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Galvanomagnetic Effects in Antimony at Liquid Helium Temperatures.

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AT LIQUID HELIUM TEMPERATURES.

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**GALVANOMAGNETIC EFFECTS IN ANTIMONY AT
LIQUID HELIUM TEMPERATURES**

A Dissertation

**Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy**

In

The Department of Physics and Astronomy

**by
Narsing G. Rao
M.Sc., Osmania University, Hyderabad, India, 1956
June, 1963**

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ABSTRACT

Galvanomagnetic effects in a single crystal of antimony at liquid helium temperatures were studied in magnetic fields up to 18 kG. An orientation study of the Shubnikov-de Haas oscillations was made in order to map the Fermi surfaces of electrons and holes. While the electrons were found to be in accordance with the tilted ellipsoid model proposed by Shoenberg, the Fermi surface of the holes was found to be of more complicated shape. Two alternate possibilities for the Fermi surface for the holes were studied in order to fit the experimental data. The monotonic part of σ_{11} and σ_{12} computed from the experimental coefficients, ρ_{11} and ρ_{21} , were used to separate the bands on the basis of Sondheimer-Wilson theory. A rather good fit was achieved with the two band model yielding equal number of electrons and holes; the mobilities of the electrons were found to be five times larger than that of the holes. A comparison of the amplitudes of the oscillations in σ_{11} and σ_{12} was made with Lifshitz and Kosevitch theory. The results were off within a factor of 10 and 100, respectively. However, the experimental amplitudes in σ_{11} were in closer approximation with Zil'berman's theory.

CHAPTER I

INTRODUCTION

Galvanomagnetic effects in antimony at liquid helium temperatures were measured to obtain information on its band structure. The oscillations in magneto-resistance were decomposed into de Haas-van Alphen type of oscillations, periodic in $1/H$. The periods of these oscillations at different orientations of the magnetic field (H) with respect to the crystallographic axes give the information about the Fermi surfaces (FS) of the carriers in the metal. The gross effects upon which the oscillations were superimposed, were also analyzed on the basis of Sondheimer and Wilson theory of two-band model. The oscillations in conductivities were studied in the light of Lifshitz and Kosevitch, and Zilberman's theories.

Investigations have been made to determine the band structure of antimony. These studies include de Haas-van Alphen effect,¹ Cyclotron Resonance,² Ultrasonic Attenuation,³ Shubnikov-de Haas effect,⁵ Galvanomagnetic effects at room temperatures,^{6,7} and liquid helium

¹D. Shoenberg, Phil. Trans. Roy. Soc. A245, 1 (1952).

²W. R. Datars and R. N. Dexter, Phys. Rev. 124, 75 (1961).

³W. R. Datars, Can. J. Phys. 39, 1922 (1961).

⁴Y. Eckstein, Phys. Rev. 129, 12 (1963).

⁵J. Ketterson and Y. Eckstein, Bull. Am. Phys. Soc. Ser. II, 8, 548, (1962).

⁶S. J. Freedman and H. J. Juretschke, Phys. Rev. 124, 1379 (1961).

⁷S. Epstein and H. J. Juretschke, Phys. Rev. 129, 1148, (1963).

temperatures.⁸

The available data lead to a three ellipsoidal model for electrons^{1,2,4,7} but there remain discrepancies in the properties of holes. The present work was undertaken to study the galvanomagnetic effects at liquid helium temperatures in order to map the Fermi surfaces of both electrons and holes.

A model for the electronic part of the FS was first established experimentally from the de Haas-van Alphen oscillations. This portion of the FS consists of three ellipsoids in momentum space whose centers lie on the binary axes in the basal (1-2) plane shown in the Figure 1. Each ellipsoid is tilted by an angle 35° out of the basal plane toward the trigonal axis.

An indication of the existence of holes was found by Datars,³ Ketterson,⁵ and Epstein⁷ but the exact shape of the FS for holes has been uncertain. In the present work both electrons and holes were found and the data is interpreted on the basis of the usual set of three ellipsoids for the electrons. For the holes two alternative interpretations are proposed, firstly a three ellipsoidal set band and secondly a two hole band model.

⁸M. C. Steele, Phys. Rev. 99, 1751 (1955).

Fig. 1

CHAPTER II

EXPERIMENTAL DETAILS

The single crystal of antimony was grown by modified Bridgman technique^{9,10} under helium gas. The antimony ingot, from which the crystal was prepared was obtained from Johnson Matthey and Co. Limited, London, with the Lab No. 20209 and Catalogue No. J.M. 660. The spectroscopic examination of the ingot by the company did not show any ferromagnetic impurities which were either absent or were outside the range of detection. The other impurities reported were Ca, Si, and Na each one part per million and Cu, Mg and Ag were less than one part per million.

The single crystal obtained was cleaved in the basal plane (Figure 2) at room temperature and was cut with a spark cutter¹¹ under kerosene oil. The final size of the crystal was 10 x 2 x 2 mm. The binary axis was parallel to the length of the crystal. The back reflection of Laue photographs showed no signs of strain in the crystal. The crystallographic axes with respect to the specimen dimensions are shown in the Figure 2. The ratio $R_{300^{\circ}\text{K}}/R_{4.2^{\circ}\text{K}}$ was found to be 720.

The specimen was mounted on a lucite holder,¹² directly in contact with liquid helium. This arrangement also ensures the isothermal

⁹P. W. Bridgman, Proc. Am. Acad. Arts and Sci, 60, 305, (1925).

¹⁰K. S. Balain, Dissertation, Louisiana State University, 1960.

¹¹B. S. Chandrasekhar, Rev. Sc. Inst. 32, 368, (1961).

¹²S. A. Ali, Dissertation, Louisiana State University, 1958.

Fig. 2

conditions under which this experiment was done. The connections for current and potential leads were made with No. 34 Formvar insulated copper wire soldered with (Bi-Cd) eutectic mixture.¹³

The dewar flask for liquid helium was described elsewhere.¹⁴ The potentials were measured with a Rubicon potentiometer, the off balance of which was recorded on a Brown Recorder after amplification with a low impedance Becker D. C. Amplifier. The circuit for current through the crystal, and for potential measurements has already been described.¹⁴ The currents passed through the crystal were of the order of 500 mA in the low field and 50 mA in the high field.

The magnets used in the present investigations were the same as used by Sybert¹⁴ and Gillingham.¹⁵ The electromagnet, for the field range of 130 gauss to 18 kG was an iron core Weiss magnet with 8 inch diameter pole pieces separated by 1 5/8 inch air gap. It could be rotated through 360° about its vertical axis. The calibration of the field was made by using a nuclear resonance gauss-meter.

For the lower ranges of the field,¹⁵ a pair of helmholtz coils were used which were calibrated with a ballistic galvanometer.

¹³Metal Reference Book (Interscience Publishers, Inc. N. Y. 2nd edition) Vol. II, pp. 959.

¹⁴J. R. Sybert, Dissertation, Louisiana State University, 1961.

¹⁵R. J. Gillingham, S. J., Dissertation, Louisiana State University, 1963.

CHAPTER III

THEORY AND EXPERIMENTAL RESULTS

1. Analysis of the Shubnikov-de Haas Oscillations

Antimony is a semi-metal. It is believed that the first five Brillouin zones are almost filled with some electrons overlapping into the sixth zone, namely the conduction band and an equal number of holes are created in the fifth band known as valence band. There is experimental^{1,6,7} evidence that the number of carriers is of the order of 10^{-3} electrons per atom. For such a low carrier density, an ellipsoidal Fermi surface may be anticipated. Theoretical work on the band structure of semi-metals¹⁶ showed that the Fermi surface should be nearly ellipsoidal.

There have only been a few experimental studies made on antimony to study its band structure. Shoenberg¹ investigated the de Haas-van Alphen effect in antimony at low temperatures and interpreted his data on the basis of a three-ellipsoid set, which have now been associated with an electron band.

Each ellipsoid has a principal axis along the binary on which it is centered with the two other principal axes making an angle of 35° with the basal plane toward trigonal direction. The set is completed by two other ellipsoids obtained from the former by the three symmetry. This set of ellipsoids is recognized as being electrons.

¹⁶M. H. Cohen, Phys. Rev. 121, 387 (1961).

There exists also a hole band (or bands) which for all indications could be interpreted with an analogous set of ellipsoids.

The tilted ellipsoids of the Fermi surface (FS) of the carriers in momentum (p) space is given by¹ its equation using the center of the ellipsoid as the origin of the coordinate system,

$$\alpha_{11}p_1^2 + \alpha_{22}p_2^2 + \alpha_{33}p_3^2 + 2\alpha_{23}p_2p_3 = 2m_0\xi_0 \quad (1)$$

where the subscripts 1, 2, 3 refer to binary, bisectrix and trigonal directions respectively. ξ_0 is the chemical potential of the carriers, m_0 is the mass of the free electron and α 's are the dimensionless constants related to the inverse mass tensor $\hat{\alpha} = \hat{m}^{-1}$ where the coefficients are

$$\hat{\alpha} = \begin{bmatrix} \alpha_{11} & 0 & 0 \\ 0 & \alpha_{22} & \alpha_{23} \\ 0 & \alpha_{23} & \alpha_{33} \end{bmatrix} \quad (2)$$

where m 's are written in units of m_0 . The other two ellipsoids are obtained by rotating Eq. (1) through $\pm 120^\circ$ about the Z axis.

The α 's can easily be related to the periods of the de Haas-van Alphen type of oscillations in $1/H$ by cutting the ellipsoid in Eq. (1) with the plane perpendicular to the magnetic field H . Then the extremum area of cross-section S_m of the Fermi surface is given by

$$P = \frac{eh}{cS_m} \quad (3)$$

where P is the corresponding period of the Shubnikov-de Haas oscillations in $1/H$. e , c , and h are charge of an electron, and the velocity of

light and the Plank's constant. Expressing the plane in spherical polar coordinates and using the Equation (3) we get for the periods

$$P^2 = [A \cos^2 \theta + B(\sin^2 \psi + c \cos^2 \psi) \sin^2 \theta - 2D \sin \theta \cos \theta \sin \psi] \quad (4)$$

where

$$\begin{aligned} A &= \left(\frac{eh}{2m_o c \xi_o} \right)^2 \cdot \alpha_{11} \alpha_{22} \\ B &= \left(\frac{eh}{2m_o c \xi_o} \right)^2 \cdot \alpha_{11} \alpha_{33} \\ C &= \left(\frac{eh}{2m_o c \xi_o} \right)^2 \cdot (\alpha_{22} \alpha_{33} - \alpha_{33}^2) \\ D &= \left(\frac{eh}{2m_o c \xi_o} \right)^2 \cdot \alpha_{11} \alpha_{23} \end{aligned} \quad (5)$$

and θ is the angle between the magnetic field and the trigonal axis, and ψ is the azimuthal angle.

The two other ellipsoids give rise to periods whose expressions are similar to Eq. (4) in which ψ is replaced by $\psi \pm 120^\circ$. Experiments were performed with the field orientation applied in three different crystallographic planes, as the crystal was placed in the cryostat in the following positions:

(i) With the binary vertical so that H is in the (2-3) plane.

Equation (4) becomes for

$$\psi = 90^\circ, P_1^2 = A \cos^2 \theta + B \sin^2 \theta - 2D \sin \theta \cos \theta$$

$$\begin{aligned} \psi &= 210^\circ \\ \psi &= -30^\circ \end{aligned} \quad P_2^2 = P_3^2 = A \cos^2 \theta + \frac{B+3c}{4} \sin^2 \theta + D \sin \theta \cos \theta$$

(6)

where P_1, P_2, P_3 are the periods corresponding to the three ellipsoids.

(ii) With the bisectrix vertical and the field in (1-3) plane.

Equation (4) becomes for

$$\begin{aligned}\psi = 0, \quad Q_1^2 &= A \cos^2 \theta + c \sin^2 \theta \\ \psi = 120^\circ, \quad Q_2^2 &= A \cos^2 \theta + \frac{3B+c}{4} \sin^2 \theta + 3 \sin \theta \cos \theta \\ \psi = -120^\circ, \quad Q_3^2 &= A \cos^2 \theta + \frac{3B+c}{4} \sin^2 \theta - 3 \sin \theta \cos \theta\end{aligned}\quad (7)$$

where Q_1, Q_2 and Q_3 are the periods of the three ellipsoids under condition (ii).

