

crystal as well as field orientation must be taken into account.

We have also considered the possibility of observing magnetoresistance oscillations in silicon, where  $\omega\tau$  is smaller by a factor  $\sim 3$  than that in germanium owing to the larger cyclotron masses. Preliminary magnetoresistance measurements performed on heavily doped

silicon samples in magnetic fields up to 110 kOe exhibited, as expected, no oscillatory behavior.

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## Electron Cyclotron Resonance in CdS\*†

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Electron cyclotron resonance has been observed in single-crystal CdS platelets at temperatures below 4.2°K. The single resonance seen in all orientations is consistent with a single-ellipsoid conduction-band model for CdS. The cyclotron effective masses measured with the crystal  $c$  axis parallel and perpendicular to the magnetic field are  $m_{c1B}^*/m_0=0.171$  and  $m_{c1B}^*/m_0=0.162$ , implying that the constant-energy surfaces near the conduction-band minimum are oblate spheroids having transverse and longitudinal effective masses  $m_t^*/m_0=0.171$  and  $m_l^*/m_0=0.153$ . The effective mass values determined from cyclotron resonance are 15% lower than those measured in other experiments. The difference cannot be due to depolarization or optical polaron effects, but can be accounted for in terms of an electron self-energy correction resulting from the piezoelectric electron-phonon interaction in CdS. Electron collision times of order  $10^{-11}$  sec were calculated from the 70-Gc/sec cyclotron resonance data taken between 1.25 and 4.2°K. The magnitude and temperature dependence of the collision times are best described by the theoretical predictions for piezoelectric scattering along with possibly a small neutral-impurity scattering contribution.

### INTRODUCTION

OPTICAL<sup>1-3</sup> and galvanomagnetic<sup>4,5</sup> experiments have indicated that the conduction band of cadmium sulfide is characterized by a single, nearly spherical, constant-energy surface with an electronic effective mass about one-fifth of the free electron mass. Preliminary cyclotron resonance experiments reported by Dexter<sup>6</sup> proved to be nonreproducible, and the tentative effective mass values quoted then are erroneous. This article describes the observation of reproducible electron cyclotron resonance at 72 Gc/sec and liquid-helium temperatures in several CdS platelets

obtained from two separate sources. Recently, Sawamoto<sup>7</sup> has reported cyclotron resonance of both electrons and holes in CdS in one orientation. The present study was undertaken to measure directly the effective mass tensor of electrons in CdS and to gain information on the scattering mechanisms important at low temperatures through a determination of the electronic collision times from the widths of the cyclotron resonance peaks.

### EXPERIMENTAL

Successful cyclotron resonance experiments were carried out using CdS single-crystal platelets grown from the vapor phase under the direction of D. C. Reynolds at the Wright-Patterson Aeronautical Research Center and high resistivity platelets supplied by J. E. Powderly of the Eagle-Picher Company. The Wright-Patterson platelets were of dimensions  $1 \times 1 \times 0.02$  mm, while  $1 \times 1 \times 0.2$ -mm samples were cleaved from somewhat larger Eagle-Picher platelets. No etching or other surface treatment was employed. Resonances were not seen in Eagle-Picher "high purity" or

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‡ National Science Foundation Predoctoral Fellow.

<sup>1</sup> J. J. Hopfield and D. G. Thomas, *Phys. Rev.* **122**, 35 (1961).

<sup>2</sup> W. W. Piper and D. T. F. Marple, *J. Appl. Phys.* **32**, 2237 (1961).

<sup>3</sup> M. Balkanski and J. J. Hopfield, *Phys. Stat. Solidi* **2**, 623 (1962).

<sup>4</sup> W. W. Piper and R. E. Halsted, in *Proceedings of the International Conference on Semiconductor Physics, Prague, 1960* (Academic Press Inc., New York, 1961), p. 1046.

<sup>5</sup> J. D. Zook and R. N. Dexter, *Phys. Rev.* **129**, 1980 (1963).

