

appropriate wave length. This flow of the entire electronic system will exert a uniform nonoscillating force and hence cannot excite phonons. In order to create new electron-spin excitations, a larger energy is required than a single quantum of translation can provide, unless the velocity of the general motion is high. The final possible source of resistance is a transfer of energy of general electron motion to the existing electron-spin excitations. Here, as in the case of the phonons, the force on the excitation must vary in space, whereas the general electron motion yields only a uniform force. These energy-transfer prohibitions are similar to those operating for the superflow in liquid He II.

We conclude that there is no mechanism for transfer of the energy of a slow motion of the entire electronic system. Thus we have the infinite conductivity without any conflict with the Bloch theorem, which requires the state with current flow to have higher energy than the state of zero current.

We have already noted the proof by Bardeen<sup>2</sup> that an energy-level system of this type will show the Meissner effect.

Recently Corak and collaborators<sup>10</sup> showed that the electronic heat capacity of superconductors at temperatures below follows  $T_c$  the exponential equation

$$C = \gamma T_c a e^{-bT_c/T}, \quad (3)$$

where the constants  $a$  and  $b$  have values near 9.17 and 1.50, respectively, for several metals. The energy-level pattern given by our theory yields just this type of equation with  $\epsilon = b k T_c$ . This is evidence for our earlier assumption that the transition temperature is proportional to the energy of excitation  $\epsilon$ .

Since our energy term  $\epsilon \cong k T_c$  depends primarily on conduction electron-lattice interactions which are the cause of resistance in the normal metal, we may conclude that  $T_c$  will be roughly proportional to the resistance for metals with equal densities of conduction electrons. While superconductors generally have high resistance in the normal state, one cannot claim that any such quantitative relationship holds. The variety of complicating conditions, however, is such that lack of quantitative agreement is not surprising.

We should note that, in contrast to the proposals of Frohlich and Bardeen,<sup>11</sup> our theory gives no minimum magnitude of lattice interaction below which the metal will fail to become superconducting even at 0° K. We predict merely that  $T_c$  will be much lower for metals with small lattice interaction. However, there is another source of interference with superconductivity which will prevent some metals from attaining that state even at absolute zero. This is atomic magnetic moment from inner electron shells or possibly even nuclear magnetic moment. If the effective magnetic field from this source exceeds the critical field for superconductivity, then no superconductivity occurs. This effect eliminates ferromagnetic (also probably antiferromagnetic) metals from the list of possible superconductors. Since the critical field  $H_0$  is roughly proportional to  $\epsilon$  (and to  $T_c$ ), even the nuclear magnetic moment might prevent superconductivity in cases where  $\epsilon$  is very small. However, tests for superconductivity have not been pushed to low enough temperatures and external fields to make the nuclear moment an important criterion yet.

We believe that we have here the basis for a theory of superconductivity. It yields the observed properties of the superconductive state near 0° K. At a later

date we hope to discuss the nature of the transition to the normal state and, if possible, to add some more quantitative aspects to the general theory.

The writer wishes to thank the Guggenheim Foundation for a fellowship and Oxford University for its hospitality during the period this paper was being prepared.

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<sup>2</sup> J. Bardeen, *Phys. Rev.*, **97**, 1724, 1955.

<sup>3</sup> See the treatment of Feynman, in C. J. Gorter (ed.), *Progress in Low Temperature Physics* (Amsterdam: North Holland Publishing Co., 1955), chap. ii.

<sup>4</sup> See, for example, R. E. Peierls, *Quantum Theory of Solids* (London: Oxford University Press, 1955), p. 108.

<sup>5</sup> L. Pauling, *Nature of the Chemical Bond* (2d ed.; Ithaca, N.Y.: Cornell University Press, 1945), p. 402; *Proc. Roy. Soc. London, A*, **196**, 343, 1949.

<sup>6</sup> C. A. Reynolds, B. Serin, and L. B. Nesbitt, *Phys. Rev.*, **84**, 691, 1951.

<sup>7</sup> J. M. Lock, A. B. Pippard, and D. Shoenberg, *Proc. Cambridge Phil. Soc.*, **47**, 811, 1951.

<sup>8</sup> D. Pines, *Phys. Rev.*, **92**, 626, 1953; see also D. Bohm and D. Pines, *Phys. Rev.*, **85**, 338, 1952; **92**, 609, 1953.

<sup>9</sup> See T. E. Faber and A. B. Pippard, in C. J. Gorter (ed.), *Progress in Low Temperature Physics* (Amsterdam: North Holland Publishing Co., 1955), chap. ix.

<sup>10</sup> W. S. Corak, B. B. Goodmann, C. B. Satterthwaite, and A. Wexler, *Phys. Rev.*, **102**, 656, 662, 1956.

<sup>11</sup> J. Bardeen, *Revs. Mod. Phys.*, **23**, 261, 1951, and references there cited, including H. Fröhlich, *Phys. Rev.*, **79**, 845, 1950.