ISC-901

UNCLASSIFIED
A.E.C. RESEARCH AND DEVELOPMENT REPORT

ISC-901

**AMES
LABORATORY
IOWA STATE
COLLEGE**

PHYSICS
SEMI-ANNUAL SUMMARY RESEARCH REPORT
JANUARY- JUNE , 1957

DISCLAIMER

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

DISCLAIMER

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

U N C L A S S I F I E D

ISC-901

U N I T E D S T A T E S A T O M I C E N E R G Y C O M M I S S I O N

SEMI-ANNUAL SUMMARY RESEARCH REPORT IN PHYSICS

For January through June, 1957

by

Ames Laboratory Staff

September 11, 1957

Ames Laboratory
at
Iowa State College
F. H. Spedding, Director
Contract W-7405 eng-82

U N C L A S S I F I E D

This report is distributed according to the category Physics and Mathematics (UC-34) as listed in TID-4500, August 15, 1957.

Legal Notice

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

Printed in USA. Price \$1.00 . Available from the

Office of Technical Services
U. S. Department of Commerce
Washington 25, D. C.

TABLE OF CONTENTS

<u>PHYSICS</u>	<u>PAGE</u>
<u>Theoretical Physics</u>	
1. Beta Decay of p^{32}	5
2. Orthogonalization Procedures.....	7
3. Magnetic Moments of Hyperons.....	7
4. Electromagnetic Multipole Radiation.....	8
5. Approximations for Coulomb Wave Functions.....	8
6. Transmission of Electrons through Metal Surfaces.....	9
7. Wave Equation for a Massless Particle with Arbitrary Spin...	9
<u>Experimental Physics</u>	
1. Nuclear Studies.....	10
1.1 Beta-Ray Spectra.....	10
1.2 Nuclear Quadrupole Moments of Rhenium Isotopes.....	12
1.3 Oxygen Analysis in Pure Metals.....	12
1.4 Search for the Beta-Decay of H^5	14
1.5 Electron-Capture Decay of Ba^{133}	15
2. Solid State Studies.....	16
2.1 Specific Heat of High-Purity Iron by a Pulse-Heating Method.....	16
2.2 Electrical Resistivity and Thermal Diffusivity of Nickel.....	17
2.3 Semiconducting Properties of Mg_2Si Single Crystals.....	21
2.4 Semiconducting Properties of Mg_2Ge Single Crystals.....	23
2.5 Measurement of Minority Carrier Lifetimes in Semiconductors.....	25
2.6 Dilatometric Measurements.....	26
2.7 Magnetic Properties of Single Crystals.....	26
2.8 Mass Spectrometric Studies of Metallic Cohesive Energies.....	27
2.9 Carrier Trapping in a Diamond Conduction Counter.....	28
2.10 A Study of Surface Ionization.....	28
2.11 Nuclear Quadrupole Resonance Spectra of Group IIIB Trihalides and of Other Compounds.....	29
APPENDIX I: LIST OF REPORTS FROM THE AMES LABORATORY.....	30
1. Reports for Cooperating Laboratories.....	30
2. Publications.....	31
APPENDIX II: LIST OF SHIPMENTS.....	35

SEMI-ANNUAL SUMMARY RESEARCH REPORT IN PHYSICS

For the Period January through June, 1957

This report is prepared from material
submitted by the group leaders of
the Laboratory

Previous summary research reports in this series are:

ISC-35
ISC-41
ISC-56
ISC-69
ISC-74
ISC-76
ISC-79
ISC-113
ISC-130
ISC-133
ISC-137
ISC-171
ISC-193
ISC-220
ISC-246
ISC-283
ISC-301
ISC-338
ISC-395
ISC-422
ISC-451
ISC-508
ISC-533
ISC-577
ISC-608
ISC-645
ISC-707
ISC-758
ISC-833

Under the direction of F. H. Spedding, G. W. Fox, R. G. Barnes,
 B. C. Carlson, G. C. Danielson, R. H. Good, Jr.,
 C. L. Hammer, D. E. Hudson, E. N. Jensen,
 J. M. Keller, S. Legvold, M. G. Stewart,
 C. A. Swenson, D. J. Zaffarano

Theoretical Physics

1. Beta Decay of P^{32} (B. C. Carlson)*

Small deviations from the allowed spectrum shape have recently been found in the spectrum of P^{32} at the Argonne National Laboratory¹ and at this laboratory. The shape factor is slightly higher at low energies (just above the end point of any P^{33} impurity) than at the high-energy end. The difference amounts to 3 per cent in the Argonne spectrum and 2 per cent in the spectra taken here. A calculation has been made to find out whether the observed deviation can be attributed to interference between the allowed matrix element and second-forbidden matrix elements with the same selection rules. The result shows, as discussed below, that the interference terms are more than large enough to account for the observed deviation. If this interpretation is correct, the P^{32} spectrum is the first instance of observed interference between beta-decay matrix elements of different orders of forbiddenness.

For a tensor interaction (the scalar or vector interaction does not contribute to this decay), the shape factor of P^{32} is proportional to

$$L_0 = (4qN_0/3) c_1 - 2(N_0 - qL_0/3) c_2,$$

* Names indicate group leaders in charge of work.

