After an anneal at 600°C, numerous small spots appear throughout the sample. At 800°C, most of the defects have annealed out, leaving a small number of large defects resolvable in the electron microscope as dislocation loops. Among these large loops both interstitial and vacancy types are found. It is suggested that the trapping of carbon atoms at the irradiation-induced defects strengthens the barriers and hence is responsible for the radiation-anneal hardening.

[1]A portion of this work was done while on assignment at Battelle Institute, Geneva, Switzerland.

DOSE AND TEMPERATURE DEPENDENCE OF PLASTIC DEFORMATION IN NEUTRON-IRRADIATED NIOBIUM

R. P. Tucker, M. S. Wechsler,[1] and R. E. Reed

Single-crystal and polycrystalline samples of electron-beam-zoned niobium were irradiated over a range of doses up to about 4×10^{18} n/cm^2, E > 1 MeV, at temperatures below about 100°C. The radiation hardening is consistent with the dispersed barrier model only at low doses. Above about 2×10^{17} n/cm^2 for the single crystals and 1×10^{18} n/cm^2 for the polycrystals, the rate of hardening is substantially lower than predicted by the model.

Tensile tests were performed as a function of test temperature on niobium single crystals in the unirradiated condition and after irradiation to 2.8×10^{17} n/cm^2. The yield stress increased upon irradiation approximately the same amount at all test temperatures between 300° and 90°K, indicating a radiation-produced increase only in the athermal stress component. Some indication was seen for the suppression of twinning at low test temperatures for the irradiated samples. The critical resolved shear stress, τ, was found to be proportional to the reciprocal test temperature for unirradiated and irradiated samples. The data are also consistent with the temperature dependence predicted by the Fleischer model

of hardening from tetragonal distortions, i.e., $(\tau/\tau_o)^{1/2} = 1 - (T/T_o)^{1/2}$ where τ_o and T_o are constants.

[1]A portion of this work was done while on assignment at Battelle Institute, Geneva, Switzerland.

WORK HARDENING CHARACTERISTICS OF NEUTRON-IRRADIATED IRON

S. M. Ohr

This paper describes observations on the work hardening characteristics of neutron-irradiated polycrystalline iron. A close examination of the work hardening portion of the tensile curves reveals that the curves for the irradiated samples can be superimposed on the unirradiated curve by shifts along the strain axis. The implication of the superposition is that the neutron irradiation may be considered as being equivalent to plastic prestraining. The effective prestrain increases in proportion to the neutron fluence to the 1/6 power. Observations of the deformation structures of unirradiated and neutron-irradiated iron by transmission electron microscopy indicate that the structure in the irradiated sample corresponds to that of a somewhat more heavily deformed unirradiated sample. The severe clustering of dislocations in neutron-irradiated iron, believed to be due to dislocation channeling, could account for the analogy between neutron irradiation and plastic prestraining. [Abstract of paper to be published in Scripta Metallurgica.]

THE TEMPERATURE DEPENDENCE OF YIELDING IN AN IRRADIATED LOW-CARBON PRESSURE VESSEL STEEL

M. S. Wechsler and N. E. Hinkle

The dependence of the tensile parameters (yield stress, ultimate tensile strength, uniform elongation, and stress, strain, and reduction in area at fracture) upon test temperature has been investigated for a low-carbon pressure vessel steel (ASTM A-212-B) in the unirradiated condition and after neutron irradiation to about 10^{19} n/cm^2 (E > 1 MeV) at about 60°C.

The tests were conducted under uniaxial loading conditions at temperatures from 475°K to about 20°K.

The unirradiated steel exhibits a strong increase in yield stress upon decreasing the test temperature; at 77°K the yield stress is more than three times its value at room temperature. The shape of the curve of yield stress, σ, versus temperature, T, fits an expression of the form $\sigma = \sigma_o + (B/T)$ where σ_o and B are constants. Upon irradiation, the increase in yield stress is roughly independent of temperature, with perhaps a slight tendency for larger increases at lower temperatures. This result suggests that the irradiation introduces barriers to dislocation motion that cannot be overcome by thermal activation.

The reduction in area at fracture and the uniform elongation exhibit a sharp decrease at about 70°K, which is a measure of the ductile-brittle transition temperature for smooth samples under uniaxial loading conditions. Upon irradiation, the reduction in area at fracture and the uniform elongation were reduced and the transition temperature was increased. However, the fracture stress in the ductile range was not changed upon irradiation.

THE RELATIONSHIP BETWEEN RADIATION HARDENING AND EMBRITTLEMENT IN A LOW-CARBON PRESSURE VESSEL STEEL

M. S. Wechsler, R. G. Berggren, N. E. Hinkle, and W. J. Stelzman

It is known that there is a close interconnection between the strength and ductility of metals. To obtain a better understanding of the mechanism of radiation hardening and embrittlement of pressure vessel steels, the tensile and impact properties of a well characterized heat of ASTM A-212-B steel are being studied.

Impact tests on standard Charpy notched bars in the unirradiated and irradiated conditions were conducted as a function of test temperature. The impact samples were prepared from the same heat of steel and the irradiation conditions were the same (10^{19} n/cm^2, E > 1 MeV, at 60°C) as for the tensile tests described in the previous abstract.

The degree of radiation embrittlement of the steel under notch-impact loading was evaluated in terms of fracture energy (the absorbed energy required to break the sample) and fracture appearance (the fraction of the fracture surface having a fibrous appearance indicating ductile fracture). Both properties indicated an increase in the ductile-brittle transition temperature of about 100°C upon irradiation.

The relationship between the radiation hardening observed in the tensile tests and the radiation embrittlement observed in the impact tests was analyzed in terms of the Ludwig-Davidenkov criterion. The criterion states that the ductile-brittle transition occurs at the temperature where the appropriate yield stress and cleavage fracture stress curves intersect. To apply the criterion, the tensile results were corrected for the increased strain rate and triaxiality near the root of the notch in the impact bar. On the assumption of cleavage fracture initiation at the point of maximum triaxiality, the predicted notch-impact ductile-brittle transition temperature for the unirradiated steel agreed with the observed one to within 20°C. However, for the irradiated steel it was necessary to assume that the cleavage fracture is initiated at a point where the degree of triaxiality is less than the maximum amount, presumably closer to the surface of the sample.

The present conclusion of this investigation is that the increase in the ductile-brittle transition temperature upon irradiation is chiefly a consequence of the increase in yield stress and not due to a change in the fracture properties as such.

THE ANNEALING AND STRAIN-AGING OF A LOW-CARBON PRESSURE VESSEL STEEL

R. G. Berggren, W. J. Stelzman, J. T. Stanley, and M. S. Wechsler

Post-irradiation annealing studies for a low-carbon pressure vessel steel have continued during the past year. The recovery of yield stress and changes in the shape of the stress-strain curve have been followed as a function of time and temperature of annealing. In the as-irradiated

condition, the samples exhibit a rounded yield drop and a short Lüders strain region. Upon low-temperature, short-time annealing, there is no yield drop or Lüders region. Finally, for high-temperature, long-time annealing, the stress-strain curve shows a sharp yield drop and a long Lüders region, characteristic of the unirradiated material. These consistent changes in the stress-strain behavior are being analyzed in terms of the trapping of interstitial solutes at radiation-produced defects and their rearrangement during annealing.

