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ELECTROMAGNETIC EXCITATION OF SHEAR ACOUSTIC WAVES

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The Influence of Magnetoacoustic Oscillations on
Electromagnetic Excitation of Shear Acoustic Waves*

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Abstract

An oscillatory, non-local contribution to the electromagnetic generation of shear acoustic waves in metals has been observed when the magnetic field is perpendicular to the propagation direction. Previous observations of electromagnetic generation of shear acoustic waves have been limited to the field being parallel to the propagation direction. Our observations are explained by considering forces on the lattice that arise from both the directly induced skin depth electric field and the electric fields due to Gantmakher splash current sheets.

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The electromagnetic excitation of acoustic waves in metals has been observed in the non-local limit of electrical conductivity only for shear waves in zero magnetic field or, when a steady field, H , is present, for shear waves propagating parallel to H .^{1,2,3,4} In this Letter, we report the first observation of electromagnetic excitation of shear waves when the magnetic field is perpendicular to the propagation direction. In this geometry, the non-local generation efficiency depends upon the conduction electron dynamics in a very dramatic way; the generation efficiency exhibits an oscillatory magnetic field dependence. This behavior is to be contrasted with the nearly monotonic field dependence that is observed for shear waves propagating parallel to H .

As in the case of conventional magnetoacoustic oscillations in the attenuation, the oscillations in the generation efficiency are also periodic in $1/H$. However, the origin of the generation efficiency oscillations is not a simple attenuation effect. The following discussion shows that they are due to an interference between a surface shear force and forces arising from current sheets created in the bulk of the conducting specimen at even multiples of the cyclotron radius, R_c , beneath the surface. These current sheets have precisely the same origin as those giving rise to the field-parallel Gantmakher size-effect and are often referred to as Gantmakher

splashes.⁵

Depending upon the excitation field orientation, the direction and magnitude of the steady magnetic field and the magnitude of $q\ell$ ($q = 2\pi/\lambda$ is the acoustic wavevector and ℓ is the carrier mean free path), a variety of acoustic modes may be produced by electromagnetic excitation. In the limit of local conductivity where a magnetic field is necessary, the polarization excited is parallel to the Lorentz force acting upon the induced (eddy) currents and the acoustic wave amplitude is proportional to the Lorentz force. In the non-local limit, transverse acoustic waves having a polarization direction parallel to the induced electric field can be excited in the absence of a steady magnetic field. When a magnetic field is applied and non-local conductivity conditions prevail, the situation is much more complex. If H is parallel to the surface as shown in Fig. 1b, it is observed that the amplitude of the resulting transverse acoustic wave oscillates periodically in $1/H$.

Measurements were performed on a high purity single-crystal of silver having a residual resistance ratio (RRR) of 1400; it was oriented so that the normal to the two large faces was within 1° of a (110) direction. One flat face was chemically polished to eliminate the ^{Small} amount of surface damage that results from the hand lapping which is necessary

splashes.⁵

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for achieving adequate surface parallelism and flatness. The other face was left in the as-lapped condition to facilitate bonding a 10 MHz AC cut quartz transducer.

An efficient double spiral coil shown in Fig. 1a was used for electromagnetic excitation of the acoustic waves. This type of coil generates a linearly polarized acoustic wave having a uniform acoustic intensity over the central region to which the quartz transducer is sensitive. From other experiments, it has been observed that signals exhibit the expected exponential decay regardless of whether the coil or quartz transducer is used to excite the acoustic waves.

The quartz transducer was bonded to the sample so that it was sensitive only to the slow shear wave. An electro-magnet-dewar system was used for these measurements; the magnetic field direction could be rotated in a manner such that it was always perpendicular to $\vec{q}$. Fig. 1 shows the various orientations of the coil (which could be rotated in the dewar), sample and magnetic field that were involved. Pulse-echo techniques involving typical pulse widths of 2μ sec were used for these measurements. All quantitative data were taken at 4.2°K, although qualitative results were obtained as the sample slowly warmed.

For simplicity in the discussion that follows, a number of vectors are defined in Fig. 1. $\vec{K}_{sd}$ is the skin depth current

density and is parallel to the wires of the coil. ξ_{ss} is the amplitude and polarization of the slow shear wave and is always parallel to $\bar{Q}$, the polarization direction of the quartz transducer.

With H perpendicular to ξ_{ss} (Fig. 1b), about ten magneto-acoustic oscillations in the attenuation (therefore $q_1 \approx 30$) were observed at 48 MHz when transmitting and receiving with the quartz transducer. The upper dashed curve in Fig. 2 shows the measured attenuation of the slow shear wave as a function of $1/\lambda H$ at 48 MHz. As expected, the attenuation is periodic $1/\lambda H$. The measured period is related to the Fermi momentum p_F . We find $p_F = 1.2 \times 10^{-19}$ g-cm/sec, a number that corresponds roughly to the minimum dimension of the belly orbit and is in excellent agreement with previous, more accurate magneto-acoustic attenuation measurements.⁶

With $H = 0$ and using the coil for excitation ($K_{sd} \parallel Q$ (as shown in Fig. 1b)), the expected electromagnetic generation signal was observed using the quartz transducer. With H applied perpendicular to ξ_{ss} , the acoustic signal undergoes oscillations as H is increased. These oscillations cannot be explained completely by the known oscillations in the acoustic attenuation. That is, there is an oscillatory contribution to the process of electromagnetic generation. The upper solid curve in Fig. 2 shows the amplitude of electromagnetic generation as a function of $1/\lambda H$ after attenuation changes have been

taken into account. Electromagnetic generation has the same period in $1/\lambda H$ as the magnetoacoustic attenuation but the phase is slightly different. Similar attenuation and electromagnetic generation results were obtained at 10 and 28 MHz.