¹ Porter, Wagner, and Freedman, Bull. Am. Phys. Soc. 2, 229 (1957).

where the c 's are real ratios of second-forbidden to allowed matrix elements:

$$c_1 = \int (\vec{\beta} \cdot \vec{r}) \vec{r} / \int \vec{\beta} \cdot \vec{r}$$

$$c_2 = \int \vec{\beta} \times \vec{r} / \int \vec{\beta} \cdot \vec{r}$$

L_0 is very nearly equal to unity; the coefficients of the c 's are known functions of energy. The second-forbidden matrix elements are calculated under the assumption that a $d_{3/2}$ neutron (coupled to an $s_{1/2}$ proton, to give a spin of 1 for P^{32}) transforms into an $s_{1/2}$ proton. If these configurations were pure, $|\int \vec{\beta} \cdot \vec{r}|$ would vanish because of ℓ -forbiddenness; its actual value, inferred from the experimental log ft of 7.9, is 0.008, in contrast to normal values of order 0.1 to 1. If the radial wave functions are chosen for simplicity to be those of a harmonic-oscillator potential (with spring constant adjusted to fit the Coulomb energy difference between the mirror nuclei of mass number 31), the value of $|\int (\vec{\beta} \cdot \vec{r}) \vec{r}|$ is calculated to be 4.6×10^{-5} . The magnitude of c_1 is then 0.006; its sign is unknown because the sign of $\int \vec{\beta} \cdot \vec{r}$ is unknown. Since the coefficient of c_1 changes from 20 to 0 (almost linearly with energy) over the observed part of the spectrum, the change in the shape factor is 12 per cent. So large a change is certainly not observed, and it cannot be compensated by c_2 because $\int \vec{\beta} \times \vec{r}$ can be shown to vanish for the present choice of harmonic-oscillator radial functions. In order to find out whether the matrix elements are sensitive to the details of the radial wave functions, the calculations are being repeated with the radial wave functions of a square-well potential.

2. Orthogonalization Procedures (B. C. Carlson)

The least-squares property of the Landshoff-Löwdin orthogonalization procedure has been shown to extend also to the approximation of Slater determinants formed from given non-orthogonal one-electron states f_i ($i = 1, 2, \dots, n$) by Slater determinants of orthonormal linear combinations ϕ_i of the f 's. For a problem involving p electrons ($p < n$), the $n! / [p! (n - p)!]$ Slater determinants of the ϕ 's taken p at a time are required to approximate the corresponding determinants of the f 's as closely as possible in the least-squares sense that $\sum \|A(\phi) - A(f)\|^2$ is a minimum. If the Slater determinants A are left unnormalized, the minimizing ϕ 's are the Landshoff-Löwdin functions (apart from an irrelevant common phase factor that can only be a p th root of unity).

3. Magnetic Moments of Hyperons

A paper entitled "Anomalous Magnetic Moments of Hyperons and Mirror Theorem"* by Hiroshi Katsumori was submitted for publication in *PROGR. THEORET. PHYS.* (Japan).

The anomalous magnetic moments of hyperons are calculated, in accordance with the theory of d'Espagnat and Prentki, to lowest-order perturbation approximation. It is further shown that their charge-independent interaction Hamiltonian leads to a mirror theorem for the anomalous magnetic moments of baryons (and of K mesons) without use of a perturbation approximation. Finally, the anomalous magnetic moments of $\sum$ hyperons determined from the mirror theorem and from

* Of interest to, but not supported by the A.E.C. Work was performed by Hiroshi Katsumori, Institute for Atomic Research, Iowa State College.

the experimental mass differences of the $\sum$ particles are compared with the perturbation results. Agreement can be obtained by choosing reasonable values for the cutoff in the first method and for the coupling constants in the second.

4. Electromagnetic Multipole Radiation (R. H. Good, Jr.)

A paper entitled "Electromagnetic Multipole Radiation" by R. H. Good, Jr., was published, ANNALS OF PHYSICS 1, 213 (1957).

ABSTRACT

This paper gives a derivation of the electromagnetic multipole radiation formulas which emphasizes the parallel between the radial problem for photons and the radial problem for Schrodinger or Dirac particles. The Maxwell equations are rewritten in Hamiltonian form, simultaneous eigenfunctions of the square of the angular momentum operator, its z component, and the Hamiltonian are found, and the outgoing waves are selected from these.

5. Approximations for Coulomb Wave Functions (R. H. Good, Jr.)

A paper entitled "Approximations for Coulomb Wave Functions" by R. H. Barlett, M. H. Rice, and R. H. Good, Jr., was accepted for publication in ANNALS OF PHYSICS.

ABSTRACT

This paper gives a discussion of WKB-type approximations to the solutions of the radial wave equation for a Schrodinger particle in a Coulomb field. Approximations based on Airy

integrals, $(L + 1/2)$ -order Bessel functions, and $(2L + 1)$ -order Bessel functions are considered. The results indicate that important factors in the choice of the basic function for the approximation are the poles in the effective potential.

6. Transmission of Electrons through Metal Surfaces (R. H. Good, Jr.)

A paper entitled "Transmission of Electrons through Metal Surfaces" by R. H. Good, Jr., was submitted for publication in J. APPL. PHYS.

ABSTRACT

This paper is a review of recent developments in the theory of electron emission from metals. The main subjects discussed are the periodic deviations in the Schottky effect and the transition between thermionic and field emission. The indications are that each of these phenomena can be understood in terms of the free electron model for the metal and the transmission of the electrons through the image force barrier at the metal surface.

7. Wave Equation for a Massless Particle with Arbitrary Spin

(R. H. Good, Jr.)

A paper entitled "Wave Equation for a Massless Particle with Arbitrary Spin" by C. L. Hammer and R. H. Good, Jr., was submitted for publication in PHYS. REV.

ABSTRACT

A wave equation for a non-interacting particle with zero mass and arbitrary spin s is given in this paper. The Hamiltonian is proportional to the inner product of the momentum and spin operators so that the wave function has $2s + 1$ components. As an auxiliary condition, solutions with spins not parallel or anti-parallel to the momentum are discarded. With this condition the theory is Lorentz-covariant. The energy, momentum, and angular momentum are defined in terms of expected values of the usual type of displacement operator. The specialization $s = 1/2$ is the two-component neutrino theory and $s = 1$ gives Maxwell's equations for the photon.

