Magnetic-field and polarization dependence of the direct electromagnetic generation of ultrasound in potassium

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(Received 8 December 1986)

The magnetic-field and polarization dependence of the direct electromagnetic generation of ultrasound in single-crystal potassium was studied for various angles between the incident radio-frequency electric field and the [110] direction. The studies were done at 4.2 K for the slow shear mode for propagation in the [110] direction. A cusp in the magnetic-field dependence has been observed and the position of the cusp is strongly dependent on the direction of the applied electric field. The position of the cusp was used to determine the Hall coefficient. The results are compared with recent theoretical studies of the electromagnetic generation of ultrasound.

INTRODUCTION

The direct electromagnetic generation of ultrasound in potassium has been the subject of a number of investigations, both experimental and theoretical.

Using pancake coils as generators and detectors, Chimenti, Kukkonen, and Maxfield[1] (CKM) observed a nonmonotonic variation of the electromagnetically generated acoustic amplitude with magnetic field for the C_{44} shear mode for propagation along [100]. This effect cannot be explained by the free-electron model, assuming specular scattering of electrons at the metal interface. In addition, the zero-field amplitude and the ultrasonic attenuation which they observed were larger than predicted by the free-electron theory.

Feyder, Kartheuser, Ram Mohan, and Rodriguez[2] (FKRR), recently extended the free-electron calculations of the generation of ultrasound by electromagnetic radiation to include diffuse scattering of conduction electrons. For an elastically isotropic medium, their calculations show that the magnetic-field dependence of the generation amplitude, assuming diffuse scattering, is significantly different from the case for specular scattering. The diffuse scattering results can account for the nonmonotonic magnetic-field dependence observed by CKM, but the detailed fit of the theory with experiments is only fair. Similar results were obtained earlier by Banik and Overhauser.[3]

A more recent experimental study[4(a)] done at this laboratory reported results for the slow shear mode. A flattened solenoid coil was used as a generator and a pancake coil was used as a detector. The sharp minimum in magnetic-field dependence of the generation amplitude observed for fields below the Kjeldaas edge[4(b)] resulted in several theoretical studies designed to explain this observation. Extending the earlier calculations to include elastic anisotropy, Gopalan *et al.*[5] showed that a minimum in the magnetic-field dependence exists for certain polarization directions of the applied rf electric field. Quite surprisingly the calculations also show that the distinction between diffuse and specular scattering of electrons is not very pronounced for the C' mode.

Lacueva and Overhauser[6] have recently reported results of a theoretical study of the polarization dependence of the generation amplitude as a function of applied static magnetic field. For certain orientations of the incident radiation field, a cusp in the magnetic-field dependence of the acoustic amplitude is predicted. The calculations also show that the position of this minimum can be used to determine the Hall coefficient. The position of the minimum will occur at lower fields if a charge-density-wave (CDW) ground state rather than a free-electron ground state is present. Recent neutron scattering experiments[7] have provided direct experimental evidence for the existence of a CDW state in potassium. There is some experimental evidence that deviations in R_H as large as 30% can arise if the charge-density domains have a preferred orientation. Electromagnetic generation studies, therefore, could provide a very valuable technique for measuring both **Q**-domain texture and anisotropies in R_H.

A very clear and physical description of the origin of the cusp has also been given by Lacueva and Overhauser.[6] For $\mathbf{q}_{\parallel}[110]$, two shear acoustic modes are generated; a fast shear mode, C_{44}, with polarization parallel to [001], and a slow shear mode, C', with polarization parallel to $[1\bar{1}0]$. In the nonlocal limit—electron mean free path greater than the skin depth—for arbitrary polarization of the incident rf radiation, the force on the ions consists of the direct force and a collision drag force. While the direct electric force is along E_{rf}, the collision drag force rotates with increasing H from a position antiparallel with E_{rf} to a position parallel with B_{rf}. If the rf electric field is at an arbitrary angle with respect to $[1\bar{1}0]$, the C' polarization direction, the components of the two forces along $[1\bar{1}0]$ are antiparallel and for some magnetic field value will cancel. If H_0 is reversed, the collision drag force rotates in the opposite direction and the components of the force on the ions add along $[1\bar{1}0]$ so that no cusp will occur for the slow shear mode. The results of the calculations are shown in Fig. 1 for various values of the orientation of the rf field. These results can account for the cusp observed in our earlier experimental study[4] if ϕ is assumed to be approximately 20°.

