Cyclotron Resonance in Antimony*†

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Measurements of cyclotron resonance using the trigonal plane in single-crystal antimony have been made with linearly- and circularly-polarized radiation (23.5 kMc/sec) in magnetic fields up to 8500 oe at liquid helium temperatures. The observed oscillations for magnetic field directions parallel to the crystal surface were identified as Azbel'-Kaner resonances. The tilted-ellipsoidal Fermi-surface model proposed by Shoenberg was successfully used to interpret the data. The mass parameters in this model were determined from a combination of present data with some of Shoenberg's de Haas–van Alphen data to be $m_1/m_0=0.050$, $m_2/m_0=1.03$, $m_3/m_0=0.53$, and $|m_4|/m_0=0.67$. Analysis of data obtained with circularly polarized radiation suggests that the carriers responsible for these Azbel'-Kaner resonances in antimony are electrons.

1. INTRODUCTION

CYCLOTRON resonance provides a means of obtaining effective-mass values of carriers at extremal regions of the Fermi surface in a very pure metal. This fact was best appreciated after Azbel' and Kaner[1] predicted the existence of an oscillatory behavior of the surface impedance of a metal under anomalous skin-effect conditions with a steady magnetic field contained in the plane of the sample. Subsequently, other theoretical studies of this effect were made by Heine,[2] Rodriguez,[3] and Mattis and Dresselhaus.[4]

Early experimental work[5,6] showed the feasibility of performing cyclotron resonance experiments in metals and a cyclotron resonance experiment under classical skin-effect conditions was used to determine band structure parameres of bismuth.[7] Cyclotron resonance of the Azbel'-Kaner type has been observed in copper,[8,9] tin,[9,10] zinc,[11] aluminum,[12] bismuth,[13] and lead.[14]

The zone structure of antimony suggests that the first four Brillouin zones are full and that the fifth zone is not quite full, as it slightly overlaps the next highest zone. This results in an equal number of electrons and holes. The Fermi surface of carriers, which were assumed to be electrons, was determined by Shoenberg[15] in a de Haas–van Alphen experiment to be a set of either three of six ellipsoids tilted from the threefold symmetry axis. A model for the Fermi surface of carriers of opposite sign to those on the tilted-ellipsoidal Fermi surface has not been established experimentally.

The present work[16] was undertaken to investigate the Fermi surface of antimony using cyclotron resonance techniques. The tilted-ellipsoidal Fermi surface parameters were determined with the aid of some de Haas–van Alphen data,[15] but the Fermi surface of holes was not obtained. It is, therefore, a preliminary account of cyclotron resonance in antimony and additional cyclotron resonance experiments which are in progress will result in a more complete determination of the Fermi surface of antimony.

2. EXPERIMENTAL

Experiments were performed at liquid helium temperatures using circularly-polarized and linearly-polarized radiation at 23.5 kMc/sec with magnetic field strengths up to 8500 oe. A sample surface of about 8-mm diameter formed part of the end wall of a cylindrical cavity excited in a TE_{111} mode.

In experiments in which linear polarization was used, the microwave power from a stabilized klystron was fed through a magic tee to the microwave cavity, and the reflected power from the cavity was detected in the fourth arm of the magic tee by a crystal detector. The sample-cavity axis was set in either a horizontal or a vertical plane. The crystal surface was oriented with respect to magnetic-field direction by turning the sample cavity and connecting waveguide about a vertical axis and by rotating the bottom half of the cavity, which included the sample, about the cylindrical axis of the cavity. By means of these adjustments it was also pos-

