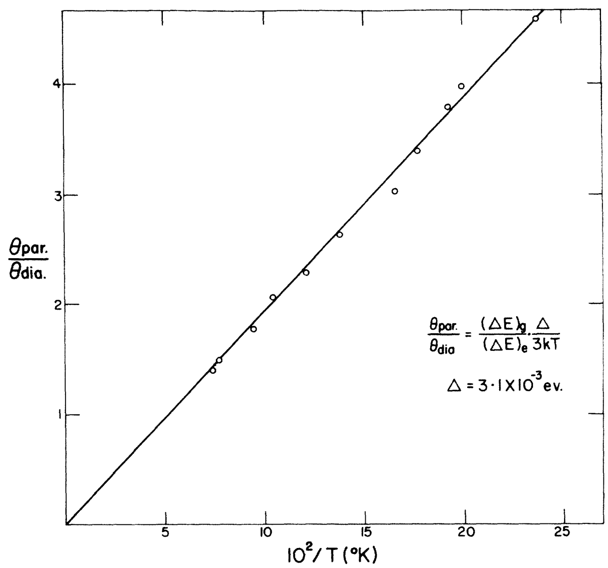

FIG. 3. $\theta_{par}/\theta_{dia}$ versus $1/T$. The points were obtained from an analysis of the data given in Fig. 1.

diamagnetic rotation value, as a function of $1/T$. The fact that the experimental points lie close to a straight line passing through the origin supports the validity of the assumptions made. It appears, therefore, that the simple atomic model explains the experimental results surprisingly well even though some modification of the transition probabilities may occur due to the effect of lattice interactions. The slope of the line in Fig. 3 gives a value of $\Delta = 3.1\times10^{-3}$ eV. Moreover, Δ is found to be negative, i.e., the $P_{1/2}$ level lies above the $P_{3/2}$ level. If this were not the case then θ_{par} would be in the opposite sense to θ_{dia}, in direct contradiction to experimental observation.

The measurements are being extended to other alkali halides in an effort to learn how the spin-orbit splitting of the excited F state is influenced by the ions surrounding the F center. Further results will be reported in the near future.

The authors are indebted to Professor Frederick C. Brown for his constant interest and valuable suggestions. Discussions with Professor C. P. Slichter and Mr. Charles H. Henry were of great value. The assistance of Professor W. Dale Compton and Mr. W. D. Smith is also appreciated.

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CURRENT AND VOLTAGE SATURATION IN SEMICONDUCTING CdS†

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In several recent experiments the current-voltage characteristics of piezoelectric semiconductors (CdS, GaAs, ZnO) and of a semimetal (Bi) have shown severe departures from Ohm's law at certain critical fields. In the work of Smith[1] and McFee[2] on semiconductors, the current saturates when the electron drift velocity v_d exceeds the velocity of sound v_s. In Esaki's[3] experiment on bismuth in the presence of a strong perpendicular magnetic field, the voltage saturates when the cross-drift velocity of carriers in the direction perpendicular to both the E and B fields exceeds v_s. Hutson[4] has shown by an extension of the small signal theory of acoustic wave amplification[5,6] that these effects may be interpreted in terms of the "acoustoelectric current" which flows in the region of elastic wave amplification. This current flows counter to the conduction current initiating the amplification, subtracting from the conduction current in the Smith and McFee cases, but adding to the conduction current in the Esaki case due to the additional interaction with the magnetic field. The experiment to be reported here shows that both effects, the current and the voltage saturation, can be obtained in the same CdS crystal. It therefore demonstrates experimentally the essentially similar nature of the two effects, without the complications of two different materials, cross checks of mobility, different temperature regions, piezoelectric vs deformation potential coupling, or the presence of two types of carriers. It is the first experiment to demonstrate the conduction-current – elastic-wave interaction in crossed electric and magnetic fields using a one-carrier semiconductor.