(iii) With the trigonal axis vertical, and the field in (1-2) plane

$$\begin{aligned}R_1^2 &= B \sin^2 \psi + c \cos^2 \psi \\ R_2^2 &= B \sin^2(\psi + 120) + c \cos^2(\psi + 120) \\ R_3^2 &= B \sin^2(\psi - 120) + c \cos^2(\psi - 120)\end{aligned}\quad (8)$$

where the periods here are denoted by R_1, R_2 , and R_3 .

The above nine equations for the periods which are related to the areas of cross-sections of the (FS) in three different positions of the crystal can be used for the electrons and the holes as well, with the two sets of α 's (or m 's), one for the former and one for the latter. The components of the mass tensor for the carriers ($m_1 m_2 m_3 m_4$) are obtained if ξ_0 's are known. The number of carriers in each ellipsoid can be directly obtained from the experimental determination of A, B, C and D as

$$N = \frac{1}{3\pi^2} \cdot \left(\frac{2e}{ch}\right)^{3/2} \cdot [c(AB-D^2)]^{-1/4}\quad (9)$$

To find ξ_0 the temperature dependence of the amplitudes (a, for electrons and b, for holes) of the oscillations in magneto resistance is studied at $\theta = 101.3^\circ$ and $\theta = 0^\circ$. At $\theta = 101.3^\circ$ two types of carriers were observed with two different chemical potentials whereas at $\theta = 0^\circ$ only one period of oscillation was observed (see Figures 3 and 7a). For a particular carrier the plot of $\ln_e \left(\frac{a}{T}\right)$ against T shows a linear relationship in the first approximation (Figure 7b). In fact there was a slight deviation from the straight line. It can be shown that this case arises when $\frac{\lambda}{T} \geq 1$ where $\lambda = 2\pi^2 kT \cdot \frac{c}{e\hbar H} \cdot \frac{m^*}{H}$ where k is the Boltzmann constant and m^* is the effective mass and T is the temperature. The deviation from the straight line can be shown to be proportional to $e^{-\lambda}$. After this correction with iterative procedure the double effective Bohr magnetons β^* and ξ_0 are computed from the relations

$$\begin{aligned}\beta^* &= \frac{2\pi^2 k}{H s} \\ \xi_0 &= \frac{\beta^*}{P}\end{aligned}\tag{10}$$

where s is the slope in Figure 7b. m^* could also be estimated from the expression

$$m^* = \frac{e\hbar}{\beta^* c}\tag{11}$$

The values of ξ_0 for holes and electrons are given in Table X.

The values of A, B, C, and D. were directly computed from the periods Eq. (6), (7) and (8), and by using the graphical method. There was uncertainty in direct computation of C for electrons and A for holes. The period for the holes at $\theta = 0$, case (1) and Figure 3 and the

Fig. 3

Fig. 4

Fig. 5a

Fig. 5b

Fig. 6

Fig. 7b

periods for the electrons at $\theta = -90^\circ$ in case (ii), Figure 4 and at $\psi = 0^\circ$ in case (iii), Figure 5, are too small to observe or too complicated due to beats and (or) harmonics superimposed on the main oscillations which could not be decomposed. To obtain the value of C for electrons use has been made of the relation

$$R^2 = (B - C) \cos^2 \psi + C \quad (12)$$

which gives a straight line if R^2 is plotted against $\cos^2 \psi$, Figure 6. The extrapolated value of C, at $\psi = 0$ is given in the Table IX. The value of A for holes is taken to be 9×10^{-14} (gauss⁻²) (see Figure 4) which seems to be a good approximation. The extrapolated value of C is in good agreement with the value computed from the cyclotron² mass in the bisectrix direction, from the equation

$$P = \frac{e\hbar}{c} \cdot \frac{1}{E_0} \cdot \frac{1}{m_0 m^*} \quad (13)$$

where m^* is in units of m_0 .

2. Electrons

The set of periods $P_1, P_2, P_3; Q_1, Q_2, Q_3$ and R_1, R_2, R_3 shown in Figures 3, 4 and 5 are characteristic of the three ellipsoid set discussed previously. The electronic character of this band has already been claimed^{1,2,4,7} and further evidence of it is discussed in the next chapter. Analysis (i.e., determination of A, B, C, and D) were attempted (a) by separate least squares fitting, (b) by simultaneous least squares fitting with different weights given to the experimental values. Also direct consideration of the periods leads to a good approximation for the determination of parameters of the ellipsoids.

Thus P_1 has a minimum value $P_1(36^\circ)$ and a maximum at $P_1(-54^\circ)$ and together with the extrapolated minimum $Q_1(-90^\circ)$ leads to the angle of tilt, the direct determination of the principal axes of the ellipsoids and its population. The least squares fit allows slightly better approximation for those values as follows:

$$\alpha_{11} = 17.9$$

$$\alpha_{22} = 6.5$$

$$\alpha_{33} = 12.0$$

$$\alpha_{23} = 7.3$$

$$n = 2.66 \times 10^{19} \text{ electrons/cm}^3$$

$$m^* = .093$$

The α 's, Table XI, agree well with the calculated values of Datars² values and slightly different from Eckstein⁴ and computed values from Shoenberg's¹ data. The cyclotron masses computed from the Eq. (13) are given in the Table XII which are in good agreement with the values obtained by others.

The number of electrons per unit volume, n and ξ_0 , Table XI, are in accordance within the experimental error, with Eqstein's⁷ and slightly different from Schoenberg's¹ values. This difference can be understood in view of the uncertainty of the exact value of C ; in the present experiment, it is estimated from the extrapolation of $Q(-90^\circ)$.

3. Holes

The relatively good fit found for a three ellipsoid set for holes seems to indicate that if the idea of two hole bands suggested by Datars³ results should be included without additional bands, then this should be attained by a minor deformation of the three ellipsoids. The

result of the two holes band should be very similar to the three ellipsoid set. For example a star-like shaped band formed by points of the three ellipsoids and two triangles-like bands, Figures 8a and 8b, which would be generated if the three ellipsoids could be centered at the center of the zone. There will be a relation between the different cyclotron masses m_{triangle}^* and m_{star}^* around triangular or star-like pattern respectively and the m_{ellipse}^* of the generating ellipsoids. The computed values are as follows:

$$m_{\text{ellipse}}^* = 0.48$$

$$m_{\text{triangle}}^* = 0.24$$

$$m_{\text{star}}^* = 0.96$$

which do not seem to agree with 0.11 and .32 values of Datars. It should be noted that the values .11 and .30 for cyclotron masses for holes have been found in the present study when the field was along the binary direction (see Figure 4 and Table XIV) which corresponds to the periods $12.9 \times 10^{-7} (\text{gauss}^{-1})$ and $4.7 \times 10^{-7} (\text{gauss}^{-1})$.

HOLES

Fig. 8a

HOLES

Fig. 8b

CHAPTER IV

SONDHEIMER-WILSON THEORY

The knowledge of experimentally calculated values of the resistivity tensor, namely ρ_{11} and ρ_{21} , in the present investigations, allows the conductivities to be computed as

$$\begin{aligned}\sigma_{11} &= \rho_{11}/(\rho_{11}^2 + \rho_{21}^2) \\ \sigma_{12} &= \rho_{21}/(\rho_{11}^2 + \rho_{21}^2)\end{aligned}\tag{14}$$

where σ_{11} and σ_{12} are magnetoconductivity and Hall conductivity respectively.

The monotonic part of both σ_{11} and σ_{12} were analyzed in terms of a modified Sondheimer-Wilson Theory¹⁷ (SW). The expressions obtained assume a quase-continuum of states in "parabolic" bands with the sharp Fermi distribution functions and isotropic relaxation times τ_j which are assumed to be independent of energy. Under these conditions

σ_{11} and σ_{12} are given by

$$\sigma_{11} = ec \sum_j a_j n_j H_j L_j\tag{15}$$

and

$$\sigma_{12/H} = ec \sum_j (\pm) n_j L_j$$

where the summation extends over all the bands. The factor a_j is an adjustable parameter introduced to account for non-circular orbits of the carriers. Hence $a_j = 1$ for circular orbits. n_j is the number of carriers per unit volume and $H_j = \frac{cm_j}{e\tau_j}$, henceforth called as the

¹⁷A. H. Wilson, The Theory of Metals (Cambridge University Press, Cambridge, 1954).

saturation field which is inversely proportional to τ_j and hence to the zero field mobilities q_j^0 . The Lorentz term L_j is given by

$$L_j = (H^2 + H_j^2)^{-1} \quad (16)$$

the subscript j indicates the band.

HL_j is of the form $\text{sech}(\alpha - \alpha_j)$ where $\alpha = \ln H$ and $\alpha_j = \ln H_j$. When the functions $H\sigma_{11}$ and σ_{12} are plotted against $\ln H$, there exist extrema at $H = H_j$ with the extremum value $A_j/2$ where $A_j = eca_j n_j$ for $H\sigma_{11}$ and $A_j = ecn_j/H_j$ for σ_{12} . Thus one can separate the bands graphically and compute the values A_j and H_j which are characteristic of the carriers in different bands.

The values A_j and H_j can also be estimated if $H^2\sigma_{11}$ and $H\sigma_{12}$ are plotted against H^{-2} in the high field region and σ_{11} , $\frac{\sigma_{12}}{H}$ are plotted against H^2 in the low field region. These functions are the sum of hyperbolic terms and they can be decomposed into different bands contribution using standard geometrical and analytical properties of hyperbolas.¹⁸

The factor a_j as introduced in Eq. (15) is defined as follows:

$$a_j = \frac{1}{2} (\sqrt{\alpha_{11}/\alpha_{22}} + \sqrt{\alpha_{22}/\alpha_{11}})$$

where α 's are the components of the inverse mass tensor. a_j can also be written as

$$a_j = \frac{1}{2}(r + r^{-1})$$

where r is the ratio between the axes of the elliptical orbit in the basal plane.

¹⁸ H. J. Mackey, Dissertation, Louisiana State University, 1963.

With the approximate values of A_j and H_j , from these graphical methods, the least squares technique is used to compute the parameters A_j and H_j more accurately by solving the simultaneous equation for $H\sigma_{11}$ and σ_{12} separately using an iterative procedure.¹⁸ The best fit for the peaking functions $H\sigma_{11}$ and σ_{12} was found by using two bands, and gave a mean error of less than 5 per cent. Attempts to use more than two bands for the curve fitting were unsuccessful as the iterative procedure diverged. The parameters A_j and H_j^2 for different bands at different temperatures are given in Tables I through VIII; the curve fit for the peaking functions are shown in Figures 9 through 16. The fit for the hyperbolic functions at 3.5°K is shown in Figures 17 through 18. Note that the ratio of H_2 and H_1 is about 5, i.e. electrons are five times more mobile than the holes. From the previous chapter, the ratio of the masses in the trigonal direction Tables XIII and XV for the holes and electrons also give a value of the order of 5.

This verifies that the assumption about the types of carriers in the previous chapter was correct, i.e. the tilted ellipsoids correspond to the electron, the holes correspond to the untilted ellipsoids.

There is the possibility then to determine from the electrons and holes mapping the value of the coefficient a_j , in view of comparison with the value obtained from the Sondheimer-Wilson curve fit. Some discrepancies are apparent, that is, values for a_1 and a_2 obtained from

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17a

Fig. 17b

Fig. 18a

Fig. 18b

the gross effects are about 2.0 and 2.5 respectively whereas from the oscillatory effects, $a_1 = 1.1$ and $a_2 = 1.7$. Disagreement also exists in the saturation fields obtained from σ_{12} and $H\sigma_{11}$. A qualitative explanation can be given for these discrepancies by assuming either (i) that the relaxation time τ_j is a function of the applied magnetic field, i.e. $H_j = H_j(H)$ or (ii) that each band could be split into two equal sub-bands. Also, the idea of one electron and two holes band as discussed in the previous chapter, is in accordance with this scheme (ii).

A simultaneous fit on $H\sigma_{11}$ and σ_{12} data with a mean error of less than 5 percent gave the following values.

$$\begin{aligned}n_1 &= 5.05 \times 10^{19} \text{ electrons/cm}^3 \\n_2 &= 5.05 \times 10^{19} \text{ holes/cm}^3 \\a_1 n_1 &= 8.1 \times 10^{19} / \text{cm}^3 \\a_2 n_2 &= 13.2 \times 10^{19} / \text{cm}^3 \\H_1 &= 90.7 \text{ gauss} \\H_2 &= 466.5 \text{ gauss.}\end{aligned}$$

With these values, a_1 and a_2 are found to be 1.6 and 2.6 respectively.