Since interstitial solutes play an important part in the strain aging of steel, strain aging experiments are being conducted on unirradiated and irradiated tensile samples. These experiments are still preliminary, but indications are that the strain aging is reduced upon irradiation because of the trapping of interstitial solutes at radiation-produced defects.

RADIATION DAMAGE TO PRESSURE VESSEL STEELS

M. S. Wechsler

The effects of neutron irradiation on the properties of structural materials are of significant interest to the reactor industry because of their possible relation to the integrity of reactor pressure vessels. Irradiation effects on pressure vessel steels are considered.

The variables that affect the nil conductivity transition temperature are separated into two categories--materials variables and radiation variables. Among the materials variables considered are chemical impurities (such as boron, carbon, and nitrogen), grain size, and metallurgical structure associated with welding. The radiation variables include dose, dose rate, neutron spectra, and irradiation temperature.

Other areas reviewed include possible applications (and limitations) of fracture mechanics to the problem of radiation embrittlement in pressure vessel steels and the effects of irradiation on the fatigue strength of steels. [Abstract of published paper: Nucl. Safety 8, 461 (1967).]

CHARACTERIZATION OF THICK-SECTION PRESSURE VESSEL STEELS

R. G. Berggren and T. N. Jones

The Heavy Section Steel Technology (HSST) Program was initiated to evaluate the effects of flaws on the structural reliability of light-water-reactor pressure vessels fabricated from thick-section steels. All steels procured for the program will be characterized by mill and fabrication history, mechanical property tests, metallography, and chemical analyses as a function of location within the plate or other product.

Mechanical tests are now in progress on a portion of the first 12-inch-thick plate of ASTM A-533, Grade B, Class I, manganese-molybdenum-nickel steel. Tensile, notch-impact, drop weight, and hardness tests have shown uniform properties through the central eight inches thickness of the plate, with increased strengths and lower transition temperatures as the plate surface is approached. This effect is due primarily to the higher cooling rates near the plate surface during quenching from the austenite range. This effect is not as great near the quenched edge of the plate, although the cooling rates during quenching should be at least as high as for the same distance from the surface of the plate.

SURFACE STUDIES AND ANOMALOUS X-RAY TRANSMISSION

ABSOLUTE INTENSITIES OF X-RAYS DIFFRACTED IN ANOMALOUS TRANSMISSION THROUGH NEARLY PERFECT COPPER CRYSTALS: A COMPARISON BETWEEN THEORY AND EXPERIMENT

T. O. Baldwin, A. Merlini,[1] and F. W. Young, Jr.

The absolute integrated intensities diffracted in anomalous transmission through nearly perfect crystals of copper were measured for various wavelengths and reflections by means of a double crystal spectrometer. Great care was taken to mount and support the crystal in such a way as to minimize the effect of elastic strains. The experimental data are compared with those calculated by using: (1) the formulae of the dynamical theory of diffraction, (2) the semi-classical theory of photoelectric

absorption to determine the ratio between the dynamical and the average absorption coefficient, and (3) the experimental value of the average absorption coefficient. The agreement between experiment and theory is satisfactory provided that the Debye temperature of Cu is taken equal to about 300°K. This value is in good agreement with that reported from the dependence of anomalous transmission intensities on temperature, but it is somewhat lower than the Debye temperature (315-317°K) deduced from data obtained by neutron inelastic scattering, Bragg x-ray measurements on powders and single crystals, and calculations from specific heat data. An analysis is made of the various factors which can influence the experimental or calculated intensities, such as: lattice defects, thickness measurements, ratio between dynamical and average absorption coefficients, contribution of the thermal diffuse and Compton scatterings to the absorption coefficient of x-rays, and the choice of the Debye temperature. [Abstract of published paper: Phys. Rev. 163, 591 (1967).]

[1]C.C.R.-Euratom, Ispra (Varese), Italy.

THE TEMPERATURE DEPENDENCE OF THE BORRMANN EFFECT IN COPPER

T. O. Baldwin

The temperature dependence of the anomalous transmission of x-rays (Borrmann effect) in copper has been measured in the temperature range 77-377°K. From the slopes of the curves obtained, the apparent Debye temperature θ has been determined to be 306 ± 4°K. This value is 3-4% less than that previously reported from the temperature dependence of x-ray diffraction from powders and single crystals. Using this value of θ in the calculations of absolute Borrmann intensities, however, good agreement is obtained between calculated and experimental values. It is suggested that the difference in the θ values may arise from thermal diffuse scattering and/or anharmonic contributions to the temperature dependence of the Borrmann intensities. [Abstract of paper to be published in Physica Status Solidi.]

THE INFLUENCE OF ORIENTATION ON THE EARLY STAGES OF DEPOSITION AND DISSOLUTION ON METALLIC SINGLE CRYSTALS

L. H. Jenkins

Measurements of current vs potential relationships for variously oriented copper single crystalline surfaces have been completed under conditions such that the rate controlling step was associated with electrocrystallization phenomena. The data demonstrate that on most orientations the energy necessary to support the initial stages of either deposition or dissolution was equal. However, on certain orientations in some systems, this relationship was not observed and relatively more energy was required for the anodic process. Also, the data suggested that deposition of less than a monolayer of material apparently occurred at non-lattice sites, and further, that diffusion of the deposited material over the surface (barring further deposition) to occupy normal surface lattice sites occurred at an extremely low rate.

A THEORETICAL TREATMENT OF THE INFLUENCE OF TIME-DEPENDENT IMPURITY ADSORPTION ON ELECTROCRYSTALLIZATION

U. Bertocci

The influence of time-dependent impurity adsorption on the electrochemical deposition and dissolution of metal single crystals is examined on the basis of a proposed model. Curves giving the rate of motion of steps as a function of overtension and of parameters related to the kinetics of adsorption of impurities are computed. The predictions of the theoretical treatment are compared with experimental results and their significance and applicability to the study of the kinematics of step motion are discussed. [Abstract of paper to be published in Surface Science.]

INTERACTION OF STEP MOTION IN TWO-DIMENSIONAL NUCLEATION IN CRYSTAL GROWTH

U. Bertocci

The combined effect of step motion and random two-dimensional nucleation on crystal growth is being studied by simulating its occurrence with a computer. Two models have been examined. The first simulates a section of a crystal surface on which steps move at constant velocity, whereas new steps are generated at random with uniform probability. The results of the computations give a measure of the steady-state step density as a function of the misorientation of the surface and of the ratio between nucleation probability and step velocity. The steady-state distribution of step spacings has also been examined. A mathematical interpretation of the machine calculations has been developed. The second model simulates the surface in two dimensions. Again, steps representing the misorientation are made to move on the surface at constant speed and random nucleation is superimposed. Surfaces having threefold and fourfold symmetry for the velocity vectors are being employed. The results give the rate of crystal growth as a function of nucleation rate, step velocity, step direction, and misorientation.