<sup>6</sup> R. N. Dexter, *Phys. Chem. Solids* **8**, 494 (1959).

<sup>7</sup> K. Sawamoto, *J. Phys. Soc. Japan* **18**, 1224 (1963); also (private communications).

"ultrahigh purity" samples, although Sawamoto's results<sup>7</sup> were reported for these commercial crystals. The procedure to select samples which would satisfy the resonance condition  $\omega\tau > 1$  at 70 Gc/sec was essentially one of trial and error. A number of specimens could be surveyed during a preliminary experiment at 24 Gc/sec, and a value of  $\omega\tau$  for each could be estimated from the nonresonant microwave absorption versus magnetic field traces. Those samples with the highest values of  $\omega\tau$  were retained for the higher frequency experiments.

A standard cyclotron resonance bridge spectrometer operating between 68 and 72 Gc/sec was used for the high-frequency work. A selected sample was cemented in a horizontal plane at the end of a tapered, quartz light pipe inside a cylindrical TE<sub>113</sub> resonant cavity. The light pipe could be maneuvered up and down in order to place the specimen in a region of high electric field. The cavity and sample were immersed in liquid helium and cooled to 1.25°K by pumping on the bath. A 12-in. Varian magnet produced fields up to 24 000 G in a 1-in. gap.

The hexagonal *c* axis lay in the plane of the sample and was readily determined before mounting by rotating the sample between crossed polaroids. In order to measure the effective mass tensor, the angle between the crystal *c* axis and the magnetic field could be varied in two independent ways. The light pipe and sample could be rotated about a vertical axis within the stationary cavity, or the light pipe, sample, cavity, and entire microwave assembly could be rotated with respect to the fixed Dewars and magnetic field direction. For either method a dial calibrated in degrees allowed measurement of the rotation angle.

Free electrons and holes were excited in the CdS sample by mechanically chopped, 95-cps visible and/or infrared light transmitted through the quartz light pipe. The optical system consisted of a 1000-W tungsten projection lamp, a telescope and mirror to focus light on the upper end of the light pipe, and various combinations of filters placed above the light pipe to

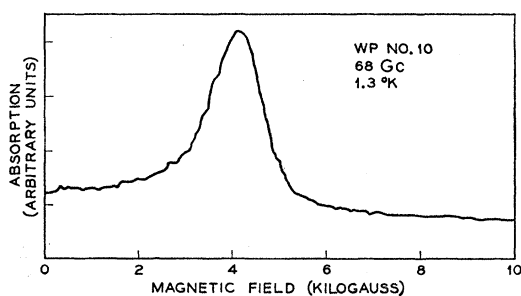


FIG. 1. Cyclotron resonance in CdS at 68 Gc/sec. The single resonance at 4100 G corresponds to an effective mass  $m_c^*/m_0 = 0.165$ , with the crystal *c* axis perpendicular to the magnetic field. Although  $\omega\tau \approx 5$ , the peak is not symmetric about the resonant field.

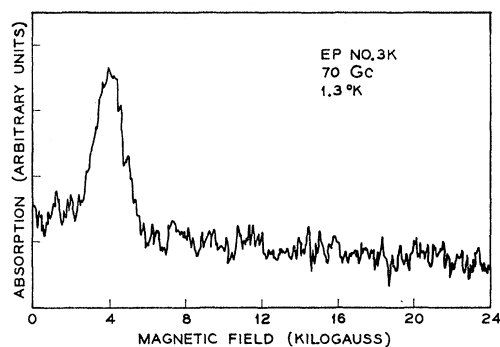


FIG. 2. Cyclotron resonance in CdS at 70 Gc/sec in magnetic fields up to 24 000 G. The electron peak near 4000 G is the only structure seen for this high-mobility platelet. No resonant absorption attributable to free holes was seen in any sample at 70 Gc/sec.

limit the spectrum incident on the sample. The best data were taken with about one-half inch of heat-absorbing glass over the light pipe, which minimized sample heating and infrared quenching of visible light photoconductivity. A conventional chopped light detection system used a phase-sensitive detector to compare the microwave crystal detector signal reflected from the cavity with a 95-cps reference signal. The dc output of the phase-sensitive detector, proportional to the microwave power absorbed by the sample, was fed to one axis of an X-Y recorder. A current sample from the Varian magnet drove the other axis of the recorder. The magnetic field was calibrated with a Rawson rotating-coil Gaussmeter and checked at several points by nuclear magnetic resonance, so that the field values measured on the recorder are estimated to be correct within  $\frac{1}{2}\%$ .