The conditions for obtaining the Smith-type current saturation in piezoelectric CdS are, first, that $E_{xS} \geqslant v_S/\mu$, and second, that the crystals have enough conductivity and length such that the net total ultrasonic gain be sufficient to generate the large-amplitude acoustic waves needed to effectively lock most of the mobile charge to the sound waves. This conductivity may be obtained by doping the CdS into the semiconducting range or by illumination. For simplest interpretation the applied electric field and the corresponding current flow should be along or parallel to the c axis of the crystal.[7]

In the case of the voltage or Esaki-type saturation, the sharp increase in longitudinal current occurs at the "kink" field $E_{xE} \geqslant v_S B_z$. The conditions for this equation to apply are that the magnetic field be "strong" ($\mu B_z \gg 1$ where μ is the electron or hole mobility) and that no Hall field be set up to oppose the cross drift of the carriers. Since electron and hole concentrations are equal in the semimetal and the mobilities are quite large at 2°K, both conditions are satisfied by bismuth in moderate magnetic fields.

In CdS only the electrons have appreciable mobility. Even in a one-carrier semiconductor, however, the Hall voltage may be eliminated by the use of a cylindrical geometry in which the applied electric field and current are radial, the magnetic field is axial, and the cross-drift current is circumferential. This geometry is, of course, the well-known Corbino disc. For CdS with $\mu_e < 1000$ cm^2/V-sec, it is difficult to make $\mu B \gg 1$, but with pulsed magnetic fields it has been possible to reach $\mu B \approx 2$ which is large enough to see the effect. The radial Esaki kink field is then given by

$$E_{rE} = (v_S/\mu)(1+\mu^2B^2)/\mu B = E_{rS0}(1+\mu^2B^2)/\mu B. \quad (1)$$

E_{rS0} is the critical radial field for the onset of the Smith-type current saturation at 0 magnetic field. For $\mu B \gg 1$, Eq. (1) reduces to the expression given by Esaki.

In the presence of the axial magnetic field, E_{rS} should be similarly modified to account for the effective reduction in μ for the radial flow:

$$E_{rS} = (v_S/\mu)(1+\mu^2B^2) = E_{rS0}(1+\mu^2B^2). \quad (2)$$

Equations (2) and (3) can be obtained by simple recasting of the expressions given by Hopfield[8] or by Dumke and Haering[9] into the form most convenient for the present experiment.

The sample was cut in the shape of a disc washer, inner radius $r_1 = 0.032$ cm, outer radius $r_2 = 0.095$ cm, approximately 0.012 in. thick, from a boule of Eagle Picher 2 ohm-cm CdS. The C axis of the crystal was along the disc axis. Gallium Ohmic electrodes were applied to the inner and outer circumferences. The coaxial magnetic field was supplied by a condenser discharge into a small solenoid. A 10μsec voltage pulse, positive at the outer electrode, was applied at the peak magnetic field, which was sensibly constant during the pulse. Pulse current corresponding to a given pulse voltage was measured for each magnetic field discharge. Thus the current-voltage characteristic was traced out point by point for each value of magnetic field. The coil, disc, and mounting were all immersed in liquid nitrogen.

The I-V curve is shown in Fig. 1 with B as parameter. With $B = 0$, the curve is very similar to those obtained by Smith. Beyond the knee, V_{rS0}, the current pulse frequently shows oscilla-

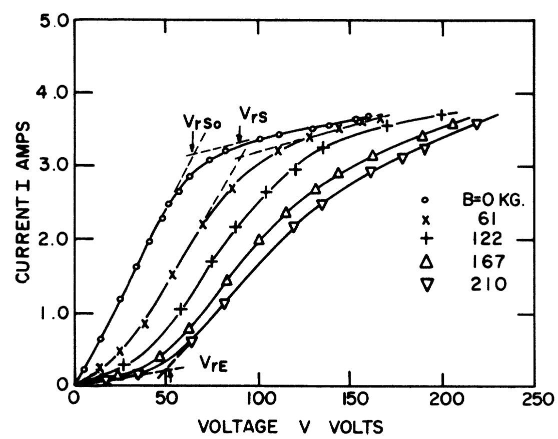

FIG. 1. Current-voltage curve for a CdS Corbino disc. The parameter is the axial magnetic field. The position of the critical voltage V_{rS0} and typical values of V_{rS} and V_{rE} are obtained by extrapolation as shown.

tions at ~2 mc/sec corresponding to a fundamental acoustic mode between the electrodes. With the magnetic field on, the current at first is linear with the applied voltage but with a smaller conductance than for $B=0$, showing the effect of magnetoresistance. At a critical voltage V_{rE} the current rises rapidly until at a second critical voltage V_{rS} the current saturates as for $B=0$. V_{rE} and V_{rS} are evidently the Esaki kink point for the circumferential current and the Smith saturation for the radial current, respectively. Both currents are perpendicular to the c axis of the crystal.