MASS TRANSFER AND EQUILIBRIA IN SYSTEMS OF COPPER AND α-BRASS IN AQUEOUS AMMONIA

U. Bertocci and L. H. Jenkins

By analysis of mass transfer phenomena in the diffusion layer adjacent to a corroding metal, a model has been developed whereby increases in corrosion rate are explained in terms of enhanced transport of the oxidizing agent across the diffusion layer. The model permits calculation of the composition of the solution immediately in contact with the metal surface so that predictions can be made regarding the onset of precipitation and subsequent film formation. Studies have been conducted on variously oriented copper single crystal surfaces exposed to ammoniacal solutions containing cupric ions. Conditions necessary for film formation have been established and reaction rates determined. All the

data support the proposed reaction model. In an effort to understand stress-corrosion cracking phenomena in α-brass systems, extensive investigations of the rate of film growth have been made. Presently, similar data are being obtained for single crystalline α-brass surfaces, and the studies are continuing.

RESEARCH MATERIALS

EVALUATION OF NIOBIUM SOURCE MATERIALS SUITABLE FOR ELECTRON BEAM FLOAT ZONE MELTING

R. E. Reed and C. L. Brooks

Niobium metal from three sources was electron beam float zone melted (EBFZM) in an evaluation test to find a suitable starting material for purification and growth of single crystals. An initial evaluation of niobium starting material prepared by electrodeposition from a molten salt revealed that this type material was very promising as a source of low Ta and W niobium metal. However, it was generally received as a powder or porous chips and required an additional consolidation step to obtain a rod form suitable for EBFZM. Extensive material characterization results were obtained on Wah Chang Corp. electron beam drip melt ingot, Dupont Co. D3 granules, and CIBA Ltd. dendritic powder after purification and crystal growth using a practical standard EBFZM schedule.

The granular material was consolidated by drop casting in an arc melter with a tungsten electrode and tantalum striking peg. This resulted in both Ta and W contamination to the material. The dendritic powder was compacted by swaging powder-filled copper tubes that had been evacuated and sealed off prior to swaging. The copper was then chemically etched off the powder compact.

All materials were given three EBFZM passes at 10 cm/hr with the last pass in 5×10^{-8} Torr vacuum. Some of the CIBA material was given the first pass in 1×10^{-5} Torr oxygen environment. An anneal at 2350°C for 5 hours at 2×10^{-9} Torr was given to some of the as-zoned niobium.

The material characterization results indicated that the CIBA material with oxygen treatment during EBFZM is an excellent source of high-purity niobium single crystals with a low Ta and W content. The high temperature anneal was very effective in attaining high resistance ratios and low flow stresses. The annealed CIBA material had a flow stress of 940 gm/mm^2 with a resistance ratio of 1330. However, chemical analyses indicated that the effect of the anneal may be a redistribution of the interstitial impurities rather than a purification.

PURIFICATION, GROWTH, AND EVALUATION OF SINGLE CRYSTALS OF KCl

C. T. Butler, J. R. Russell, and R. B. Quincy, Jr.[1]

During the past several years the Research Materials Program has developed methods for producing very pure KCl powder, polycrystalline ingots, and single crystals of KCl. Some of these crystals have been supplied to cooperating laboratories for comparative analyses and for special experiments of interest to the AEC. A quantity of both purified starting ingots (15) and single crystals (9) was stockpiled in order that the purification and growth facilities could be used to produce KCl:Na for research projects of interest to several groups within the Solid State Division. A single crystal of KCl containing 0.4% Na was grown, and crystals containing other dopant concentrations and possibly other dopants are anticipated. The equipment for purification and crystal growth can be reconverted at some future date, if the demand for pure single crystals exceeds the current supply.

[1]Analytical Chemistry Division, ORNL.

CRYSTAL GROWTH AND EVALUATION OF MgO

C. T. Butler, J. R. Russell, and R. B. Quincy, Jr.

During the past year we have started on a program that is aimed at providing large single crystals of MgO of nominally 10-ppm total impurity

content. It is of interest that the Research Materials Information Center received more requests for information regarding the availability of single crystals of MgO during the period from July 1966 to July 1967 than for any other material. A two-electrode carbon arc furnace was built and crystals of nominally 100-ppm total impurity have been grown. The chemical and physical perfection of these crystals has been studied to determine the direction to proceed in future work on purification of starting material and crystal growth. The Research Materials Program has purchased the right to duplicate the furnace design and crystal growth techniques of W. & C. Spicer, Ltd., Winchcomb, England, and parts have been ordered for construction of a 3-phase, 3-electrode arc furnace of a similar design. Characterization of available starting materials, pilot growth of crystals with the existing equipment, and development of processes to produce starting materials of better purity than is currently available has been the primary program to date.

PURIFICATION, GROWTH, AND EVALUATION OF SINGLE CRYSTALS OF SEMICONDUCTING MATERIALS

R. D. Westbrook

A new program has been established to develop a competence within the Research Materials Program in purification, single-crystal growth, and evaluation of semiconducting materials. Production methods in current practice have not provided materials of sufficiently high purity and uniformity as required by solid state physicists, nuclear chemists, and nuclear physicists and device people who are concerned with the development of solid state (semiconducting) radiation detectors. Equipment has been placed in operation that is capable of growing crystals up to at least 3 in. in diameter and is versatile enough for a variety of crystal growth techniques on a number of materials. Such ancillary equipment as required for crystallographic optical orientation, precision cutting, vacuum drying, and air abrasive sanding has also been obtained and placed in operation.

The technology of crystal growth of semiconductors includes such operations as washing, drying, melting, and storage, each requiring handling and

exposure to the surroundings and, therefore, each being capable of contamination. It is necessary that one establish a very clean environment, since one is dealing with a total impurity content in the order of one part in 10^{12}, or one part in one million million. To this end, a section of Building 2000 has been remodeled as a "clean" room where the specific requirements are designed to (a) prevent entry of particulate matter by filtration, (b) purge existing particulate matter by frequent room air changes, and (c) minimize generation of particulate matter by use of proper surfaces in the room. It is anticipated that the crystal growth apparatus will be transferred to this room in the very near future.

The primary objective of the program to date has been to obtain large (~2-in. diameter), high-purity ($\leq 10^{13} cm^{-3}$) single-crystal ingot sections of germanium with a high degree of uniformity and crystalline perfection. The problem of lithium drifting that has plagued the fabricator of PIN gamma-ray detectors has been examined in considerable detail, using in part a procedure that is being investigated as an ASTM standard. There is considerable evidence that oxygen inhibits lithium drifting. Using methods designed to remove as much of the oxygen as possible from the melt and to inactivate the remaining oxygen, germanium crystals grown at this laboratory now show excellent lithium drift characteristics. Driftable germanium, however, does not necessarily make a good detector material, since the physical perfection of the crystal and the nature and concentration of certain impurities influences the carrier lifetime and affects the charge collection efficiency. Consequently, there may be additional work ahead in these areas before the Ge (Li) material problem is resolved. Alternatively, if one could grow Ge crystals with less than 10^{10} impurities cm^{-3}, it would be possible in principle to make detectors without the need of lithium drifting and the problem of device storage at low temperature. This attack will be investigated in the coming year.

STUDIES ON THE PREPARATION OF SINGLE-CRYSTAL GOLD FILMS

T. S. Noggle and J. C. Crump, III

Single-crystal gold films employed in the studies of channeling of heavy ions contain high densities of dislocations (~10^9 lines/cm^2) and micro twins. The high defect density leads to a mosaic structure in the films which is measured by x-ray rocking curves. To date, specimens employed in the channeling studies have given rocking curves of 10'-15' FWHM. Studies are being made of the effect of parameters of crystal growth, annealing, and substrate surfaces on the mosaic structure of the specimens. This study has led to improved control of the specimen preparation parameters such that present specimens give rocking curves of 6'-12' FWHM.

