

was determined by numerically evaluating the complex transmission coefficient⁵ (including multiple reflections in the sample).

For a very pure specimen ($\rho=40$ ohm cm) the contribution of the carriers to κ is negligible at room temperature and for these conditions a value of 16.0 ± 0.5 was obtained. This value was used for κ_0 in Eq. 5 and is in good agreement with infrared data for the index of refraction⁶ which leads to $\kappa=16.55$ for $\lambda=2.60$ microns.

The results of the measurements are given in Figs. 1 and 2 where $\Delta\kappa=\kappa_0-\kappa$ is plotted as a function of temperature for samples with room temperature dc resistivities of 5.72 ohm cm

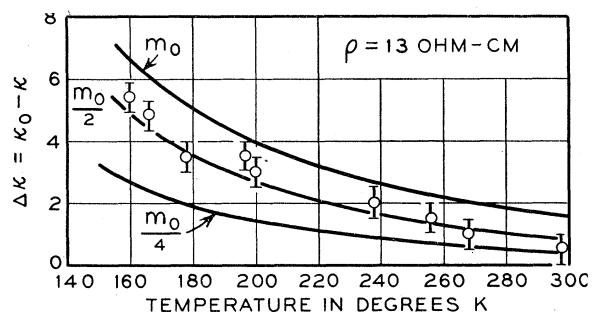


FIG. 2. Plot of $\Delta\kappa = \kappa_0 - \kappa$ vs absolute temperature for germanium ($\rho = 13.0$ ohm cm).

and 13.0 ohm cm. The solid curves are the theoretical curves predicted by Eq. 5 for various effective masses. It is seen that both sets of measurements predict an effective mass of about 0.6 times the free electron mass. It also is seen that the simple theory presented here predicts the proper temperature dependence from which we obtain $\tau = 6.6 \times 10^{-9} T^{-3}$ sec for the relaxation time.

The authors wish to thank G. L. Pearson for preparing the samples and M. B. Prince for providing the mobility data prior to publication.

¹ For a recent review and references see E. Conwell, Proc. Inst. Radio Engrs. 40, 1327 (1952).

² The electron contribution to the dielectric constant has recently been used as a correction term for measurements made at room temperature with 10 cm microwaves. [J. M. Goldey and S. C. Brown, Bull. Am. Phys. Soc. 28, No. 1, 7 (1953)].

³ This treatment is essentially that of the Drude-Zener theory. See for example, F. Seitz, *Modern Theory of Solids* (McGraw-Hill Book Company, Inc., New York, 1940), Sec. 147.

⁴ Drift mobilities of electrons in *p* type germanium of comparable impurity density have recently been measured by M. B. Prince. These values were used for the theoretical curves.

⁵ E. G. Montgomery, *Technique of Microwave Measurements* (McGraw-Hill Book Company, Inc., New York, 1947), pp. 565-584.

⁶ H. B. Briggs, Phys. Rev. 77, 287 (1950).

The Hall Coefficient of Calcium

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IN the course of other investigations regarding the Hall effect, we have measured the Hall coefficient of calcium which seems not to have been determined before.¹ A sample of calcium was kindly put at our disposal by the Metallurgical Laboratory, Technical University of Denmark. The purity was not specified but was supposed to be high. As it seems rather laborious to analyze calcium for small impurities (e.g., CaO), we have measured the electric resistivity, the density, and the lattice constant in order to give a specification of our calcium.

The resistivity was found by passing a known current through a rod of the material and measuring (with a potentiometer) the potential difference between two probes placed over various lengths of the rod. The density was found by weighing a cylinder of known dimensions. The lattice constant was determined with cobalt K_{α} radiation in a Debye-Scherrer camera calibrated with copper.

The results were, at room temperature:

Resistivity	$(3.60 \pm 0.03) \times 10^{-6} \Omega \text{ cm.}$
Density	$1.543 \pm 0.004 \text{ g cm}^{-3}.$
Lattice constant	$(5.59 \pm 0.01) \times 10^{-8} \text{ cm (face-centered cubic).}$
For comparison we may quote: ²	
Resistivity	$4.3 \times 10^{-6} \Omega \text{ cm.}$
Density	$1.542 \text{ g cm}^{-3}.$
Lattice constant	$5.57 \times 10^{-8} \text{ cm.}^3$

The density found corresponds well with the ordinarily accepted values of density and lattice constant, whereas the lattice constant found by us is a little too high. The resistivity found is very low, however, and as one would hardly expect the resistivity to decrease as a consequence of impurities, we think we can be pretty sure that our calcium was of high purity, say at least 99 percent.