Experimental Physics1. Nuclear Studies1.1 Beta-Ray Spectra (E. N. Jensen)1.1.1 Spectrum of Yb¹⁶⁹

Coincidence data were taken between the entire internal conversion spectrum and gamma rays with energies greater than 100 kev, with the interval conversion spectrum delayed more than 0.5 μ sec with respect to the gamma rays. The interval conversion coincidence spectrum thus gave the transitions which lie above the 0.66 μ sec metastable level. Only the 63-kev and 93-kev transitions were found to lie above the 0.66 μ sec metastable level.

A delayed coincidence curve between X-rays and the 93-keV internal conversion "K" line established that the level from which the 93-keV transition originates is definitely prompt to less than 0.02 μ sec.

Evidence was found for the existence of a 240-keV gamma ray in coincidence with the 130-keV transition.

A triple-coincidence delay curve was run between X-rays, the 63-keV transition and gamma rays with energies greater than 100 keV. This was done to eliminate the 0.66 μ sec half-life which is obtained when a delayed coincidence curve is run between X-rays and the 63-keV transition. This arises because of the Compton electrons which are counted along with the 63-keV transition. The triple-coincidence delay curve indicates that there is no 0.4 μ sec metastable level in Tm^{169} which lies above and feeds the level from which the 63-keV transition originates. No evidence has been found to substantiate the existence of a reported 0.4 μ sec metastable level in Tm^{169} .

A delayed coincidence curve between the 93-keV internal conversion "K" line and the 63-keV gamma ray showed the existence of a metastable state, with a half-life of approximately 0.06 μ sec, between the two transitions.

1.1.2 Spectrum of Tb^{160}

The radiations from Tb^{160} have been examined by means of thin-lens and intermediate-image spectrometers. Coincidence measurements were also made by means of the intermediate-image spectrometer. Three beta spectra were observed having end-point energies of

865 $\pm$ 6 kev, 561 $\pm$ 9 kev, and 446 $\pm$ 27 kev with branching ratios of 35, 57, and 8 per cent, respectively. The log ft values were found to be 8.5, 8.1 and 8.8, respectively. From internal conversion and photoelectron spectra the following gamma-ray transitions were observed: 86.4 $\pm$ 0.3, 196.5 $\pm$ 1.6, 213.3 $\pm$ 3.5, 294.3 $\pm$ 1.7, 871.4 $\pm$ 1.6, 958.8 $\pm$ 2.3, and 1174.3 $\pm$ 2.1 kev.

1.2 Nuclear Quadrupole Moments of Rhenium Isotopes (R. G. Barnes)

The pure quadrupole spectra of the rhenium isotopes Re^{185} and Re^{187} were detected and measured in the dimeric pentacarbonyl, $\text{Re}_2(\text{CO})_{10}$. These are the first quadrupole resonances of rhenium to be detected, and they yield an accurate value for the ratio of the quadrupole moments of the rhenium isotopes: $Q(\text{Re}^{185})/Q(\text{Re}^{187}) = 0.056 \pm 0.005$.

1.3 Oxygen Analysis in Pure Metals (D. J. Zaffarano)

It appears to be possible to detect the beta activity from trace oxygen impurities in certain metals activated by X-ray bombardment, provided fluorine or zirconium is not present in comparable amounts. Two samples of yttrium metal of nearly identical shape and size were bombarded with approximately the same dose from the Iowa State College Synchrotron. A scintillation spectrometer with a well-type anthracene crystal was used with bias so that only beta-rays having an energy greater than approximately 0.8 Mev were counted. Typical data are shown in Figure 1. The first sample, labeled 1850 ppm O_2 , was the standard which had been analyzed by the optical spectroscopy group. A second sample of unknown oxygen

Figure 1. Oxygen activity in yttrium samples.

content was activated and its decay curve was also plotted. It is clear that the ratio of activity, corrected for dosage, should give the relative oxygen content. The ratio of oxygen activity integrated over time, i.e., total oxygen activity, gave values of 3.22, 3.55 and 3.67. The ratio of oxygen content obtained by optical spectroscopic analysis gave values of 3.24 and 3.68.

The above samples were prepared by melting the metal in tantalum crucibles. Similar samples prepared in zirconium crucibles could not be analyzed by this method because of the competing $\text{Zr}^{90}(\gamma, n) \text{Zr}^{89}$ reaction whose 4.4 minute half-life obscures the $\text{O}^{16}(\gamma, n) \text{O}^{15}$ activity. Similarly, the presence of fluorides gives 70-second F^{17} activity with positron emission almost identical in energy to that of oxygen.

It would appear that it is possible to estimate the oxygen content in favorable cases as low as 500 ppm on the basis of present results, although improvements in technique may lower this figure. Examination of reported activities shows that it should be possible to assay the oxygen content of Ce, Eu, Gd, Tb, Tm, Yb, Lu and Hf, provided they are prepared without zirconium or fluorine impurities. The metals Sm, Dy, Ho and Er can probably be assayed, but Pr and Nd cannot, because of interfering activities.

1.4 Search for the Beta-Decay of H^5 (D. J. Zaffarano)

A suggestion by Blanchard that the isotope, hydrogen 5, may be stable to nucleon emission¹ would imply, if true, that the reaction

¹ C. H. Blanchard and R. G. Winter, Phys. Rev. 107, 774 (1957).

should occur. To test this speculation, we bombarded lithium metal with 48-Mev X-rays to obtain the reaction $\text{Li}^7(\gamma, 2p)\text{H}^5$. The resulting radioactivity was counted in between beam bursts, using a gate 10 milliseconds long delayed 400 microseconds after each X-ray burst. A 25 millisecond activity was indeed found, and an X-ray threshold energy of 30 Mev was established. However, further investigation proved that the activity seen arose from nitrogen absorbed in the lithium metal, and was identified as arising from the reaction $\text{N}^{14}(\gamma, 2p)\text{B}^{12}$. A copious yield of $\text{Li}^7(\gamma, p)\text{He}^6$ was also found. A sample of pure lithium, isolated from air, gave no detectable high energy beta-ray activity ascribable to H^5 . On the supposition that the transition sought is a low energy beta-transition, the remaining possibility is that the alpha particles from the reaction may be seen. Work is continuing on this phase of the experiment.

