

Ultrasonic Attenuation in Copper*

R. J. KOLOUCH AND K. A. MCCARTHY

Department of Physics, Tufts University, Medford, Massachusetts

(Received 18 January 1965)

The absolute electronic attenuation of longitudinal ultrasonic waves in a single crystal of pure copper at low temperatures has been measured at three frequencies: 23.2, 29.8, and 47.8 Mc/sec. The attenuation due to the dislocation-phonon interaction has been completely suppressed by a Co^{60} gamma irradiation. Comparison of the experimental results with the theory of Pippard suggests that the relaxation time for the ultrasonic attenuation is equal to that for the electrical resistivity, and that the fit of the experimental data requires that only the coefficient of Pippard's attenuation expression be adjusted. Such an adjustment can be explained by considering the true Fermi surface of copper, and the distortions the Fermi surface undergoes when the crystal is sustaining an ultrasonic wave.

THE absolute electronic attenuation of longitudinal ultrasonic waves in a single crystal of pure copper at low temperatures has been observed experimentally. In this crystal the attenuation due to the dislocation-acoustic-wave interaction in the crystal has been completely suppressed by a Co^{60} gamma irradiation.

The single-crystal copper specimen was obtained from Metals Research Ltd., of Cambridge, England, and was prepared for the ultrasonic measurements at the Lincoln Laboratories.¹ The crystal was a cylinder 0.5 inches long and 0.5 inches in diameter, and was oriented with the end faces perpendicular to the $[111]$ crystallographic axis to $\pm \frac{1}{2}^\circ$. The resistivity ratio ($R_{293^\circ\text{K}}/R_{4.2^\circ\text{K}}$) was 545 as determined by the eddy-current technique of Bean, DeBlois, and Nesbitt.²

The pulse-echo technique was employed to exhibit the attenuation which was measured with the aid of a calibrated attenuator. The results of the measurement after the specimen had been irradiated with 5×10^7 R of gamma rays are shown in Fig. 1 for 23.2- and 29.8-Mc/sec pulses, and in Fig. 2 for 47.8-Mc/sec pulses of 2 μsec duration. Above 55°K the attenuation is independent of temperature. Before irradiation the attenuation increased with temperature in the temperature range from 45 to 77°K. The temperature-independent part of the attenuation has been considered to be the residual absorption due primarily to bonding of the transducer to the sample, and has been subtracted from the measured attenuation to obtain the data in Figs. 1 and 2. The attenuation shown is believed to be due only to the interaction of the ultrasonic wave with the conduction electrons in the crystal.

The experimental data are compared with Pippard's³

theoretical result for the amplitude attenuation,

$$\alpha = \frac{Nme}{2\rho v_s \tau} \left[\frac{(ql)^2 \tan^{-1} ql}{3(ql - \tan^{-1} ql)} - 1 \right], \quad (1)$$

where N is the electron density, m and e the electronic mass and charge, respectively, q the acoustic wave number, l the electron mean free path, v_s the acoustic wave velocity, τ the relaxation time, and ρ the density of the metal. The fit of theory to experiment requires that the theoretical values be multiplied by 1.78, 1.79, and 1.71 for the 23.2-, 29.8-, and 47.8-Mc/sec data, respectively; the results of the adjusted theory are shown by the dashed lines in the two figures. It should be noted that the general form of Pippard's equation is used because the value of ql is equal to 1.2 at 4.2°K for a frequency of 47.8 Mc/sec. For these calculations the relaxation time and mean free path for the ultrasonic attenuation are obtained by assuming that they are

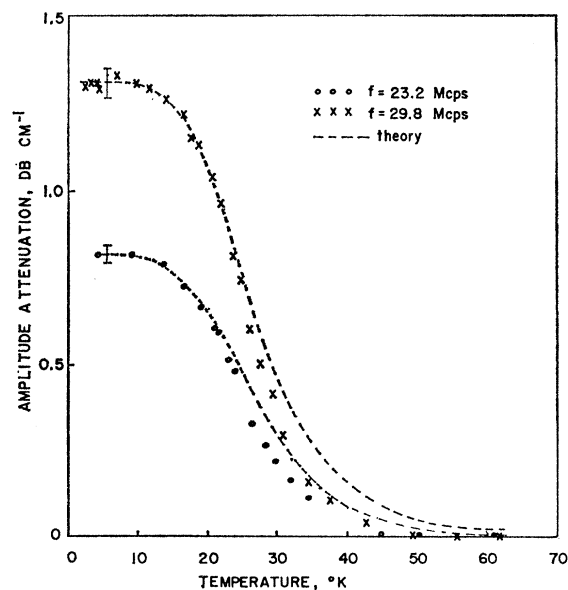


FIG. 1. Ultrasonic attenuation of copper at frequencies of 23.2 and 29.8 Mc/sec.