Measurements involving other relative orientations of the magnetic field and coil (induced current) were also made. With the magnetic field oriented parallel to the polarization of the acoustic wave, that is with $K_{sd} \parallel \epsilon_{ss} \parallel H \parallel Q$, an expected monotonic decrease of the electromagnetic generation signal with increasing field is observed. In zero field with $K_{sd} \perp Q$, no signal could be detected. In this case, only the fast shear wave, to which the quartz transducer is not sensitive, is generated. With $K_{sd} \perp Q$ and a magnetic field applied either parallel or perpendicular to K_{sd} , the observed signal is reduced by about 40 db as shown by the lower solid curve in Fig. 2. However, as shown in the lower dashed curve in Fig. 2, electromagnetic generation is observed in an oblique magnetic field; the oscillations are a mixture of periods resulting from contributions of a number of carrier orbits having different Fermi surface dimensions.

Qualitatively, when the sample was allowed to warm up, the oscillatory field dependence disappeared quickly, but as expected the zero field electromagnetic generation signal did not decrease as rapidly. Such behavior is expected because

the number of magnetoacoustic oscillations increases approximately linearly with l for $ql \gg 1$, while the zero field electromagnetic generation becomes relatively independent of mean free path once $ql > 1$.

The general theory presented by Quinn⁷ perhaps includes the problem studied here although we have carried out no detailed analysis. Even if this analysis were done, it would be limited to a free electron metal. Below we present a qualitative description of our observations which implicitly takes into account the effects of the shape of the Fermi surface.

The oscillations in electromagnetic generation are believed to result from interference between forces generated within the skin depth and forces generated by Gantmakher splashes⁵; this is illustrated in Fig. 3. Since the magnitude of progressively higher order splashes decreases rapidly, the significant contribution must come from the first one or two splashes.

In an acoustic medium having a free surface, the amplitude of an acoustic wave generated by a force, $F(z)$, is given by

$$\xi(z) = \frac{1}{\rho_{sw}} e^{iqz} \int_0^{\infty} F(z_0) \cos qz_0 dz_0$$

Let us consider only one Gantmakher splash and assume that for our purposes the forces can be approximated by highly localized sources, namely

$$F(z) = F_0(H) \delta(z) + F_1(H) \delta(z - 2R_c)$$

where δ is the Dirac delta function and $F_0(H)$ and $F_1(H)$ are functions of the magnetic field. From rf size effect calculations,⁸ it follows that the force due to the first splash is ~~opposite in direction to~~ ^{in the same direction as} the force in the skin depth region; hence F_0 and F_1 will be of ~~opposite~~ ^{the same} sign with

$$|F_1| < |F_0|.$$

The acoustic amplitude resulting from the above force is then

$$\xi = \xi_0(H) + \xi_1(H) \cos 2qR_c$$

where ξ_0 and ξ_1 are positive field dependent constants.

Maxima in ξ should occur for $2R_c = N\lambda$ where N is an integer. This is also the rough criterion for maxima in the magnetoacoustic attenuation oscillations.

This model is not exact in that it does not consider the influence of non-extremal orbits, the finite skin depth, and the detailed nature of the surface scattering (specular or diffuse). Non-extremal orbits will cause phase shifts in magnetoacoustic oscillations and undoubtedly also cause phase shifts in the electromagnetic generation process. Both the amplitude and phase of electromagnetic generation would be affected by diffuse surface scattering. Since there is probably considerable diffuse surface scattering, a small phase

difference between the type of electromagnetic generation under consideration and the oscillatory attenuation is to be expected.

References

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1. B. Abeles, Phys. Rev. Letters 19, 1181 (1967).
 2. G. Turner, R. L. Thomas, and D. Hsu, Phys. Rev. B3, 3097 (1971).
 3. W. D. Wallace, M. R. Gaerttner, B. W. Maxfield, Phys. Rev. Letters 27, 995 (1971).
 4. Y. Goldstein and A. Zemel, Phys. Rev. Letters 28, 147 (1972).
 5. V. F. Gantmakher, Soviet Phys. JETP 15, 982 (1962).
 6. V. J. Easterling and H. V. Bohm, Phys. Rev. 125, 812 (1962).
 7. J. J. Quinn, Phys. Letters 25A, 522 (1967).
 8. G. E. Juras, Phys. Rev. 187, 784 (1969).

Figure Captions

Figure 1: (a) Relative orientation of rotatable coil, quartz transducer and specimen crystal axes for case (b). The coil used in our measurements had nine straight parallel wires in the central region which was the only area that excited acoustic waves that were detectable by the quartz transducer. K_{sd} is parallel to the central windings. (b), (c) and (d) define three field orientations which result in dramatically different magnetic field dependences for electromagnetic generation.

Figure 2: (a) The magnetic field (B_0) dependence of the slow shear wave attenuation (right hand scale) with $H \perp \epsilon_{ss}$, (b) electromagnetic generation (EG) with $H \perp q$ as shown in Fig. 1(b) after attenuation of the acoustic wave though the specimen has been taken into account, (c) EG with H at a 45 degree angle to ϵ_{ss} as shown in Fig. 1(d), and (d) EG with $K_{sd} \perp Q$ and H either parallel or perpendicular to K_{sd} as shown in Fig. 1(c). Signal/noise was approximately unity for (d). Both scales are in db; *the Sample thickness is 0.43 cm.*

Figure 3: Model used to explain the oscillatory electromagnetic generation. In a magnetic field, extremal orbit

carriers (their trajectories are shown as circles)
create Gantmakher splash current sheets beneath
the surface.

(a)

(b)

(c)

(d)

Fig. 2

Fig. 3