first order only are included when two waves are exactly parallel or perpendicular to each other. However, $\Delta\omega/\Delta k v_T$ is not a small parameter for our experimental conditions. It should also be noted that some terms, which are not small, are ignored in the above references without any reasons given.

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Effect of Magnetic Fields on Stress Relaxation in the Mixed-State Superconducting Pb-In Alloys*

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The magnetic field dependence of the stress changes associated with the normal-to-superconducting–state transition was measured for single crystals of Pb–5 at.% In and Pb–10 at.% In, and was found to be in agreement with the magnetic field dependence of the ultrasonic wave attenuation in type-II superconductors.

Plastic deformation of metals takes place through the motion of dislocations, and this motion is retarded by lattice defects and by drag on the dislocations due to interactions of the dislocations with phonons and conduction electrons.[1-4] At low temperatures the retardation of dislocation motion by phonons is thought to be negligible, while the role of the conduction electrons in low-temperature deformation has received very little attention. Recent experiments,[5-15] however, have shown the influence of the transition from the normal-to-superconducting state on the plastic properties of metals and, thus, the influence of the conduction electrons. It was originally suggested that this effect was associated with a viscous electron drag acting on moving dislocations, but no satisfactory model has been given.[5] More recently, a theory has been given by Granato[9] and independently by the present authors[10] to describe the effect of the superconducting state on dislocation motion. The theory is based on the vibrating-string model of dislocation motion.[11,12] In this model a pinned dislocation segment can bow out an additional amount in the superconducting state, compared with the normal state, because of the reduction in the electron viscosity in the superconducting state. Hence, the line tension on the pinning point is larger in the superconducting state than in the normal state. Consequently, the applied stress required to depin a dislocation segment from a pinning point is less in the superconducting state than in the normal one. The difference in the stress, $\Delta\sigma_{n-s}$, is given by[9,10]

$$\Delta\sigma_{n-s} \cong f_c B_n(1-B_s/B_n)[16b^3(\pi\rho G)^{1/2}]^{-1}, \qquad (1)$$

where f_c is the pinning force; B_n and B_s are the viscosity in the normal and the superconducting states, respectively; and b, ρ, and G are the Burger's vector, the density of the material, and the shear modulus, respectively. Also, at low temperatures B_n and B_s are assumed to be mainly due to the conduction electrons.

In addition, some interesting measurements have been made on some lead[8] and lead-based alloys[13] of the temperature dependence of the stress changes during the stress relaxation, $\Delta\sigma_R(t)$, associated with the superconducting transition at various reduced temperatures $t=T/T_c$ (where T is the temperature and T_c the critical temperature of the metal), and these results have been found to correspond approximately to the attenuation of an ultrasonic wave in a superconductor. It has also been suggested that the temperature dependence of the drag force on mobile dislocations in the superconducting state is similar to that of the attenuation of an ultrasonic wave in a superconductor.[4,14,15] It is of interest then to consider the influence of the magnetic field on the stress-relaxation (or flow stress) changes in some lead-based, type-II superconducting alloys since measurements and theories exist for the influence of the magnetic