Since the average error in the simultaneous fit of $H\sigma_{11}$ and σ_{12} is not much larger than those in the separate $H\sigma_{11}$ and σ_{12} fit, the apparent discrepancy in the saturation field in this latter case may be just caused by experimental error.

Should it be more than two bands in the same range of mobility the preceding curve fitting will not be able to separate them.

CHAPTER V

OSCILLATIONS IN CONDUCTIVITIES

1. Lifshitz and Kosevitch Theory

Some information can be obtained from a detailed study of the dHvA type oscillations in high magnetic fields. For an understanding of the transport processes, one must explain the scattering mechanisms and their magnetic field dependence. Attempts have been made to obtain a theory of the Shubnikov-de Haas oscillations, first by Levinger and Grimsal¹⁹ and later by Lifshitz and Kosevitch²⁰ who related the field dependent oscillations in the conductivity tensor $\sigma_{\alpha\beta}$ to the susceptibility oscillations through the classical mobility tensor $q^{\alpha\beta}$. Zil'berman²¹ and others²² have also studied the influence of Landau quantizations on various galvanomagnetic and thermomagnetic effects. The Zil'berman theory is discussed in the next section.

In the Lifshitz and Kosevitch (L-K) theory, the oscillatory part of the conductivity tensor can be written as

$$\tilde{\sigma}_{\alpha\beta} = \sigma_{\alpha\beta} + l\sigma_{\alpha\beta} \quad (17)$$

where the first term is due to the field dependent oscillations in the number of carriers in various bands under the assumption of a constant Fermi energy ξ . The second term comes from oscillation

¹⁹J. S. Levinger, E. G. Grimsal, Phys. Rev. 94, 772 (1958).

²⁰I. Lifshitz and L. M. Kosevitch, Soviet Physics JETP, 6, 67 (1958).

²¹G. E. Zil'berman, Soviet Physics JETP, 2, 650 (1956).

²²List of references can be found in the review article by A. H. Kahn and H. P. R. Frederikse in Solid State Physics edited by F. Seitz and P. Turnbull (Academic Press, Inc., New York, 1960) Vol. 9.

in the number of carriers in different bands by varying ξ but $\sum_j (\pm) n_j$ assumed constant. Then if $q_{mj}^{\alpha\beta}$ is the classical mobility tensor for the carriers on the extremal area of cross-section of the j^{th} pocket (or band) perpendicular to H , the first term in Eq. (17) is written as

$$\sigma_{\alpha\beta} = \sum_j q_{mj}^{\alpha\beta} \tilde{n}_j \quad (18)$$

where $\tilde{n}_j$ is the oscillation in the number of carriers in the j^{th} band. The explicit expression for $\tilde{n}$ for a pocket of carriers with an ellipsoidal FS with major axis parallel to H is

$$\tilde{n} = 4pRh^{-3} \left(\frac{e\hbar H}{c} \right)^{3/2} \Sigma_{\kappa}^{-2/2} \left(\frac{\kappa\lambda}{\sinh \kappa\lambda} \right) \exp \left[i \left(\frac{c}{e\hbar H} \right) S_m - i \left(2\pi\kappa\gamma + \frac{3}{4} \pi \right) \right] \quad (19)$$

where p is the multiplicity of the ellipsoids and $R = \frac{3}{4} \frac{V}{S_m^{3/2}} (\pi)^{-1/2}$ where V is the volume of the ellipsoid. S_m is the extremal area of cross-section of the ellipsoid perpendicular to the field H , λ is $2\pi^2 kT m^* c / e\hbar H$, γ is a parameter defined such that $\gamma c / e\hbar H$ is the area of the lowest Landau level and is equal to one-half for free electrons and k is Boltzman's constant. Note that the period in $1/H$ is

$$P = e\hbar / c S_m$$

The second term in Eq. (17) is

$$\Delta_1 \sigma_{\alpha\beta} = - \left[\sum_i \left(\frac{\partial \overline{q_i^{\alpha\beta}}}{\partial \xi_0} \right) N_i^0 + \sum_i \overline{q_i^{\alpha\beta}} Z_i^0 \right] \left[\sum_i Z_i^0 \right]^{-1} \sum_j \tilde{n}_j \quad (20)$$

where i and j are summed over all bands, $q_i^{\alpha\beta}$ is the classical mobility tensor of the band carriers averaged over all elliptical cross-sectional areas perpendicular to H . Here N_i^0 denotes the number of states in

band i , where the zero index refers to zero magnetic field.

The Equations (17), (18), (19) for σ_{12} show that no oscillations should be expected at high magnetic field values where all bands are asymptotic. This is evident since the classical mobility $(\pm) ecH(H^2 + H_j^2)^{-1}$ reduces to $q_{mj}^{12} = q_j^{-12} = (\pm)ec/H$ for $H \gg H_j$. Experimentally the oscillations are quite pronounced in the high field range as shown in Figs. 19 and 20. The implication is that in antimony some band (or bands) has not reached the asymptotic value in the field range used in the experiment. If the relaxation time is assumed to be independent of energy, $\tilde{\sigma}_{11} \Big|_{L-K}$ can be written as

$$\tilde{\sigma}_{12} \Big|_{L-K} = ec \sum_i \sum_j \left\{ \frac{H}{H^2 + H_j^2} - \frac{H}{H^2 + H_i^2} \right\} \frac{Z_i}{Z} (\pm) \tilde{n}_j \quad (21)$$

where the density of states $Z = \sum_i Z_i$. For the present experimental purposes (two bands), the above equation reduces to

$$\tilde{\sigma}_{12} \Big|_{L-K} = \bar{\sigma}_{12} \cdot \frac{Z_2}{Z} \cdot \frac{\tilde{n}}{n} \quad (22)$$

where $\bar{\sigma}_{12}$ is the gross Hall conductivity, $Z = Z_1 + Z_2$ and $n = n_1 = n_2$, the number of carriers, either electrons or holes, per unit volume.

Using similar arguments we find for $\tilde{\sigma}_{11}$

$$\tilde{\sigma}_{11} \Big|_{L-K} = \sigma_{11} \cdot \frac{Z_2}{Z} \cdot \frac{\tilde{n}}{n} \quad (23)$$

The above expressions for $\tilde{\sigma}_{11} \Big|_{L-K}$ and $\tilde{\sigma}_{12} \Big|_{L-K}$ can further be simplified if we substitute

$$\frac{Z_2}{Z} = \frac{\xi_1}{\xi_1 + \xi_2}$$

where $Z_i \sim \frac{1}{\xi_i}$

Fig. 19

Fig. 20

$$\left. \frac{\tilde{\sigma}_{12}}{\sigma_{12}} \right|_{L-K} = \left. \frac{\tilde{\sigma}_{11}}{\sigma_{11}} \right|_{L-K} = \frac{\tilde{n}}{n} \cdot \frac{\xi_1}{\xi_1 + \xi_2} \quad (24)$$

where $\frac{\tilde{n}}{n} = \frac{3}{2\pi} \cdot \left(\frac{PH}{2}\right)^{3/2} \cdot \frac{\lambda}{\sinh \lambda} \cdot \cos\left(\pi \frac{m^*}{m_0}\right)$ and $\lambda = \frac{2\pi^2 kT}{\xi_0} \left(\frac{1}{PH}\right)$. The P is the period of the oscillation in $1/H$.

The values of $\left. \tilde{\sigma}_{11} \right|_{L-K}$ and $\left. \tilde{\sigma}_{12} \right|_{L-K}$ computed using the Equation (24) are given in Table XVII.

2. Zil'berman Theory

The influence of Landau quantization on the electron scattering on lattice imperfections has been studied by Zil'berman in the isotropic case of the quadratic distribution law. The amplitudes of the oscillations in the conductivity tensor $\left. \tilde{\sigma}_{11} \right|_{Zil}$ due to this theory is given by

$$\left. \tilde{\sigma}_{11} \right|_{Zil} = \sigma_{11,j} \left(\frac{5}{4}\sqrt{2}\right) \left(\frac{\lambda_j}{\sinh \lambda_j}\right) (P_i H)^{1/2} \quad (25)$$

where $\sigma_{11,j}$ is σ_{11} due to the j^{th} band. The above equations are the results of a modification of the Zil'berman theory by Horton.²³

Rewriting the Eq. (9) in a more convenient form

$$\left. \frac{\tilde{\sigma}_{11}}{\sigma_{11}} \right|_{Zil} = \left(1 - \frac{a_2 H_2}{a_1 H_1 + a_2 H_2}\right) \frac{5}{4} \cdot \sqrt{2} \cdot \frac{\lambda}{\sinh \lambda} (PH)^{1/2} \quad (26)$$

²³P. Horton, Private Communication.

where $a_1 = 1.6$, $a_2 = 2.6$, $H_1 = 90.7$ gauss, $H_2 = 466.5$ gauss. (See Chapter III).

The values computed from Eq. (26) are given in Table XVII.

The experimental values of $\tilde{\sigma}_{11}|_{\text{exp}}$ are about 25 times larger than the expected values of $\tilde{\sigma}_{11}|_{L-K}$. If we consider the dependence of the relaxation time on energy

$$\tilde{\sigma}_{11}|_{L-K} = \frac{\tilde{n}}{n} \cdot \frac{\xi_1}{\xi_1 + \xi_2} \cdot \left\{ \bar{\sigma}_{11} + \frac{2}{3} \mu (\sigma_{11,2} - \sigma_{11,1}) \right\} \quad (27)$$

where μ is defined by $\tau \sim E^\mu$ and depends on the scattering mechanism, for example $\mu = 0$ for point defects, $\mu = \frac{3}{2}$ for ionized impurity scattering and $\mu = -\frac{1}{2}$ for phonon scattering. Eq. (24) is then valid for point defect scattering. The effect of scattering of electrons by phonons ($\mu = -\frac{1}{2}$) can be dismissed, as this process induces a strong temperature dependence, whereas the experiments were performed in the residual temperature range.

An appreciable change would be obtained for $\mu = \frac{3}{2}$ from Eq. (27) which is about twice the value obtained from the Eq. (24) and ten times smaller than $\tilde{\sigma}|_{\text{exp}}$.

As regards $\tilde{\sigma}_{12}|_{\text{exp}}$, $\tilde{\sigma}_{12}|_{L-K}$ computed from Eq. (24) is smaller by a factor of 100. This is also the case if the scattering terms are included.

$$\tilde{\sigma}_{12}|_{L-K} = \bar{\sigma}_{12} \cdot \frac{\tilde{n}}{n} \left(\frac{\xi_1}{\xi_1 + \xi_2} - \frac{4}{3} \mu \right) \quad (28)$$

These discrepancies suggest the assumption $q_m^{\alpha\beta} = \bar{q}$ used in deriving Eqs. (27) and (28) should be reconsidered. Then for the two band model, neglecting μ

$$\tilde{\sigma}_{\alpha\beta} = \frac{\tilde{n}}{n} \left\{ z_1 (q_{m1}^{\alpha\beta} - \bar{q}_1^{\alpha\beta}) + z_2 (q_{m1}^{\alpha\beta} + \bar{q}_2^{\alpha\beta}) \right\} \frac{n}{z} \quad (29)$$

It may be seen that the $\tilde{\sigma}_{12}$ component for antimony would be vanishingly small if $q_{mj}^{12} = \bar{q}^{12}$ is assumed; whereas a six percent difference between the "extremal" electron Hall conductivity q_{m1}^{12} and negative of the average hole Hall conductivity ($-\bar{q}_2^{12}$), yields for example theoretical expectations matching the $\tilde{\sigma}_{12}|_{\text{exp}}$. This change does not appreciably alter the value of $\tilde{\sigma}_{11}|_{L-K}$ of Eq. (24) unless the differences between q_{mj}^{11} and $\bar{q}_j^{11}$ are large.

In the Zil'berman's theory, the oscillations due to a particular carrier depends upon the characteristic parameters of this carrier alone. The experimental $\tilde{\sigma}_{11}|_{\text{exp}}$ and the expected $\tilde{\sigma}_{11}|_{\text{Zil}}$, from the Eq. (26), agree well within an order of magnitude as shown in Table XVII. Comparison of the position of the maxima or minima of the oscillations in $1/H$ of $\tilde{\sigma}_{11}|_{\text{exp}}$ and $\tilde{\sigma}_{12}|_{\text{exp}}$ show that these two effects are out of phase by $80^\circ \pm 10^\circ$ in the field range 16.7 to 17.8 kG. This phase difference would be in agreement if $\tilde{\sigma}_{11}|_{\text{exp}}$ is explained by the Zil'berman theory while the Hall oscillations, $\tilde{\sigma}_{12}|_{\text{exp}}$ are interpreted with Lifshitz and Kosevitch theory in the form of Eq. (29).

