the substrate film by a liquid-nitrogen cold trap. This retards oxidation, which is mainly due to the water vapor pressure as had been observed formerly.[6] The width of the observed edge (Fig. 1) is about 0.3 eV. This is in qualitative agreement with older results by Skinner and Johnston,[7] who have also remarked the final width of the edge. We thus believe that at least part of the width of the exciton peaks may be due to the limited lifetime of the empty K level, modified by the halogen ions.

We would like to thank Professor W. Jentschke and Professor P. Stähelin for their stimulating interest in our experiments, Professor T. Sasaki for helpful discussions, and the accelerator staff for operating the machine. We also thank the Deutsche Forschungsgemeinschaft for financial support.

[1]K. Teegarden and G. Baldini, Phys. Rev. 155, 896 (1966).
[2]A. P. Lukirskii, O. A. Ershov, T. M. Zimkina, and E. P. Savinov, Fiz. Tverd. Tela 8, 1787 (1966) [translation: Soviet Phys.—Solid State 8, 1422 (1966)].
[3]M. Creuzburg, Z. Physik 196, 433 (1966).
[4]R. Haensel and C. Kunz, Z. Angew. Phys. 23, 276 (1967).
[5]J. A. Bearden, Rev. Mod. Phys. 39, 78 (1967).
[6]C. Kunz, Z. Physik 196, 311 (1966).
[7]H. W. B. Skinner and J. E. Johnston, Proc. Roy. Soc. (London), Ser. A 161, 420 (1937).

INTERACTIONS OF DISLOCATIONS WITH ELECTRONS IN METALS

C. Elbaum and A. Hikata
Brown University, Providence, Rhode Island
(Received 9 October 1967)

Recently Hikata and Elbaum[1] reported experimental results on the interaction of moving dislocations with electrons in normal and in superconducting lead. One of their results was that in the normal state this interaction with electrons (or damping due to electrons) was independent of temperature, at least in the range investigated, i.e., $4.2 < T \lesssim 15$°K. The fact that this interaction is temperature independent can be interpreted qualitatively as follows: A Fourier decomposition of the lattice displacements u associated with a dislocation[2] yields

$$u = \sum_q u_q e^{i\vec{q}\cdot\vec{r}}.$$

Each component u_q may then be treated as a "phonon" traveling through the lattice with the dislocation velocity v_d (v_d is much smaller than the velocity of sound in the solid v_s; typically $v_d \leq 10^{-2} v_s$) and the energy lost by these "phonons" to the conduction electrons can be determined using the established formalism of electron-phonon interactions.[2,3] It is important to note that, for example, the atomic displacements associated with an edge dislocation decrease rapidly with distance from the dislocation core (at a distance from the core of the order of five atomic diameters, these displacements become comparable with the amplitude of thermal phonons near the Debye temperature θ_D), and that they are substantially temperature independent (their temperature dependence is of the order of the thermal expansion of the solid). It follows that the components u_q dominant in the interaction with electrons have magnitudes of the wave vector q ranging from approximately the reciprocal of the lattice spacing to the reciprocal of about 10 lattice spacings, i.e., $10^7 \lesssim |q| \lesssim 10^8$ cm^{-1}. Thus, for most temperatures of interest and certainly in the range $T \lesssim \theta_D$ these magnitudes of q correspond to the condition $ql_e \gg 1$, where l_e is the electron mean free path. It follows that the interaction of dislocations with conduction electrons should be treated in the spirit $ql_e \gg 1$ and is, therefore, independent of l_e.[2,4,5] Since $\vec{q}$ as well as the dislocation density are also temperature independent, the interaction process is temperature independent.

In another recent publication[6] Huffman and Louat presented results of a calculation of the dislocation-electron interaction which indicate a temperature dependence equal to that of the electrical conductivity.[7] These authors also propose that the temperature dependence of the mechanical yield stress of a metal is determined by the (calculated) temperature dependence of the dislocation-electron interaction.