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[1] M. Ia. Azbel' and E. A. Kaner, Soviet Phys.—JETP **3**, 772 (1956); J. Phys. Chem. Solids **6**, 113 (1958).
[2] V. Heine, Phys. Rev. **107**, 431 (1957).
[3] Sergio Rodriguez, Phys. Rev. **112**, 1616 (1958).
[4] D. C. Mattis and G. Dresselhaus, Phys. Rev. **111**, 403 (1958).
[5] J. K. Galt, W. A. Yager, F. R. Merritt, B. B. Cetlin, and H. W. Dail, Phys. Rev. **100**, 748 (1955).
[6] R. N. Dexter and B. Lax, Phys. Rev. **100**, 1216 (1955).
[7] J. K. Galt, W. A. Yager, F. R. Merritt, B. B. Cetlin, and A. D. Brailsford, Phys. Rev. **114**, 1396 (1959).
[8] D. N. Langenberg and T. W. Moore, Phys. Rev. Letters **3**, 328 (1959).
[9] E. Fawcett, Phys. Rev. **103**, 1582 (1956).
[10] A. F. Kip, D. N. Langenberg, B. Rosenblum, and G. Wagoner, Phys. Rev. **108**, 494 (1957).
[11] J. K. Galt, F. R. Merritt, W. A. Yager, and H. W. Dail, Phys. Rev. Letters **2**, 292 (1959).
[12] D. N. Langenberg and T. W. Moore, Phys. Rev. Letters **3**, 137 (1959); E. Fawcett, *ibid.* **3**, 139 (1959).
[13] J. E. Aubrey and R. G. Chambers, J. Phys. Chem. Solids **3**, 128 (1957).
[14] M. S. Khaikin, Soviet Phys.—JETP **10**, 1044 (1960).
[15] D. Shoenberg, Phil. Trans. Roy. Soc. (London) **A245**, 1 (1952).
[16] W. R. Datars and R. N. Dexter, Bull. Am. Phys. Soc. **2**, 345 (1957).

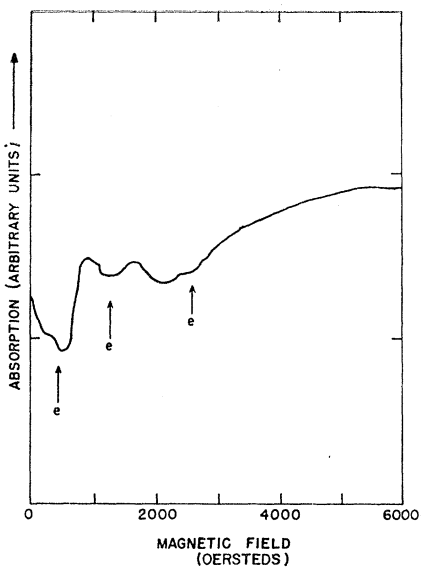

FIG. 1. Power absorption vs magnetic field for magnetic field strengths up to 6000 oe with the magnetic field along the binary axis and parallel to the plane of microwave polarization. The letter *e* at low fields ($H<1000$ oe) marks the position of the low-field fundamental and subharmonic resonances. The high-field fundamental and its harmonic are each marked by the letter *e*.

sible to set E_{rf} at any desired angle to the external magnetic field.

Circularly polarized radiation in a TE_{111} cavity was obtained by using the method of Galt *et al.*[7] During experiments the paramagnetic resonance was observed in a sample of diphenyl-picryl hydrazyl placed at the outer edge of the antimony surface. The circular-polarization ratio which was at least 15:1 in all experiments, was determined from the ratio of the amplitudes of the paramagnetic-resonance signals for the two cavity positions which made the cylindrical axis of the cavity parallel to the magnetic-field direction.

The crystal structure of antimony is rhombohedral. A major cleavage plane is perpendicular to the threefold axis, called the trigonal axis, and contains two other nonequivalent principal directions, which are the binary axis and the bisectrix axis. Samples in the form of thin crystal slabs were cleaved at liquid air temperature from a large, single, zone-refined crystal prepared by The Battelle Memorial Institute. Part of the shiny, cleaved surface was exposed to the inside of the microwave cavity and the remainder of the surface was attached to the end of the microwave cavity with low-melting-point solder.

The resistivity ratio ($R_{4.2°K}/R_{295°K}$) was measured and found to be 0.0017. The resistivity ratio determined by Steele[17] for other antimony single crystals was 0.014. Thus there was an order of magnitude greater purity for our samples.

The signal derivative was obtained by using magnetic-field modulation at a frequency of 100 cps. Alternatively changes in dc signal were detected by using a sensitive electronic voltmeter. Recorded traces of either the signal or the signal derivative were taken as a function of magnetic field on an *x-y* recorder. The magnetic field, supplied by a Varian twelve-inch magnet, was calibrated during each trace with a nuclear magnetic-resonance signal.