The present study was undertaken to check the polari-

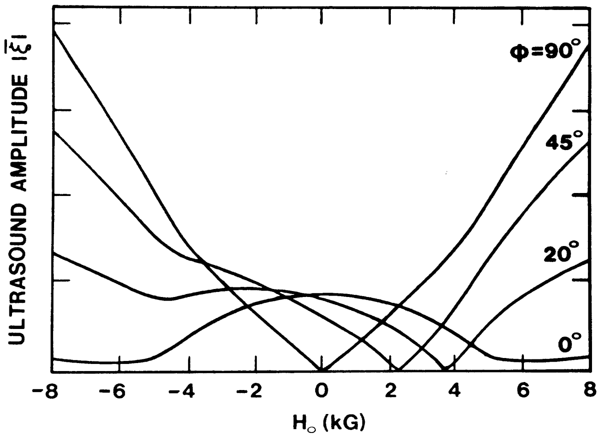

FIG. 1. Theoretical generation amplitude of the slow shear acoustic mode in potassium as a function of H_0 for various polarization angles of the rf electric field relative to [1$\bar{1}$0]. The frequency is 10 MHz.

zation dependence of the generation amplitude as a function of magnetic field and to compare the position of the cusp with the free-electron curves shown in Fig. 1. The presence of an anomalous Hall coefficient is a manifestation of a charge-density-wave ground state, and the net effect is that the minimum in the generation amplitude will occur at lower fields. Since the CDW is also a symmetry-breaking state, other nonsymmetrical effects might also be present in the magnetic-field dependence of the generation amplitude.

EXPERIMENTAL TECHNIQUES

A probe was constructed so that the transmitter coil could be rotated at liquid-helium temperatures, and the receiver coil was fixed. The technique for growing, orienting, and cutting the single crystals of potassium were the same as those employed in previous studies of potassium in this laboratory.[4] However, a more elaborate lapping technique was used to polish the acoustic specimens since the electron mean-free path in the skin depth should be as large as it is in the bulk in order to observe the zero-field signal. A wheel in a vertical plane was rotated asynchronously with the sample which was mounted in a lapping ring held by a magnetic chuck. The sample was positioned so that it did not make contact with the wheel; it did, however, make contact with an etchant on a paper spread over the wheel. After each face was lapped, the sample was covered with Vaseline to prevent oxidation and it was then immersed in a mineral-oil bath. Before being loaded in the probe, the sample in the mineral-oil bath was put in a vacuum chamber. This procedure removed the Vaseline and any oxides on the faces. The specimen was then removed from the mineral oil, placed in xylene and loaded into the probe under an argon atmosphere. The probe was then immersed in liquid nitrogen.

A gated coherent phase-sensitive detection system in conjunction with boxcar integration was employed for the measurement of electromagnetically generated ultrasound. In this setup, the generated signals are detected by a receiving coil and sent to a fast-recovery linear amplifier. The rf output of the amplifier is sent to a power splitter whose outputs are sent to two identical mixers operated in quadrature. Since the two reference signals are 90° out of phase, a peaked echo at the output of one mixer ensures that the same echo is nulled at the output of the other mixer. The field dependence of the echo amplitude is determined by sending the output of the two phase-sensitive detectors to a boxcar integrator, while the magnetic field is linearly swept. The output of the boxcar integrator is then sent to a Nicolet digital scope operating in the transient mode. Four thousand points are taken for each sweep and these data are sent to an Apple IIe microcomputer.