## RESULTS AND DISCUSSION

### Cyclotron Resonance

A large number of CdS specimens were investigated at microwave frequencies of 9, 24, and 70 Gc/sec. Four Wright-Patterson platelets and four samples cleaved from the Eagle-Picher platelets displayed cyclotron resonance with  $\omega\tau > 1$  at 70 Gc/sec. For the best samples  $\omega\tau$  was about 6, giving a well-defined resonance as shown in Fig. 1. Figure 2 illustrates cyclotron resonance for another sample in magnetic fields up to 24 000 G. The single resonance observed in all orientations is consistent with the existence of a single conduction band minimum for CdS at  $\mathbf{k}=0$ . These experiments with linearly polarized microwaves did not determine the sign of the resonant carriers directly, but previous experiments<sup>1-5</sup> identify them as electrons. No resonances due to holes were seen, although our highest magnetic fields of 24 000 G could resolve a resonance for a hole effective mass equal to the free-electron mass and would suggest effects for a larger mass by an upturn of the absorption curve at

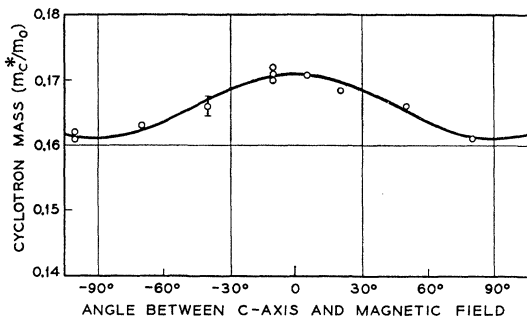


FIG. 3. Electron cyclotron mass anisotropy in one CdS sample. The experimental points are in good agreement with the solid line calculated for a single, spherical energy surface.

high fields. In one sample high-field absorption probably due to free holes was seen at 24 Gc/sec, but we cannot confirm quantitatively Sawamoto's observation of a carrier with an effective mass  $m^*=0.80 m_0$ . Evidently, the free holes excited in these experiments are trapped too quickly or have too low mobilities to be observable.

The variation of the cyclotron effective mass with the angle between the  $c$  axis and the magnetic field is shown in Fig. 3. Good agreement is obtained between the experimental points and the theoretical curve drawn for a spheroidal energy surface. The longitudinal and transverse principal masses of the energy spheroid are computed from the cyclotron masses:

$$m_{t}^* = (m_{c\perp B}^*)^2 / m_{c\parallel B}^* \quad m_{t}^* = m_{c\parallel B}^*, \quad (1)$$

where  $m_{c\perp B}^*$  and  $m_{c\parallel B}^*$  refer to the cyclotron masses measured with the crystal  $c$  axis perpendicular and parallel, respectively, to the magnetic field. The effective mass values for the three samples with highest  $\omega\tau$  are presented in Table I. The small but measurable effective mass anisotropy, with  $m_{t}^* > m_{l}^*$ , implies that the constant energy surfaces near the conduction-band minimum are oblate spheroids. This is in agreement with previous measurements.<sup>1,2</sup>

The electron effective mass values of Table I, however, are significantly lower than those deduced from other experiments. Table II lists the published effective masses for electrons in CdS. None of the first six experiments listed in Table II measures the effec-

TABLE I. Electron effective mass values in CdS from cyclotron resonance.