Considering only the effect of the magnetic field on the radial current saturation, we plot V_{rS}/V_{rS0} against B in Fig. 2. The inset shows the same plot extended into the region reachable by dc magnetic field, where the quadratic dependence of the critical voltage on B predicted by Eq. (2) requires the curve to approach the Y axis with zero slope. Independent experiments on rectangular samples at $B=0$ with $E \parallel c$ and $E \perp c$ were used to estimate μ from $E_{xS}=v_S/\mu$. It was found that the critical field was about 600 V/cm at 77°K, and approximately the same for both orientations, in spite of the fact that $v_{S\parallel}=4.4\times10^5$ cm/sec and $v_{S\perp}=1.75\times10^5$ cm/sec.[6] In order to get a reasonable value for mobility at both room and nitrogen temperature, it is necessary to choose $v_{S\parallel}$. This agrees with Smith[1] but is opposite to McFee[2] who also found that the critical field was approximately the same for $E \parallel c$ and $E \perp c$, but found it necessary to choose $v_{S\perp}$. The reason for this discrepancy is not clear. With the choice of $v_{S\parallel}$, μ comes out 700 cm^2/V-sec, and this value together with Eq. (2) was used to plot the solid line in Fig. 2. Had the mobility been determined merely by best fit to Eq. (2), the result would not have been materially different.

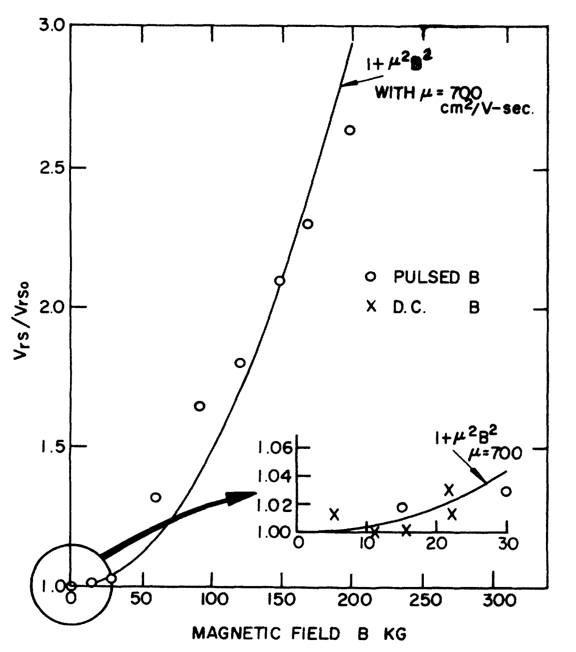

FIG. 2. V_{rS} relative to V_{rS0} as a function of magnetic field. The inset shows an enlargement of the low-field region obtained with both pulsed and dc magnetic fields. The solid line is Eq. (2).

Since $r_2 \approx 3r_1$, E_r is not uniform along r. The question arises: How can one calculate the critical field in the disc sample from the observed critical voltage? If a rectangular (uniform field) sample has a conductance σ_1 below a sharp critical field E_{xS0}, and conductance σ_2 above, with $\sigma_1 \gg \sigma_2$, then one can calculate that the same material in disc shape should show a somewhat rounded I_r-V_r curve with a critical voltage V_{rS0} (obtained by extrapolation) at $E_{xS0}(r_2-r_1)$, provided Ohm's law is obeyed in both field regions. From the observed V_{rS0} in the Corbino disc, this method yields $E_{xS0}=1020$ V/cm. On the other hand, we may alternatively assume that σ is independent of E, and using $E_r=[V_{rS0}/\ln(r_2/r_1)]\times(1/r)$ obtain $E_{r_1}=1810$ V/cm and $E_{r_2}=610$ V/cm. The latter field agrees with the observed critical field in rectangular samples. This agreement implies that the critical field must be exceeded everywhere along a radial line before acoustic gain becomes sufficient to affect the I-V curve. We assume this is due to the small dimensions of the sample. This limitation presumably does not apply to the circumferential current, since

