*Work supported by the U. S. Army Research Office (Durham) under Grant No. DA-ARO-D-31-124-G844.

†Alfred P. Sloan Research Fellow.

[1]Yu. V. Sharvin, Zh. Eksperim. i Teor. Fiz.—Pis'ma Redakt. 2, 287 (1965) [translation: JETP Letters 2, 183 (1965)]; in Proceedings of the Tenth International Conference on Low Temperature Physics, 1966 (to be published).

[2]Other convincing experiments are the dc-transformer (coupled-superductor) experiments done independently by Giaever and Solomon: I. Giaever, Phys. Rev. Letters 15, 825 (1965); P. R. Solomon, Phys. Rev. Letters 16, 50 (1966).

[3]B. S. Chandrasekhar, D. E. Farrell, and S. Huang, Phys. Rev. Letters 18, 43 (1967).

[4]The superconducting transition temperature of the microscopic bridge (in the presence of current flow) is lower than that of the macroscopic thin-film patches connected by the bridge because of the higher current density in the bridge. Therefore the measured resistance comes entirely from the microbridge.

[5]Yu V. Sharvin, Zh. Eksperim. i Teor. Fiz. 33, 1341 (1957) [translation: Soviet Phys.—JETP 6, 103 (1958)].

[6]The peculiar shape of the peaks (spiked structure) is presumably due to the nonlinear response of the probe to the magnetic field. This is of no serious consequence in the present experiment since the purpose was to measure only the position of the laminas. The asymmetry of the peaks is perhaps due to sample surface roughness effects which could affect the probe-to-sample distance and hence the probe reading.

[7]C. J. Gorter, Physica 23, 45 (1957).

[8]This may be a type-II superconductor or a sufficiently thin type-I superconductor in a perpendicular field —e.g., see G. Lasher, Phys. Rev. 154, A347 (1967).

ELECTRON SCATTERING IN NICKEL AT LOW TEMPERATURES

G. K. White and R. J. Tainsh
Commonwealth Scientific and Industrial Research Organization, Division of Physics, Sydney, Australia
(Received 5 June 1967)

The electrical resistivity of pure metals at low temperatures can be expressed as the sum of two terms: an impurity scattering term ρ_0, which is constant, and an "ideal" term ρ_i, which is temperature dependent. In monovalent metals and others which do not belong to the transition or rare-earth groups,

$$\rho_i \approx cT^n,$$

where $n \approx 5$ for $T \ll \theta$.

By contrast it has been observed[1-4] in many transition elements (including the ferromagnets Fe, Co, and Ni) that a T^2 rather than T^5 term predominates at low enough temperatures. Of the order of $10^{-11}T^2$ Ω cm in magnitude, it was first observed in platinum and attributed[5] to mutual interaction of itinerant electrons from different parts or branches of the Fermi surface. In the case of the ferromagnetic metals an alternative explanation was suggested, namely scattering by spin waves or magnons.[6]

In order to resolve which of these explanations is the more important for the ferromagnets, we have measured both the electrical and thermal resistivities on a rod of high-purity nickel[7] (resistivity ratio $\rho_{273}/\rho_4 \approx 2500$). As in the electrical case, the thermal resistivity W can be separated into an impurity term, $W_0(=A/T)$, and an "ideal" term, W_i, i.e., $W = W_0 + W_i$. For many monovalent metals $W_i \approx CT^m$, where $m \approx 2 (T \ll \theta)$.

If electron-electron interaction is important, a term should be observed in the thermal resistivity[8] W which corresponds to the T^2 term in ρ; this term would be proportional to T and give rise to a Wiedemann-Franz-Lorenz ratio, $L_i = \rho_i / W_i T$, having a constant finite value as the temperature approaches 0. On the other hand, if electron-magnon scattering is a major source of resistance, then we should expect this ratio L_i to decrease noticeably at low temperatures: Interband scattering by magnons will become frozen out at temperatures below, say, 20°K in nickel as the wave vector of the excited spin waves becomes smaller.[9] Likewise, intraband scattering by magnons should cause a very low Lorenz ratio as $T \to 0$ because of its inelastic nature.

Our observations show that below 20°K,

$$\rho = \text{constant} + bT^2$$

and

$$WT = \text{constant} + bT^2,$$

i.e., $W = A/T + BT$. Figure 1 illustrates this dependence and the rather puzzling fact that the magnitude of the T^2 term increases significantly below 5°K.[10]

Thus from 5 to 20°K,

$$\rho_i \approx 26 \times 10^{-12} T^2 \ \Omega \text{ cm}$$

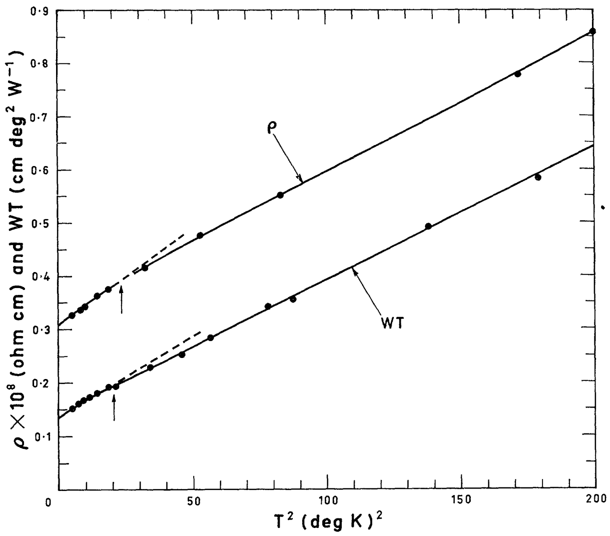

FIG. 1. Graphical deduction of the important terms in the electrical resistivity (ρ) and thermal resistivity (W): below *ca* 20°K, both ρ and WT are well represented by an expression of the form $a + bT^2$. Some points below 5°K have been omitted for the sake of clarity.