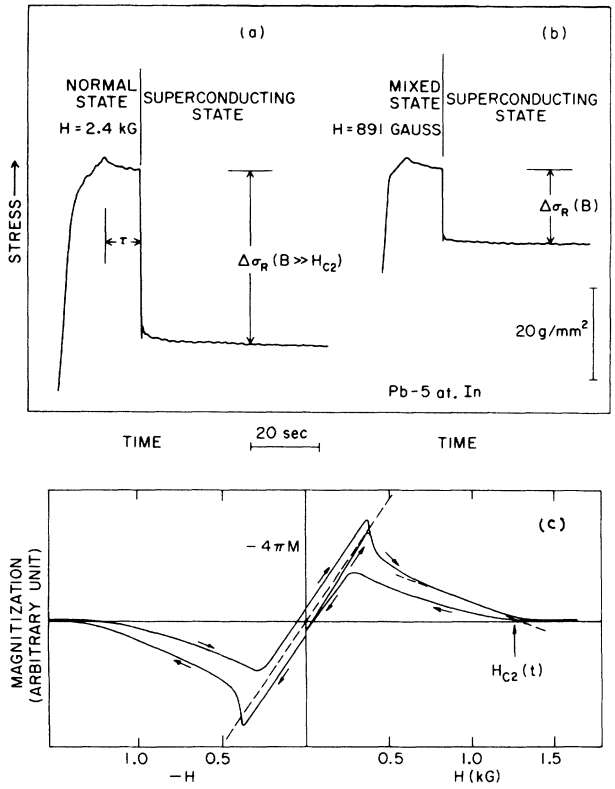

FIG. 1. Typical stress changes during stress relaxation as the applied magnetic field changed from (a) $H \geq H_{c2}$ and (b) $H_{c2} \geq H \geq H_{fp}$ to 0. (c) A magnetization curve of the Pb–5 at.% In single crystal.

fields on the ultrasonic wave attenuation in mixed-state, type-II superconductors. In this Letter, measurements of the magnetic field dependence of the stress changes, $\Delta\sigma_R(B)$, in single crystals of Pb–5 at.% In and Pb–10 at.% In are reported, and the results are compared with theories of the magnetic field dependence of ultrasonic attenuation of longitudinal waves, $\alpha(H)$, in a mixed-state superconductor. These results are discussed in terms of dislocation motion in metals, especially at low temperatures, and in relation to Eq. (1).

The stress-relaxation measurement consisted of deforming a specimen to a stress σ in a given magnetic field H, stopping the deformation for a period τ, and then switching the applied field to 0 [Figs. 1(a) and 1(b)]. A change in stress, $\Delta\sigma_R(B)$, is a function of both τ and σ in general; $\Delta\sigma_R(B \geq H_{c2})$ decreases slowly with increasing τ, and the significance of such an effect of τ on $\Delta\sigma_R$ has been discussed elsewhere, including methods of specimen preparation and testing techniques.[8] In alloys, $\Delta\sigma_R$ varies very little with increasing applied stress σ beyond the macroscopic yield stress of the alloys in contrast to the case for pure lead crystals.

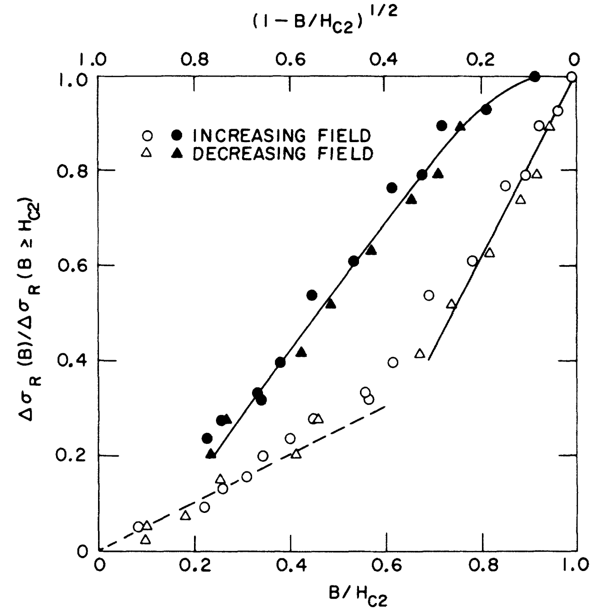

FIG. 2. The magnetic field dependence of stress changes $\Delta\sigma_R(B)$ as functions of B/H_{c2} (open symbols) and $(1-B/H_{c2})^{1/2}$ (closed symbols) for Pb–5 at.% In.

