ferent.

A more complete and extensive study is underway in which we are investigating the effects of pressure, temperature, ortho-para ratio, and isotopic species on the transition.

We wish to express our appreciation to Mr. John Bailey for his fine craftsmanship in constructing various items of our equipment.

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[1]W. H. Keesom, J. De Smedt, and H. H. Mooy, Commun. Kamerlingh Onnes Lab. Univ. Leiden 19, 209d (1930).

[2]J. Van Kranendonk and H. P. Gush, Phys. Letters 1, 22 (1962).

[3]V. S. Kogan, A. S. Bulatov, and L. F. Yakimenko, Zh. Eksperim. i Teor. Fiz. 46, 148 (1964) [translation: Soviet Phys.–JETP 19, 107 (1964)].

[4]M. Clouter and H. P. Gush, Phys. Rev. Letters 15, 200 (1965).

[5]G. W. Smith and R. M. Housley, Phys. Rev. 117, 732 (1960).

[6]R. W. Hill and B. W. A. Ricketson, Phil. Mag. 45, 277 (1954).

[7]G. Ahlers and W. H. Orttung, Phys. Rev. 133, A1642 (1964).

[8]A. F. Schuch and R. L. Mills, Phys. Rev. Letters 8, 469 (1962).

[9]H. W. Woolley, R. B. Scott, and F. G. Brickwedde, J. Res. Natl. Bur. Stds. 41, 379 (1948).

EFFECTS OF HIGH MAGNETIC FIELDS ON THE ULTRASONIC VELOCITY AND ATTENUATION IN Nb–25% Zr

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In this Letter we report the observation of changes in the velocity and attenuation of ultrasonic waves propagating in the superconducting and normal states of Nb–25% Zr, caused by the presence of a high dc magnetic field. These changes are abrupt near the upper critical field H_{c2}, determined by magnetization measurements.[1] The conventional interpretations of the changes in the ultrasonic attenuation[2] and the velocity[3] near H_{c2} do not apply to this high-field superconductor because the effects of the magnetic field necessary to destroy superconductivity are large.[4] On the other hand, the velocity and attenuation changes observed in the <u>superconducting state</u> agree with the predictions of the Alpher-Rubin[5] (AR) theory which was originally derived for impure metals in the <u>normal state</u>. This agreement is particularly good for sound waves in the megacycle range, although deviations are observed at higher frequencies. As expected, the AR theory also accounts for the results in the normal state.

The macroscopic theory of AR[5] predicts that the velocity V_S of a sound wave of frequency ω propagating in a metal with electrical conductivity σ increases by ΔV_S in the presence of a magnetic field H. For a shear wave

$$\frac{\Delta V_S}{V_S}=\frac{\mu H^2\cos^2\theta}{8\pi\rho V_S^{\,2}(1+\beta^2)}, \tag{1}$$

where μ is the permeability, ρ is the density of the metal, θ is the angle between $\vec{H}$ and the wave vector $\vec{q}$ of the sound, and

$$\beta=c^2\omega/4\pi\sigma V_S^{\,2}. \tag{2}$$

Rodriguez[6] has shown that Eq. (1) can be derived from a microscopic theory in the case of impure metals in which $ql, \omega_c\tau, \omega\tau \ll 1$, where l is the electron mean free path, ω_c is the cyclotron frequency, and τ is the electron relaxation time. These conditions are well satisfied in the normal state of our Nb–25% Zr sample. Starting from the assumptions of AR one can show that the amplitude of sound wave decays with the distance x as $e^{-\alpha x}$ where, for a shear wave,

$$\alpha=\frac{\sigma H^2\mu^2\beta^2\cos^2\theta}{2\rho V_S c^2(1+\beta^2)}\ \mathrm{cm}^{-1}. \tag{3}$$

For a longitudinal wave the $\cos^2\theta$ term in Eqs. (1) and (3) is replaced by $\sin^2\theta$. Equation (1) has been tested experimentally in a number of metals,[7] in the <u>normal state</u>, and has been found to hold when $\beta \ll 1$. When $\beta \gtrsim 1$ the sound velocity increases quadratically with H, but the increase is somewhat different, in some cases, from that given by the AR theory. To our knowledge, Eq. (3) has not been previously tested experimentally.

Ultrasonic experiments were conducted on an unannealed Nb–25% Zr cylinder, ~0.7 in. long and 0.26 in. in diameter, kindly provided by the Westinghouse Corporation. The ultrasonic velocities were measured by the conventional pulse technique.[2] At 4.2°K the shear and longitudinal velocities are 1.88 and 4.7×10^5 cm/sec, respectively. Changes in the ultrasonic velocity due to the magnetic field were measured by a method similar to that used by Mavroides et al.[8] With this technique a fractional change of $\sim3\times10^{-5}$ in the sound velocity could be detected. Changes in the ultrasonic attenuation were measured using an apparatus which has previously been described.[9] The large number of observed echoes (10-20) permitted the resolution of a change of $\sim5\times10^{-3}$ dB/cm in the attenuation. The accuracy of the measurements of the attenuation changes is ~5%.