(c.f. ~$20\times10^{-12}T^2$ in previous measurements[2,4]), and

$$W_i \approx 25\times10^{-4}T \text{ cm deg } W^{-1}$$

from which

$$L_i \approx 1.0\times10^{-8}V^2 \text{ deg}^{-2}.$$

Below 4°K,

$$\rho \approx 34\times10^{-12}T^2,$$

and

$$W_i \approx 34\times10^{-4}T,$$

so that L_i remains constant down to the lowest temperatures of observation (Fig. 2). Indeed, in the region from 20 to 50°K also, L remains fairly constant despite the fact that ρ_i and W_i vary more rapidly, approximately as T^3 and T^2, respectively.

If L is calculated from the total observed resistivities, then it approaches the Sommerfeld value of $2.4\times10^{-8}V^2$ deg K^{-2} at the lowest temperatures where elastic scattering by impurities predominates.

The magnitude of L_i implies that the effective mean free path or relaxation time for the conduction electrons when engaged in thermal transport is almost half that when engaged in electrical transport. Since it remains nearly constant down to the lowest temperatures of measurement (~2°K), it is unlikely that scat-

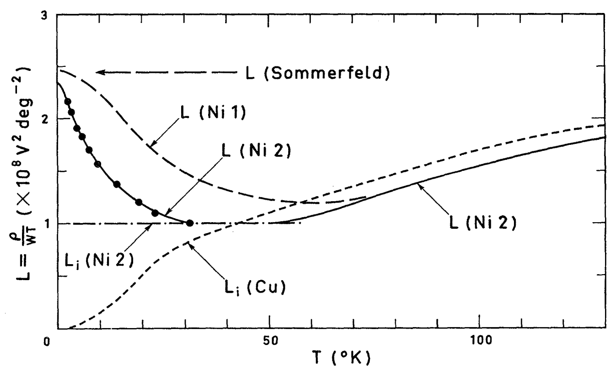

FIG. 2. Variation of Lorenz ratio, $L = \rho/WT$ and $L_i = \rho_i/W_iT$ for nickel. Data for Ni 1 are from White and Woods (Ref. 2) and Ni 2 is the present high-purity sample.

tering by spin waves can be important. We conclude that the temperature-dependent terms arising at low temperatures originate chiefly in interaction between itinerant electrons.

We are indebted to Dr. Conyers Herring and Dr. J. G. Collins for very interesting correspondence and discussions of these problems in electron transport.

[1]W. J. de Haas and J. de Boer, Physica 1, 609 (1933).

[2]G. K. White and S. B. Woods, Phil. Trans. Roy. Soc. London. Ser. A 251, 273 (1959).

[3]N. V. Volkenshteyn, L. S. Starostina, V. Ye Startsev, and Ye. P. Romanov, Fiz. Metal. i Metalloved. 18, 85 No. 6 (1964) [translation: Phys. Metals Metallog. (USSR) 18, 888 (1964)].

[4]A. I. Sudovtsov and E. E. Semenenkov, Zh. Eksperim. i Teor. Fiz. 31, 525 (1956) [translation: Soviet Phys.—JETP 4, 592 (1957)]; also E. Kondorsky, O. S. Galkina, and L. A. Tchernikova, J. Appl. Phys. 29, 243 (1958); P. Radhakrishna and M. Nielsen, Phys. Status Solidi 11, 111 (1965).

[5]W. G. Baber, Proc. Roy. Soc. (London) A158, 133 (1937); see also J. Appel, Phil. Mag. 8, 1971 (1963).

[6]T. Kasuya, Progr. Theoret. Phys. (Kyoto) 22, 227 (1959); A. E. Turov, Fiz. Metal. i Metalloved. 6, 13 No. 2 (1958) [translation: Phys. Metals Metallog. (USSR) 6, 203 (1958)]; D. A. Goodings, Phys. Rev. 132, 542 (1963); A. Hasegawa, S. Wakoh, and J. Yamashita, J. Phys. Soc. Japan 20, 1865 (1965).

[7]A nickel crystal, given to us through the kindness of Dr. E. Fawcett, was prepared by V. J. Albano and R. Soden at Bell Telephone Laboratories, Murray Hill, New Jersey. We rolled it to suitable dimensions (0.1 cm × 0.1 cm × 7 cm) and annealed it at *ca* 500°C in vacuum of 10^{-7} Torr.

[8]D. Pines, Can. J. Phys. 34, 1379 (1956); also J. Ziman, Electrons and Phonons (Oxford University Press, Oxford, England, 1960), p. 417.

[9]C. Herring, private communication.

[10]A plot on larger scale shows clearly that both ρ and WT vary as T^2 between 2 and 4°K.