FLUX GROWTH AND CHARACTERIZATION OF HEXAGONAL GERMANIUM DIOXIDE SINGLE CRYSTALS

C. B. Finch[1] and G. W. Clark[1]

Single crystals of hexagonal GeO_2 up to 2 × 2 × 3 mm were grown from $Li_2O \cdot 2MoO_3$ and $Li_2O \cdot 2WO_3$ fluxes by slow cooling from 1100° to 950°C at ≤1°C/hr. Optically clear crystals contain 50 ppm Mo (or W) and 30 ppm Li as impurities. [Abstract of paper to be published in American Mineralogist.]

[1]Metals and Ceramics Division, ORNL.

SYNTHESIS OF GRUNERITE AND OTHER PHASES IN THE CRYSTAL SiO_2-NaOH-Fe-H_2O

O. C. Kopp[1] and L. A. Harris[2]

Grunerite has been synthesized in the system SiO_2-NaOH-Fe-H_2O under dynamic conditions at about 400°C and a total pressure of about 1.6 Kb. The grunerite was most abundant near the bases of the vessels (temperature range 400°-430°C) but also occurred in the upper part of the vessels (temperature range 360°-410°C). In the uppermost part of the vessels, grunerite

is supplanted by micaceous phases and an unusual fibrous glass. The micaceous phases most closely resemble Na-nontronite or Na-vermiculite, but also have some properties like stilpnomelane. The role of sodium ions in the formation of grunerite and the micaceous phases was demonstrated by similar experiments using KOH as a solvent which produced no amphibole and only the mica, ferriannite. [Abstract of published paper: The American Mineralogist 52, 1681 (1967).]

[1]University of Tennessee, Knoxville, and Metals and Ceramics Division, ORNL.

[2]Metals and Ceramics Division, ORNL.

VERNEUIL GROWTH OF FERRIMAGNETIC SPINELS

G. W. Clark and H. A. Mook

An electromagnetic neutron-beam chopper has been proposed by H. A. Mook.[1] The heart of this device is a single crystal of certain ferrimagnetic spinels. For evaluation we have grown the following iron spinels: nickel-zinc, titanium, lithium-titanium, lithium-manganese, lithium-iron, and lithium. In general, these crystals have been greater than 8 mm in diameter and 20 mm long. Initial results have been encouraging. An iron (^{7}Li) spinel crystal grown on a [331] seed held this orientation and was 1 cm in diameter and 8 cm long. The neutron rocking curve line width was 0.31° and the neutron Laue diffraction line was sharp and straight the whole length of the crystal. Other crystals will be grown to adjust the composition, perfection, and size to optimize the crystals for this device.

[1]See page 87 of this report.

MOLTEN SALT GROWTH OF SINGLE CRYSTALS

C. B. Finch and G. W. Clark

The growth of 2-mm ThO_2 crystals doped with the radioactive isotope ^{244}Cm (Cm:Th::1:3000) has been accomplished. The growth method has been described,[1] except for the setup now being in an isolated glove box because of the radiation hazard. The resulting octahedral Cm^{3+}-doped ThO_2 crystals were initially pink but became nearly colorless after several hours at room temperature. Luminescent and absorption spectra studies are now in progress; data have been obtained at room and liquid nitrogen temperatures.

Crystals of a hitherto unreported compound, $LiErMo_2O_8$, of scheelite structure were grown up to 5 mm in size from $Li_2O \cdot 2MoO_3$ solvent at 1150° to 900°C. The crystals display marked magnetocrystalline anisotropy and will be used for magnetic susceptibility studies. Described techniques[1,2] were used to grow CeO_2 and ThO_2 crystals up to 3 mm in size doped with U:(Ce or Th)::1:200. These crystals were subjected to electron spin resonance and optical absorption studies. Crystals of CeO_2 doped with the isotope ^{161}Dy and ThO_2 doped with ^{144}Nd were grown for electron spin resonance studies. Crystals of ThO_2 doped with ^{157}Gd were grown for some electron-nuclear double resonance experiments.

[1] C. B. Finch and G. W. Clark, J. Appl. Phys. 36, 2143 (1965).

[2] C. B. Finch and G. W. Clark, J. Appl. Phys. 37, 3910 (1966).

URANIUM DIOXIDE CRYSTAL GROWTH

D. E. Hendrix,[1] A. T. Chapman,[2] and G. W. Clark

We are continuing the study of the crystal growth of UO_2 by the internal centrifugal zone growth (ICZG) technique.[3] Crystals approximately 1 cm in diameter and 4 cm long can be grown within 2° of a desired orientation by seeding the melt. A comparison of the perfection of UO_2 crystals grown by this method, arc-melted specimens, and vapor-grown crystals is under way, using etch-pit patterns, dislocation densities revealed by transmission

electron microscopy, and x-ray topography. Preliminary results indicate that the dislocation densities are comparable (approximately $10^6/cm^2$), although substructure is more pronounced in our ICZG UO_2 than in arc-melted UO_2 (from Battelle Northwest), and fewer inclusions exist in the ICZG crystals. Good correlation was obtained among the three analysis techniques. Melts of UO_2-ThO_2 solid solution of up to 60% ThO_2 have been made using the ICZG technique. Single-crystal grains up to 3 mm in diameter and 10 mm long have been grown of UO_2-50% ThO_2. We have supplied UO_2 single crystals to workers in both this and other laboratories. Studies under way on these crystals include creep properties, dislocation movement, diffusion measurements, infrared spectroscopy, thermal conductivity, crystalline perfection, and fission gas release.

[1]Metals and Ceramics Division, ORNL.

[2]Consultant with Metals and Ceramics Division, from Georgia Institute of Technology.

[3]A. T. Chapman and G. W. Clark, Metals and Ceramics Div. Ann. Progr. Rept. for Period Ending June 30, 1965, ORNL-3870, pp. 3-4.

CONTROLLED GROWTH OF URANIUM DIOXIDE-TUNGSTEN COMPOSITE

D. E. Hendrix, A. T. Chapman, and G. W. Clark

Highly ordered composites of the ceramic uranium dioxide and the metal tungsten have been grown by our method for growing UO_2 crystals. The composite is basically a single crystal of uranium dioxide containing a highly ordered array of very fine rod- or plate-shaped crystals of tungsten. The tungsten rods in the eutectic structure are typically 1 to 2 μ in diameter and about 1 mm long. Lamellae are 2/3 μ thick, 10 to 100 μ wide, and longer than 1 mm. Such materials have shown double the compressive strength (both parallel and perpendicular to the rodlet axes) and, in the direction of the tungsten rodlets, 30% greater thermal conductivity as compared with pure single-crystal uranium dioxide. These early results are most impressive, and the broad implication of controlling rod and lamellar structures in cermets is exciting.

RESEARCH MATERIALS INFORMATION CENTER

T. F. Connolly and H. S. Pomerance

In 1967 the RMIC answered 876 inquiries concerning 2772 separate questions on the properties, availability, and methods of preparation of ultrapure inorganic solid materials. A count of these inquiries that were identifiable by supporting agency showed the usage of the center as: AEC, 6%; Department of Defense, 23%; commercial organizations, 29%, universities, 37%, and other Government agencies, 5%. The figure for the AEC does not include ORNL. When ORNL is included, the figure is approximately 20%. By source, the inquiries were 67% from the U.S. and 33% foreign.