The variation of the sound velocity of 4.3-, 10-, and 14.3-Mc/sec shear waves was measured as a function of an applied magnetic field, $\vec{H}$, directed along the direction of propagation of the sound wave, at 4.2 and 1.7°K. Some of the results are shown in Fig. 1. The change $\Delta V_S/V_S$ at fields above H_{c2} is in reasonable agreement with the prediction of the AR theory. For a 4.3-Mc/sec shear wave $\Delta V_S/V_S \cong 5\times10^{-4}$ at 100 kG, as compared with the theoretical prediction $\Delta V_S/V_S = 3.6\times10^{-4}$ calculated using the measured density $\rho = 8.1$ g/cm^3 and the normal resistivity 27.5 $\mu\Omega$ cm at 4.2°K.[1] Similar agreement between experiment and theory is found for 10- and 14.3-Mc/sec waves. The slight discrepancy between experiment and theory in the normal state is not surprising, since the experiments were performed in the region $\beta > 1$ where slight deviations from theory have previously been observed.[7] Measurements with 4.3-Mc/sec shear waves with $\vec{q} \parallel \vec{H}$ carried out at 77°K gave similar results to those obtained in liquid helium at $H > H_{c2}$.

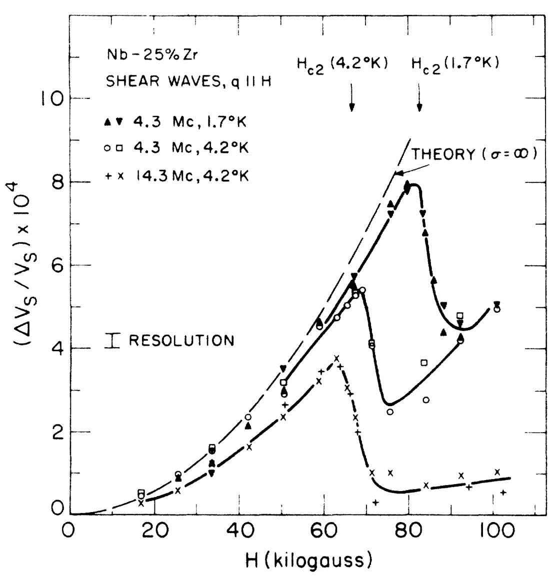

FIG. 1. Change of the ultrasonic velocity of shear waves in a parallel magnetic field. The broken line is calculated on the basis of Eq. (1) with $\sigma = \infty$, $\mu = 1$.

One striking feature of the velocity measurements is the fact that in the superconducting state the observed change $\Delta V_S/V_S$ for shear waves is in good agreement with the prediction of Eq. (1) if one lets $\sigma = \infty$ and $\mu = 1$.[10] As shown in Fig. 1, this agreement is particularly good at frequencies below ~10 Mc/sec. As a further test of the validity of Eq. (1) in the superconducting state, the velocity of a 4.3-Mc/sec shear wave with $\vec{q} \perp \vec{H}$ was measured at 4.2°K in fields up to 100 kG. No change in the velocity was observed in this case, in agreement with Eq. (1). Experiments with 10-Mc/sec longitudinal waves, performed at 4.2°K with $\vec{q} \perp \vec{H}$, indicate the presence of small changes in the sound velocity as a function of H. At 84 kG, $\Delta V_S/V_S \sim 1.4\times10^{-4}$, which agrees, within experimental accuracy, with the theoretical value $\Delta V_S/V_S = 1.1\times10^{-4}$. Because the magnitude of the change in the sound velocity is small in this case, it was impossible to ascertain whether any abrupt change in the sound velocity occurs at H_{c2}. For a 10-Mc/sec longitudinal wave propagating in a parallel magnetic field at 4.2°K no change in the velocity was observed up to 100 kG, in agreement with the AR theory. This result also indicates that the velocity changes observed at liquid helium with shear waves in a parallel magnetic field are not due to changes in the length of the specimen.