It is clear that these calculations are not

consistent with the character of the interaction as discussed above and that the proposed temperature dependence conflicts with the experimental results of a direct measurement.[1] Furthermore, in order to correlate the energy W dissipated by the dislocations in the conduction electron gas with the macroscopic yield stress S, Huffman and Louat[6] equate W with the work done by S (both per atomic displacement of the dislocation). This procedure is certainly very questionable, because the stress S is very highly dependent on microstructural characteristics, impurity content, etc. The temperature dependence of S is also known experimentally to depend on these factors.

It should also be emphasized that the direct determination[1] of the conduction-electron interaction with dislocations specifically shows no temperature dependence in the temperature range where the calculations of Huffman and Louat[6] predict the largest temperature dependence of the entire range. The fact that these experiments[1] were carried out on a metal with the fcc structure seems irrelevant, since the calculation by Huffman and Louat[6] does not involve any crystallographic features and should apply equally well to all metals.

We conclude that the interaction of dislocations with conduction electrons is temperature independent (at least for $T < \theta_D$) and that the temperature dependence of the yield stress of metals is due to other causes.

[1]A. Hikata and C. Elbaum, Phys. Rev. Letters 18, 750 (1967).

[2]T. Holstein quoted by B. R. Tittmann and H. E. Bömmel, Phys. Rev. 151, 178 (1966).

[3]C. Kittel, Quantum Theory of Solids (John Wiley & Sons, Inc., New York, 1963).

[4]A. B. Pippard, Phil. Mag. 46, 104 (1955).

[5]V. Ya. Kravchenko, Fiz. Tverd. Tela 8, 927 (1966) [translation: Soviet Phys.—Solid State 8, 740 (1966)].

[6]C. P. Huffman and N. P. Louat, Phys. Rev. Letters 19, 518 (1967).

[7]A similar temperature dependence was also discussed by W. P. Mason, Phys. Rev. 143, 229 (1966).

NUCLEAR SPIN-LATTICE RELAXATION IN PURE AND IMPURE SUPERCONDUCTING INDIUM

J. Butterworth and D. E. MacLaughlin*†

Solid State Physics Division, Atomic Energy Research Establishment, Harwell, Didcot, Berkshire, England

(Received 8 January 1967)

Nuclear spin-lattice relaxation measurements in the superconducting state of pure indium and of indium-lead solid solutions show behavior consistent with an essentially impurity-independent broadening of the superconducting energy gap, this conflicting with previous ideas on the importance of energy-gap anisotropy.

Measurements of nuclear spin-lattice relaxation rate $R_S(T)$ in type-I superconductors have revealed the existence of a maximum in $R_S(T)/R(T_C)$ at $(T/T_C) \simeq 0.8$-0.9.[1-5] The maximum value of $R_S(T)/R(T_C)$, $[R_S(T)]_{max}/R(T_C)$, is always found to be smaller than that predicted by the unmodified BCS theory of superconductivity.[1,6] Two main explanations of this discrepancy have been favored so far. One attributes it to energy-gap anisotropy (EGA) over the Fermi surface.[2,4] The other invokes electron-phonon interactions and shows that, if these are sufficiently strong, they will broaden the conduction-electron energy levels and lead to the same results.[7]

If either of the mechanisms were dominant, its effects should be experimentally distinguishable by the dependence of $[R_S(T)]_{max}/R(T_C)$ on the concentration of nonmagnetic impurities in the superconductor since, according to Anderson's theory,[8] elastic scattering by solute atoms effectively reduces EGA. Consequently, if EGA is a controlling factor, the value of $[R_S(T)]_{max}/R(T_C)$ should increase with solute concentration.[4,9,10] On the other hand, electron-phonon interactions alone should yield a substantially constant value of $[R_S(T)]_{max}/R(T_C)$ since, in the dilute limit, the effect of impurities on the strength of electron-phonon interactions should be small.[11]

The only previous observations of $[R_S(T)]_{max}/R(T_C)$ in impure type-I superconductors were made by Masuda in aluminum-based solid solutions,[4] where he found distinct evidence in favor of the presence of EGA. We present here the results of measurements made in pure in-