Sample	Cyclotron masses		Principal masses		Anisotropy
	$m_{c\parallel}^*/m_0$ $B\parallel c\text{-axis}$	$m_{c\perp}^*/m_0$ $B\perp c\text{-axis}$	$m_{l}^*/m_0$	$m_{t}^*/m_0$	
WP#10	0.175	0.166	0.175	0.158	1.11
EP#3D1	0.170	0.161	0.170	0.153	1.11
EP#3K	0.171	0.161	0.171	0.152	1.12
Average values	0.171	0.162	0.171	0.153	1.12
	$\pm 0.003$	$\pm 0.003$	$\pm 0.003$	$\pm 0.003$	$\pm 0.03$

tive mass as precisely as does cyclotron resonance, and the measured combination of mass tensor components may differ slightly for different types of experiments, but the difference between cyclotron resonance mass values and those measured by other methods is beyond experimental error. Sawamoto's cyclotron resonance results<sup>7</sup> for electrons are in agreement with the present work and serve to accentuate the discrepancy.

The most obvious explanation for the difference in mass values would be that the effective masses measured in these cyclotron resonance experiments are shifted from their true values by plasma or depolarization effects.<sup>8,9</sup> The plasma frequency  $\omega_p$  in a semiconductor with carrier concentration  $N$  is defined by

$$\omega_p^2 = [L/(1+\chi L)](Ne^2/m^*), \quad (2)$$

where  $e$  is the electronic charge,  $\chi$  is the electric susceptibility, and  $L$  is a geometric depolarization factor. When the plasma frequency becomes comparable to the working frequency  $\omega$ , a shift in effective mass is expected in cyclotron resonance measurements:

$$\Delta m_c^*/m_c^* = \omega_p^2/\omega^2. \quad (3)$$

In the present experiments a carrier concentration of  $10^{13}/\text{cm}^3$  would have lowered the measured mass by 10%. If plasma effects were present, however, a large change in effective mass should have been observed as the carrier concentration was varied by a variation of the light intensity. No such shift was seen, although the light intensity was increased by a factor of two over the minimum required to bring out the resonance. As a further check, dc Hall measurements were made on a sample from the best Eagle-Picher platelet. The difficulty of obtaining contacts which would remain Ohmic at low temperatures made these measurements no better than order-of-magnitude estimates, but the results indicated a carrier concentration of  $2 \times 10^{11}/\text{cm}^3$  at 1.3°K under illumination conditions comparable to those in the resonance experiments. This carrier concentration is sufficiently small that any plasma shift is well under  $\frac{1}{2}\%$ .

An optical mode polaron effect on the electron effective mass is to be expected in CdS.<sup>1,3</sup> For the case of weak coupling between free carriers and longitudinal optical phonons, the polaron mass  $m_p^*$  is predicted<sup>10</sup> to be larger than the bare effective mass  $m^*$  by a factor  $(1+\alpha/6)$ , where the coupling constant  $\alpha$  is given by

$$\alpha = \frac{e^2}{\hbar} \left( \frac{m^*}{2\hbar\omega_l} \right)^{\frac{1}{2}} \left( \frac{1}{\epsilon_0} - \frac{1}{\epsilon_s} \right). \quad (4)$$

Here  $\omega_l$  is the longitudinal optical phonon frequency and  $\epsilon_0$  and  $\epsilon_s$  are the optical and static dielectric con-

<sup>8</sup> G. Dresselhaus, A. F. Kip, and C. Kittel, Phys. Rev. **100**, 618 (1955).

<sup>9</sup> R. E. Michel and B. Rosenblum, Phys. Rev. **128**, 1646 (1962).

<sup>10</sup> H. Frohlich, Advan. Phys. **3**, 325 (1954).

TABLE II. Electron effective mass values in CdS from several experiments.