1.5 Electron-Capture Decay of Ba^{133} (M. G. Stewart)

The directional correlation of the 357-82 kev gamma cascade in Cs^{133} following the electron capture decay of Ba^{133} has been measured. The source was solid BaCl_2 in the form of a thin cylinder 0.79 inch long and 0.036 inch in diameter. The walls were made of 0.002-inch mylar.

A least-squares fit to the data gives for the correlation function, after correcting for the finite detector and source size,

$$W(\theta) = 1 + (.031 \pm .006) P_2(\cos \theta) - (.006 \pm .010) P_4(\cos \theta).$$

The data can be explained by an assignment of pure E2 for the 357-kev gamma ray and 98.1% M1, 1.9% E2 for the 82-kev gamma ray.

2. Solid State Studies

2.1 Specific Heat of High-Purity Iron by a Pulse-Heating Method (G. C. Danielson)

A pulse heating method for measuring the specific heats of metals at high temperatures has been developed. The method has been applied to a sample of high purity iron and the estimated errors were less than two per cent over the entire temperature range 25°C to 1000°C. The specific heat at any temperature was obtained from the equation:

$$C_p = \frac{1}{m \frac{d\theta}{dt}} \left[I^2 R - \left(\frac{dQ}{dt} \right)_{\text{cond.}} - \left(\frac{dQ}{dt} \right)_{\text{rad.}} \right],$$

where the heat loss terms owing to conduction and radiation were only a few per cent of the total heat input $I^2 R$. The rate of change of temperature ($d\theta/dt$) was found from a measurement of the resistance (by means of Kelvin bridge) and from a calibration curve of resistance versus temperature. Details of the new method have been given by Wallace.¹

The iron wire was obtained from Johnson, Matthey and Co., London. The principal impurities were carbon, 0.03 per cent; oxygen, 0.01 per cent; and nitrogen, 0.01 per cent. Other foreign

¹ D. C. Wallace, Specific Heat of High-Purity Iron by a Pulse-Heating Method, unpublished M. S. thesis, Iowa State College, 1957.

elements, each present to less than 0.0005 per cent, were copper, nickel, sodium, silver, magnesium, and silicon. The mass of the wire sample was 17.554 mg, the length was 4.3837 cm, and the radius was 0.0125 cm.

The resistance as a function of temperature is shown in Figure 2. From this curve the Curie temperature was estimated to be $761 \pm 3^\circ\text{C}$ and the alpha-gamma phase transition temperature was $898 \pm 5^\circ\text{C}$. A discontinuity of 0.37 per cent in the resistance was observed at this alpha-gamma phase transition.

The specific heat as a function of temperature is shown in Figure 3. The sharp peak indicated a Curie temperature of 769°C , which is in good agreement with the results of other investigators. The momentary dip in specific heat just above the Curie temperature is not understood. A temperature hysteresis effect was observed when the sample was pulse-heated through the alpha-gamma phase transition. The specific heat became infinite at 945°C rather than at 898°C . The explanation of this effect is probably associated with the formation of strains resulting from the change in structure. Such strains must be relieved by diffusion, which would take an appreciable time for a heating rate of 2500°C per second. The latent heat of transformation from the alpha to the gamma phase was calculated to be 3.3 cal/gm, which is in good agreement with accepted values.

2.2 Electrical Resistivity and Thermal Diffusivity of Nickel

(G. C. Danielson)

The electrical resistivities of four samples of nickel have been measured from 25°C to 1000°C . The results are shown in Figure 4.

Figure 2. Resistance as a function of temperature for the iron sample.

Figure 3. Specific heat as a function of temperature for the iron sample.

Figure 4. Electrical resistivity of pure nickel and some nickel alloys.

The resistivity values for "A" nickel, which is 99.4 per cent nickel, are not very different from those of the Matthey spectrographically standardized nickel. The resistivity values for "D" nickel, which contains 95.2 per cent nickel and 4.5 per cent manganese, and for permanickel are greatly different. The effects of the impurities (as shown in Figure 4) are to increase the resistivities and to lower the Curie temperature.

The thermal diffusivities of the same samples of nickel were measured at the same time over the same temperature range (25°C to 1000°C). The results are shown in Figure 5. The thermal diffusivity values for "A" nickel are significantly lower than for Matthey nickel, so thermal diffusivity seems more sensitive to small amounts of impurities than does electrical resistivity. The effects of impurities (as shown by Figure 5) are to lower the thermal diffusivities and to lower the Curie temperature.

2.3 Semiconducting Properties of Mg_2Si Single Crystals

(G. C. Danielson)

Both n- and p-type single crystals of magnesium silicide (Mg_2Si) have been prepared. The p-type crystals were obtained when the melt was doped with 0.2 to 0.02 per cent by weight of silver or copper. Preliminary measurements were reported previously (ISC-833) and final results have been reported by Morris.¹

Carrier concentrations in the saturation region were as low as $8 \times 10^{16} \text{ cm}^{-3}$ for n-type and $4 \times 10^{17} \text{ cm}^{-3}$ for p-type samples.

¹ R. G. Morris, Semiconducting Properties of Mg_2Si Single Crystals, unpublished Ph. D. thesis, Iowa State College, 1957.

Figure 5. Thermal diffusivity of pure nickel and some nickel alloys.

Electrical resistivity and Hall coefficient have been measured from 77°K to 1000°K. Hall mobility showed a temperature dependence in the intrinsic range of about $T^{-5/2}$ for all samples. At room temperature the Hall mobility was as high as 400 cm²/volt-sec for n-type and 56 cm²/volt-sec for p-type. The energy gap, determined from curves of $\log (RT^{3/2})$ versus $1/T$, was 0.78 ev.