In the course of the experiment, complete magnetization curves were obtained before the initial deformation and after every two or three $\Delta\sigma_R(B)$ measurements so that the reduction in the cross-sectional area could be followed with increasing deformation. A typical magnetization curve is shown in Fig. 1(c).[16] In addition, the normal-state resistivity of the tensile specimen was also measured as a function of applied stresses by a standard four-probe, resistivity-measuring technique. Since the length and the cross-sectional area of the specimen vary as it is deformed, the measured resistivity ρ_n has to be corrected for such changes. The corrected values of ρ_n are found to be constant within the present experimental sensitivity. This is consistent with no observable change in H_{c2} since H_{c2} is a function of ρ_n.

Finally, by using magnetization curves, values of B were measured for each $\Delta\sigma_R(B)$, and the results plotted in a normalized form, e.g., $\Delta\sigma_R(B)/\Delta\sigma_R(B \geq H_{c2})$ vs B/H_{c2}, in Fig. 2. For the three alloys (two Pb–5 at.% In and one Pb–10 at.% In) which were tested, all showed nearly a parabolic dependence of $\Delta\sigma_R(B)/\Delta\sigma_R(B \geq H_{c2})$ on

B/H_{c2}. It is of interest to note that such a dependence of $\Delta\sigma(B)$ on B is the same, for all practical purposes, as the dependence of the ultrasonic attenuation on H in a mixed-state, type-II superconductor.[17] H_{c2} for the alloys was measured from magnetization curves using the criteria which were used by Farrell and Chandrasekhar,[18] as indicated in Fig. 1(c).

It is of interest to compare the present results with the theoretical mixed-state, longitudinal-wave ultrasonic attenuation calculations. Some pertinent theoretical results are first briefly summarized. For the type-II superconductors, the magnetic field behavior can be divided into three regions, (a) $H \gtrsim H_{fp}$, (b) $H_{fp} < H < H_{c2}$, and (c) $H \lesssim H_{c2}$, where H_{fp} is the initial flux-penetration field.

In the region (a), the longitudinal-wave electronic attenuation ratio $\alpha(B,t)/\alpha_n$ is proportional to B/H_{c2},[19] where $\alpha(B,t)$ and α_n are the attenuation for $H=0$ and for the normal state, respectively.

In the region (b), the theoretical expressions for the attenuation are on a qualitative basis,[20,21] and it has been suggested that a parabolic relationship between $\alpha(H)/\alpha_n$ and H should hold, e.g., $[1-\alpha(H)/\alpha_n] \propto (1-h)^{1/2}$, where $h=H/H_{c2}$.

Finally, for the region (c), a theoretical expression for $\alpha(H)/\alpha_n$ is given[22-24] as

$$\alpha(H)/\alpha_n = 1 - \frac{e\rho_N c}{8\pi^2 k_\mathrm{B} T_c} \frac{H_{c2}-H}{[2\kappa_2^2(t)-1]\beta} c_2(t), \tag{2}$$

where $c_2(t)$ is a universal function[22] of $t=T/T_c$ and $\beta = 1.16$.

We first give a qualitative comparison of the theoretical expressions for the electronic attenuation of a longitudinal ultrasonic wave with the present experimental data on the stress changes. In Fig. 2 it is seen that $\Delta\sigma(B)/\Delta\sigma(B \geqslant H_{c2})$ varies linearly with applied fields in the two regions (a) and (c). Also plotted in Fig. 2 is $\Delta\sigma(B)/\Delta\sigma(B \geqslant H_{c2})$ as a function of $(1-B/H_{c2})^{1/2}$; there is a large magnetic field region (b) where $\Delta\sigma(B)/\Delta\sigma(B \geqslant H_{c2})$ is linear with $(1-B/H_{c2})^{1/2}$. Hence, in all regions of H, a very good qualitative correlation between $\Delta\sigma(B)/\Delta\sigma(B \geqslant H_{c2})$ and $\alpha(B)/\alpha_n$ exists. Furthermore, one can make a quantitative comparison with the theoretical expression in region (c). We can obtain $\kappa_2(t)$ from Eq. (2) and also from a magnetization curve; the two independent values for $\kappa_2(t)$ so obtained are compared. Also, for simplicity, B and H are used interchangeably in the regions (b) and (c).