The discrepancies between the experimental values and Lifshitz and Kosevitch theory, Eq. (24) or (27), could be due also to the beats in σ 's (or ρ 's) and noise in the experiment. The beats arise because of the non-zero angle between the trigonal axis and the field direction, Fig. 3. Also influential is the fact that the so-called experimental amplitudes of $\tilde{\sigma}_{12}|_{\text{exp}}$ are much smaller than the amplitudes of $\tilde{\sigma}_{11}|_{\text{exp}}$ and may have been given weight from experimental errors on

the $\rho^{\alpha\beta}$ together with the tensorial manipulation. It will also be noted that if there exists a low mobility band, the oscillations in σ_{12} are expected to be strongly enhanced.

CHAPTER V I

CONCLUSION

Some of the conclusions which can be drawn from the experimental results on the band structure of antimony are the following:

(i) The mapping of the electron Fermi surface from the Shubnikov-de Haas oscillations is in good accord, within the experimental error, with Datars, Eckstein, Epstein and Shoenberg. The results show that the electrons in antimony do satisfy the tilted ellipsoid model. The determination of the hole Fermi surface, on the other hand suffers from inaccuracy and ambiguity due to uncertainty in the periods at certain orientations of the crystal with respect to the magnetic field. Besides the possibility of a three untilted ellipsoid set, Fig. 8a, one can also consider a two sub-band system in some agreement with the results of Datars and Nanney²⁴ as sketched in Fig. 8b, namely star and triangular-like shapes. The discrepancy in the cyclotron masses for these pockets that differ appreciably with others is unexplained.

(ii) Sondheimer and Wilson theory has successfully been applied to separate the bands by an analysis in terms of a two band model. However, there are some weak points in this method, as the values of the parameters a_j computed from this theory and the values obtained from the oscillatory effects do not agree very well. Also there is a difference in the mobility parameters obtained from magnetoconductivity and Hall conductivity. Some qualitative explanation can be found for these discrepancies.

²⁴C. Nanney, Phys. Rev. 129, 109 (1963).

(iii) The oscillations in conductivities are larger than expected from a simplified formulation of Lifshitz and Kosevitch theory. The oscillations in the coefficient, $\tilde{\sigma}_{11}$, are in good agreement with Zil'berman's prediction, thus making Lifshitz and Kosevitch theory account for this effect is unnecessary. However, matching of the oscillations in $\tilde{\sigma}_{12}$ coefficients with the Lifshitz and Kosevitch theory can be attained by adjustment of some parameters.

(iv) A few experiments could be suggested on the basis of the results of the present work for further understanding of the band structure of antimony: (a) Determination of cyclotron mass and chemical potential of each carrier at different orientations of the crystal to establish the exact shape of the Fermi surface for holes, (b) Analysis of the band structure based on Sondheimer-Wilson theory for the measurements taken in all the field ranges in the same run in order to have the same experimental conditions in different field ranges.

APPENDIX B

TABLES

Notations in Tables I through VIII

For $H\sigma_{11}$ vs. H (Tables I - IV)

$$P(1) = eca_1 n_1$$

$$P(2) = H_1^2$$

$$P(3) = eca_2 n_2$$

$$P(4) = H_2^2$$

σ_{12} vs. H (Tables V - VIII)

$$P(1) = ecn_1/H_1$$

$$P(2) = H_1^2$$

$$P(3) = ecn_2/H_2$$

$$P(4) = H_2^2$$

S stands for σ

X stands for H

Y stands for $H\sigma_{11}$ or σ_{12}

Y bar stands for theoretical value of Y .

Del stands for $Y - \bar{Y}$

PD stands for percentage Del.

$\Delta P(1)$ represents the difference in $P(1)$ in two successive iterations

$W(K)=1$ indicates minimization of RMS percent error.

TABLE NO. 1

HS11 VS H

2 BAND MODEL T=4.2 DEGREES KELVIN W(K)=1.

```

1
1      P(1)      DP(1)
1      2.01109587901754E+11      2.26323129928725E+08
2      1.34298453304403E+04      1.33154835364434E+01
3      9.11098174757967E+11      -1.67877597158561E+08
4      2.95283258256992E+05      2.94102163840220E+02
VAR= .1868E+08      NO. OF ITERATIONS= 4

```

X	Y	YBAR	DEL	PD
3.4100E-00	6.3423E+07	6.1541E+07	-1.8818E+06	-2.9671E-00
6.8100E-00	1.2591E+08	1.2263E+08	-3.2733E+06	-2.5997E-00
1.0220E+01	1.8817E+08	1.8338E+08	-4.7656E+06	-2.5432E-00
1.3630E+01	2.4809E+08	2.4335E+08	-4.7390E+06	-1.9102E-00
1.7030E+01	3.0675E+08	3.0212E+08	-4.6249E+06	-1.5077E-00
2.0440E+01	3.6470E+08	3.5982E+08	-4.8707E+06	-1.3355E-00
2.3850E+01	4.1994E+08	4.1508E+08	-3.8550E+06	-9.1799E-01
2.7250E+01	4.7238E+08	4.7055E+08	-1.8273E+06	-3.8684E-01
3.0660E+01	5.2312E+08	5.2339E+08	2.7471E+05	5.2515E-02
3.4070E+01	5.7095E+08	5.7431E+08	3.3651E+06	5.8940E-01
4.0880E+01	6.6041E+08	6.6984E+08	9.4397E+06	1.4293E-00
4.7690E+01	7.3818E+08	7.5674E+08	1.8566E+07	2.5152E-00
5.4510E+01	8.1085E+08	8.3491E+08	2.4061E+07	2.9673E-00
6.1320E+01	8.7461E+08	9.0422E+08	2.7610E+07	3.3856E-00
6.8130E+01	9.3729E+08	9.6514E+08	2.7858E+07	2.9722E-00
8.1760E+01	1.0300E+09	1.0641E+09	3.4140E+07	3.3146E-00
9.5350E+01	1.1031E+09	1.1368E+09	3.3760E+07	3.0605E-00
1.1456E+02	1.2173E+09	1.2060E+09	-1.1228E+07	-9.2241E-01
1.2264E+02	1.2118E+09	1.2263E+09	1.4571E+07	1.2024E-00
1.3627E+02	1.2434E+09	1.2520E+09	8.6144E+06	6.7281E-01
1.4989E+02	1.2742E+09	1.2695E+09	-4.6663E+06	-3.6621E-01
1.6352E+02	1.3001E+09	1.2813E+09	-1.8767E+07	-1.4435E-00
1.8015E+02	1.2870E+09	1.2904E+09	3.4104E+06	2.6499E-01
1.9595E+02	1.3060E+09	1.2954E+09	-1.0591E+07	-8.1095E-01
2.1181E+02	1.3190E+09	1.2980E+09	-2.0921E+07	-1.5861E-00
2.4365E+02	1.3300E+09	1.2990E+09	-3.0932E+07	-2.3257E-00
2.7569E+02	1.3370E+09	1.2964E+09	-4.0552E+07	-3.0330E-00
3.0791E+02	1.3350E+09	1.2912E+09	-4.3741E+07	-3.2765E-00
3.4030E+02	1.3190E+09	1.2837E+09	-3.5225E+07	-2.6705E-00
3.7288E+02	1.3050E+09	1.2740E+09	-3.0958E+07	-2.3722E-00
4.3853E+02	1.2630E+09	1.2480E+09	-1.4913E+07	-1.1807E-00
5.0484E+02	1.2180E+09	1.2144E+09	-3.5119E+06	-2.8833E-01
5.7178E+02	1.1660E+09	1.1750E+09	9.0935E+06	7.7989E-01
6.3930E+02	1.1040E+09	1.1319E+09	2.7949E+07	2.5316E-00
7.0739E+02	1.0530E+09	1.0868E+09	3.3864E+07	3.2160E-00

8.7986E+02	9.3610E+08	9.7426E+08	3.8162E+07	4.0767E-00
1.0551E+03	8.3030E+08	8.7082E+08	4.0524E+07	4.8807E-00
1.2327E+03	7.4610E+08	7.8056E+08	3.4467E+07	4.6196E-00
1.4122E+03	6.7740E+08	7.0341E+08	2.6013E+07	3.8401E-00
1.5930E+03	6.1840E+08	6.3790E+08	1.9505E+07	3.1541E-00
1.7747E+03	5.6890E+08	5.8221E+08	1.3314E+07	2.3404E-00
1.9420E+03	5.3670E+08	5.3827E+08	1.5793E+06	2.9426E-01
2.1190E+03	4.9640E+08	4.9806E+08	1.6600E+06	3.3441E-01
2.4730E+03	4.3200E+08	4.3259E+08	5.9322E+05	1.3732E-01
3.1810E+03	3.4220E+08	3.4143E+08	-7.6409E+05	-2.2328E-01
3.8890E+03	2.8360E+08	2.8145E+08	-2.1441E+06	-7.5603E-01
5.1280E+03	2.1410E+08	2.1489E+08	7.9624E+05	3.7190E-01
6.0130E+03	1.8390E+08	1.8372E+08	-1.7265E+05	-9.3884E-02
7.0750E+03	1.5840E+08	1.5643E+08	-1.9603E+06	-1.2375E-00
8.1430E+03	1.3760E+08	1.3608E+08	-1.5165E+06	-1.1021E-00
9.0200E+03	1.2380E+08	1.2293E+08	-8.6431E+05	-6.9814E-01
1.0065E+04	1.1100E+08	1.1023E+08	-7.6322E+05	-6.8759E-01
1.1018E+04	1.0250E+08	1.0074E+08	-1.7580E+06	-1.7151E-00
1.2006E+04	9.4060E+07	9.2480E+07	-1.5790E+06	-1.6787E-00
1.3024E+04	8.6790E+07	8.5273E+07	-1.5160E+06	-1.7467E-00
1.4040E+04	8.0580E+07	7.9119E+07	-1.4609E+06	-1.8130E-00
1.5035E+04	7.5560E+07	7.3894E+07	-1.6652E+06	-2.2039E-00
1.6040E+04	7.0920E+07	6.9273E+07	-1.6461E+06	-2.3211E-00
1.7025E+04	6.7040E+07	6.5272E+07	-1.7670E+06	-2.6358E-00
1.8030E+04	6.3240E+07	6.1640E+07	-1.5998E+06	-2.5297E-00
NO. OF ITERATIONS= 4 VAR= .1868E+01 PDMEAN= 1.815 PDRMS= 2.184				

TABLE NO. 11

HS11 VS H

2 BAND MODEL T=3.5 DEGREES KELVIN W(K)=1.

```

1
1      2.11345754697004E+11      -1.66650958264801E+07      DP(1)
2      1.32717647087992E+04      -9.16382931135202E-01
3      8.85996105994766E+11      1.21872177843916E+07
4      2.81883182644835E+05      -2.06620589321610E+01
VAR= .2214E+08      NO. OF ITERATIONS= 5