For measurement of the Hall coefficient the material was rolled down to a thickness of (0.203 ± 0.002) mm. The rolling was carried out at room temperature and in the atmosphere, but the material was protected by an oil film; one annealing (by heating in a very good vacuum) was necessary. The specimens were cut out in rectangular shape, 48 by 17 mm, and measured in air, still being protected against oxidation by an oil film. Immediately

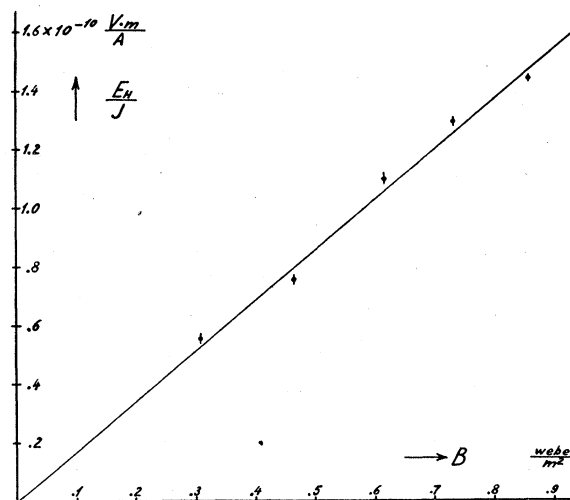


FIG. 1. Ratio E_H/J as a function of magnetic induction B .

before measuring, the surface was scraped clean under oil; no change in the measured Hall potential difference was noticeable for hours afterwards.

The dc was supplied through two circular contacts (2 mm diameter) placed symmetrically at a distance of 40 mm between centers. Reversal of the current direction did not influence the results. Each measurement was performed by measuring the change in Hall potential difference caused by reversal of the magnetic field while the current through the specimen was kept constant.

The two points on the edges of the specimen between which the Hall PD was measured were situated on the same equipotential of the current-field in the absence of the magnetic field. (This was secured in the usual way by connecting one of the leads not to the edge but to a copper wire connected to two points of the edge, and sliding the lead along the copper wire until no change in PD between the two leads appeared on reversal of the current. To minimize thermoelectric forces, this copper wire and all connecting wires were taken from the same piece of wire).

Figure 1 shows the ratio of the measured Hall-field strength E_H to the current density J as a function of the magnetic induction B . Each point is the result of several measurements with different current densities, and the standard deviation ("root mean square error") is indicated. As will be seen, the Hall-coefficient (slope of

the line) is constant for magnetic fields up to about 1 weber/m² (=10 000 gauss). The value of the slope is $(17.0 \pm 0.5) \times 10^{-11}$ m³/coulomb.

In order to obtain the Hall coefficient, this figure has to be increased by 5 percent owing to short-circuiting of the Hall-field by the contacts for the primary current.⁴

The sign was found to be negative (the same sign as for copper, "normal" Hall-effect). The final result is thus

$$R_H = -(17.8 \pm 0.5) \times 10^{-11} \text{ m}^3/\text{coulomb}.$$

The authors wish to thank Professor H. Højgaard Jensen for much valuable advice and Professor T. Bjerger for his interest in the work.

¹ R. H. Kingston, *Phys. Rev.* **84**, 944 (1951).

² A. E. van Arkel, *Reine Metalle* (J. Springer, Berlin, 1939).

³ In van Arkel's Fig. 5.56, A refers to the "Siegbahn-angstrom," 1.002×10^{-8} cm.

⁴ See forthcoming publication by V. Frank.

Mixing of States and Antiferromagnetism*

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THE phenomenon of antiferromagnetism has been discussed by Anderson¹ in terms of Kramers² theory of superexchange. In essence the theory as applied to an antiferromagnetic material such as MnO attributes the magnetic interaction of the Mn²⁺ ions to the intermediary O²⁻ ions. Anderson points out that simple O²⁻ ions could not lead to superexchange, but there is good reason to believe that the wave function included an admixture of other states.

There exists in the literature much direct evidence for this mixing of states, in particular that provided by x-ray absorption spectroscopy. As has been shown in many studies,^{3,4,5} the fine structure within a few tens of volts of the edge is principally due to transitions to low energy states associated with the atom rather than with the crystal as a whole, and thus provides information about the bonding.