Experiment	Carrier conc./cm <sup>3</sup>	Temp. (°K)	Polaron mass?	Electron effective mass		Reference
				Measured mass $m^*/m_0$	Mass corrected to polaron mass $m_p^*/m_0$	
Impurity activation energy	$1 \times 10^{15}$	77	yes	0.19	0.19	4
Hall mobility versus temp.	$5 \times 10^{15}$	77-300	yes	0.20	0.20	4
Free carrier absorption	$3-14 \times 10^{17}$	300	no	$0.22 \pm 0.02^{a,b}$	$0.24 \pm 0.02^{a,b}$	2
Exciton Zeeman splitting	$< 10^{15}$	1.6	yes	$0.204 \pm 0.010$	$0.204 \pm 0.010$	1
Faraday rotation	$5 \times 10^{18}$	300	no	$0.20 \pm 0.01^b$	$0.22 \pm 0.01^b$	3
Mobility versus temperature	$1.8 \times 10^{15}$	77-300	yes	$0.19 \pm 0.01$	$0.19 \pm 0.01$	5
Cyclotron resonance	$\sim 10^7$	1.7	yes	0.17	0.17	7
Cyclotron resonance	$2 \times 10^{11}$	1.3	yes	$0.165 \pm 0.003$	$0.165 \pm 0.003$	this work

<sup>a</sup> It should be noted that the masses reported by Piper and Marple<sup>2</sup> include two lower values, 0.14  $m_0$  and 0.15  $m_0$ , measured in samples with lower carrier concentrations and not averaged into the final result of 0.22  $m_0$ .

<sup>b</sup> The referee has pointed out that the masses measured by free-carrier absorption and Faraday rotation suffer from a relatively unsophisticated treatment of the Hall effect data used to determine carrier concentrations.

stants. Since in CdS  $\alpha \approx 0.6$ , experiments at frequencies  $\omega \ll \omega_l$  will presumably measure a mass 10% larger than experiments for which  $\omega \gg \omega_l$ . The longitudinal optical phonon frequency<sup>11</sup> in CdS is two orders of magnitude greater than 70 Gc/sec, so that the present cyclotron resonance experiments should measure the polaron mass and not the bare band mass.

The only experiments listed in Table II which do not measure a polaron mass are Faraday rotation and free-carrier absorption. In the next-to-last column of Table II, the mass values determined from these two experiments have been increased by 10% to enable direct comparison with the other polaron masses. The agreement among the mass values is not improved by the addition of a polaron mass shift, and the data of Table II provide no experimental evidence that such an effect actually occurs in CdS. If optical polaron effects are included, the difference between cyclotron resonance effective masses and those measured in other experiments becomes more pronounced.

Recently, Mahan and Hopfield<sup>12</sup> have proposed an electron-energy correction of piezoelectric origin to account for this observed mass difference. The piezoelectric electron-phonon interaction<sup>13-15</sup> has previously been shown to be important in CdS, giving rise to such phenomena as amplification of acoustic waves<sup>16</sup> and current saturation at high electric fields.<sup>17</sup> Using second-order perturbation theory, Mahan and Hopfield calculate an electron energy

$$E(k) = \frac{\hbar^2 k^2}{2m^*} - \frac{\pi (K^2)_{av} \hbar^2 k_0 T}{2 a_0 k}, \quad (5)$$

<sup>11</sup> R. J. Collins, J. Appl. Phys. **30**, 1135 (1959).

<sup>12</sup> G. D. Mahan and J. J. Hopfield, Phys. Rev. Letters **12**, 241 (1964).

<sup>13</sup> H. J. G. Meyer and D. Polder, Physica **19**, 255 (1953).

<sup>14</sup> W. A. Harrison, Phys. Rev. **101**, 903 (1956).

<sup>15</sup> A. R. Hutson, Phys. Rev. Letters **4**, 505 (1960); J. Appl. Phys. **32**, 2287 (1961).

<sup>16</sup> A. R. Hutson, D. L. White, and J. H. McFee, Phys. Rev. Letters **7**, 237 (1961); D. L. White, J. Appl. Phys. **33**, 2347 (1962).