```

X	Y	YBAR	DEL	PD
3.4100E-00	6.7060E+07	6.4972E+07	-2.0874E+06	-3.1128E-00
6.8100E-00	1.3366E+08	1.2946E+08	-4.1908E+06	-3.1354E-00
1.0220E+01	1.9966E+08	1.9358E+08	-6.0718E+06	-3.0411E-00
1.3630E+01	2.6297E+08	2.5686E+08	-6.1031E+06	-2.3208E-00
1.7030E+01	3.2527E+08	3.1886E+08	-6.4033E+06	-1.9686E-00
2.0440E+01	3.8596E+08	3.7971E+08	-6.2472E+06	-1.6186E-00
2.3850E+01	4.4210E+08	4.3900E+08	-3.0977E+06	-7.0069E-01
2.7250E+01	4.9808E+08	4.9637E+08	-1.7058E+06	-3.4247E-01
3.0660E+01	5.4898E+08	5.5199E+08	3.0174E+06	5.4964E-01
3.4070E+01	6.0093E+08	6.0555E+08	4.6284E+06	7.7022E-01
4.0880E+01	6.9320E+08	7.0592E+08	1.2721E+07	1.8351E-00
4.7690E+01	7.7652E+08	7.9703E+08	2.0511E+07	2.6414E-00
5.4510E+01	8.5353E+08	8.7879E+08	2.5267E+07	2.9603E-00
6.1320E+01	9.1882E+08	9.5110E+08	3.2288E+07	3.5140E-00
6.8130E+01	9.7721E+08	1.0144E+09	3.7270E+07	3.8139E-00
8.1760E+01	1.0795E+09	1.1168E+09	3.7395E+07	3.4641E-00
9.5390E+01	1.1481E+09	1.1916E+09	4.3525E+07	3.7911E-00
1.1456E+02	1.2787E+09	1.2613E+09	-1.7381E+07	-1.3593E-00
1.2264E+02	1.2573E+09	1.2814E+09	2.4130E+07	1.9191E-00
1.3627E+02	1.3015E+09	1.3063E+09	4.8316E+06	3.7123E-01
1.4989E+02	1.3383E+09	1.3227E+09	-1.5560E+07	-1.1627E-00
1.6352E+02	1.3643E+09	1.3331E+09	-3.1111E+07	-2.2803E-00
1.8015E+02	1.3310E+09	1.3404E+09	9.4316E+06	7.0861E-01
1.9595E+02	1.3530E+09	1.3435E+09	-9.4416E+06	-6.9600E-01
2.1181E+02	1.3640E+09	1.3443E+09	-1.9645E+07	-1.4402E-00
2.4365E+02	1.3780E+09	1.3415E+09	-3.6475E+07	-2.6469E-00
2.7569E+02	1.3740E+09	1.3351E+09	-3.8851E+07	-2.8276E-00
3.0791E+02	1.3860E+09	1.3263E+09	-5.9678E+07	-4.3058E-00
3.4030E+02	1.3510E+09	1.3153E+09	-3.5656E+07	-2.6392E-00
3.7288E+02	1.3420E+09	1.3022E+09	-3.9723E+07	-2.9600E-00
4.3853E+02	1.2880E+09	1.2701E+09	-1.7807E+07	-1.3825E-00
5.0484E+02	1.2320E+09	1.2312E+09	-7.5355E+05	-6.1164E-02
5.7178E+02	1.1650E+09	1.1873E+09	2.2307E+07	1.9147E-00
6.3930E+02	1.1090E+09	1.1403E+09	3.1387E+07	2.8302E-00
7.0739E+02	1.0570E+09	1.0922E+09	3.5222E+07	3.3322E-00

8.7386E+02	9.3170E+08	9.7434E+08	4.2642E+07	4.5768E-00
1.0551E+03	8.2620E+08	8.6800E+08	4.1809E+07	5.0604E-00
1.2327E+03	7.3900E+08	7.7624E+08	3.7242E+07	5.0395E-00
1.4122E+03	6.7230E+08	6.9835E+08	2.6059E+07	3.8761E-00
1.5930E+03	6.1340E+08	6.3255E+08	1.9157E+07	3.1232E-00
1.7747E+03	5.6310E+08	5.7681E+08	1.3714E+07	2.4355E-00
1.9420E+03	5.4020E+08	5.3294E+08	-7.2524E+06	-1.3425E-00
2.1190E+03	4.9300E+08	4.9286E+08	-1.3378E+05	-2.7137E-02
2.4730E+03	4.2410E+08	4.2775E+08	3.6584E+06	8.6263E-01
3.1810E+03	3.3430E+08	3.3733E+08	3.0317E+06	9.0689E-01
4.2430E+03	2.5350E+08	2.5536E+08	1.8682E+06	7.3698E-01
5.1280E+03	2.1380E+08	2.1213E+08	-1.6629E+06	-7.7782E-01
6.0130E+03	1.8380E+08	1.8134E+08	-2.4578E+06	-1.3372E-00
7.0750E+03	1.5690E+08	1.5439E+08	-2.5078E+06	-1.5983E-00
1.0065E+04	1.1010E+08	1.0877E+08	-1.3214E+06	-1.2002E-00
1.1018E+04	1.0140E+08	9.9406E+07	-1.0930E+06	-1.9654E-00
1.2006E+04	9.3150E+07	9.1253E+07	-1.8961E+06	-2.0356E-00
1.3024E+04	8.6140E+07	8.4141E+07	-1.9987E+06	-2.3203E-00
1.4040E+04	7.9700E+07	7.8067E+07	-1.6328E+06	-2.0487E-00
1.5035E+04	7.4700E+07	7.2911E+07	-1.7863E+06	-2.3941E-00
1.6040E+04	6.9950E+07	6.8351E+07	-1.5982E+06	-2.2849E-00
1.7025E+04	6.6220E+07	6.4403E+07	-1.8163E+06	-2.7429E-00
1.8030E+04	6.2410E+07	6.0818E+07	-1.5910E+06	-2.5493E-00

NO. OF ITERATIONS= 5 VAR= .2214E+08 PDMEAN= 2.166 PDRMS= 2.488

TABLE NO. 111

HS11 VS H

2 BAND MODEL T=2.1 DEGREES KELVIN W(K)=1.

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1          P(1)          DP(1)
1      2.23008132140683E+11      2.65422215740660E+08
2      1.263333880742637E+04      1.32164736478204E+01
3      8.56985601127679E+11      -2.01338909620789E+08
4      2.68656300876669E+05      3.20722047992131E+02
VAR= .2468E+08      NO. OF ITERATIONS= 3

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X	Y	YBAR	DEL	PD
3.4100E-00	7.3500E+07	7.1016E+07	-2.4839E+06	-3.3795E-00
6.8100E-00	1.4511E+08	1.4149E+08	-3.6181E+06	-2.4934E-00
1.0220E+01	2.1802E+08	2.1151E+08	-6.5049E+06	-2.9836E-00
1.3630E+01	2.8799E+08	2.8056E+08	-7.4279E+06	-2.5792E-00
1.7030E+01	3.5622E+08	3.4813E+08	-8.0826E+06	-2.2689E-00
2.0440E+01	4.2022E+08	4.1436E+08	-5.8574E+06	-1.3938E-00
2.3850E+01	4.8431E+08	4.7878E+08	-5.5240E+06	-1.1406E-00
2.7250E+01	5.4261E+08	5.4100E+08	-1.6042E+06	-2.9564E-01
3.0660E+01	5.9967E+08	6.0119E+08	1.5277E+06	2.5475E-01
3.4070E+01	6.5211E+08	6.5901E+08	6.9071E+06	1.0591E-00
4.0880E+01	7.5196E+08	7.6691E+08	1.4955E+07	1.9889E-00
4.7690E+01	8.4187E+08	8.6425E+08	2.2384E+07	2.6589E-00
5.4510E+01	9.2152E+08	9.5098E+08	2.9464E+07	3.1974E-00
6.1320E+01	9.8861E+08	1.0270E+09	3.8456E+07	3.8899E-00
6.8130E+01	1.0513E+09	1.0931E+09	4.1842E+07	3.9800E-00
8.1760E+01	1.1538E+09	1.1983E+09	4.4512E+07	3.8578E-00
9.5390E+01	1.2335E+09	1.2731E+09	3.9654E+07	3.2147E-00
1.1456E+02	1.3629E+09	1.3402E+09	-2.2622E+07	-1.6598E-00
1.2264E+02	1.3425E+09	1.3587E+09	1.6251E+07	1.2105E-00
1.3627E+02	1.3824E+09	1.3805E+09	-1.8899E+06	-1.3671E-01
1.4989E+02	1.4164E+09	1.3935E+09	-2.2849E+07	-1.6131E-00
1.6352E+02	1.4419E+09	1.4005E+09	-4.1309E+07	-2.8649E-00
1.8015E+02	1.3910E+09	1.4037E+09	1.2767E+07	9.1785E-01
1.9595E+02	1.3930E+09	1.4032E+09	1.0229E+07	7.3434E-01
2.1181E+02	1.4000E+09	1.4004E+09	4.9783E+05	3.5559E-02
2.4365E+02	1.4090E+09	1.3912E+09	-1.7763E+07	-1.2607E-00
2.7569E+02	1.4300E+09	1.3791E+09	-5.0891E+07	-3.5588E-00
3.0791E+02	1.4470E+09	1.3650E+09	-8.1900E+07	-5.6600E-00
3.4030E+02	1.4070E+09	1.3494E+09	-5.7582E+07	-4.0925E-00
3.7288E+02	1.3670E+09	1.3320E+09	-3.4943E+07	-2.5562E-00
4.3853E+02	1.3130E+09	1.2924E+09	-2.0535E+07	-1.5640E-00
5.0484E+02	1.2430E+09	1.2472E+09	4.2850E+06	3.4473E-01
5.7178E+02	1.1840E+09	1.1982E+09	1.4241E+07	1.2028E-00
6.3930E+02	1.1230E+09	1.1472E+09	2.4204E+07	2.1553E-00
7.0739E+02	1.0700E+09	1.0957E+09	2.5759E+07	2.4074E-00
8.7986E+02	9.0530E+08	9.7246E+08	6.7161E+07	7.4167E-00

1.0551E+03	8.2240E+08	6.6331E+08	4.0914E+07	4.9750E-00
1.2327E+03	7.361CE+08	7.7018E+08	3.4081E+07	4.630CE-00
1.4122E+03	6.6520E+08	6.9172E+08	2.6521E+07	3.9870E-00
1.5930E+03	6.090CE+08	6.2576E+08	1.6767E+07	2.7532E-00
1.7747E+03	5.581CE+09	5.7009E+08	1.1995E+07	2.1492E-00
1.9420E+03	5.1830E+08	5.2639E+08	8.0959E+06	1.5619E-00
2.1190E+03	4.7820E+08	4.8654E+08	8.3443E+06	1.7449E-00
2.4730E+03	4.1320E+08	4.2194E+08	8.7457E+06	2.1165E-00
3.1810E+03	3.2760E+08	3.3245E+08	4.8586E+06	1.483CE-00
3.8890E+03	2.7190E+08	2.7381E+08	1.9105E+06	7.0278E-01
5.1280E+03	2.0750E+08	2.0889E+08	1.3962E+06	6.7287E-01
6.0130E+03	1.7960E+08	1.7854E+08	-1.0543E+06	-5.8705E-01
7.0750E+03	1.5460E+08	1.5199E+08	-2.6053E+06	-1.6851E-00
8.1430E+03	1.3500E+08	1.3219E+08	-2.8014E+06	-2.0751E-00
9.0200E+03	1.2150E+08	1.1941E+08	-2.0833E+06	-1.7146E-00
1.0065E+04	1.0900E+08	1.0707E+08	-1.0260E+06	-1.7670E-00
1.1081E+04	1.0030E+08	9.7292E+07	-3.0073E+06	-2.9983E-00
1.2006E+04	9.2210E+07	8.9820E+07	-2.3899E+06	-2.5918E-00
1.3024E+04	8.5160E+07	8.2818E+07	-2.3419E+06	-2.750CE-00
1.4040E+04	7.8730E+07	7.6838E+07	-1.8914E+06	-2.4024E-00
1.5035E+04	7.3790E+07	7.1763E+07	-2.0265E+06	-2.7463E-00
1.6040E+04	6.9000E+07	6.7274E+07	-1.7251E+06	-2.5001E-00
1.7025E+04	6.5610E+07	6.3388E+07	-2.2214E+06	-3.3858E-00
1.8030E+04	6.1730E+07	5.9860E+07	-1.8699E+06	-3.0291E-00

NO. OF ITERATIONS= 3 VAR= .2468E+08 PDMEAN= 2.317 PD RMS= 2.708

TABLE NO. IV

HS11 VS H

2 BAND MODEL T=1.7 DEGREES KELVIN W(K)=1.

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I          P(I)          DP(I)
1          1.79374890132352E+11      9.79373057905250E+07
2          1.02188947721232E+04      9.07561662554152E+00
3          9.05880664057619E+11     -9.74281024506155E+07
4          2.03043679297902E+05      7.59634543002765E+01
VAR= .1699E+08      NO. OF ITERATIONS= 4