3. RESULTS

Examples of data taken with the magnetic field parallel to the crystal surface are given in Figs. 1–4. The temperature of the sample was 4.2°K, and the microwave frequence was 23 650 Mc/sec. Lowering the temperature to 1.3°K did not appreciably increase the resolution of resonance minima. The magnetic field was directed along the binary axis in Figs. 1 and 2, and along the bisectrix axis in Figs. 3 and 4. The results show the existence of resonant absorption in the region less than 3000 oe. The magnetic-field strengths of resonance minima for different magnetic-field directions in the binary-bisectrix plane are plotted in Fig. 5. In addition to these minima, there was a broad absorption minimum at 2220 oe for all magnetic-field directions in the binary-bisectrix plane. In the region above 3000 oe, when there was no resonant absorption, it may be noted that microwave absorption increased with magnetic field.

The same resonances were observed when the magnetic field was set either parallel or perpendicular to the direction of the linear polarization of the microwave radiation. However the several resonances had different relative intensities in the two cases and the increase of absorption with magnetic field above 3000 oe was much greater using the latter rather than the former geometry.

The greatest resonant absorption at any crystal orientation occurred when the magnetic field was aligned along the crystal surface. The resonance absorption decreased by a small amount for small angles between the magnetic-field direction and the surface, and decreased by 10% at an angle of 15 deg. High-field resonant ab-

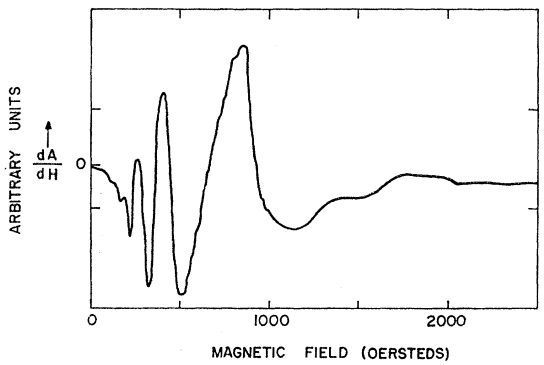

FIG. 2. Absorption derivative vs magnetic field for magnetic field strengths up to 2500 oe with the magnetic field along the binary axis and normal to the plane of microwave polarization.

[17] M. C. Steele, Phys. Rev. **99**, 1751 (1955).

sorption disappeared at an angle of 20 deg and a nonresonant absorption existed for angles larger than 32 deg. The value of the collision relaxation time τ, as obtained from the maximum number of observed harmonics, was 1.25×10^{-10} sec.

With the use of circularly-polarized radiation, data was taken for different magnetic-field directions in the binary-trigonal plane. Figure 6 shows data taken with the magnetic field perpendicular to the sample surface and parallel to the trigonal direction. When the magnetic field was rotated away from the trigonal axis, the circular polarization became less effective in distinguishing the effects of electrons from those of holes because the magnetic field was also inclined to the normal of the plane of microwave polarization. Nevertheless, when the magnetic field was directed within 40 deg of the trigonal direction, the effective polarization ratio was determined experimentally to be greater than 10:1. Then, the following observations were made; the shape of the absorption curve and the magnitude of the high-field absorption were quite independent of magnetic-field direction when the effect of holes was detected, while the shape of the absorption curve due to electrons depended strongly upon magnetic-field direction between 10 and 30 deg from the trigonal axis. Finally, when the magnetic field was parallel to the sample surface, resonance minima similar to those obtained in the linear-polarization experiments were observed. This last observation assured us that sample quality was adequate for cyclotron resonance.

4. DISCUSSION OF EXPERIMENTAL RESULTS

Cyclotron resonance of the Azbel'-Kaner type can take place in a metal when the restrictions

$$\delta/r\ll1, \tag{1a}$$

$$\tfrac{3}{2}[l/\delta]\gg(1+\omega^2\tau^2)^{\frac{3}{2}}, \tag{1b}$$

are satisfied.[1] Here δ is the classical skin depth, l is the electron mean-free path, r is the electron radius of curvature, and ω is the angular frequency of the applied radiation. It is necessary to determine that they apply to antimony since it is a semimetal. Using the measured value of the dc conductivity of 1.4×10^7 (ohm-m)$^{-1}$ and the maximum value of $\omega\tau=25$, δ is less than r in antimony for magnetic field strengths less than 20 000 oe and condition (1b) is satisfied in the present experiment by a factor of 10^2. Since conditions (1a) and (1b) are satisfied for at least low magnetic-field strengths, Azbel'-Kaner cyclotron resonance would be expected to take place in antimony, i.e., resonance from a single group of carriers would consist of a fundamental resonance at magnetic field $H\simeq\omega\ mc/e$ as well as subharmonic resonances at submultiples of the fundamental resonance field. Thus the resonance absorption minima of data typified by Figs. 1–4 are probably due to the cyclotron absorption of carriers. Three fundamental resonances are found to exist for magnetic-field directions in the trigonal plane except for binary and bisectrix magnetic-field directions where, in each case, two resonances coincide.