To test Eq. (3), the attenuation of shear and longitudinal waves was measured at 77°K in a magnetic field up to 100 kG. The measurements were carried out with 4.3- and 14.3-Mc/sec shear waves in a parallel magnetic field, and with 12- and 29-Mc/sec longitudinal waves in a transverse magnetic field. For these field directions the attenuation changes are expected to be maximal (cf. Eq. 3). The results are in very good agreement with the predictions of

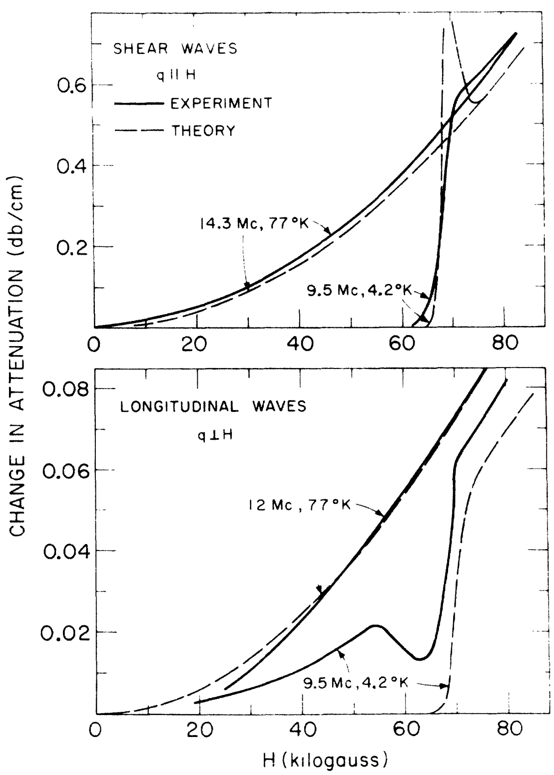

FIG. 2. Change of the ultrasonic attenuation in a magnetic field. The dashed curves are calculated on the basis of the AR theory using $\mu = 1$ and the measured resistivity, at low current densities, as a function of H.

the AR theory as shown in Fig. 2 by the curves for a 14.3-Mc/sec shear wave and for a 12-Mc/sec longitudinal wave. The theoretical curves for these cases were calculated using the resistivity 28.3 $\mu\Omega$ cm at 77°K.[1]

Measurements of the ultrasonic attenuation of 5- to 25-Mc/sec shear waves carried out in a parallel magnetic field at temperatures below the transition temperature $T_c = 10.8$°K show that there is no change in the attenuation at fields below H_{c2}. At H_{c2} the attenuation rises abruptly and then increases monotonically with H. This is illustrated in Fig. 2. by the curve for a 9.5-Mc/sec shear wave. The existence of an absorption edge for shear waves at H_{c2} was reported earlier by the authors.[11] Here we wish to point out that Eq. (3) gives a good fit to the attenuation curves of these low-frequency shear waves. In Fig. 2 we show the attenuation for a 9.5-Mc/sec shear wave calculated by using Eq. (3) and the measured resistivity,[1] at low current densities, as a function of H. As can be seen, the agreement between the theoretical curve and the experimental one is quite good except that the peak in the calculated attenuation was not observed experimentally. It can be shown that Eq. (3) predicts the existence of a finite peak in the attenuation near H_{c2} if $\beta > 1$ in the normal state, and if the electrical conductivity in the normal to superconducting transition region is uniform throughout the sample. It is not clear whether the failure to observe this peak experimentally is due to a nonuniform conductivity in the superconducting to normal transition region. The magnitude $\Delta\alpha$ of the rise in the attenuation of a 10-Mc/sec shear wave at H_{c2} was measured at 4.2°K as a function of the angle θ. These measurements were made both with the direction of particle motion in the plane containing $\vec{q}$ and $\vec{H}$, and with direction of particle motion always perpendicular to $\vec{H}$. In both cases $\Delta\alpha$ was found to be approximately proportional to $\cos^2\theta$, as predicted by Eq. (3).

Measurements of the attenuation of 9- to 30-Mc/sec longitudinal waves were performed at liquid-helium temperatures in a transverse magnetic field. The results resemble those obtained with 5- to 25-Mc/sec shear waves in a parallel magnetic field, except for the appearance of a slight increase in the attenuation at fields well below H_{c2}. This is illustrated in Fig. 2 by the curve for a 9.5-Mc/sec longitudinal wave. The increase in the attenuation at fields below H_{c2} was more pronounced at higher frequencies and was also present in the case of shear waves with frequencies higher than ~30 Mc/sec. The attenuation curves of these high-frequency sound waves resemble the resistance curves obtained in some type-II superconductors at moderately high current densities.[12] This suggests that this type of resistance, rather than the resistance at low current densities, is important in the case of high-frequency sound waves.