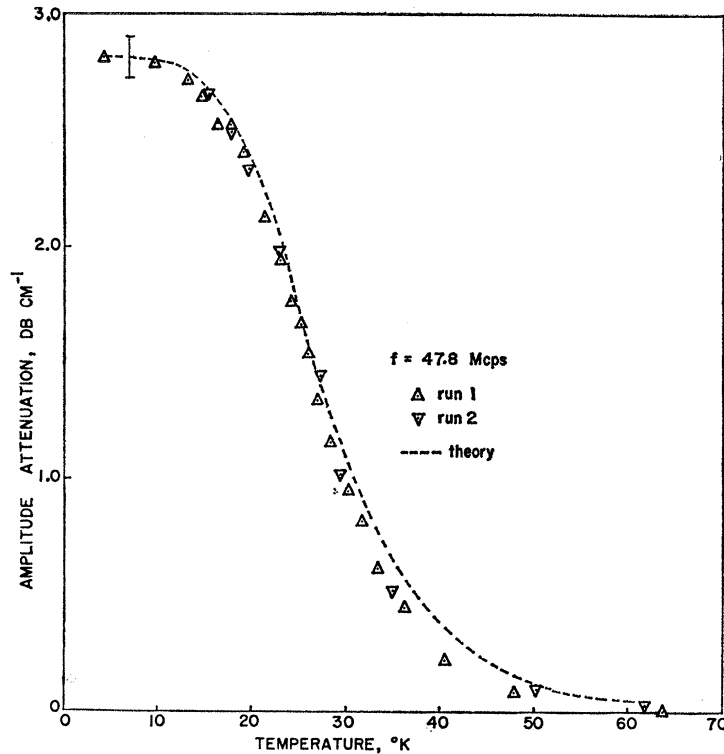
* Supported in part by the U. S. Air Force [Contract No. AF19(628)-4029] and the National Science Foundation. Computations for this work were done at the Tufts University Computer Center.

¹ Massachusetts Institute of Technology, Lexington, Massachusetts.

² C. P. Bean, R. W. DeBlois, and L. B. Nesbitt, *J. Appl. Phys.* **30**, 1976 (1959).

³ A. B. Pippard, *Phil. Mag.* **46**, 1104 (1955).

FIG. 2. Ultrasonic attenuation of copper at a frequency of 47.8 Mc/sec.



equal, respectively, to the relaxation time and mean free path for electrical resistivity. τ , and consequently l , are determined as a function of temperature, using the measured value of resistivity at 4.2°K and an empirically determined temperature dependence for the resistivity as found by Berman and MacDonald,⁴ and White⁵ for copper of similar purity; the attenuation is then calculated from Eq. (1).

If one were to fit the experimental data with theory by varying the acoustic relaxation time with respect to the electrical relaxation time, the agreement of the frequency dependence of the attenuation with theory would be violated. The results of this experiment indicate that by an appropriate irradiation of the sample it is possible to obtain the absolute electronic attenuation

and that the electrical and acoustical relaxation times seem to be equivalent. These results suggest that only the coefficient of the attenuation expression of Pippard need be adjusted to fit the data. This would not be obvious if one were examining the attenuation only in a range where $ql \ll 1$, and where the attenuation is directly proportional to the relaxation time.

Calculations and experimental results in other orientations indicate that values of attenuation larger than those predicted from the free-electron model may be obtained if one considers the true Fermi surface of copper, and the possible distortions the Fermi surface undergoes when the crystal is sustaining an ultrasonic wave.

The authors wish to thank Professor L. M. Roth for many discussions of the theory, and W. J. Burke and E. Y. Wang for their assistance with the experimental work.

⁴R. Berman and D. K. C. MacDonald, Proc. Roy. Soc. (London) A211, 122 (1952).

⁵G. White, Australian J. Phys. 6, 397 (1953).