RESULTS

In order to check the selectivity of the transmitter coil and the alignment of the probe, a room-temperature study of a silver crystal oriented along [110] was done. Typical plots of generation amplitude as a function of magnetic field for the C' mode—both in the forward and reverse directions—are shown in Fig. 2 for various orientations, ϕ, of the rf electric field relative to the [110] axis. The curves exhibit the parabolic field dependence which is expected for a coil-coil configuration. For a fixed value of the magnetic field, the amplitude should vary as $|\sin(\phi)|$ as the transmitted coil is rotated if the wave is linearly polarized. This is more clearly shown in Fig. 3 where the amplitude is plotted as a function of ϕ for $H=12$ kG. While the curve does not vary exactly as $|\sin(\phi)|$, it does show that the transducers are quite selective. Our investigations have established that the selectivity of electromagnetic transducers (EMATS) depends on the distance between the transmitter and the sample surface, the size of the transmitted coil relative to the receiver coil and the size of the active area of the transmitter relative to the sample diameter. A similar rotation plot for potassium is shown in Fig. 4. These data were taken at 77 K. The plots again show that the transducers are quite selective, and it should be noted that when the C_{44} signal is at a minimum, the C' signal is at a maximum. The deviation

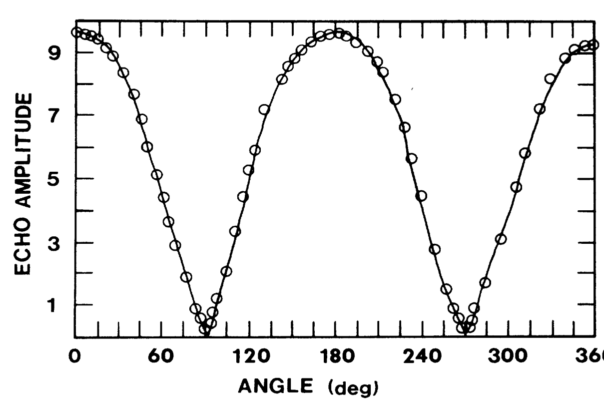

FIG. 2. Measured echo amplitude of the slow shear mode in silver as a function of polarization angle. The frequency is 8.6 MHz and $T=300$ K.

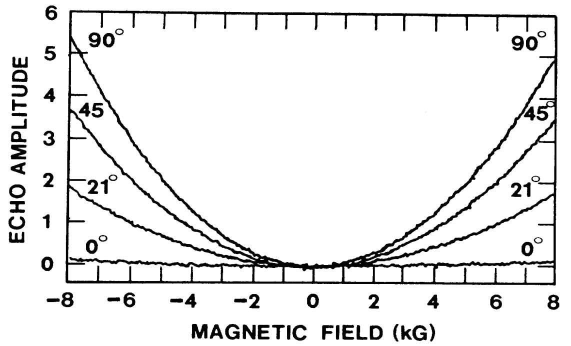

FIG. 3. Magnetic-field dependence of the echo amplitude of the slow shear mode in silver for various polarization angles. $\nu = 9.14$ MHz and $T = 300$ K.

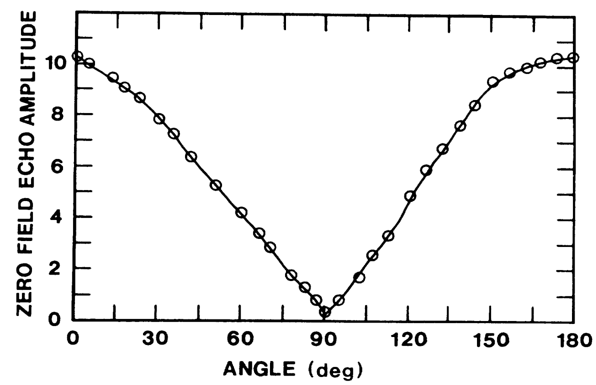

FIG. 5. Measured zero-field echo amplitude of the slow shear mode in potassium as a function of polarization angle. $\nu = 6.57$ MHz and $T = 4.2$ K.

from the $|\sin(\phi)|$ dependence of the amplitude is more pronounced in potassium compared to silver, a phenomenon which is not understood. In any case, the plots show that transducers can be made with excellent selectivity even in potassium so that the polarization dependence of the generation amplitude can be studied. An example of the angular variation of the zero-field generation amplitude in potassium is shown in Fig. 5. This plot is for the slow shear mode. The temperature is 4.2 K and the frequency is 6.57 MHz. The angular variation is quite similar to the expected behavior and is another indication of the selectivity of our transducers.