<sup>17</sup> R. W. Smith, Phys. Rev. Letters **9**, 87 (1962).

where  $k$  is the wave number of the electron,  $k_0$  is the Boltzmann constant,  $T$  is the absolute temperature,  $a_0$  is the Bohr radius  $\hbar^2 \epsilon_s / m^* e^2$ , and  $(K^2)_{av}$  is the spherical average of the square of the electromechanical coupling. The correction term is valid for carriers whose velocities exceed the velocity of sound and should apply to nearly all electrons in CdS at 1.3°K. The calculation also assumes an isotropic dielectric constant and an isotropic average of the square of the electromechanical coupling  $K^2 = (e_{ijh}^2 / \epsilon_s c_{ij})$ , where  $e_{ijh}$  and  $c_{ij}$  are the piezoelectric and elastic tensors, respectively.

An effective mass shift is easily computed from the first derivative of Eq. (5) with respect to  $k$ . One finds that the cyclotron mass is given by

$$m_c^* = m^* / \left( 1 + \frac{\pi (K^2)_{av} m^* k_0 T}{2 a_0 \hbar^2 k^3} \right). \quad (6)$$

As Mahan and Hopfield<sup>12</sup> point out, carriers of different wave numbers will resonate at different fields, resulting in a spread of mass values in addition to the natural width of the cyclotron resonance line. Using an effective mass  $m^* = 0.20 m_0$  and Hutson's value<sup>15</sup> for the square of the electromechanical coupling, this theory predicts that the electron cyclotron mass in CdS at 1.3°K will be between 0.15 and 0.18 times the free-electron mass. This compares with the average value for the cyclotron mass measured in the present work  $\langle m_c^* \rangle_{av} = (m_i^* m_i^*)^{1/3} = 0.165 m_0$ .

The agreement with the predictions of Hopfield and Mahan is encouraging, but there remain difficulties in accepting literally the theory in its present form. Mahan and Hopfield have calculated the cyclotron effective mass for an isotropic medium. The piezoelectric constants<sup>18</sup> and elastic constants<sup>15,18</sup> in CdS are highly anisotropic, and a calculation taking into account these angular dependences might well predict an effective mass anisotropy different from that ob-

<sup>18</sup> D. Berlincourt, H. Jaffe, and L. R. Shiozawa, Phys. Rev. **129**, 1009 (1963).

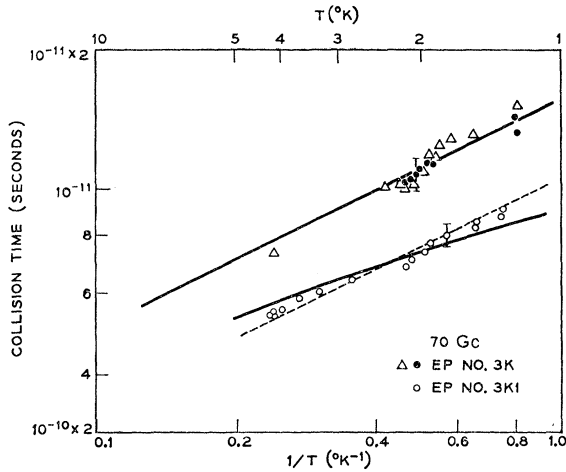


FIG. 4. Electron collision times at 70-Gc/sec plotted against inverse temperature for two CdS samples. Collision times were calculated from the linewidths of the cyclotron resonance peaks. The solid line through the topmost set of points represents a least-squares fit to a  $T^{-3/2}$  temperature dependence. The solid line through the lower points was calculated by the method of least squares assuming the same  $T^{-3/2}$  component as for the upper curve plus a temperature-independent scattering component. The dotted line through these points was obtained from a fit to a  $T^{-3/2}$  dependence alone.

served in the present experiments. Further, the 70-Gc/sec frequencies used in these experiments imply that the Landau level spacing at resonance is greater than thermal energies, so that the semiclassical approach of Mahan and Hopfield may not be fully justified for this case. A theory truly applicable to electron cyclotron resonance at high frequencies would require the explicit calculation of the positions of the first few Landau levels in the conduction band, but this would be a vastly more formidable task. It seems highly probable that piezoelectric polaron effects are responsible for the low effective mass observed in cyclotron resonance experiments and that the theory of Mahan and Hopfield provides a good estimate of the mass shift.