Two extensive bibliographies were completed: (1) Bibliography of Magnetic Materials and Tabulation of Magnetic Transition Temperatures (1960-1967), ORNL-RMIC-7, and (2) Groups IV, V, and VI Transition Metals: Selected References on Preparation, Structure, Physical Properties, Metallography, and Transport Properties, ORNL-RMIC-8. Numerous other bibliographies were compiled as a result of inquiries on special topics. These will be filmed and thus be usable as an index to the entire collection, facilitating future searches. More than 7000 documents were added to the coded microfilmed collection, which now totals about 35,000.

The first trainee (from the University of Syracuse) in a new program for information specialists spent six weeks at the Center during the summer.

PURITY AND PERFECTION OF RESEARCH SPECIMENS OF OXIDES

J. W. Cleland

Specific examples of the effects of pre-purification, crystal growth, characterization, and research involving oxides in the Research Materials Program of the Solid State Division of the Oak Ridge National Laboratory were selected to indicate the current status of the purity and perfection of these particular materials, and to examine the primary experimental problems that stand in the way of better research materials. The coded

and filmed collection of data sheets, abstracts, reports, open literature publications, and bibliographies of the Research Materials Information Center, various publications of the Electronic Properties and Defense Ceramics Information Centers, and the contents of a number of journals and books gave information on the initial purification, crystal growth, and final characterization of some general classes of oxides, as well as a number of specific materials of interest. A number of individual research groups were contacted to obtain current information on the purity and perfection of those oxides of particular interest to their own research programs. [Abstract of paper presented at the Symposium on Mass Transport in Oxides, National Bureau of Standards, Washington, D. C., October 22-25, 1967; to be published in the proceedings.]

SUMMARY OF CURRENT WORK IN THE RESEARCH MATERIALS PROGRAM

J. W. Cleland

This program is concerned with developing the necessary techniques required for the growth of ultra-high purity and controlled impurity research specimens (usually single crystal) of a composition, quality, purity, and perfection as required in materials research. The choice of materials for consideration has been made on the basis of the potential gain to a fundamental understanding of a given material, and on the basis of an expressed need for a specific type of specimen. The entire program involves a number of research divisions at ORNL. The Analytical Chemistry Division has provided a variety of special analytical techniques, and a program of research on improvement in analytical techniques. Most of the work on crystal growth has been carried out by research groups within the Metals and Ceramics, Reactor Chemistry, and Solid State Divisions, and these groups have also conducted a wide variety of physical property measurements. Selected samples have also been supplied to research groups outside ORNL for comparative analyses, cooperative measurements that increase the characterization, and for special experiments of interest to the AEC. Examples are given below:

LOAN OF SINGLE CRYSTALS FOR RESEARCH OUTSIDE ORNL

Material	Type of Study	To Whom Sent	Organization
MgO	Rebinder effect	D. L. Goldheim	RIAS, Baltimore
MgO	Impurity ion diffusion	B. J. Wuensch	MIT, Cambridge
MgO	Mechanical properties	R. W. Armstrong	Brown University
MgO	Ion bombardment	W. Primak	Argonne Nat'l. Lab.
ThO_2	Electrical conductivity	R. A. Rapp	Ohio State Univ.
ThO_2	Intrinsic defects	P. L. Land	Aerospace, Wright-Patterson AFB
Ga-ThO_2	Fluorescence studies	"	"
Gd-ThO_2	Electron nucl. resonance	J. M. Baker	Oxford University
CeO_2	Fluorescence studies	P. L. Land	Aerospace, Wright-Patterson AFB
Dy-CeO_2	Thermoluminescence	"	"
Li^7F	Thermoluminescence	E. Tochilin	USN Defense Lab.
Li^7F	Radiation detector	D. E. Jones	Lawrence Rad. Lab.
50.77% Li^7F	Zero phonon line spectra	von der Osten	Phys. Inst. Darmstad
99.3% Li^6F	Zero phonon line spectra	"	"
LiF-BeF_2	Optical and spin resonance	P. J. Bray	Brown University
Be	Small angle x-ray window	P. W. Schmidt	U. of Mo., Columbia
Be	Dissolution experiments	W. J. James	" " Rolla
Be	Conductivity experiments	W. L. Gordon	Case Institute
Be	Age hardening	E. Levine	Rutgers University
KCl	Irradiation experiments	P. R. Hanley	Cornell University
KCl	Conductivity standard	V. Nelson	Univ. de Oriente, Venezuela
KCl	Paraelectric resonance	L. D. Schearer	Texas Instruments
KCl	Color centers	G. Tanton	Redstone Arsenal
KCl	Magnetic moments	C. F. Squire	Texas A&M
KCl	Color centers	P. Yuster	Argonne Nat'l. Lab.
KCl	Color centers	J. H. Crawford	Univ. of N. C.
Nb	Mechanical properties	R. W. Armstrong	Brown University
Nb	Mechanical properties	I. Guppa	U.S. Steel Corp.

(continued)

Material	Type of Study	To Whom Sent	Organization
CeO_2	Diffusion	M. S. Seltzer	Battelle Mem. Inst.
Dy-CeO_2	Mössbauer	H. H. Wickman	Bell Laboratories
$ThSiO_4$	Fission tracks	R. Brandt	C.E.R.N.
UO_2	Electron microscope	O. M. Katz	Westinghouse
UO_2	Far infrared	S. J. Allen	Bell Laboratories
Yb-ThO_2	Electron spin resonance	Z. Sroubek	U.C.L.A.

EXPERIMENTAL FACILITIES

A MAGNETICALLY PULSED NEUTRON BEAM FOR TIME-OF-FLIGHT MEASUREMENTS OF INELASTIC SCATTERING

H. A. Mook and M. K. Wilkinson

In many types of experiments, time-of-flight neutron spectrometers have the advantage of higher counting rates than crystal spectrometers, especially in view of the fact that multiple counters may be used. A method of magnetically pulsing a neutron beam has been developed that avoids the necessity of using high-speed rotating equipment.

The magnetic intensity in a Bragg reflection depends on the orientation of the atomic magnetic moments relative to the scattering vector, and it becomes zero when the moments are directed along the scattering vector. The direction of magnetization in ferrite crystals can be switched rapidly with an external magnetic field so that these crystals can serve both as a neutron monochromator and pulser. Furthermore, the neutron pulse width and repetition rate can easily be varied by changing the current pulse that produces the external field.

The nuclear contribution for the (111) or (331) reflections can be made very small for ^{7}lithium titanium ferrite of the correct composition. Large magnetic scattering intensities can be obtained in each case. The pulsed magnetic field is produced by switching the energy stored in a pulse forming network into a magnet drive coil by means of a silicon controlled

rectifier. The pulse rise time is about 1 microsecond and the pulse length in the present instrument is 12 microseconds. [Abstract of paper to be published in the Journal of Applied Physics.]