In summary, it has been shown that the AR theory accounts for (1) the effect of a magnetic field on the velocity of sound waves in the superconducting and normal states of Nb–25% Zr, (2) the abrupt change in the velocity of shear waves which occurs near H_{c2}, (3) the effect of a magnetic field on the attenuation of longitudinal and shear waves in the normal state, (4) the rise in the attenuation of shear and longitudinal waves which occurs near H_{c2}, and (5) the dependence of the magnitude of this rise on the ultrasonic frequency, the angle between $\vec{H}$ and $\vec{q}$, and the value of H_{c2} at various temperatures. We have also noted that in the superconducting state deviations from the AR theory appear as the ultrasonic frequency is increased. Finally, it must be emphasized that, as yet, the agreement between the AR theory and the ultrasonic results, at low frequencies, in the superconducting state is purely empirical.

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[1]L. J. Neuringer and Y. Shapira, to be published.

[2]R. W. Morse, in Progress in Cryogenics, edited by K. Mendelssohn (Heywood and Company, Ltd., London, 1959), Vol. I.

[3]Cf. G. A. Alers and D. L. Waldorf, IBM J. Res. Develop. 6, 89 (1962).

[4]The ratio of the superconducting to normal attenuation α_s/α_n is often used to determine the energy gap.[2] It should be emphasized that α_n is the attenuation that would have been present at zero magnetic field had the material been normal, and not the attenuation α_n' at $H > H_{c2}$. In the present experiments α_n' cannot be identified with α_n. In fact, the results indicate that at liquid-helium temperatures $\alpha_n' - \alpha_s \gg \alpha_n - \alpha_s$. The dependence of the velocity changes on the angle between $\vec{q}$ and $\vec{H}$ indicates that these changes are not related to the changes in the elastic moduli, at zero magnetic field, between the superconducting and normal states.[3]

[5]R. A. Alpher and R. J. Rubin, J. Acoust. Soc. Am. 26, 452 (1954).

[6]S. Rodriguez, Phys. Rev. 130, 1778 (1963).

[7]A. A. Galkin and A. P. Koroliuk, Zh. Eksperim. i Teor. Fiz. 34, 1025 (1958) [translation: Soviet Phys.–JETP 7, 708 (1958)]; G. A. Alers and P. A. Fleury, Phys. Rev. 129, 2425 (1963); Y. Shapira, thesis, Massachusetts Institute of Technology, 1964 (unpublished).

[8]J. G. Mavroides, B. Lax, K. J. Button, and Y. Shapira, Phys. Rev. Letters 9, 451 (1962).

[9]Y. Shapira and B. Lax, Phys. Rev. 138, A1191 (1965).

[10]At fields much greater than H_{c1} the magnetic induction B is nearly equal to H.

[11]L. J. Neuringer and Y. Shapira, Solid State Commun. 2, 349 (1964).

[12]S. H. Autler, E. S. Rosenblum, and K. H. Gooen, Phys. Rev. Letters 9, 489 (1962); Rev. Mod. Phys. 36, 77 (1964); W. DeSorbo, Rev. Mod. Phys. 36, 90 (1964); Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. 139, A1163 (1965); Y. Shapira and L. J. Neuringer, Phys. Rev. (to be published).

PHOTONEUTRON CROSS SECTIONS OF Li^6†

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The photoneutron cross sections of Li^6 were measured as a function of photon energy from 5.7 to 32 MeV, using the monoenergetic photon beam achieved by the annihilation in flight of fast positrons from the Livermore electron linear accelerator.[1]

The photon beam was allowed to strike the Li^6 sample in the center of a 4π neutron detector, which consists of a two-foot cube of paraffin in which are embedded 48 BF_3 tubes arranged in four concentric rings of 12 tubes each. Each ring is monitored independently, and the detector is gated on for 300 μsec by the beam burst. The neutron multiplicities are counted during each gate interval as well, enabling one to measure the (γ,n) and $(\gamma,2n)$ cross sections simultaneously. The total neutron-detection efficiency is well known in the energy region of interest and averages 0.39. Also, since the relative counting efficiencies of the four rings vary with neutron energy, a rough value for the average neutron energy can be determined for each photon energy.[2]

Several 95% pure Li^6 samples ranging in size from 8 to 64 moles were used during the course of the experiment. The absorption of neutrons by the Li^6 samples themselves was measured in two different ways. First, a $\frac{1}{4}$-in.-thick lead sample was sandwiched between two Li^6 samples, and the absorption of photoneutrons from the (γ,n) process on lead was measured at several photon energies. Second, a PuBe neutron calibration source was employed as the source of neutrons instead of the lead sample. Both measurements gave the same answer, either one resulting in a 6.2% correction to the data in the case of the 32-mole sample. The effect of the length of this Li^6 sample (8 in.) was accounted for by measuring the variation of detector efficiency with sample position, necessitating a 2% correction to the data. The attenuation of the photon beam in passing through this sample necessitated a 6.9% correction to the data, and varied negligibly with photon energy in the region of interest. Runs were performed on the empty thin-walled Lucite con-