An asymmetric lineshape, broadened towards low magnetic fields, was observed in these experiments, as evidenced in Figs. 1 and 2. Usual cyclotron resonance lineshapes<sup>19</sup> with  $\omega\tau \approx 5$  are symmetric about the resonant field within a few percent. All resonant samples displayed this asymmetry to a greater or lesser extent, with the Wright-Patterson platelets generally more asymmetric than the Eagle-Picher platelets. An asymmetric lineshape can arise from an energy-dependent collision time<sup>20</sup> such as would be expected for piezoelectric scattering. Mahan and Hopfield<sup>12</sup> calculate a lineshape which agrees qualitatively with the present results. An alternative explanation, however, would be that impurity inhomogeneities within each platelet re-

sulted in regions of high and low electron mobility. High-mobility electrons satisfied the criterion  $\omega\tau > 1$  and gave the usual, Lorentzian cyclotron resonance lineshape; low-mobility electrons had  $\omega\tau \approx 1$ , with the characteristic absorption curve<sup>19</sup> for nonresonant or barely resonant carriers. The addition of absorption curves for two such types of electrons would give a quantitative fit to Figs. 1 and 2.

### Electron Collision Times and Scattering Mechanisms

For samples with  $\omega\tau > 1$  at 70 Gc/sec, a collision time was calculated from the cyclotron resonance linewidth  $\Delta B$ .

$$\omega\langle\tau\rangle = 2B_0/\Delta B, \quad (7)$$

where  $\langle\tau\rangle$  represents the collision time averaged over the electron distribution.<sup>21</sup> The temperature dependence of the collision time was determined from successive cyclotron resonance traces taken as the specimen warmed from the lowest temperature (between 1.25 and 1.3°K) up to 4.2°K. Collision times versus inverse temperature are shown in Fig. 4 for two of the best samples.

Both the magnitude and the temperature dependence of the collision time can, in principle, be used to identify the scattering mechanisms present. Some care must be taken in comparing collision times determined from cyclotron resonance linewidths with those calculated for drift mobilities, since the drift mobility is proportional to an average  $\langle v^2\tau\rangle/\langle v^2\rangle$  rather than the average  $\langle\tau\rangle$ .<sup>21</sup> The numerical factor relating the two averages depends on the scattering mechanism(s) involved but is near unity for most cases. The collision time magnitudes measured in the present experiments are further complicated by the possibility of additional line broadening due to the piezoelectric self-energy corrections discussed above. Ignoring any numerical correction factor, the data of Fig. 4 correspond to electron mobilities of  $1.35 \times 10^5$  cm<sup>2</sup>/V-sec at 1.25°K for sample EP No. 3K and  $0.97 \times 10^6$  cm<sup>2</sup>/V-sec at 1.3°K for sample EP No. 3K1.

An advantage of working at temperatures below 4.2°K is that polar optical mode scattering, the dominant scattering mechanism in CdS at room temperature,<sup>4,5</sup> can be ignored. The collision time due to optical mode scattering is proportional to  $\exp(-\hbar\omega_l/k_0T)$ , with  $\hbar\omega_l/k_0$  corresponding to 440°K, so that at liquid-helium temperatures it is many orders of magnitude below the present range of interest. Deformation potential scattering<sup>22</sup> presumably can be neglected at these temperatures also. Piezoelectric scattering<sup>13-15</sup> remains as a possible lattice scattering mechanism important at low temperatures. Hutson's equation<sup>15</sup> for the piezo-

<sup>19</sup> G. Dresselhaus, A. F. Kip, and C. Kittel, *Phys. Rev.* **98**, 368 (1955).

<sup>20</sup> N. K. Hindley, *Bull. Am. Phys. Soc.* **9**, 249 (1964).