As shown in Figure 6 the electron mobility, at any temperature from 77°K to 400°K, can be explained quantitatively by a combination of scattering by optical modes and scattering by ionized impurities, if the dielectric constant were about 20. The electron mobility from 400°K to 1000°K can be explained quantitatively by a combination of acoustical mode scattering and electron-hole scattering, if the dielectric constant were about 3. It is clearly important to obtain measurements of the dielectric constant in order to find out if it is near 20 or near 3. A value near 20 is considered more likely since this value has been found for many other semiconductors.

2.4 Semiconducting Properties of Mg₂Ge Single Crystals

(G. C. Danielson)

Both n- and p-type single crystals of magnesium germanide (Mg₂Ge) have been prepared. Undoped samples were n-type and had saturated impurity carrier concentrations as low as 3×10^{15} cm⁻³. Preliminary measurements were reported in ISC-833 and final results were reported by Redin.¹

¹ R. D. Redin, Semiconducting Properties of Mg₂Ge Single Crystals, unpublished Ph. D. thesis, Iowa State College, 1957.

Figure 6. Electron mobility of Mg₂Si as a function of temperature.

The saturation Hall coefficient was about $-2300 \text{ cm}^3/\text{coulomb}$ and the room temperature resistivity was about 10 ohm-cm .

Donor levels were located about 0.04 ev and 0.08 ev below the conduction band but the donor impurities have not been identified. Silver-doped crystals were p-type and had impurity concentrations roughly proportional to the amount of added silver. There appeared to be at least two acceptor levels but it has not been possible to determine their energies. The hole mobility in the extrinsic region (120°K to 350°K) of the p-type samples and the mobility difference in the intrinsic region (350°K to 700°K) of the n-type samples varied with temperature as $T^{-2.0}$. The mobility difference increased faster than $T^{-2.0}$ above 700°K . The temperature dependence below 300°K might be determined by a combination of scattering by optical modes and ionized impurities, but it does not seem possible to explain the temperature dependence above 300°K by any reasonable combination of scattering mechanisms. The average value of the energy gap from three n-type samples and one p-type sample was $0.69 \pm 0.01 \text{ ev}$. The product of the electron concentration (n) and hole concentration (p) was

$$np = 2.12 (10)^{33} T^3 \exp (-7980/T).$$

2.5 Measurement of Minority Carrier Lifetimes in Semiconductors (G. C. Danielson)

The bulk lifetimes of minority carriers in n-type germanium and in both n- and p-type silicon have been investigated. The sample was illuminated with periodic light flashes produced by a

spark gap. The transient change in conductance gave the lifetime. In germanium and silicon the measured bulk lifetimes had values from 15 to 140 microseconds with estimated errors of 4 to 15 per cent. The general solution of the equation of continuity for the minority carriers in a rectangular sample has been obtained and the particular solution for this experiment has been examined in detail. This work is described in ISC-926.

2.6 Dilatometric Measurements (S. Legvold and F. H. Spedding)

The thermal expansions of several La-Y alloys were determined from room temperature up to 900°C. Pure lanthanum had been found to transform from hexagonal structure to face-centered-cubic structure at 300°C. This same transformation was found to occur at 485°C for a sample containing 95% La and 5% Y. It was observed further that a transformation of some kind occurs at 50°C when the Y content is increased to 15%. The nature of the transformation for this alloy is being studied by X-ray methods.

2.7 Magnetic Properties of Single Crystals (S. Legvold and F. H. Spedding)

A paper entitled "Magnetic Properties of Neodymium Single Crystals" by D. R. Behrendt, S. Legvold and F. H. Spedding was published, PHYS. REV. 106, 723-725 (1957).

ABSTRACT

Magnetic measurements have been made on single crystals of neodymium which were grown by the Bridgman technique. At 20.4°K and above, the susceptibility obtained with the field perpendicular to the c_0 axis of the hexagonal crystal is

greater than that obtained with the field parallel to the c_0 axis. In this same temperature range no anisotropy is observed in the basal plane. At 4.2°K antiferromagnetic ordering is indicated by the data and magnetic anisotropy in the basal plane is observed.

2.8 Mass Spectrometric Studies of Metallic Cohesive Energies

(D. E. Hudson and F. H. Spedding)

Eight more runs on erbium have been added to the three previously reported in ISC-833. The results of all runs gave a cohesive energy of 76.0 ± 1.2 kcal/mole reduced to 298°K. This is the only experimental determination that has been made, so no other values are available for comparison.

A report (ISC-854) entitled "Mass Spectrometric Study of Metallic Cohesive Energies" by William R. Savage, D. E. Hudson, and F. H. Spedding is being distributed.

ABSTRACT

A sensitive method was used for measuring rapidly the latent heat of vaporization or sublimation of metals of moderate volatility. A modification of the effusion method of determining vapor pressure was employed to obtain the values reported. Atoms from a saturated vapor effuse from a Knudsen-type vapor cell and impinge upon a heated ribbon. A fraction re-evaporate as positive ions and are observed with a mass spectrometer of conventional design. The Clausius-Clapeyron equation is used to obtain the latent heat of vaporization from the dependence of ion current upon the cell temperature. Only

a slight degree of surface ionization at the ribbon is required for the measurement of latent heats.

An application of the method has been made to aluminum, dysprosium, samarium, thulium, and ytterbium. The work on aluminum redemonstrated the utility of the procedure and yielded an enthalpy of vaporization of 73.54 ± 0.35 kilo-calories per mole. Values were obtained for the molar change in enthalpy for sublimation of certain rare earths. They are: dysprosium, 68.15 ± 0.89 kcal (vaporization at 1215°K); samarium, 88.63 ± 0.79 kcal (vaporization at 811°K); thulium 56.19 ± 0.98 kcal (vaporization at 937°K) and ytterbium, 39.45 ± 1.10 kcal (vaporization at 667°K). The mass spectrometric method provides a convenient measurement of first-order phase transitions.