CONSTRUCTION OF A NEUTRON SPECTROMETER USING THE MAGNETICALLY PULSED BEAM TECHNIQUE

H. A. Mook

An experimental time-of-flight spectrometer using a magnetically pulsed beam has been placed in operation at the Oak Ridge Research Reactor. The pulsed and monochromatic beam is obtained from the (111) reflection of ^{7}lithium titanium ferrite. The magnetic intensity from this reflection compares favorably with the intensity produced by typically used monochromating crystals. The magnetic field needed to pulse the neutron beam is produced by switching the stored energy of a pulse-forming network into a flux-compressing drive coil surrounding the ferrite crystal by means of an assembly of silicon-controlled rectifiers. A 500-ampere pulse is presently used with a 1-microsecond rise time. The pulse width is 15 microseconds giving an energy resolution of about 5%.

With this instrument phonons were measured along the [100] direction in copper metal, which agreed well with those previously measured by the triple-axis technique. The duty cycle of the present instrument is limited to 2% by the large fields needed to pulse the present crystal and the limited size of the pulsing apparatus. The present ferrite crystal is difficult to magnetize because of nonmagnetic inclusions and strains. Work is under way to obtain a better quality pulsing crystal, and when such a crystal is obtained, the duty cycle can be increased significantly and data obtained much faster. It is possible that coded-pulse techniques would permit a 50% duty cycle, and autocorrelation methods would be used to extract the desired scattering information. For many problems of interest such a continuously modulated beam could make the magnetic chopper more efficient than a conventional rotating chopper by more than an order of magnitude.

ON-LINE COMPUTER CONTROLLED TRIPLE-AXIS NEUTRON SPECTROMETERS AT THE HFIR

M. K. Wilkinson, H. G. Smith, W. C. Koehler, R. M. Nicklow, and R. M. Moon

Two new automatic triple-axis neutron spectrometers have been constructed and installed at horizontal beam holes of the Oak Ridge High Flux Isotope Reactor. These spectrometers have been designed to provide maximum flexibility for use in many different types of investigations. The incident neutron energy can be varied continuously and automatically through monochromator scattering angles up to 120 degrees, and the monochromator cavity contains both a polarizing and a nonpolarizing crystal. Since either monochromator can be selected and accurately positioned by external controls, the spectrometers can be modified relatively quickly for experiments requiring either polarized or unpolarized neutrons. Neutron beam collimators, Soller slits, neutron filters, and neutron velocity selectors can all be installed in the beam hole cavity with external controls for selection and adjustment.

Each spectrometer is controlled on-line by its own computer, a Programmed Data Processor (PDP-8), through pulsed motors that drive up to six spectrometer axes. The advantages of this system lie in the flexibility of experiment control by stored programs on magnetic tape, which are brought into the fast memory when the conditions of the experiment dictate it. In addition to controlling the spectrometer, each computer has interfacing that allows control of auxiliary equipment such as shutters, velocity selectors, strip-chart recorders, and temperature controllers. The usual scalers associated with neutron counting equipment have been eliminated through the use of data-break and special interrupt circuits with prescalers for the monitor counters. Several computer programs have been written for various experimental techniques, such as the "constant Q" and "constant E" methods of operation, calculation of focusing effects and dominant higher order scattering processes, etc. The data are plotted in histogram form on a chart recorder and data analysis is made possible by auxiliary magnetic tape storage in the computer. [Abstract of paper to be published in Proceedings of the IAEA Symposium on Neutron Inelastic Scattering, Copenhagen, Denmark, May 20-24, 1968.]

INSTALLATION OF THE SOLID STATE DIVISION 2.0-MeV ACCELERATOR

O. E. Schow

A High Voltage Engineering Corporation Model AK-2000 Van de Graaff accelerator has been installed and tested. In the DC electron mode of operation, the machine will produce at least 300 μamps at 2.50 MeV. It is also possible to operate at 150 keV and still obtain a 1-cm diameter spot of electrons at the rated current. In the pulsed mode it has been possible to run at 4.6 amps for pulse durations of 5, 15, and 25 nanoseconds even though the specifications indicate a maximum current of 500 milliamps for this mode of operation. The machine can be converted to provide unanalyzed proton beams of up to 150 μamps at 2.0 MeV. Moreover, it is possible that the machine can be modified to produce higher energy electrons (3 MeV and above) by replacing the nitrogen-carbon dioxide insulating gas with sulfur hexafluoride and using a new high voltage gradient accelerator tube. The only major problem encountered thus far has been that of shielding. The accelerator was installed in a one-story building built on top of a hill, and since the building was higher than any nearby structure and the roof was to remain unoccupied it was initially felt that shielding the roof area would not be necessary. However, tests made (using a gold target, an energy of 2 MeV and a current of 300 μa) indicated that the radiation level on the roof was 200 R/hr and radiation levels on the ground outside the accelerator building were as high as 300 MR/hr in some places. The tests were made using the worst possible case, i.e., gold target and high current and energy. Further tests show that shielding the ceiling of the target end of the accelerator room will be sufficient to reduce the radiation levels outside the building to safe limits even at high current and energy.

LOW TEMPERATURE IRRADIATION FACILITY IMPROVEMENTS

R. R. Coltman, Jr., C. E. Klabunde, J. K. Redman, and G. F. Fielder

A new aluminum cryostat has been constructed and installed in the low temperature irradiation facility. The smaller mass of the new cryostat

generates about one-third the gamma ray heating generated in the original cryostat of the same size, which was made of stainless and copper. Because of the small neutron absorption of the new cryostat, the thermal neutron flux in the sample chamber is increased 50% over that in the old cryostat for the same reactor power. An additional feature of this facility is that cryostats of a variety of configurations can easily be attached to the permanent liquid helium circuit, which makes feasible a wide variety of experiments. Since the Bulk Shielding Reactor power has been increased from one to two Mw, the combined gain of a factor of three in thermal neutron flux intensity has brought the present sample chamber flux up to 2.7×10^{12} n/cm^2/sec with no loss in operating capability (a typical sample irradiation temperature at full power is 3.6°K). Recent reactor improvements have increased the full power operating cycle from about 7 hours per day to sustained operation. Combined with the aforementioned improvements, the practical integrated dose obtainable in the low temperature facility has been increased by about a factor of ten.

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"Stage I Annealing of Radiation Damage," presented at the American Physical Society Meeting, Chicago, Ill., March 27-30, 1967. [Bull. Am. Phys. Soc. 12, 302 (1967).]

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D. S. Billington
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"Paramagnetic States of Some Germanate Compounds: Glassy and Polycrystalline," presented at Gordon Research Conference on Glass, Tilton, N. H., Aug. 28-Sept. 9, 1967.

L. B. Bridwell, L. C. Northcliffe, S. Datz, C. D. Moak, and H. O. Lutz
"Stopping Power of C, Al, Ni, Ag, Au, and UF_4 for 10-200 MeV ^{127}I Ions," presented at the American Physical Society Meeting, New York, N. Y., Jan. 30-Feb. 2, 1967. [Bull. Am. Phys. Soc. 12, 28 (1967).]

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"Thermoluminescence Glow Peaks and Spectra of Alkali Halides γ-Irradiated at Room Temperature," presented at the American Physical Society Meeting, Chicago, Ill., March 27-30, 1967. [Bull. Am. Phys. Soc. 12, 279 (1967).]