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X	Y	YBAR	DEL	PD
3.4100E-00	7.7065E+07	7.5001E+07	-2.0635E+06	-2.6776E-00
6.8100E-00	1.5324E+08	1.4937E+08	-3.8664E+06	-2.5231E-00
1.0220E+01	2.2875E+08	2.2315E+08	-5.5976E+06	-2.4470E-00
1.3630E+01	2.9945E+08	2.9573E+08	-3.7162E+06	-1.2410E-00
1.7030E+01	3.7008E+08	3.6655E+08	-3.5267E+06	-9.5297E-01
2.0440E+01	4.3841E+08	4.3570E+08	-2.7081E+06	-6.1772E-01
2.3850E+01	5.0282E+08	5.0268E+08	-1.3977E+05	-2.7797E-02
2.7250E+01	5.6537E+08	5.6705E+08	1.6860E+06	2.9821E-01
3.0660E+01	6.2504E+08	6.2900E+08	3.9653E+06	6.3442E-01
3.4070E+01	6.8011E+08	6.8817E+08	8.0668E+06	1.1861E-00
4.0880E+01	7.8302E+08	7.9761E+08	1.4597E+07	1.8642E-00
5.4510E+01	9.6034E+08	9.8097E+08	2.0634E+07	2.1486E-00
6.1320E+01	1.0229E+09	1.0554E+09	3.2545E+07	3.1816E-00
6.8130E+01	1.0895E+09	1.1195E+09	3.0032E+07	2.7565E-00
8.1760E+01	1.1858E+09	1.2207E+09	3.4954E+07	2.9477E-00
9.5390E+01	1.2600E+09	1.2930E+09	3.3054E+07	2.6233E-00
1.1456E+02	1.3883E+09	1.3603E+09	-2.7901E+07	-2.0097E-00
1.2264E+02	1.3768E+09	1.3803E+09	3.5260E+06	2.5610E-01
1.3627E+02	1.4097E+09	1.4060E+09	-3.6022E+06	-2.5553E-01
1.4989E+02	1.4409E+09	1.4246E+09	-1.6217E+07	-1.1255E-00
1.6352E+02	1.4599E+09	1.4382E+09	-2.1600E+07	-1.4796E-00
1.6440E+02	1.4430E+09	1.4390E+09	-3.9553E+06	-2.7410E-01
1.8015E+02	1.4640E+09	1.4502E+09	-1.3765E+07	-9.4029E-01
1.9595E+02	1.4750E+09	1.4581E+09	-1.6804E+07	-1.1393E-00
2.1181E+02	1.4880E+09	1.4637E+09	-2.4266E+07	-1.6306E-00
2.4365E+02	1.5060E+09	1.4692E+09	-3.6795E+07	-2.4432E-00
2.7569E+02	1.5030E+09	1.4685E+09	-3.4493E+07	-2.2950E-00
3.0791E+02	1.4890E+09	1.4623E+09	-2.6654E+07	-1.7901E-00
3.4030E+02	1.4620E+09	1.4511E+09	-1.0805E+07	-7.3905E-01
3.7288E+02	1.4470E+09	1.4355E+09	-1.1447E+07	-7.9113E-01
4.3853E+02	1.3850E+09	1.3932E+09	8.2130E+06	5.9299E-01
5.0484E+02	1.3120E+09	1.3403E+09	2.8341E+07	2.1601E-00
5.7178E+02	1.2490E+09	1.2815E+09	3.2540E+07	2.6053E-00
6.3930E+02	1.1920E+09	1.2204E+09	2.8415E+07	2.3838E-00
7.0739E+02	1.1280E+09	1.1594E+09	3.1460E+07	2.7890E-00

8.7986E+01	9.9420E+08	1.0168E+09	2.2658E+07	2.2790E+00
1.0551E+03	8.6890E+08	8.9459E+08	2.5694E+07	2.9571E+00
1.2327E+03	7.7800E+08	7.9279E+08	1.4796E+07	1.9018E+00
1.4122E+03	7.0800E+08	7.0856E+08	5.6416E+05	7.9684E+02
1.5930E+03	6.4300E+08	6.3868E+08	-4.3156E+06	-6.7117E+01
1.7747E+03	5.9480E+08	5.8027E+08	-1.4525E+07	-2.4421E+00
1.9420E+03	5.1730E+08	5.3475E+08	1.7453E+07	3.3739E+00
2.1190E+03	4.7930E+08	4.9346E+08	1.4167E+07	2.9557E+00
2.4730E+03	4.1590E+08	4.2694E+08	1.1049E+07	2.6568E+00
3.1810E+03	3.2980E+08	3.3550E+08	5.7091E+06	1.7311E+00
3.8890E+03	2.7230E+08	2.7594E+08	3.6408E+06	1.3370E+00
5.1280E+03	2.0890E+08	2.1026E+08	1.3661E+06	6.5397E+01
6.0130E+03	1.7950E+08	1.7963E+08	1.3513E+05	7.5286E+02
7.0750E+03	1.5550E+08	1.5287E+08	-2.6294E+06	-1.6909E+00
8.1430E+03	1.3470E+08	1.3293E+08	-1.7683E+06	-1.3128E+00
9.0200E+03	1.2130E+08	1.2006E+08	-1.2359E+06	-1.0189E+00
1.0065E+04	1.0860E+08	1.0764E+08	-9.5713E+05	-8.8133E+01
1.1018E+04	9.9840E+07	9.8359E+07	-1.4802E+06	-1.4826E+00
1.2006E+04	9.1900E+07	9.0285E+07	-1.6144E+06	-1.7567E+00
1.3024E+04	8.4810E+07	8.3243E+07	-1.5666E+06	-1.8472E+00
1.4040E+04	7.8460E+07	7.7230E+07	-1.2296E+06	-1.5672E+00
1.5035E+04	7.3680E+07	7.2127E+07	-1.5526E+06	-2.1073E+00
1.6040E+04	6.8730E+07	6.7614E+07	-1.1156E+06	-1.6232E+00
1.7025E+04	6.5510E+07	6.3707E+07	-1.8027E+06	-2.7519E+00
1.8030E+04	6.1570E+07	6.0159E+07	-1.4100E+06	-2.2901E+00

NO. OF ITERATIONS= 4 VAR= .1699E+08 PDMEAN= 1.654 PD RMS= 1.883

TABLE NO. V

S12 VS H

2 BAND MODEL T=4.2 DEGREES KELVIN W(K)=1.

I	P(I)	DP(I)				
1	-7.44295061705005E+08	9.82305021140566E-01				
2	7.46161205381057E+03	-1.07100019556415E-05				
3	7.43900580509566E+08	-9.81518637326320E-01				
4	2.42383715881734E+05	4.87665745286915E-04				
VAR= .5963E+05			NO. OF ITERATIONS= 7			
X	Y	YBAR	DEL	PD		
1.7030E+01	-1.6524E+06	-1.5829E+06	6.9442E+04	-4.2025E-00		
2.0440E+01	-1.8453E+06	-1.8681E+06	-2.2828E+04	1.2371E-00		
2.3850E+01	-2.0994E+06	-2.1374E+06	-3.8063E+04	1.8130E-00		
2.7250E+01	-2.3851E+06	-2.3887E+06	-3.6501E+03	1.5304E-01		
3.0660E+01	-2.5742E+06	-2.6223E+06	-4.8172E+04	1.8713E-00		
3.4070E+01	-2.8100E+06	-2.8368E+06	-1.8862E+04	6.6935E-01		
4.0880E+01	-3.1791E+06	-3.2069E+06	-2.7848E+04	8.7598E-01		
4.7690E+01	-3.4676E+06	-3.5007E+06	-3.3157E+04	9.5621E-01		
5.4510E+01	-3.6328E+06	-3.7234E+06	-9.0663E+04	2.4956E-00		
6.1320E+01	-3.8268E+06	-3.8817E+06	-5.4938E+04	1.4356E-00		
6.8130E+01	-3.9243E+06	-3.9844E+06	-6.0140E+04	1.5325E-00		
8.1760E+01	-4.0835E+06	-4.0574E+06	2.6025E+04	-6.3734E-01		
9.5350E+01	-4.0185E+06	-4.0051E+06	1.3325E+04	-3.3160E-01		
1.1456E+02	-3.9634E+06	-3.8084E+06	1.5495E+05	-3.9095E-00		
1.2264E+02	-3.7987E+06	-3.7020E+06	9.6646E+04	-2.5442E-00		
1.3627E+02	-3.7135E+06	-3.5077E+06	2.0571E+05	-5.5397E-00		
1.4989E+02	-3.5122E+06	-3.3065E+06	2.0563E+05	-5.8549E-00		
1.6352E+02	-3.3247E+06	-3.1066E+06	2.1809E+05	-6.5599E-00		
1.8015E+02	-2.9090E+06	-2.8715E+06	3.7451E+04	-1.2874E-00		
1.9595E+02	-2.6980E+06	-2.6611E+06	3.6842E+04	-1.3655E-00		
2.1181E+02	-2.5030E+06	-2.4643E+06	3.8698E+04	-1.5460E-00		
2.4365E+02	-2.1290E+06	-2.1129E+06	1.6017E+04	-7.5233E-01		
2.7569E+02	-1.8220E+06	-1.8142E+06	7.7647E+03	-4.2616E-01		
3.0791E+02	-1.5600E+06	-1.5615E+06	-1.5575E+03	9.9840E-02		
3.4030E+02	-1.3190E+06	-1.3479E+06	-2.8999E+04	2.1986E-00		
3.7288E+02	-1.1390E+06	-1.1671E+06	-2.8143E+04	2.4708E-00		
4.3853E+02	-8.4940E+05	-8.8336E+05	-3.3965E+04	3.9988E-00		
5.0484E+02	-6.5120E+05	-6.7710E+05	-2.5903E+04	3.9778E-00		
5.7178E+02	-5.0010E+05	-5.2553E+05	-2.5432E+04	5.0854E-00		
6.3930E+02	-3.8530E+05	-4.1291E+05	-2.7613E+04	7.1666E-00		
7.0739E+02	-3.0500E+05	-3.2824E+05	-2.3245E+04	7.6213E-00		
8.7986E+02	-1.8830E+05	-1.9395E+05	-5.6573E+03	3.0044E-00		
1.0551E+03	-1.1360E+05	-1.2173E+05	-8.1305E+03	7.1571E-00		
1.2327E+03	-7.6040E+04	-8.0379E+04	-4.3394E+03	5.7067E-00		
1.4122E+03	-5.3300E+04	-5.5391E+04	-2.0919E+03	3.9247E-00		

1.5930E+03	-3.8740E+04	-3.9586E+04	-8.4641E+02	2.1846E-00
1.7747E+03	-2.8910E+04	-2.9178E+04	-2.6873E+02	9.2954E-01
1.9420E+03	-2.4140E+04	-2.2573E+04	1.5664E+03	-6.4891E-00
2.1190E+03	-1.8860E+04	-1.7578E+04	1.2811E+03	-6.7929E-00
2.2960E+03	-1.4710E+04	-1.3951E+04	7.5844E+02	-5.1559E-00
2.4730E+03	-1.1810E+04	-1.1256E+04	9.5385E+02	-4.6896E-00
3.1810E+03	-5.7740E+03	-5.4192E+03	3.5479E+02	-6.1446E-00
3.8890E+03	-3.2410E+03	-3.0216E+03	2.1933E+02	-6.7676E-00
5.1280E+03	-1.4000E+03	-1.3587E+03	4.1275E+01	-2.9482E-00
6.0130E+03	-8.7060E+02	-8.6224E+02	8.3573E-00	-9.5995E-01
7.0750E+03	-5.5820E+02	-5.4535E+02	1.2847E+01	-2.3015E-00
8.1430E+03	-3.7780E+02	-3.6965E+02	8.1468E-00	-2.1563E-00
9.0200E+03	-2.7600E+02	-2.8002E+02	-4.0251E-00	1.4583E-00
1.0065E+04	-2.0900E+02	-2.0917E+02	-1.7002E-01	8.1353E-02
1.1018E+04	-1.6520E+02	-1.6528E+02	-8.1558E-02	4.9369E-02
1.2006E+04	-1.3270E+02	-1.3282E+02	-1.2964E-01	9.7696E-02
1.3024E+04	-1.0870E+02	-1.0850E+02	1.9136E-01	-1.7604E-01
1.4040E+04	-9.0120E+01	-9.0448E+01	-3.2850E-01	3.6452E-01
1.5035E+04	-7.7530E+01	-7.6934E+01	5.9562E-01	-7.6825E-01
1.6040E+04	-6.6540E+01	-6.6275E+01	2.6433E-01	-3.9725E-01
1.7025E+04	-5.7690E+01	-5.7966E+01	-2.7644E-01	4.7919E-01
1.8030E+04	-4.9900E+01	-5.1117E+01	-1.2172E-00	2.4394E-00

NO. OF ITERATIONS= 7 VAR= .5963E+05 PDMEAN= 2.706 PDRMS= 3.546

TABLE NO. VI

S12 VS H

2 RAND MODEL T=3.5 DEGREES KELVIN W(K)=1.

```

1      P(1)      DP(1)
1      -7.92423045163593E+08      3.30722857512566E-02
2      7.53861955387045E+03      -3.32034251367360E-07
3      7.92000705788448E+08      -3.30526749298000E-02
4      2.08712029947053E+05      1.27452047445842E-05
VAR= .8504E+05      NO. OF ITERATIONS= 7