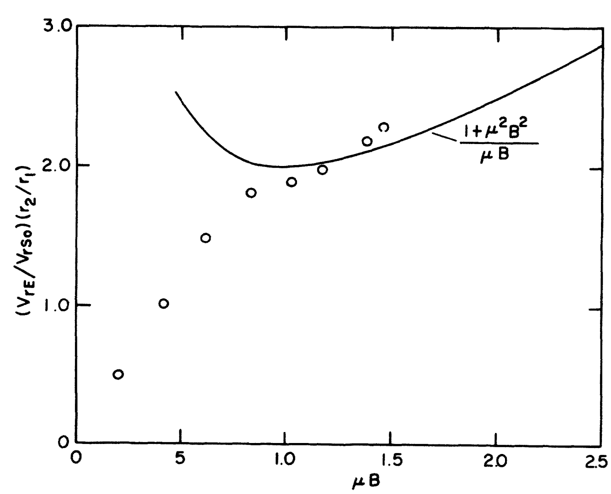

FIG. 3. $(V_{rE}/V_{rS0})(r_2/r_1)$ as a function of μB, μ taken as 700 cm^2/V-sec. The solid line is Eq. (1).

the path length is several times longer, even around r_1. With the correction, we obtain $E_{rE}/E_{rS0} = (V_{rE}/V_{rS0})(r_2/r_1)$. Figure 3 shows this ratio plotted against μB with μ again taken as 700 cm^2/V-sec. In the range $\mu B > 1$ the points approach what should be expected from Eq. (1). Whether it is strictly legitimate to use the radii ratio correction to get the critical field ratio is a question that awaits further study with samples of different size. Nevertheless, we feel that the interpretation is at least qualitatively correct and that the results lend support to the theory of acoustic-wave interaction in electric and magnetic fields.

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POSSIBLE INTERPRETATION OF THE $\pi\omega$ RESONANCE AT 1220 MeV†

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A resonance has recently been reported[1] in the interaction of π and ω mesons, its total energy being 1220 MeV and width about 100 MeV. The purpose of the present note is to suggest that this can be interpreted as the direct analog for the $\pi\omega$ system of the 33 isobar observed in π-nucleon interactions and that its spin and parity should be 2^-.

Consider the reaction

$$\pi + \omega \rightarrow \pi + \omega. \tag{1}$$

Let us assume that the basic mechanism of Reaction (1) is a coupling between π, ρ, and ω mesons. The emission of a π meson of four-momentum q by an ω meson of four-momentum p, polarization μ together with a ρ meson of four-momentum $p' = p - q$, and polarization κ is described by a vertex

$$f\epsilon_{\lambda\mu\nu\kappa}p_\lambda p_\nu'. \tag{2}$$

This is the interaction assumed, for example, by Gell-Mann, Sharp, and Wagner[2] in discussing the ω decay: Using their Eqs. (1) and (2) and taking the recent value of 9 MeV[3] for the ω width and 100 MeV[4] for the ρ width, we find $(f^2/4\pi) = 0.45$ in units where $\hbar = c = \mu_\pi = 1$.

With this interaction model, the only single-particle singularities contributing to Reaction (1) are the direct and crossed single-ρ terms illustrated in Fig. 1. We shall argue below that we can neglect coupling to all inelastic channels; then these two terms together with elastic unitarity should determine Reaction (1) at low energies. Bearing in mind the fact that both ρ and ω mesons are 1^- states and that their masses are similar and large compared with the π meson mass, we see the dynamical similarity to low-energy π-nucleon scattering.

It is well known that for the latter case the static limit[5] gives a good qualitative understanding of the importance of the 33 state and an approximate connection between the position and width of the resonance. We shall try the same approximation here, though its validity is even more suspect. In the rest frame of the ω meson, the interaction (2) becomes $Mf\epsilon_{ijk}q_k$, where M is the mass of the ω meson and ij are the polarizations of ω and ρ mesons. The three

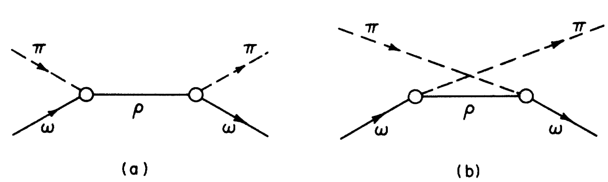

FIG. 1. Contributions to $\pi\omega$ scattering.