<sup>21</sup> D. M. S. Bagguley, R. A. Stradling, and J. S. S. Whiting, *Proc. Roy. Soc. (London)* **A262**, 340 (1961).

<sup>22</sup> J. Bardeen and W. Shockley, *Phys. Rev.* **80**, 72 (1950).

electric collision time in CdS, using his average for the square of the electromechanical coupling and the value  $m^*/m_0=0.165$ , is

$$\langle\tau_p\rangle=0.7\times 10^{-11}T^{-1/2}\text{ sec.} \quad (8)$$

The observation of a collision time of  $1.3\times 10^{-11}$  sec at  $1.25^\circ\text{K}$  would seem to require some revision in this equation, since the calculated collision time limited by lattice scattering represents an upper bound for any experimental measurement. A calculation including the angular dependences of the dielectric constant, elastic constants, and piezoelectric constants in CdS, however, might well increase the theoretical piezoelectric collision time as much as a factor of two.<sup>23</sup> The collision times we observe are thus consistent in magnitude with those calculated for piezoelectric scattering but are too large for other lattice scattering mechanisms to be important at these temperatures.

Impurity scattering might still be expected to dominate any lattice scattering below  $4.2^\circ\text{K}$ . The presence of a large piezoelectric scattering component in these samples is supported by the temperature dependence of the collision times plotted in Fig. 4. The experimental points for the sample with highest collision time are well represented by the  $T^{-1/2}$  temperature dependence predicted for piezoelectric scattering. Neutral-impurity scattering would give a temperature independent collision time,<sup>24</sup> while a collision time limited by ionized-impurity scattering would have a  $T^{3/2}$  temperature dependence.<sup>25</sup> The fit to the upper set of points is not improved by the addition of any neutral or ionized impurity scattering component. Assuming piezoelectric scattering alone, a least-squares fit to these points gives the solid line,

$$\langle\tau_p\rangle=1.36\times 10^{-11}T^{-1/2}\text{ sec.} \quad (9)$$

Data taken at 70 Gc/sec for a lower mobility sample can be represented by a collision time calculated in the usual way for a combination of piezoelectric and neutral impurity scattering. The lower solid line in Fig. 4 is drawn for  $1/\langle\tau\rangle=1/\langle\tau_p\rangle+1/\langle\tau_n\rangle$  with  $\langle\tau_p\rangle=1.36\times 10^{-11}T^{-1/2}$  and  $\langle\tau_n\rangle=1.9\times 10^{-11}$ . The neutral

impurity component corresponds to  $1.4\times 10^{15}$  scattering centers per  $\text{cm}^3$ , a reasonable value for these CdS platelets.

Although the lower points lie within experimental error along the line determined for piezoelectric and neutral impurity scattering, an equally convincing fit is obtained assuming a  $T^{-1/2}$  temperature dependence alone. The dotted line in Fig. 4 describes a collision time  $\langle\tau_p\rangle=0.91\times 10^{-11}T^{-1/2}$ . This situation in which both collision times vary as  $T^{-1/2}$  would be difficult to understand on the basis of piezoelectric scattering which represents an intrinsic upper limit to the electron collision time. One would prefer to invoke some sort of impurity or imperfection scattering which could differ from sample to sample and yet retain the same temperature dependence. Most impurity or imperfection scattering mechanisms, however, lead to a collision time which increases with increasing temperature, in qualitative disagreement with the present results. Only if the impurity scattering cross section were energy-independent (as it might be at extremely low temperatures) would a  $T^{-1/2}$  dependence of the collision time be expected.

If the  $T^{-1/2}$  dependence is correct for both specimens, it is possible that screening effects resulting from different carrier concentrations may lead to differences in magnitude of the piezoelectric collision time. Recent experiments on low-temperature transport phenomena in CdS<sup>15,23</sup> suggest that piezoelectric scattering may depend on carrier concentration as well as on temperature. Such an explanation would obviate the need to include a neutral impurity scattering component in the interpretation of these data.

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