```

X	Y	YBAR	DEL	PO
6.8100E-00	-6.7751E+05	-6.8562E+05	-8.1111E+03	1.1972E-00
1.3630E+01	-1.3613E+06	-1.3465E+06	1.4714E+04	-1.0809E-00
1.7030E+01	-1.7228E+06	-1.6592E+06	6.3540E+04	-3.6881E-00
2.0440E+01	-1.8826E+06	-1.9583E+06	-7.5723E+04	4.0222E-00
2.3850E+01	-2.3359E+06	-2.2408E+06	9.5053E+04	-4.0692E-00
2.7250E+01	-2.4170E+06	-2.5045E+06	-8.7502E+04	3.6202E-00
3.0660E+01	-2.8459E+06	-2.7496E+06	9.6211E+04	-3.3807E-00
3.4070E+01	-2.9281E+06	-2.9748E+06	-4.6750E+04	1.5966E-00
4.0880E+01	-3.3487E+06	-3.3634E+06	-1.4774E+04	4.4121E-01
4.7690E+01	-3.6189E+06	-3.6720E+06	-5.3179E+04	1.4694E-00
5.4510E+01	-3.8128E+06	-3.9059E+06	-9.3163E+04	2.4434E-00
6.1320E+01	-3.9350E+06	-4.0720E+06	-1.3702E+05	3.4820E-00
6.8130E+01	-4.1166E+06	-4.1794E+06	-6.2870E+04	1.5272E-00
8.1760E+01	-4.1496E+06	-4.2544E+06	-1.0486E+05	2.5271E-00
9.5390E+01	-4.2004E+06	-4.1363E+06	4.0517E+03	-9.6460E-02
1.1456E+02	-4.0593E+06	-3.9844E+06	7.4861E+04	-1.8441E-00
1.2264E+02	-4.1504E+06	-3.8699E+06	2.8041E+05	-6.7563E-00
1.3627E+02	-3.9315E+06	-3.6611E+06	2.7034E+05	-6.8764E-00
1.4989E+02	-3.7568E+06	-3.4449E+06	3.1184E+05	-8.3007E-00
1.6352E+02	-3.5144E+06	-3.2302E+06	2.8419E+05	-8.0866E-00
1.8015E+02	-2.9620E+06	-2.9779E+06	-1.5910E+04	5.3716E-01
1.9595E+02	-2.7500E+06	-2.7522E+06	-2.2906E+03	8.3296E-02
2.1181E+02	-2.5310E+06	-2.5414E+06	-1.0431E+04	4.1216E-01
2.4365E+02	-2.1710E+06	-2.1660E+06	4.9961E+03	-2.3013E-01
2.7569E+02	-1.8320E+06	-1.8480E+06	-1.6069E+04	8.7714E-01
3.0791E+02	-1.6020E+06	-1.5805E+06	2.1461E+04	-1.3396E-00
3.4030E+02	-1.3160E+06	-1.3557E+06	-3.9756E+04	3.0210E-00
3.7288E+02	-1.1140E+06	-1.1666E+06	-2.6614E+04	2.3345E-00
4.3853E+02	-8.2810E+05	-8.7275E+05	-4.4654E+04	5.3924E-00
5.0484E+02	-6.3800E+05	-6.6205E+05	-2.4057E+04	3.7707E-00
5.7178E+02	-4.7990E+05	-5.0922E+05	-2.9320E+04	6.1098E-00
6.3930E+02	-3.7390E+05	-3.9699E+05	-2.3095E+04	6.1769E-00
7.0739E+02	-2.9750E+05	-3.1350E+05	-1.6004E+04	5.3796E-00
8.7986E+02	-1.7530E+05	-1.8294E+05	-7.6404E+03	4.3585E-00
1.0551E+03	-1.1010E+05	-1.1386E+05	-3.7613E+03	3.4162E-00

1.327E+03	-7.3230E+04	-7.4759E+04	-1.5292E+03	2.0883E-00
1.4122E+03	-5.1760E+04	-5.1318E+04	4.4179E+02	-8.5353E-01
1.5930E+03	-3.7510E+04	-3.6575E+04	9.3497E+02	-2.4925E-00
1.7747E+03	-2.8030E+04	-2.6907E+04	1.1229E+03	-4.0062E-00
1.9420E+03	-2.1210E+04	-2.0789E+04	4.2039E+02	-1.9820E-00
2.1190E+03	-1.6760E+04	-1.6174E+04	5.8594E+02	-3.4961E-00
2.4730E+03	-1.0120E+04	-1.0345E+04	-2.2511E+02	2.2244E-00
3.1810E+03	-4.7920E+03	-4.9790E+03	-1.8702E+02	3.9028E-00
3.8890E+03	-2.7800E+03	-2.7791E+03	8.2570E-01	-2.9701E-02
4.2430E+03	-2.1850E+03	-2.1605E+03	2.4449E+01	-1.1189E-00
5.1280E+03	-1.2850E+03	-1.2542E+03	3.0754E+01	-2.3933E-00
6.0130E+03	-8.0730E+02	-7.9872E+02	8.5724E-00	-1.0618E-00
7.0750E+03	-5.4150E+02	-5.0765E+02	3.3849E+01	-6.2509E-00
8.1430E+03	-3.7220E+02	-3.4598E+02	2.6217E+01	-7.0440E-00
9.0200E+03	-2.7840E+02	-2.6335E+02	1.5049E+01	-5.4055E-00
1.0065E+04	-2.0380E+02	-1.9788E+02	5.9122E-00	-2.9010E-00
1.1018E+04	-1.6280E+02	-1.5723E+02	5.5615E-00	-3.4162E-00
1.2006E+04	-1.3090E+02	-1.2710E+02	3.7960E-00	-2.8999E-00
1.3024E+04	-1.0620E+02	-1.0445E+02	1.7442E-00	-1.6424E-00
1.4040E+04	-8.6910E+01	-8.7586E+01	-6.7672E-01	7.7865E-01
1.5035E+04	-7.4020E+01	-7.4924E+01	-9.0448E-01	1.2219E-00
1.6040E+04	-6.3320E+01	-6.4905E+01	-1.5856E-00	2.5042E-00
1.7025E+04	-5.4930E+01	-5.7069E+01	-2.1398E-00	3.8955E-00
1.8030E+04	-4.8640E+01	-5.0589E+01	-1.9493E-00	4.0077E-00

NO. OF ITERATIONS= 7 VAR= .8504E+05 PDMEAN= 3.009 PDRMS= 3.664

TABLE NO. VII

S12 VS H

2 BAND MODEL T=2.1 DEGREES KELVIN W(K)=1.

```

I          P(I)          DP(I)
1          -7.53741627294382E+08      -1.79067030990051E+04
2          6.28047019811323E+03       1.60282214419772E-01
3          7.53346308498567E+08       1.78913272206559E+04
4          2.21045243597130E+03      -8.55587799108197E+00
VAR= .8609E+05      NO. OF ITERATIONS= 3

```

X	Y	YBAR	DEL	PO
1.3630E+01	-1.6116E+06	-1.5423E+06	6.9225E+04	-4.2954E-00
1.7030E+01	-1.8079E+06	-1.8956E+06	-8.7752E+04	4.8538E-00
2.0440E+01	-2.3790E+06	-2.2305E+06	1.4845E+05	-6.2404E-00
2.3850E+01	-2.5041E+06	-2.5435E+06	-3.9437E+04	1.5749E-00
2.7250E+01	-2.8706E+06	-2.8220E+06	3.8574E+04	-1.3437E-00
3.0660E+01	-2.9417E+06	-3.0965E+06	-1.5481E+05	5.2628E-00
3.4070E+01	-3.3558E+06	-3.3355E+06	2.0270E+04	-6.0405E-01
4.0880E+01	-3.6675E+06	-3.7367E+06	-6.0264E+04	1.8885E-00
4.7690E+01	-3.9418E+06	-4.0409E+06	-9.9163E+04	2.5156E-00
5.4510E+01	-4.1128E+06	-4.2575E+06	-1.4479E+05	3.5206E-00
6.1320E+01	-4.3345E+06	-4.3977E+06	-6.3258E+04	1.4594E-00
6.8130E+01	-4.4260E+06	-4.4742E+06	-4.8250E+04	1.0901E-00
8.1760E+01	-4.5450E+06	-4.4827E+06	6.2276E+04	-1.3702E-00
9.3390E+01	-4.4608E+06	-4.3627E+06	9.8097E+04	-2.1990E-00
1.1456E+02	-4.2917E+06	-4.0813E+06	2.1031E+05	-4.9004E-00
1.2264E+02	-4.1596E+06	-3.9442E+06	2.1537E+05	-5.1777E-00
1.3627E+02	-3.9358E+06	-3.7048E+06	2.3093E+05	-5.8675E-00
1.4989E+02	-3.7184E+06	-3.4663E+06	2.5208E+05	-6.7793E-00
1.6352E+02	-3.4779E+06	-3.2355E+06	2.4233E+05	-6.9677E-00
1.8015E+02	-2.9790E+06	-2.9702E+06	8.7957E+03	-2.9525E-01
1.9595E+02	-2.7200E+06	-2.7368E+06	-1.6879E+04	6.2058E-01
2.1181E+02	-2.4870E+06	-2.5215E+06	-3.4502E+04	1.3873E-00
2.4365E+02	-2.0750E+06	-2.1429E+06	-6.7990E+04	3.2766E-00
2.7569E+02	-1.8430E+06	-1.6261E+06	1.6831E+04	-9.1325E-01
3.0791E+02	-1.6230E+06	-1.5614E+06	6.1556E+04	-3.7927E-00
3.4030E+02	-1.3240E+06	-1.3399E+06	-1.5925E+04	1.2028E-00
3.7288E+02	-1.1560E+06	-1.1539E+06	2.0719E+03	-1.7923E-01
4.3853E+02	-8.2530E+05	-8.6520E+05	-3.9903E+04	4.8350E-00
5.0484E+02	-6.1360E+05	-6.5797E+05	-4.4379E+04	7.2327E-00
5.7178E+02	-4.7350E+05	-5.0732E+05	-3.3821E+04	7.1428E-00
6.3930E+02	-3.6660E+05	-3.9639E+05	-2.2796E+04	8.1277E-00
7.0739E+02	-2.9390E+05	-3.1364E+05	-1.9748E+04	6.7194E-00
1.0551E+03	-1.0670E+05	-1.1465E+05	-7.9534E+03	7.4540E-00
1.2327E+03	-7.1670E+04	-7.5414E+04	-3.7444E+03	5.2245E-00
1.4122E+03	-4.9840E+04	-5.1831E+04	-1.9919E+03	3.9966E-00

1.9420E+03	-2.1800E+04	-2.1036E+04	7.6382E+02	-3.5037E-00
2.1190E+03	-1.6900E+04	-1.6370E+04	5.2963E+02	-3.1339E-00
2.4730E+03	-1.0620E+04	-1.0473E+04	1.4648E+02	-1.3793E-00
3.1810E+03	-5.2320E+03	-5.0402E+03	1.9179E+02	-3.6658E-00
3.8890E+03	-2.9630E+03	-2.8115E+03	1.5143E+02	-5.1108E-00
5.1280E+03	-1.3060E+03	-1.2665E+03	3.9400E+01	-3.0168E-00
6.0130E+03	-8.4730E+02	-8.0527E+02	4.2027E+01	-4.9601E-00
7.0750E+03	-5.3110E+02	-5.1065E+02	2.0442E+01	-3.8490E-00
8.1430E+03	-3.6570E+02	-3.4716E+02	1.8538E+01	-5.0692E-00
9.0200E+03	-2.7720E+02	-2.6367E+02	1.3526E+01	-4.8797E-00
1.0065E+04	-2.0760E+02	-1.9759E+02	1.2003E+01	-5.7267E-00
1.1018E+04	-1.6240E+02	-1.5661E+02	5.7864E-00	-3.5630E-00
1.2006E+04	-1.2850E+02	-1.2626E+02	2.2324E-00	-1.7372E-00
1.3024E+04	-1.0370E+02	-1.0348E+02	2.1005E-01	-2.0255E-01
1.4040E+04	-8.5680E+01	-8.6548E+01	-8.6804E-01	1.0131E-00
1.5035E+04	-7.3370E+01	-7.3849E+01	-4.7911E-01	6.5301E-01
1.6040E+04	-6.1480E+01	-6.3815E+01	-2.3358E-00	3.7994E-00
1.7025E+04	-5.5250E+01	-5.5980E+01	-7.3029E-01	1.3218E-00
1.8030E+04	-4.7110E+01	-4.9509E+01	-2.3998E-00	5.0940E-00