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"Heavy Ion Charge States at MP Tandem Energies," invited paper presented at the American Physical Society Meeting, New York, N. Y., Jan. 30-Feb. 2, 1967.

S. Datz, C. D. Moak, H. O. Lutz, L. C. Northcliffe, and L. B. Bridwell
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G. Dolling
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"Stress Dependence of Dislocation Velocity in Irradiated and Unirradiated Niobium," presented at the Symposium on Radiation Effects in BCC Metals, Annual Meeting of the AIME, Los Angeles, Calif., Feb. 19-23, 1967.

A. Hiraki
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"Experimental Evidence for Production and Annihilation of Interstitial Impurities in Electron-Irradiated Germanium," presented at the Conference on Radiation Effects in Semiconductors, Santa Fe, N. M., Oct. 3-5, 1967.

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"The Present Status of Fundamental Studies of Radiation Damage in Solids," presented at the Conference on Special Topics in Nuclear Education and Research, Gatlinburg, Tenn., Aug. 28-30, 1967.

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"Effect of Neutron Irradiation on the Superconducting Properties of Niobium," presented at the American Physical Society Meeting, Chicago, Ill., March 27-30, 1967. [Bull. Am. Phys. Soc. 12, 310 (1967).]

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"The Magnetic Structures of Rare Earth Alloys," invited paper presented at the Symposium on Neutron Scattering, 96th AIME Annual Meeting, Los Angeles, Calif., Feb. 19-23, 1967.

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T. S. Noggle and J. H. Barrett
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S. M. Ohr
"Work-Hardening Characteristics of Neutron-Irradiated Iron," presented at the Symposium on Radiation Effects in BCC Metals, Annual Meeting of the AIME, Los Angeles, Calif., Feb. 19-23, 1967.

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"Normal Vibrations in Sodium Nitrite," presented at the American Crystallographic Association, Symposium on Thermal Neutron Scattering Applied to Chemical and Solid State Physics, Atlanta, Ga., Jan. 25-28, 1967.

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"Crystal Dynamics of Sodium Nitrite," presented at the American Physical Society Meeting, Chicago, Ill., March 27-30, 1967. [Bull. Am. Phys. Soc. 12, 282 (1967).]

S. T. Sekula and R. H. Kernohan
"Fast Neutron Irradiation Effects in Superconducting Niobium," presented at the 1967 Applied Superconductivity Conference, Austin, Texas, Nov. 6-8, 1967.

S. T. Sekula, R. H. Kernohan, and C. C. Koch
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W. A. Sibley and Y. Chen
"F-Center Production in MgO Crystals," presented at the American Physical Society Meeting, Chicago, Ill., March 27-30, 1967. [Bull. Am. Phys. Soc. 12, 411 (1967).]

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H. G. Smith, R. M. Nicklow, P. R. Vijayaraghavan, G. Dolling, and M. K. Wilkinson
"The Lattice Dynamics of Lithium Fluoride," presented at the American Physical Society Meeting, Washington, D. C., April 24-27, 1967. [Bull. Am. Phys. Soc. 12, 557 (1967).]

E. Sonder, W. A. Sibley, and W. C. Mallard
"Thermoluminescence and F-Center Bleaching in Heavily Irradiated KCl," presented at the American Physical Society Meeting, Chicago, Ill., March 27-30, 1967. [Bull. Am. Phys. Soc. 12, 280 (1967).]

J. T. Stanley
"Radiation Effects in Iron and Iron Alloys," presented at the Symposium on Radiation Effects in BCC Metals, Annual Meeting of the AIME, Los Angeles, Calif., Feb. 19-23, 1967.

M. Tachiki, Z. Sproubek, P. Zimmerman, and M. M. Abraham
"Stress Dependence of the g-Factors of Yb^{3+} in Thorium Dioxide and Ho^{2+} in Calcium Fluoride," presented at the 1967 International Congress on Magnetism, Boston, Mass., Sept. 10-16, 1967.

R. P. Tucker, R. E. Reed, and M. S. Wechsler
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D. Walton
"Study of the Resonant Phonon Scattering in KCl:Li using the Spin-Phonon Interaction, presented at the International Conference on Localized Excitations in Solids, Irvine, Calif., Sept. 18-22, 1967.

M. S. Wechsler
"Radiation Hardening in Niobium and Iron," presented at the Libby-Cockcroft Exchange Meeting on the Effects of Irradiation on Structural Materials, AERE, Harwell, England, Sept. 27-29, 1967.

R. A. Weeks
"Paramagnetic States of Some Germanate Compounds: Glassy and Polycrystalline," presented at the Gordon Research Conference on Glass, Tilton, N. H., Aug. 28-Sept. 9, 1967.

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"ESR Spectra of γ-Ray Irradiated Phosphate Glasses and Polycrystalline Compounds," presented at the American Physical Society Meeting, Chicago, Ill., March 27-30, 1967. [Bull. Am. Phys. Soc. 12, 400 (1967).]

M. K. Wilkinson
"The Role of Neutron Diffraction in Solid State Physics," invited paper at Midwest Solid State Conference, University of Missouri, Columbia, Mo., Nov. 3-4, 1967.

M. K. Wilkinson
"Remarks on the Career of E. O. Wollan in the Field of Neutron Diffraction," presented at the 1967 International Congress on Magnetism, Boston, Mass., Sept. 10-16, 1967.

J. M. Williams, J. M. Stanley, and W. E. Brundage
"The Mechanism of Stage III Annealing in Neutron-Irradiated Niobium," presented at the Annual Meeting of the AIME, Los Angeles, Calif., Feb. 19-23, 1967.

E. O. Wollan
"A Molecular Field Solution for the Magnetic Properties of the Tb-Y Alloy System," presented at the 1967 International Congress on Magnetism, Boston, Mass., Sept. 10-16, 1967.

R. F. Wood

"Quantum Mechanical Calculations of the U-Center Force Constants," presented at the Conference on Localized Excitations, University of California, Irvine, Calif., Sept. 18-22, 1967.

"The Electronic Structure and Optical Properties of Insulators," presented at the Ninth Annual Latin American School of Physics, Santiago, Chile, July 3-28, 1967.

James R. Woodyard

"Many Body Effects in Low-Energy Sputtering," presented at the American Physical Society Meeting, New York, N. Y., Jan. 30-Feb. 2, 1967. [Bull. Am. Phys. Soc. 12, 80 (1967).]

"Interaction of Monoenergetic Argon Ions (0-8 keV) with Copper Targets: Sputtering and Ion Scattering," presented at 15th Annual Conference on Mass Spectrometry and Allied Topics, Denver, Colo., May 14-19, 1967.

M. Wuttig, J. T. Stanley, and H. K. Birnbaum

"Interpretation of Radiation Damage in Dilute Fe-C and Fe-N Alloys," presented at the Symposium on Radiation Effects in BCC Metals," Annual Meeting of the AIME, Los Angeles, Calif., Feb. 19-23, 1967.

K. Yosida

"The Status of the Theories of Magnetic Anisotropy," presented at the 1967 International Congress on Magnetism, Boston, Mass., Sept. 10-16, 1967.

F. W. Young, Jr.

"Dislocation Configurations in Copper in the First Stages of Plastic Flow," presented at Battelle-Seattle-Harrison Colloquium on Dislocation Dynamics, Seattle, Wash., May 1-6, 1967.