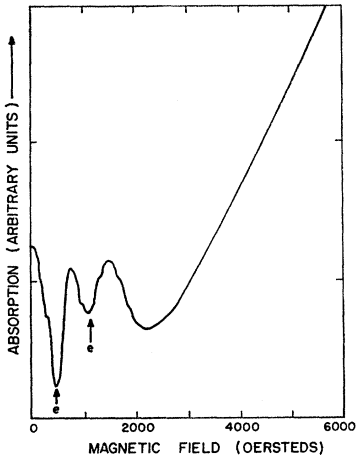

FIG. 3. Power absorption vs magnetic field strength with the magnetic field directed along the bisectrix axis and normal to the plane of microwave polarization. The letter e indicates minima attributed to electrons.

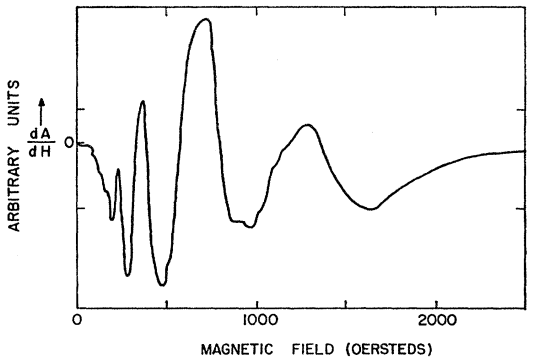

FIG. 4. Absorption derivative vs magnetic field with the magnetic field directed along the bisectrix and normal to the plane of microwave polarization.

The cyclotron mass m was determined from the magnetic field of each fundamental resonance using

$$\omega=eH/mc. \tag{2}$$

Due to the predicted existence of a phase shift of subharmonic resonances and to finite $\omega\tau$, corrections to these cyclotron masses may be necessary.[1] In the present experiment there was no clear evidence of a phase shift, and a change of $\omega\tau$ from 12 to 27 observed in one sample, gave no apparent change in the resonance field strength. This observation indicates that the resonance condition was relatively independent of $\omega\tau$. As a result, in the case of cyclotron resonance in antimony these corrections would probably be less than 5%, and no attempt has been made to apply them. Cyclotron mass values determined for magntic-field directions in the trigonal plane are shown in Fig. 5. The cyclotron mass values for the binary- and bisectrix-magnetic field directions are given in Table I.

The amplitude of the broad minimum, seen in the

TABLE I. Experimental values of cyclotron masses of the tilted-ellipsoidal Fermi surface for two magnetic field directions.

Magnetic-field direction	Cyclotron masses m_a/m_0	$m_{b,c}/m_0$
Binary axis	0.31	0.079
Bisectrix axis	0.068	0.13

binary-bisectrix plane at 2220 oe, is similar to the amplitudes of other resonance minima, but no subharmonics of the resonance are resolved. (See Figs. 1–4.) However it may be noted that the minimum occurs between the regions showing good resonant absorption and increased absorption with magnetic field. The absorption minimum is probably a result of changing skin conditions between the low and high field regions.

Contrary to expectation,[1] the amplitude of cyclotron resonance in antimony did not depend critically on the alignment of the magnetic field relative to the sample surface. It is possible to account for this result by considering the distribution of velocity components of carriers contributing to resonance. When the magnetic field was not aligned along the sample surface, those carriers with small velocity components, parallel to the magnetic field direction, presumably caused the resonance. The interpretation of data does not depend on this alignment condition since, for a particular magnetic field direction, the cyclotron mass of carriers on an ellipsoidal-Fermi surface is independent of the velocity components along the magnetic-field direction. The problem of alignment has been discussed for other Fermi surfaces by Phillips.[18]