The measured magnetic-field dependence of the generation amplitude for various values of ϕ is shown in Fig. 6. The data have been corrected to take into account the electronic contribution to the ultrasonic attenuation which is present below the Kjeldaas edge. A free-electron value of the attenuation with ql of six was used to make the correction. The experimental curves are seen to be very similar to the corresponding theoretical curves shown in Fig. 1. In particular, the position of the cusp exhibits the same angular dependence as shown in Fig. 1. In addition, when the magnetic field is reversed, the cusp as predicted by theory is not present. Our experiments also show that if the frequency is increased, the cusp will move to higher fields. In the local limit, that is, for fields much larger

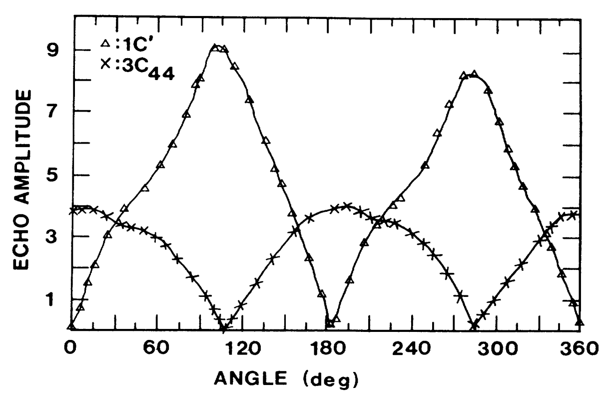

FIG. 4. Measured echo amplitude for fast and slow shear waves as a function of polarization angle in potassium. $\nu = 6.02$ MHz and $T = 77$ K.

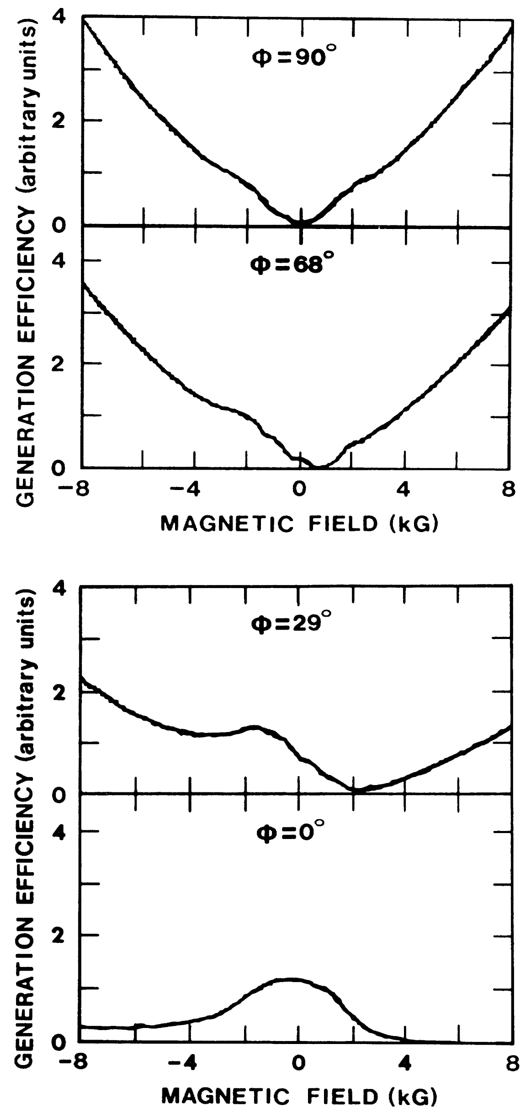

FIG. 6. The measured generation amplitude of the slow shear mode in potassium as a function of H_0 for various polarization angles. $\nu = 6.57$ MHz and $T = 4.2$ K.

than the Kjeldaas edge, the amplitude exhibits the normal field dependence that varies as H_0^2 for two transducers or linearly with H for a single transducer.