"Initial Stage of Dislocation Motion and Multiplication in Copper," presented at the American Physical Society Meeting, New York, N. Y., Nov. 16-18, 1967. [Bull. Am. Phys. Soc. 12, 1072 (1967).]

"Observations of Dislocations in Nearly Perfect Copper Crystals," presented at the Southeastern Section, American Physical Society Meeting, Clemson, S. C., Nov. 3-4, 1967.

PATENT

J. C. Pigg

"Phase Modulated Solid State Device," U. S. Patent No. 3,358,245 (Dec. 12, 1967).

SEMINARS

Solid State Division Seminars at ORNL:

W. A. Sibley succeeded O. S. Oen as Seminar Chairman in September 1967. The following seminars were held during the period covered by this report:

"Studies of Antiferromagnetism and Ferroelectricity with Neutron Inelastic Scattering"
Gerald Dolling, ORNL

"Positron Annihilation in Rare-Earth Single Crystals"
Ronald Williams, Iowa State University, Ames

"Ferroelectrics and Neutron Spectroscopy"
W. Cochran, University of Edinburgh, Scotland

"The Search for the Electric Dipole Moment of the Neutron at ORNL"
P. D. Miller, Jr., ORNL

"The Calculation of Electronic Energy Bands for Metals and Ordered Compounds: A Progress Report"
Harold Davis, ORNL

"Axial and Planar Channeling in Silicon Single Crystals"
B. R. Appleton, Bell Telephone Labs., Murray Hill, N. J.

"Holography"
K. L. Vander Sluis, ORNL

"The Influence of Jahn-Teller Ions on the Acoustic and Magnetic Properties of Crystals"
E. M. Gyorgy, Bell Telephone Labs., Murray Hill, N. J.

"Ultraviolet Optical Properties and Electronic Band Structure in Crystalline MgO"[1]
D. M. Roessler, University of California, Berkeley

"The Ewald Lattice Sum Method and Some Modification"
C. B. Clark, Univ. of North Carolina at Greensboro

"Paramagnetic Defects and Surface Reactivity in Alkaline Earth Oxides"
A. Tench, AERE, Harwell, England

"Radiative Capture by Impurity Centers in Semiconductors"[2]
John Blakemore, Florida Atlantic University, Boca Raton, Fla.

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[1] Sponsored jointly by Health Physics and Solid State Divisions.

[2] Sponsored jointly by Instrumentation and Controls and Solid State Divisions.

"Point Defects and Self-Diffusion Mechanisms in Uranium Carbide"
Wolfgang Schüle, CCR-EURATOM, Ispra, Italy

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Educational Lectures and Seminars:

Members of the Division presented lectures at five universities under the auspices of the University Traveling Lecture Program sponsored by ORAU.

J. W. Cable	Kent State College, Kent, Ohio Oberlin College, Oberlin, Ohio "The Application of Neutron Scattering to Problems in Solid State Physics"
J. F. Cooke	North Carolina State University, Raleigh, N. C. "A Green's Function Description of the Heisenberg Model of Ferromagnetism"
E. Sonder	Illinois Institute of Technology, Chicago, Ill. "Recent Evidence for Interstitial Halide in KCl Irradiated at and below Room Temperature"
	Worcester Polytechnic Institute, Worcester, Mass "Color Centers in Ionic Crystals"

Other lectures and seminars presented by Division members during the year included the following:

M. M. Abraham	Emory University, Atlanta, Ga. "Methods and Applications of EPR"
T. O. Baldwin	University of Missouri, Columbia, Mo. "Studies of Radiation Damage in Crystals by X-Ray Diffraction Techniques"
	Kansas State College, Pittsburg, Kan. "The Use of Anomalous X-Ray Transmission for the Study of Defects in Crystals"
C. T. Butler	University of Parma, Parma, Italy "Some Recent Investigations at ORNL in the Fields of Materials Purification and Thermoluminescence"
J. W. Cable	University of Connecticut, Storrs, Conn. "Application of Neutron Diffraction to Problems in Solid State Physics"

J. W. Cleland	University of Kentucky, Lexington, Ky. "Photon and Neutron-Induced Defects in Semiconducting Materials"
S. Datz	University of Chicago, Chicago, Ill. Florida State University, Tallahassee, Fla. FOM Institute for Atomic and Molecular Physics, Amsterdam, The Netherlands Physical Institute, University of Freiburg, Freiburg, West Germany "Channeling - Crystallographic Effects on the Motion of Energetic Ions in Solids"
L. H. Jenkins	Bulgarian Academy of Sciences, Sofia, Bulgaria "Some Effects of Structure of Single Crystal Copper Electrodes on Dissolution and Deposition in Perchlorate Solutions"
H. O. Lutz	Florida State University, Tallahassee, Fla. Kansas State University, Manhattan, Kan. "Channeling of Heavy Ions in Solids"
A. Meyer	Georgetown University, Washington, D. C. Northern Illinois University, DeKalb, Ill. American University, Washington, D. C. Antioch College, Yellow Springs, Ohio "Electronic Transport Properties of Liquid Metals"
O. S. Oen	Tennessee Technological University, Cookeville, Tenn. "Radiation Damage Physics in Solids"
S. M. Ohr	Korean Atomic Energy Research Institute, Seoul, Korea "Radiation Damage in Metals"
	Korean Physical Society, Seoul, Korea "Lattice Defects"
	Japan Atomic Energy Research, Tokai-Mura, Japan "Radiation Damage and Radiation Hardening in bcc Metals"
R. E. Reed	University of Maryland, College Park, Md. "Purification of Refractory Metals by Electron Beam Float Zoning"
W. A. Sibley	University of Missouri, Columbia, Mo. "Radiation Damage in MgO"
	Iowa State University, Ames, Iowa "Color Centers in KCl"

W. A. Sibley	Brookhaven National Laboratory, Upton, N. Y. University of Delaware, Newark, Del. "A Comparison of Radiation Damage in MgO and KCl"
	Princeton University, Princeton, N. J. "Coloration and Hardening of KCl"
	Wake Forest University, Winston-Salem, N. C. "Color Centers in MgO"
	University of North Carolina, Chapel Hill, N. C. "Radiation Damage in MgO and KCl"
D. Walton	Northwestern University, Evanston, Ill. "The Spin-Phonon Interaction and the Effect of a Magnetic Field on the Thermal Conductivity"
	Purdue University, Lafayette, Ind. "The Spin-Phonon Interaction and its Effect on the Thermal Conductivity"
M. S. Wechsler	Associazione Italiana di Metallurgia, Politecnico di Torino, Torino, Italy "Radiation Effects on Structural Metals"
	Euratom Research Center, Ispra, Italy "Radiation Effects on the Mechanical Properties of Metals and Alloys"
	Max Planck Institute, Stuttgart, Germany "Radiation Hardening of Iron and Niobium"
	Research Establishment Risö, Roskilde, Denmark "Radiation Damage to Reactor Structural Materials"
R. A. Weeks	University of Georgia, Athens, Ga. "Paramagnetic Defects in Phosphate Compounds: Glassy and Polycrystalline"
	University of Missouri, Rolla, Mo. "Paramagnetic Defects in Some Germanates"
	Tennessee Technological University, Cookeville, Tenn. "Paramagnetic Defects in Insulating Diamagnetic Solids"
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