In order to obtain $\kappa_2(t)$ from the stress changes, it is reasonable to assume the following relationship between $\Delta\sigma_R(B)$ and $\alpha(B)$:

$$\frac{\Delta\sigma_R(B)}{\Delta\sigma_R(B \geqslant H_{c2})} = \frac{\sigma_R(B)-\sigma_R(0)}{\sigma_R(B \geqslant H_{c2})-\sigma_R(0)} = \frac{\alpha(B)-\alpha_s}{\alpha_n-\alpha_s} = \frac{\alpha(B)/\alpha_n - \alpha_s/\alpha_n}{1-\alpha_s/\alpha_n}. \tag{3}$$

Then from Eq. (2), $\kappa_2(t)$ can be calculated. Also, $\kappa_2(t)$ is obtained from the magnetization of the specimen[25] using $-4\pi(dM/dH)_{H=H_{c2}} = \{\beta[2\kappa_2^2(t)-1]\}^{-1}$. The calculated values of $\kappa_2(t)$ for alloys are $\kappa_2(\text{Pb}-5\text{ at.\% In}) = 1.44$ and 1.85 by the magnetization and by the stress relaxation methods, respectively; for Pb−10 at.% In, the respective values are 2.42 and 2.90. Recognizing that Eq. (2) is most applicable for $\kappa_2 \gg 1$, the values for $\kappa_2(t)$ which were determined by two methods are in reasonably good agreement for all the alloys tested. Also, the values of the measured-normal state resistivity of the alloys are probably higher than the actual values since the measurements of the cross-sectional area of the tensile specimens were made at the smallest part of the gauge sections. Such an overestimate of the resistivity also tends to increase values of $\kappa_2(t)$ in Eq. (2). Hence, an improvement in the resistivity measurements would, perhaps, decrease the present differences.

It is clear from these observations that some portion of the flow stress of Pb alloys is related to a frictional drag on dislocation motion from the conduction electrons. This is in very strong contrast to standard interpretations of flow-stress measurements, which generally involve only interactions of dislocations and defect barriers.[1] In addition, the frictional drag on dislocation motion by electrons in the superconducting state is thought to be similar to the electron attenuation of ultrasonic waves in the superconducting state as shown in the present experiment, e.g., $B_s/B_n \cong \alpha_s/\alpha_n$ in Eq. (1). The earlier experiment on the temperature dependence of $\Delta\sigma_R(t)$ for Pb indicated a similar result.[11]

In summary, the stress changes associated with the transition from the normal to the superconducting state were found to be in good agreement with the attenuation of an ultrasonic wave in the mixed-state type-II superconductors. This indicates that the resistance to motion of dislocations by the conduction electrons plays an important role in deformation processes at low temperatures, in contrast to ideas about totally thermally activated processes at barriers, and that the viscosity for dislocation in motion is closely related to the ultrasonic attenuation by electrons.

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Nuclear Quadrupole Interaction in Cadmium Metal

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The nuclear quadrupole interaction of the 247-keV level of ^{111}Cd in pure Cd metal has been measured by the time-differential perturbed angular correlation method. The interaction frequency $\nu_Q = (e^2qQ/h) = 125(1)$ MHz at 298°K. A measurement at 77°K shows an increase of ν_Q by 10% instead of a decrease expected from the contraction of the unit lattice of Cd metal.

Cadmium metal has been the subject of several recent solid-state investigations, both theoretical and experimental,[1] partly because of its exceptional nature among hcp metals. One of the few types of information which is still lacking is the quadrupole interaction (QI), presumably because the vanishing quadrupole moments of all stable Cd isotopes prevent the application of conventional resonance techniques. We report here the discovery of a strong QI in pure Cd metal at 298°K by the method of time-differential perturbed angular correlations (TDPAC) involving the 247-keV level in ^{111}Cd. An interaction of this strength has not been reported before although Kraushaar and Pound[2] attempted to measure it in the same level using the inherently less sensi-