The increase in absorption with magnetic field strength above 3000 oe (Figs. 1–4) is probably caused by carriers which do not satisfy the conditions required for Azbel'-Kaner resonance. The carriers could be those on the tilted-ellipsoidal Fermi surface if classical skin-effect conditions hold at large magnetic field strengths. However information about the band structure has become available through quite accurate measurements of the electronic specific heat in antimony.[19] The value for the electronic specific heat is 6300 ergs/°K mole. However the contribution to the specific heat from the carriers on the tilted-ellipsoidal surface is only 705 ergs/°K mole. Shoenberg[20] accounted for this discrepancy by assuming the existence of heavy holes in antimony. Also, measurements of the anomalous skin effect in antimony[21] indicated a mean-effective mass of the holes equal to 1.5 m_0. It is likely therefore, that holes with insufficient $\omega\tau$ to cause resonance are the carriers which cause absorption at high magnetic field strengths. The results shown in Fig. 6 appear consistent with this assumption but give no numerical estimates.

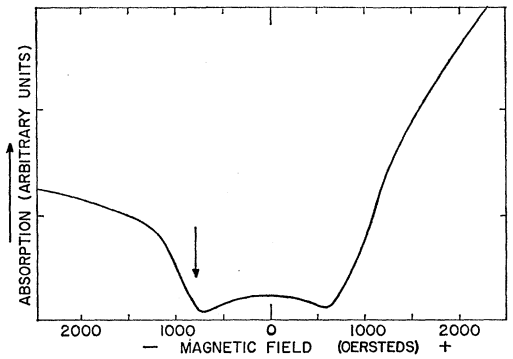

FIG. 6. Power absorption vs magnetic-field strength with the magnetic field set normal to the surface and parallel to the trigonal axis. The circularly-polarized radiation was set to detect electrons for negative fields and to detect holes for positive fields. The arrow locates the resonance field assumed for this orientation from Shoenberg's work.

The absorption curve Fig. 6, taken with the magnetic field normal to the sample plane and along a threefold axis, was also observed under anomalous skin-effect conditions. Since the analysis of this data is limited by the lack of knowledge of the theoretical shape of the absorption curve, the effective mass of carriers cannot be obtained reliably from this data. However using the method of interpretation of Galt *et al.*,[7] we obtained a cyclotron mass in fair agreement with that found by Shoenberg[15] for this orientation. Figure 6 shows the nature of this agreement. The shape of the absorption curve also distinguishes the effects of electrons from the effects of holes[22] and should depend on the effective mass of carriers contributing to absorption. In experiments using circularly-polarized radiation with the magnetic field inclined to the sample surface, the dependence of

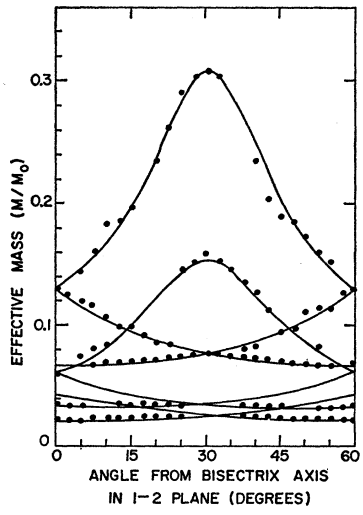

FIG. 5. Magnetic field strength of resonance minima in units of cyclotron mass defined by $\omega=eH/mc$ vs magnetic-field direction in the binary-bisectrix plane. The solid lines are theoretical curves calculated using the mass-tensor components of Eq. (5).

[18] J. C. Phillips, Phys. Rev. Letters **3**, 327 (1959).

[19] N. M. Wolcott (to be published).

[20] D. Shoenberg (to be published).

[21] A. J. Greenfield, G. E. Smith, and A. W. Lawson, Bull. Am. Phys. Soc. **4**, 409 (1959).

[22] In the case of highly anisotropic Fermi surfaces, circularly polarized radiation is not necessarily effective [M. Tinkham, Phys. Rev. **101**, 902 (1956); G. Dresselhaus, A. F. Kip, and C. Kittel, Phys. Rev. **98**, 368 (1955).]

the shape of the absorption curve for *electrons* on magnetic-field direction suggested the existence of several groups of carriers on highly anisotropic surfaces. The dependence of the absorption curve for *holes* on magnetic field direction was relatively independent of angle. The data, consequently, make it appear likely that the carriers seen on the tilted-ellipsoidal surfaces are electrons.