NO. OF ITERATIONS= 3 VAR= .8609E+05 PDMEAN= 3.555 PDRMS= 4.184

TABLE NO. VIII

S12 VS H

2 BAND MODEL T=1.7 DEGREES KELVIN W(K)=1.

```

1
1      P(1)      DP(1)
1      -7.87830709175800E+08      -7.50577665786415E+02
2      6.32512573305035E+03      7.43049504504361E-03
3      7.87438149146853E+08      7.50151308884248E+02
4      2.12385330396684E+05      -2.88479553437541E-01
VAR= .1134E+06      NO. OF ITERATIONS= 4

```

X	Y	YBAR	DEL	PD
1.3630E+01	-1.8163E+06	-1.5987E+06	2.1753E+05	-1.1976E+01
1.7030E+01	-1.9408E+06	-1.9651E+06	-2.4333E+04	1.2537E-00
2.0440E+01	-2.2922E+06	-2.3125E+06	-2.0338E+04	8.8730E-01
2.3850E+01	-2.7253E+06	-2.6373E+06	8.7945E+04	-3.2269E-00
2.7250E+01	-2.9467E+06	-2.9368E+06	9.8397E+03	-3.3392E-01
3.0660E+01	-3.1443E+06	-3.2115E+06	-6.7282E+04	2.1398E-00
3.4070E+01	-3.5252E+06	-3.4599E+06	6.5233E+04	-1.8504E-00
4.0880E+01	-3.8941E+06	-3.8772E+06	1.6805E+04	-4.3156E-01
4.7690E+01	-3.4898E+06	-4.1941E+06	-7.0432E+05	2.0182E+01
5.4510E+01	-4.5246E+06	-4.4201E+06	1.0445E+05	-2.3085E-00
6.1320E+01	-4.5448E+06	-4.5667E+06	-2.1238E+04	4.8272E-01
6.8130E+01	-4.6114E+06	-4.6471E+06	-3.5702E+04	7.7423E-01
8.1760E+01	-4.6985E+06	-4.6572E+06	4.1275E+04	-8.7847E-01
9.5390E+01	-4.6247E+06	-4.5330E+06	9.1603E+04	-1.9807E-00
1.1456E+02	-4.4622E+06	-4.2404E+06	2.2171E+05	-4.9686E-00
1.2264E+02	-4.1813E+06	-4.0775E+06	8.3746E+04	-2.0028E-00
1.3627E+02	-3.9888E+06	-3.8478E+06	1.4092E+05	-3.5331E-00
1.4989E+02	-3.7178E+06	-3.5988E+06	1.1897E+05	-3.2000E-00
1.6352E+02	-3.5203E+06	-3.3578E+06	1.6249E+05	-4.6160E-00
1.9595E+02	-2.8620E+06	-2.8366E+06	2.5343E+04	-8.8552E-01
2.1181E+02	-2.6660E+06	-2.6115E+06	5.4436E+04	-2.0418E-00
2.4365E+02	-2.2420E+06	-2.2161E+06	2.5898E+04	-1.1551E-00
2.7569E+02	-1.9030E+06	-1.8853E+06	1.7636E+04	-9.2675E-01
3.0791E+02	-1.6080E+06	-1.6093E+06	-1.3428E+03	8.3508E-02
3.4030E+02	-1.3660E+06	-1.3787E+06	-1.2710E+04	9.3048E-01
3.7288E+02	-1.1010E+06	-1.1853E+06	-4.3800E+03	3.7087E-01
4.3853E+02	-8.8250E+05	-8.8604E+05	-3.5441E+03	4.0159E-01
5.0484E+02	-6.4740E+05	-6.7197E+05	-2.4574E+04	3.7958E-00
5.7178E+02	-4.9810E+05	-5.1686E+05	-1.8769E+04	3.7682E-00
6.3930E+02	-3.8070E+05	-4.0302E+05	-2.2326E+04	5.8646E-00
7.0739E+02	-3.0310E+05	-3.1833E+05	-1.5235E+04	5.0267E-00
8.7986E+02	-1.7760E+05	-1.8585E+05	-8.2592E+03	4.6504E-00
1.0551E+03	-1.0730E+05	-1.1572E+05	-8.4250E+03	7.8518E-00
1.2327E+03	-7.1370E+04	-7.6003E+04	-4.6335E+03	6.4922E-00
1.4122E+03	-5.0060E+04	-5.2180E+04	-2.1206E+03	4.2361E-00

1.5930E+03	-3.5590E+04	-3.7192E+04	-1.6025E+03	4.5026E-00
1.7747E+03	-2.6820E+04	-2.7361E+04	-5.4161E+02	2.0194E-00
1.9420E+03	-2.1690E+04	-2.1140E+04	5.4988E+02	-2.5352E-00
2.1190E+03	-1.6950E+04	-1.6445E+04	5.0445E+02	-2.9761E-00
2.4730E+03	-1.1330E+04	-1.0516E+04	8.1372E+02	-7.1820E-00
3.8890E+03	-2.9210E+03	-2.8202E+03	1.0078E+02	-3.4503E-00
5.1280E+03	-1.2830E+03	-1.2698E+03	1.3114E+01	-1.0221E-00
6.0130E+03	-8.2940E+02	-8.0712E+02	2.2274E+01	-2.6855E-00
7.0750E+03	-3.7490E+02	-3.1165E+02	6.3240E+01	-1.1000E+01
8.1430E+03	-3.8250E+02	-3.4772E+02	3.4775E+01	-9.0916E-00
9.0200E+03	-2.7490E+02	-2.6402E+02	1.0873E+01	-3.9556E-00
1.0065E+04	-2.0670E+02	-1.9779E+02	8.9065E-00	-4.3089E-00
1.1018E+04	-1.6510E+02	-1.5672E+02	8.3794E-00	-5.0753E-00
1.2006E+04	-1.3190E+02	-1.2631E+02	5.5869E-00	-4.2357E-00
1.3024E+04	-1.0500E+02	-1.0349E+02	1.5068E-00	-1.4351E-00
1.4040E+04	-8.4050E+01	-8.6422E+01	-1.5728E-00	1.8514E-00
1.5035E+04	-7.1920E+01	-7.3804E+01	-1.8948E-00	2.6207E-00
1.6040E+04	-6.1280E+01	-6.3758E+01	-2.4783E-00	4.0443E-00
1.7025E+04	-5.4060E+01	-5.5013E+01	-0.5387E-01	1.7355E-00
1.8030E+04	-4.6740E+01	-4.9437E+01	-2.5972E-00	5.7706E-00

NO. OF ITERATIONS= 4 VAR= .1134E+06 PDMEAN= 3.581 PDRMS= 4.960

TABLE IX
The Coefficients A, B, C, D for Electrons and Holes

	A	B	C	D
Electrons	101.0	180	8.4	124
Holes	9.0	212.0	22	12.7

A, B, C. and D are in units of 10^{-14} (gauss⁻¹).

TABLE X
 m^* , ξ_0 for Electrons and Holes from Temperature
 Dependents Amplitudes in ρ_{11}

θ	Electrons		Holes	
	m^*	$\xi_0 \times 10^{14}$ ergs	m^*	$\xi_0 \times 10^{14}$ ergs
110.3	0.082	19.7	.10	13.0
0	.09	20.3	---	---

m^* is in units of m_0 , where m_0 is free electron mass.

TABLE XI
The Components of Inverse Mass Tensor, α 's for
Electrons and Holes

Carriers	α_{11}	α_{22}	α_{33}	α_{23}
Electrons	19.1	[6.3]	11.3	7.8
Holes	6.0	0.7	17.3	1.0

TABLE XII
Comparison of α 's, ξ_0 , n for
Electrons with Others

Reference	α_{11}	α_{22}	α_{33}	α_{23}	$\xi_0 \times 10^{14}$ ergs	$n \times 10^{-19}$ per cm^3
Present Work	19.1	6.3	11.3	7.8	20.32	4.15
Eckstein ⁴	16.7	5.98	11.61	7.54	18.6	--
Datar ²	20.0*	6.05*	11.9*	7.79*	--	--
Shoenberg ¹	20.0	10.0	5.2	6.5	18.0	3.7
Juretschke ⁶	--	--	--	--	20.8	4.3

TABLE XIII

Cyclotron Masses for Electrons

	m^* in units of m_0 along			Components of mass tensor in units of m_0			
	Trigonal	Binary	Bisectrix	m_1	m_2	m_3	m_4
Present Work	.0903	.31	.069	.052	1.09	.64	.75
Eckstein ⁴	.1	--	--	.6*	.92*	.48*	.6*
Datars ²	.088 $\pm .005$	.31	.068	.05	1.03	.53	.67
Shoenberg ¹	.071*	--	--	.05	1.0	.52	.65
Smith [‡]	--	--	.088	--	--	--	--

‡G. E. Smith, J. K. Galt and F. R. Merritt, Phys. Rev. Letters, 4 (6), 276, 1960.

*Computed from the author's data.

TABLE XIV

Comparison of α 's, ξ_0 , n for
Holes with Others

	α_{11}	α_{22}	α_{33}	α_{23}	$\xi_0 \times 10^{14}$ ergs	$n \times 10^{-19}$ per cm^3
Present Work	6.0	0.7	17.3	1.0	13.0	3.80
Datars ³	--	--	--	--	--	--
Juretschke ⁷	--	--	--	--	9.6	4.3
Freedman ⁶	--	--	--	--	--	3.7

TABLE XV

Cyclotron Masses for Holes

	m* in units of m_0 along			Components of mass tensor in units of m_0			
	Trigonal	Binary	Bisectrix	m_1	m_2	m_3	m_4
Present Work	.48	.11 .303	.098	.154	1.47	.06	.006
Datars ³ and	.32 $\pm .02$.11 $\pm .005$	--	--	--	--	--	--
Juretschke ⁷	.34	--	--	--	--	--	--
Freedman ⁶	--	--	--	--	--	--	--

TABLE XVI

 n_1 , n_2 , $a_1 n_1$, $a_2 n_2$, H_1 and H_2

Computed from Tables I-VIII

$T^{\circ}\text{K}$	$n_1 \times 10^{-19}/\text{cm}^3$	H_1 gauss	$n_2 \times 10^{-19}/\text{cm}^3$	H_2 gauss	$a_1 n_1 \times 10^{-19}/\text{cm}^3$	a_1	H_1 gauss	$a_2 n_2 \times 10^{-19}/\text{cm}^3$	a_2	H_2 gauss
4.2	4.7143	86.38	4.649	492.32	10.718	(2.27)	114.733	10.591	(2.28)	540.252
3.5	4.952	86.825	4.95	456.85	11.46	(2.31)	115.203	10.43	(2.11)	530.927
2.1	4.7055	79.225	4.703	473.205	12.1558	(2.58)	110.48	10.532	(2.24)	512.188
1.7	4.9338	79.618	4.9313	459.443	11.272	(2.28)	101.122	12.438	(2.52)	452.508

TABLE XVII

Amplitudes of $\tilde{\sigma}_{11}$ and $\tilde{\sigma}_{12}$

H_{KG}	$\tilde{\sigma}_{11} \text{ L-K}$	$\tilde{\sigma}_{11} \text{ Zil}$	$\tilde{\sigma}_{11} \text{ exp}$	$\tilde{\sigma}_{11} \text{ Sus}$	$\sigma_{12} \text{ exp}$	$\sigma_{12} \text{ L-K}$
17.766	6.4×10^{-1}	56	16.57	--	1.1	9.1×10^{-3}
16.949	6.45×10^{-1}	44.5	17.19	--	--	9.5×10^{-3}
15.885	6.4×10^{-1}	36.5	26.08	--	--	10.1×10^{-3}
14.776	6.32×10^{-1}	29.0	36.76	--	--	10.9×10^{-3}
13.620	6.18×10^{-1}	22.1	24.25	--	--	11.86×10^{-3}
14.286	--	--	--	7.7×10^{-2}	--	--

Units of σ are (mho cm^{-1})

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VITA

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EXAMINATION AND THESIS REPORT

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Major Field: Physics

Title of Thesis: Galvanomagnetic Effects in Antimony at Liquid Helium Temperatures

Approved:

Charles J. Grier
Major Professor and Chairman

Max Goodrich
Dean of the Graduate School

EXAMINING COMMITTEE:

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Date of Examination:

May 17, 1963