A more meaningful comparison of the polarization dependence of the cusp is shown in Fig. 7. Here the field at which the minimum occurs is plotted as a function of ϕ. The solid lines are the theoretical value calculated by Lacueva and Overhauser[6] scaled for a frequency of 6.57 MHz. As mentioned earlier, the position of the cusp can be used to determine the value of the Hall coefficient. The parameter t is the factor by which the Hall coefficient exceeds its classical value if a CDW ground state is present; $t=1$ corresponds to the free-electron value of R_H. The effect of an altered Hall coefficient is incorporated into the theory by replacing ω_c by $t\omega_c$. The figure also shows curves for $t=1.25$ and 1.5. The data points shown in Fig. 7 are seen to be in fairly good agreement with the free-electron curve assuming specular scattering of electrons. To compare the results with theory, one must accurately determine the frequency, ultrasonic velocity, and the polarization angle. The latter presents the most difficulty. In addition, the theory assumes linearly polarized waves. Since the transmitter coil did not produce pure linearly polarized plane waves, small deviations from the free-electron theory are expected to be difficult to observe. For samples such as those used in the present study, variation[8] of R_H from the free-electron value are not expected to exceed a value of $t=1.05$. Hence, the deviation from the free-electron theory is expected to be relatively small. In addition, for such small deviations the diffuse scattering can also be a significant factor.

There is one interesting feature of the high-field data obtained in the present study which should be pointed out. For H_0 greater than 8 kG, one expects the generation amplitude to be the same in the forward and reverse directions. This symmetry was not observed at 4.2 K for the slow shear mode, but was observed for temperatures greater than 20 K. A test made on a silver single crystal at liquid helium temperatures also exhibited the expected symmetry as did the fast shear mode in potassium. The origin of the asymmetry in the slow shear mode in potassium at 4.2 K is not understood and additional experiments are planned to more thoroughly examine this effect.

It should be pointed out that electromagnetic generation occurs within the skin depth and deviations of R_H from its free-electron value depends only upon domain texture within the skin depth. If the domains in this region can be aligned, one might expect large variations in the Hall coefficient. Since the CDW wave vector is along [110], etching the sample faces immediately before immersion in liquid helium might be one way of obtaining highly ordered domain textures in the skin depth. Apparently the technique used to prepare the faces did not produce the required domain texture necessary to observe a deviation in R_H even though they yielded surfaces which were of sufficiently high quality to obtain electron mean free paths comparable to the bulk mean free path since nonlocal generation of ultrasound was observed.

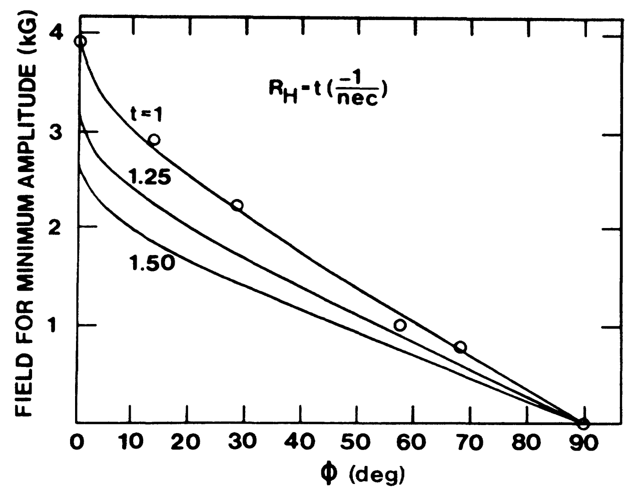

FIG. 7. Variation of theoretical and experimental field value of the cusp as a function of orientation of the rf field. The theoretical curves are shown for three values of the Hall coefficient factor t. $\nu=6.57$ MHz, $T=4.2$ K, n is the electron density, e is electron charge magnitude, and c is the speed of light.

In summary, the magnetic-field dependence of the generation amplitude in potassium and its dependence on the polarization of the incident electric field is in fairly good agreement with the calculations of Lacueva and Overhauser,[6] and exhibit all the main features predicted by that theoretical study. We feel that if a more linearly polarized transducer can be developed and measurements extended to higher ultrasonic frequencies, this technique can be used to examine the deviation of the Hall coefficient from its classical value that is present in the alkali metals.

ACKNOWLEDGMENTS

The authors would like to thank Professors A. W. Overhauser and G. Lacueva for many valuable discussions. They would also like to express appreciation to Dan Talenti, Joe Szente, and Mark Wolanski for their valuable laboratory assistance. This work was supported by National Science Foundation Grant No. DMR 83-14946.

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