2.9 Carrier Trapping in a Diamond Conduction Counter (D. E. Hudson)

The conduction counting properties of diamond are being used to explore directly the trapping levels responsible for carrier capture. It has been established that the cross section for photo-electric emptying of traps rises rapidly as the photon energy rises through about 2.0 to 2.5 electron volts. If it can be assumed that electrons are the majority carriers in gamma-induced conductivity in this particular diamond, then this result indicates the existence of a trapping level about 2.5 ev. below the conduction band.

2.10 A Study of Surface Ionization (D. E. Hudson)

The mass spectrometer has been used in a preliminary study of the surface ionization efficiency of tungsten for most of the rare earth atoms. The most extensive data have been obtained from

studies on dysprosium and erbium. The results show a characteristic family of curves of efficiency vs. $1/T$ for various atom fluxes. These curves are interpreted to indicate either that a very tiny fraction of a monolayer has a strong effect on the work-function of tungsten or the current theories of the process are in error.

2.11 Nuclear Quadrupole Resonance Spectra of Group IIIB Trihalides and of Other Compounds (R. G. Barnes)

The aluminum resonances in AlBr_3 and AlI_3 have been detected and measured. These resonances add further confirmation to the close structural similarity of AlBr_3 , AlI_3 , GaCl_3 , GaBr_3 , GaI_3 , InBr_3 , and InI_3 in the solid phase. Work now in progress involves the examination of the temperature dependence of the spectra of GaI_3 and InI_3 in order to shed more light on the phase transitions in these compounds.

The halogen pure quadrupole spectra of CrCl_3 , CrBr_3 , ZrBr_4 , and TiBr_4 have been detected and measured. The chlorine quadrupole spectrum of AuCl_3 has also been measured, and the data confirm the crystallographic evidence that this compound is dimeric in the solid phase. It appears to undergo several phase transitions below room temperature, one of which is analogous to the transitions observed in GaI_3 and InI_3 .

APPENDIX I: LIST OF REPORTS FROM THE AMES LABORATORY

1. Reports for Cooperating Laboratories

- ISC-687 John Gibson and J. M. Keller. Multi-Band Electrical Conduction.
- ISC-700 D. A. McCutchan and Glenn Murphy. The Stress-Strain Characteristics of Uranium.
- ISC-726 R. M. Henry and D. S. Martin. Comparative Yields of $\text{Fe}^{54}(\gamma, \text{pn})\text{Mn}^{52}$ and $\text{Fe}^{54}(\gamma, 2\text{n})\text{Fe}^{52}$.
- ISC-729 Thomas Hendrickson and J. M. Keller. Ferromagnetic-Antiferromagnetic Phase Transitions.
- ISC-746 Joseph I. Genco, M. Griffel, F. R. Duke and L. D. Jennings. The (C-H) Bond Dissociation Energy in the Methyl Group of Toluene.
- ISC-757 Ames Laboratory Staff. Chemistry. Semi-Annual Summary Research Report. January-June, 1956.
- ISC-758 Ames Laboratory Staff. Physics. Semi-Annual Summary Research Report. January-June, 1956.
- ISC-759 Ames Laboratory Staff. Metallurgy. Semi-Annual Summary Research Report. January-June, 1956.
- ISC-777 Charles Apel and H. J. Svec. Kinetics of the Reaction Between Calcium and Water Vapor.
- ISC-779 Dale Gibbs and H. J. Svec. Kinetics of the Reaction Between Magnesium and Water Vapor.
- ISC-802 Ernest L. Koerner, Jr., Morton Smutz and H. A. Wilhelm. Separation of Niobium and Tantalum by Liquid Extraction.
- ISC-804 G. W. Eakins, B. J. Loupee, W. A. Rhinehart, G. Schupp and E. N. Jensen. A Method for Reducing Time-Jitter in the Output of a Single Channel Analyzer.
- ISC-812 K. A. Gschneidner, D. J. Beerntsen, R. W. Vest, J. A. Kingston and J. F. Smith. Tabulation, Bibliography, and Structure of Binary Intermetallic Compounds. II. Compounds of Beryllium, Magnesium and Calcium.
- ISC-833 Ames Laboratory Staff. Physics. Semi-Annual Summary Research Report. July-December, 1956.

2. Publications

- Atoji, M., J. W. Richardson and R. E. Rundle
On the Crystal Structures of the Magnus Salts,
 $\text{Pt}(\text{NH}_3)_4\text{PtCl}_4$. J. Am. Chem. Soc. 79, 3017-3020 (1957).
- Banks, C. V. and R. E. Bisque
Spectrophotometric Determination of Zinc and Other
Metals with Alpha-, Beta-, Gamma-, Delta-Tetraphenyl-
porphine. Anal. Chem. 29, 522-526 (1957).
- Barnes, R. G., S. L. Segel, P. J. Bray and P. A. Casabella
Dimerization of Solid Group IIIB Trihalides. III.
Bromine, Gallium, and Indium Quadrupole Resonances
in GaBr_3 , GaI_3 , InBr_3 , and InI_3 . J. Chem. Phys. 26,
1345-1346 (1957).
- Barson, F., S. Legvold and F. H. Spedding
Thermal Expansion of Rare Earth Metals. Phys. Rev.
105, 418-424 (1957).
- Behrendt, D. R., S. Legvold and F. H. Spedding
Magnetic Properties of Neodymium Single Crystals.
Phys. Rev. 106, 723-725 (1957).
- Beyer, G. H. and R. B. Edwards
Flooding Characteristics of a Pulse Extraction Column.
Section 2 of Reactor Operational Problems, D. J. Hughes,
Stuart McLain and Clark Williams, Editors, 102-110
(1957). Pergamon Press, New York, London, Paris.
- Blue, M. D. and G. C. Danielson
Electrical Properties of Arc-Evaporated Carbon Films.
J. Appl. Phys. 28, 583-586 (1957).
- Bureau, A. J. and C. L. Hammer
Isomeric State of W^{181} . Phys. Rev. 105, 1006-1011
(1957).
- Carlson, B. C. and J. M. Keller
Orthogonalization Procedures and the Localization of
Wannier Functions. Phys. Rev. 105, 102-103 (1957).
- Carlson, O. N., P. E. Armstrong and H. A. Wilhelm
Zirconium-Germanium Alloy System. Trans. A.S.M.
48, 843-854 (1956).
- Carlson, O. N., J. M. Dickinson, H. E. Lunt and H. A. Wilhelm
Thorium-Columbium and Thorium-Titanium Alloy Systems.
J. Metals 8, 132-136 (1956).