5. DISCUSSION OF EFFECTIVE MASS DATA

The tilted-ellipsoidal model of the Fermi surface of electrons, proposed by Shoenberg,[15] consists of at least three ellipsoids, one of which, when referred to an origin at its center, is represented in momentum space (p space) by

$$\alpha_1 p_1^2+\alpha_2 p_2^2+\alpha_3 p_3^2+2\alpha_4 p_2 p_3=2m_0 E_0, \quad (3)$$

where subscripts 1, 2, and 3 refer to the binary, bisectrix, and trigonal directions in momentum space respectively. E_0 is the Fermi energy, m_0 is the mass of the free electron, and the α's are dimensionless constants. The effective mass tensor for the ellipsoid represented by Eq. (3) has the form

$$m=\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & m_4 \\ 0 & m_4 & m_3 \end{bmatrix}, \quad (4)$$

where m_1, m_2, m_3, and m_4 are component masses in units of m_0.

The component masses for the tilted ellipsoids may be obtained by solving the appropriate expressions[23] of effective mass for tilted ellipsoids and magnetic-field directions corresponding to the crystallographic axes. The solution requires cyclotron mass values for magnetic-field directions along the binary, bisectrix, and trigonal axes. However there are only three independent cyclotron masses and four component masses. The additional information may be supplied by knowing the tilt angle of the ellipsoids from the trigonal axis. In our calculation, the cyclotron masses of Table I were used. A third independent mass for a trigonal-directed magnetic field having a value of 0.095 m_0 was assumed from de Haas–van Alphen data.[15] This mass was used in our calculation rather than the corresponding one determined from the present data because of the uncertainty in interpreting cyclotron resonance data with the magnetic field normal to the sample surface. Shoenberg obtained a value of 35 deg for the ellipsoid-tilt angle. Using the present cyclotron resonance data, the ellipsoid-tilt angle was obtained from the symmetry of cyclotron-resonance minima for crystal orientations obtained by tilting the magnetic field from the sample surface. The tilt angle was found to be 36±3 deg. However, since the magnetic field had to be within 25 deg of the crystal surface for the observation of cyclotron resonance and thus could not be set close to the direction of tilt of the ellipsoids, Shoenberg's value was probably obtained more reliably and was used in calculating the mass tensor components. Our set of values derived from the above data are

$$m_1/m_0=0.050, \quad m_2/m_0=1.03, \quad m_3/m_0=0.53, \quad |m_4|/m_0=0.67. \quad (5)$$

The sensitivity of the mass-component values on experimental error depended on the grouping of the equations[23] for the cyclotron masses. Proper grouping gave answers which were relatively insensitive to experimental error. Each of the values is believed to be accurate to ±15%. The corresponding tensor components for a single ellipsoid are

$$m_{1'}/m_0=0.050, \quad m_{2'}/m_0=1.49, \quad m_{3'}/m_0=0.064, \quad (6)$$

where the primes refer to the principal axis system of the ellipsoid. Axis 3′ is 35 deg from axis 3, and the binary axis is also the 1′ axis of the ellipsoid.

The anisotropy of the resonance minima, which is expected for the ellipsoidal surfaces with the above mass components, is shown in Fig. 5. The curves include the fundamental resonances and some harmonics. The agreement between the theoretical curves and experimental points is within experimental error. This justifies the use of the tilted-ellipsoidal model, at least with experiments of the present accuracy.

The mass-tensor components of antimony determined in the de Haas–van Alphen experiment[15] are

$$m_1/m_0=0.050, \quad m_2/m_0=1.00, \quad m_3/m_0=0.52, \quad |m_4|/m_0=0.65. \quad (7)$$

The striking agreement between the above two sets of results is of course in large part due to our use of one of Shoenberg's mass values and his ellipsoid-tilt angle. The mass components from the two experiments are in much worse agreement if correction for finite relaxation time is made to our data.[24]

The present results may be compared with other recent effective-mass data obtained in antimony. Freedman and Juretschke,[25] through a study of galvanomagnetic effects in antimony, obtained values for the mobilities of electrons and holes and concluded that the carriers on the tilted-ellipsoidal Fermi surface were holes. The present cyclotron-resonance data do not support this conclusion. In another resonance experiment,[26] Smith *et al.* used circularly-polarized radiation with the static field normal to the sample surface. They claimed to have measured an electron effective mass of

[23] B. Lax, K. J. Button, H. J. Zeiger, and L. M. Roth, Phys. Rev. **102**, 715 (1958).