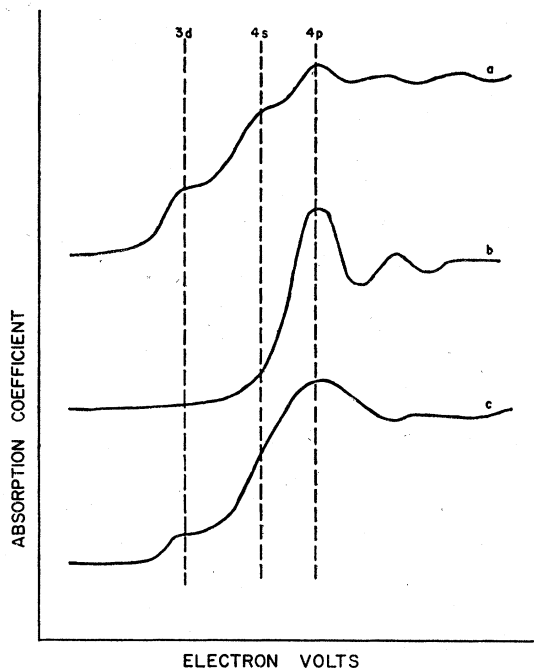


FIG. 1. Typical edge structures for the transition elements and their compounds. (a) *K* edge for the metal; (b) edge for the ion when observed in solution and in ionic compounds such as the chlorides, nitrates, etc., and (c) edge for sulfides and oxides.

Over a period of years, the data have been taken by different experimenters using techniques and spectrometers of varying reliability and resolving power. There are, however, some generalizations that may be safely drawn. In the idealized curves of Fig. 1, we see edge structures which are quite typical for the transition elements and their compounds. Figure 1, curve (a) shows the *K* edge for the metal. The structure has been ascribed to transitions of the 1s electron to 3*d*, 4*s*, and 4*p* levels as indicated in the figure. This apparent violation of the free atom selection rules is in keeping with the mixing of states required for metallic behavior. Figure 1, curve (b) shows the edge for the ion when observed in solution and in ionic compounds such as the chlorides, nitrates, etc. Studies on manganese salts show small but observable absorption into the 3*d*-4*s* region, the magnitude of which seems correlated in an inverse fashion to the electronegativity of the anion. The edge for the transition elements combined as the sulfides and the oxides are represented by curve (c). Actually this group shows the greatest variation among the members, and it is difficult to draw a truly typical curve. In each case, however, there is a very significant absorption into the 3*d*-4*s* region. The essential similarity to metallic edge structure has been commented on by Coster and Kiestra⁵ and by Yoshida.⁶ Qualitatively, for those compounds for which the x-ray and magnetic information exists, it appears that, the greater the mixing of states as indicated by the magnitude of the 3*d*-4*s* absorption, the stronger is the antiferromagnetic effect as revealed by the height of the Curie temperature.

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† On leave from the University of Florida, Gainesville, Florida.

¹ P. W. Anderson, *Phys. Rev.* **79**, 350 (1950).

² H. A. Kramers, *Physica* **1**, 182 (1934).

³ C. G. Shull and J. S. Smart, *Phys. Rev.* **76**, 1256 (1949).

⁴ W. W. Beeman and J. A. Bearden, *Phys. Rev.* **61**, 455 (1942).

⁵ D. Coster and S. Kiestra, *Physica* **14**, 184 (1948).

⁶ S. Yoshida, *Sci. Papers Inst. Phys. Chem. Research (Tokyo)* **38**, 272 (1941).

The Calculation of *F* Center Energy Levels*

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ENERGY levels of electrons trapped at vacant negative ion sites in ionic crystals are usually obtained using the model that treats the vacancy as a hole surrounded by a continuous, isotropic dielectric. This model has been used by various investigators,¹ and it has been pointed out that the levels should be evaluated by a self-consistent method, since the equilibrium positions of the ions surrounding the vacancy are determined, in part, by the charge distribution of the trapped electron. Simpson¹ has made self-consistent calculations using a variational method. Pincherle¹ has obtained results substantially in agreement with those found by Simpson. Although Pincherle did not use a self-consistent field, he found it necessary to modify the form of the potential energy, in evaluating the energy of the excited state, in order to obtain agreement with Simpson's calculations.

The main purpose of this note is to question the choice of the depth of the potential well which is used in the calculation of the energy levels of *F* centers. The usual assumption is that the potential well is of the form shown in Fig. 1. The potential energy of the electron when at the center of the vacancy is V_0 with respect to the bottom of the conduction band. At large distances it is $e^2/\kappa_0 r$ where κ_0 is the optical dielectric constant, since in the course of the electron motion the ionic displacements cannot follow. The present comments concern the choice of V_0 . The usual argument goes as follows: (a) At the center of the vacancy which the electron is to occupy to form an *F* center, the principal contribution to V_0 is the Madelung potential V_m . From this is subtracted the electron affinity χ . (b) In addition, since there is a vacancy, there exists a potential at its center resulting from