- Carlson, O. N., F. A. Schmidt and H. A. Wilhelm
Preparation of Zirconium and Hafnium Metals by Bomb
Reduction of Their Fluorides. J. Electrochem. Soc.
104, 51-56 (1957).
- Chiotti, P., H. H. Klepfer and K. J. Gill
Uranium-Zinc System. J. Metals 9, 1-7 (1957).
- Corbett, J. D., S. von Winbush and F. C. Albers
The Solubility of the Post-Transition Metals in Their
Molten Halides. J. Am. Chem. Soc. 79, 3020-3024
(1957).
- Dahl, L. F., E. Ishishi and R. E. Rundle
Polynuclear Metal Carbonyls. I. Structures of
 $Mn_2(CO)_{10}$ and $Re_2(CO)_{10}$. J. Chem. Phys. 26, 1750-1751
(1957).
- Dahl, L. F. and R. E. Rundle
Polynuclear Metal Carbonyls. II. Structure of Iron
Tetracarbonyl by X-Ray Diffraction. J. Chem. Phys.
26, 1751-1752 (1957).
- Duke, F. R. and R. A. Fleming
Density and Electrical Conductance in the System
 $KCl-ZnCl_2$. J. Electrochem. Soc. 104, 251-254 (1957).
- Duke, F. R., R. W. Laity and B. Owens
Transport Numbers and Structures in Fused $AgNO_3-NaNO_3$
Mixtures. J. Electrochem. Soc. 104, 299-300 (1957).
- Fisher, R. W. and G. R. Winders
High-Temperature Loop for Circulating Liquid Metals.
A.I.Ch.E. Chem. Engr. Prog. Symp. Series, No. 20,
Vol. 53, 1-6 (1957).
- Fritz, J. S., W. J. Lane and Ann Sutton Bystroff
Complexometric Titrations Using Azoxine Indicators.
Anal. Chem. 29, 821-825 (1957).
- Fritz, J. S., Marlene J. Richard and Ann Sutton Bystroff
Complexometric Titrations Following Cupferron
Separation of Interferences. Anal. Chem. 29, 577-579
(1957).
- Fritz, J. S., S. S. Yamamura and Marlene J. Richard
Titration of Sulfate Following Separation with Alumina.
Anal. Chem. 29, 158-161 (1957).
- Gibson, J. B. and J. M. Keller
Modified Deformable Potential for Thermal Scattering
of Electrons. Phys. Rev. 105, 476-479 (1957).

- Good, R. H., Jr.
Electromagnetic Multipole Radiation. *Annals of Physics* 1, 213-220 (1957).
- Goodman, L., I. G. Ross and H. Shull
On the Application of the Molecular Orbital Method to the Spectra of Substituted Aromatic Hydrocarbons. *J. Chem. Phys.* 26, 474-480 (1957).
- Graham, D. and R. S. Hansen
The Structure of Adsorbed Monolayers. I. Normal Aliphatic Alcohols and Carboxylic Acids Adsorbed from Aqueous Solutions on Graphon. *J. Phys. Chem.* 60, 1153-1156 (1956).
- Grimes, D. M., S. Legvold and E. F. Westrum, Jr.
Molecular Field Fluctuation Effects in Mixed Nickel-Zinc Ferrites. *Phys. Rev.* 106, 866-867 (1957).
- Hammer, C. L. and M. G. Stewart
Isomeric Transitions in the Rare-Earth Elements. *Phys. Rev.* 106, 1001-1007 (1957).
- Hansen, R. S. and Ursula H. Mai
Idealized Models for Adsorption from Solution. I. Van der Waals Adsorption from Regular Solutions. *J. Phys. Chem.* 61, 573-577 (1957).
- Hansen, R. S. and Mirella Miotto
Relaxation Phenomena and Contact Angle Hysteresis. *J. Am. Chem. Soc.* 79, 1765 (1957).
- Horrocks, D. L. and A. F. Voigt
The Formation of Thallium Chloride Complexes and Their Extraction into Ether. *J. Am. Chem. Soc.* 79, 2440-2443 (1957).
- Jacobsen, F. M. and G. H. Beyer
Operating Characteristics of a Centrifugal Extractor. *A.I.Ch.E. Journal* 2, 283-289 (1956).
- King, A. M. and A. F. Voigt
Relative Yields of Nuclear Isomers of Br^{80} Produced by a (γ, n) Reaction. *Phys. Rev.* 105, 1310-1311 (1957).
- Kross, R. D. and V. A. Fassel
Regularities in the Infrared Spectra of Picric Acid Molecular Complexes. *J. Am. Chem. Soc.* 79, 38-41 (1957).
- Moser, H. C. and A. F. Voigt
Dismutation of the Mercurous Dimer in Dilute Solutions. *J. Am. Chem. Soc.* 79, 1837-1839 (1957).