[24] R. N. Dexter and W. R. Datars, International Conference on Electronic Properties of Metals at Low Temperatures, Geneva, New York, 1958 (unpublished), quoted such corrected numbers based on theoretical phase shifts which were not justified in this experiment.

[25] S. J. Freedman and H. J. Juretschke, Technical Report No. 6, Polytechnic Institute of Brooklyn, 1959 (unpublished).

[26] G. E. Smith, J. N. Galt, and F. R. Merritt, Phys. Rev. Letters **4**, 276 (1960).

0.088 m_0, when the magnetic field was along a bisectrix axis, but did not observe the second effective mass expected for the crystallographic orientation. We cannot explain the apparent disagreement with our results which were obtained with the magnetic field in the plane of the surface.

An independent determination of electron Fermi-surface parameters from cyclotron-resonance data in antimony requires a value of the cyclotron mass for a trigonal-directed magnetic field which lies in the plane of the surface. A bisectrix-trigonal plane in the sample surface would permit the determination of this cyclotron mass as well as an accurate value of the tilt angle. We are still trying to prepare a satisfactory surface by electropolishing techniques.

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Magnetic Field at the Nucleus in Spinel-Type Crystals*

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Measurements of the magnetic field at the Fe^{57} nucleus were obtained on powder samples at room temperature using the Mössbauer effect for the spinel-type ferrites γ-Fe_2O_3, "ordered" lithium ferrite ($Li_{0.5}Fe_{2.5}O_4$), and "disordered" lithium ferrite giving values of $|496\pm20|$ koe, $|508\pm20|$ koe, and $|510\pm20|$ koe. These compounds contain only trivalent and no divalent iron. The Mössbauer spectra of all of these compounds were very similar and no difference could be detected between the "ordered" and "disordered" compounds. Only one set of lines was observed indicating that the fields at the octahedral and tetrahedral sites are about the same value. The value of the hyperfine interaction constant A obtained from electron paramagnetic resonance spectrum of the divalent Mn^{55} (isoelectronic with trivalent Fe) impurity in single crystals of the isomorphous spinel-type crystal "disordered" lithium aluminate ($Li_{0.5}Al_{2.5}O_4$) was found to be $|77.2\pm1.0| \times10^{-4}$ cm^{-1}. The angular variation of the spectrum indicated that the divalent Mn^{55} ions were located substantially on octahedral sites. The corresponding magnetic field for the Mn^{55} nucleus is around 550 koe, which is close to the value obtained elsewhere for the Mn^{55} nucleus located on a tetrahedral site in a spinel-type aluminate. This is in good agreement with the Mössbauer results.

INTRODUCTION

THE determination of the magnetic field at the nucleus of magnetic ions in crystals can be carried out by several different methods. A direct determination can be achieved for ions in ferromagnetic and antiferromagnetic crystals by measurements of the Mössbauer effect or nuclear magnetic resonance (NMR). The results of such measurements can be related to the hyperfine interaction parameter A obtained from the electron paramagnetic resonance (EPR) spectrum of magnetic impurity ions in diamagnetic crystals. To a first approximation, the hyperfine spectrum can arise only through the anomalous interaction of the s electrons with the nuclear spin (Fermi contact interaction)

TABLE I. Crystallographic parameters and symmetries.

Compound	Ordering	Lattice constant (angstroms)	Space group	A-site symmetry (tetra.)	B-site symmetry (octa.)
$\gamma-Fe_2O_3$		8.338[a]	$O_h(7)-Fd3m$[a,b]	$\bar{4}3m$	$\bar{3}m$
$Li_{0.5}Fe_{2.5}O_4$	Ordered	8.33[c,d]	$O(6)-P4_32$[c] or $P4_13$	3	2
$Li_{0.5}Fe_{2.5}O_4$	Disordered	8.33[c,d]	$O_h(7)-Fd3m$[c]	$\bar{4}3m$	$\bar{3}m$
$Li_{0.5}Al_{2.5}O_4$	Disordered	7.92[d]	$O_h(7)-Fd3m$[c]	$\bar{4}3m$	$\bar{3}m$

[a] I. David and A. J. E. Welch, Trans. Faraday Soc. 52, 1642 (1956).
[b] Some investigators (see, for example, reference 14) have reported superstructure lines indicating the $O(6)-P4_32$ space group and ordering.
[c] P. B. Braun (reference 14).
[d] Values obtained on powders prepared from single crystals grown at the Naval Research Laboratory.

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