- Peterson, D. T. and D. J. Beerntsen
Vacuum Fusion Determination of Oxygen and Nitrogen in Lanthanum. Anal. Chem. 29, 254-257 (1957).
- Rundle, R. E.
Electron Deficient Compounds. J. Phys. Chem. 61, 45-50 (1957).
- Rundle, R. E. and J. D. Corbett
Concerning the Symmetry of Benzene-Positive Ion Complexes; Unipositive Third Group Ions. J. Am. Chem. Soc. 79, 757 (1957).
- Smith, J. F. and D. M. Bailey
The Structures of $ZrGe_2$, $HfSi_2$ and $HfGe_2$. Acta Cryst. 10, 341-342 (1957).
- Smith, J. F. and A. E. Ray
The Structure of $V_4Al_{12}O_{23}$. Acta Cryst. 10, 169-172 (1957).
- Spedding, F. H., S. Legvold, A. H. Daane and L. D. Jennings
Some Physical Properties of the Rare Earth Metals. Chapter XII of Progress in Low Temperature Physics, Vol. II, C. J. Gorter, Editor, 368-394 (1957). North-Holland Publishing Company, Amsterdam, Holland.
- Svec, H. J. and C. Apel
Metal-Water Reactions. IV. Kinetics of the Reaction between Calcium and Water Vapor. J. Electrochem. Soc. 104, 346-349 (1957).
- Voigt, A. F.
Liquid Metal Extraction for Processing of Spent Fuel. Section 2 of Reactor Operational Problems, D. J. Hughes, Stuart McLain and Clark Williams, Editors, 132-137 (1957). Pergamon Press, New York, London, Paris.
- Wilhelm, H. A.
Thorium. Chapter 2 of Progress in Nuclear Energy, Series V, Metallurgy and Fuels, Vol. 1, H. M. Finniston and J. P. Howe, Editors, 205-268 (1956). Pergamon Press Ltd., London.
- Zaslow, B. and R. E. Rundle
The Crystal Structure of Tetraphenylarsonium Tetrachloroferrate(III), $(C_6H_5)_4AsFeCl_4$. J. Phys. Chem. 61, 490-494 (1957).

APPENDIX II: LIST OF SHIPMENTS

<u>Destination</u>	<u>Item</u>
Dr. Gilbert Eggert Sandia Corp. Albuquerque, New Mexico	650 gm zinc-zirconium alloy
University of Minnesota Minneapolis, Minnesota	1 gm hafnium metal
University of Kansas Lawrence, Kansas	25 gm cerium metal
State University of Iowa Iowa City, Iowa	5 gm terbium oxide 2 gm special N ¹⁵ sample
Union Carbide Nuclear Company Oak Ridge, Tennessee	100 gm yttrium oxide 10 gm lanthanum oxide 10 gm neodymium oxide 10 gm samarium oxide 10 gm gadolinium oxide 10 gm dysprosium oxide 5 gm praseodymium oxide 1 gm ytterbium oxide 500 mg holmium oxide 500 mg erbium oxide 250 mg terbium oxide 250 mg thulium oxide 100 mg lutetium oxide 2 kgm dysprosium oxide 1 kgm ytterbium oxide 20 gm samarium metal 20 gm gadolinium metal
General Electric Research Laboratory Schenectady, New York	5 gm holmium metal
Brookhaven National Laboratory Upton, Long Island, New York	1 gm holmium oxide 1 gm thulium oxide 1 gm terbium oxide 1 gm lutetium oxide 4 pieces erbium metal 100 mg thulium metal
Princeton University Palmer Physical Laboratory Princeton, New Jersey	3 gm hafnium oxide
Lansen-Naeve Corp. New York 4, New York	10 gm ytterbium metal

<u>Destination</u>	<u>Item</u>
Oak Ridge Institute of Nuclear Studies Oak Ridge, Tennessee	1 gm holmium oxide 1 gm lutetium oxide
University of Kentucky Lexington, Kentucky	2 gm samarium oxide 2 gm neodymium oxide
Dr. John Owen The Clarendon Laboratory Oxford, England	2 specimens of gadolinium-yttrium alloy
Heavy Minerals Company Chattanooga, Tennessee	1 gm lanthanum oxide 1 gm cerium oxide 1 gm praseodymium oxide 1 gm neodymium oxide 1 gm samarium oxide 1 gm yttrium oxide 1 gm gadolinium oxide 100 mg terbium oxide 100 mg dysprosium oxide 100 mg holmium oxide 100 mg erbium oxide 100 mg ytterbium oxide 100 mg thulium oxide 100 mg lutetium oxide
University of California Los Alamos Scientific Laboratory Los Alamos, New Mexico	20 gm yttrium oxide 20 gm lanthanum oxide 20 gm praseodymium oxide 20 gm neodymium oxide 20 gm samarium oxide 20 gm gadolinium oxide 5 gm erbium oxide 5 gm ytterbium oxide 3 gm terbium oxide 3 gm dysprosium oxide 3 gm holmium oxide 3 gm thulium oxide 3 gm lutetium oxide
Institut für Physikalische Chemie an der Technischen Hochschule Vienna, Austria	10 gm hafnium metal
Dr. Frank Benner National Research Corp. Cambridge, Massachusetts	5 samples yttrium metal

<u>Destination</u>	<u>Item</u>
Purdue University Lafayette, Indiana	10 gm cerium oxide
Massachusetts Institute of Technology Cambridge, Massachusetts	2 gm yttrium oxide 2 gm lanthanum oxide 2 gm erbium oxide 3 gm dysprosium metal 1 gm gadolinium metal
Columbia-Southern Chemical Corp. Barberton, Ohio	50 gm xenotime sand
Physikalisches Institut der Technischen Hochschule Munich, Germany	1 gm terbium metal 1 gm holmium metal 1 gm thulium metal
National Bureau of Standards Washington 25, D. C.	2/10 gm each of the following oxides: cerium dysprosium holmium thulium ytterbium thorium
Universitetet Institute for Teoretisk Fysik Copenhagen, Denmark	1 gm dysprosium oxide 1 gm erbium oxide
Dr. Joseph Graca Iowa State College Ames, Iowa	9.7 gm yttrium oxide 13.45 gm erbium oxide 11.17 gm dysprosium oxide 200 ml each of the following 5% solutions: holmium ethylenediamine- tetraacetate yttrium chloride thulium chloride ytterbium chloride terbium chloride holmium chloride cerium chloride dysprosium chloride samarium chloride gadolinium chloride erbium chloride