from the anomalous lattice expansion near T_c. The question that remains, which can be answered only by further experimentation, is whether critical lattice effects play a dominant role in the explanation of the resistivity maximum near T_c observed in other systems (e.g., $GdNi_2$[6] and $GdPt_2$[5]).

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[1]P. P. Craig, W. I. Goldburg, T. A. Kitchens, and J. I. Budnick, Phys. Rev. Lett. 19, 1334 (1967).

[2]F. C. Zumsteg and R. D. Parks, Phys. Rev. Lett. 24, 520 (1970).

[3]D. C. Wallace, P. H. Sidles, and G. C. Danielson, J. Appl. Phys. 31, 168 (1960).

[4]H. E. Nigh, S. Legvold, and F. H. Spedding, Phys. Rev. 132, 1092 (1963).

[5]M. P. Kawatra, J. A. Mydosh, and J. I. Budnick, Phys. Rev. B 2, 665 (1970).

[6]M. P. Kawatra, S. Skalski, J. A. Mydosh, and J. I. Budnick, Phys. Rev. Lett. 23, 83 (1969).

[7]P. G. de Gennes and J. Friedel, J. Phys. Chem. Solids 4, 71 (1958).

[8]M. E. Fisher and J. S. Langer, Phys. Rev. Lett. 20, 665 (1968).

[9]F. J. Cadieu and D. H. Douglass, Jr., J. Appl. Phys. 40, 2376 (1969).

[10]F. C. Zumsteg, F. J. Cadieu, S. Marčelja, and R. D. Parks, in Fordham Conference on Dynamic Aspects of Critical Phenomena, 1970 (to be published).

[11]R. M. Bozorth and T. Wakiyama, J. Phys. Soc. Jap. 18, 97 (1963).

[12]F. J. Cadieu and D. H. Douglass, Jr., Phys. Rev. Lett. 21, 680 (1968).

[13]V. M. Kontorovich, Zh. Eksp. Teor. Fiz., Pis'ma Redakt. 4, 189 (1966) [JETP Lett. 4, 129 (1967)].

[14]It is interesting to note that Eq. (2) is precisely the functional form of the resistivity above T_c due to spin-disorder scattering according to the (mean-field) de Gennes–Friedel model (Ref. 7). Thus, an examination of the functional form only of the resistivity above T_c does not allow one to separate lattice effects from spin-disorder scattering effects calculated in the mean-field approximation.

[15]The approximate size of the region where the spin-disorder scattering is strong can be deduced from the a-axis resistivity data.

[16]R. A. Stager and H. G. Drickamer, Phys. Rev. 133, A830 (1964).

[17]I. Wakabayashi, H. Kobayashi, H. Nagasaki, and S. Minomwa, J. Phys. Soc. Jap. 25, 227 (1968).

Magnon Heat Conduction and Magnon-Electron Scattering in Fe-Ni

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The thermal and electrical conductivities of several transition alloys have been measured at low temperatures at high magnetic fields. The Permalloys 70Ni-30Fe and 81Ni-19Fe show a 3% magnon conductivity at 4 K. The temperature dependence of the magnon conductivity for these two alloys implies that the magnons are scattered by the electrons through the s-d exchange.

Magnon thermal conductivity has already been observed in ferromagnetic and antiferromagnetic insulators[1-3] and there is some evidence of such conduction in the ferromagnetic rare earths,[4] but there is no similar evidence in transition metals. We have measured the thermal and electrical conductivities of several transition alloys in the temperature range 1.2-4.5 K and in magnetic fields up to 6 T. The results for the Permalloys 81Ni-19Fe and 70Ni-30Fe are consistent with a model for magnon thermal conduction which assumes s-d exchange scattering of magnons by the conduction electrons.

The apparatus is conventional, using carbon resistance thermometers with an ac phase-sensitive bridge. With it we have been able to make measurements accurate to about 0.2% in most cases.

For the 70Ni-30Fe alloy, the thermal conductivity was measured at zero external field ($B_E = 0$) and at three longitudinal fields above saturation. The curve showing the difference in the thermal conduction from $B_E = 0$ to $B_E = 0.781$ T (Fig. 1) can be predicted[5] from the corresponding variation of the electrical conductivity by assuming that the Wiedemann-Franz law is obeyed, i.e., that the change is an electronic effect. This law should hold exactly for these alloys since

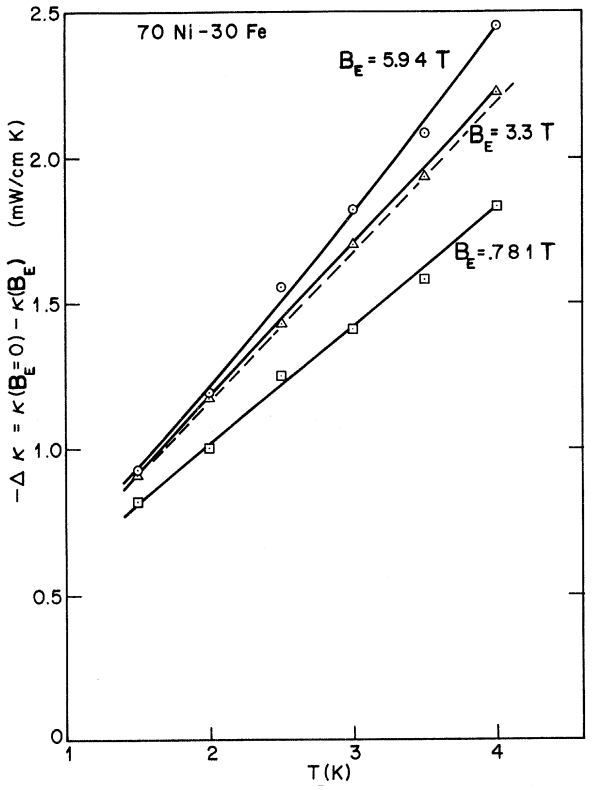

FIG. 1. The change in thermal conductivity for several applied fields B_E as compared with the thermal conductivity at $B_E = 0$. The dashed curve is the computed change for 3.3 T based on the change from 0.781 to 5.94 T.

electron scattering is by impurities and is elastic. If there is a change in the magnon thermal conductivity for these fields, it would not be seen because it is much smaller than the electronic change and is lost in the uncertainties of the Wiedemann-Franz calculation. However, the data for the two higher fields cannot be explained on the basis of the change in the electrical conductivity by using the Wiedemann-Franz law and must therefore be due to the changing magnon thermal conductivity.

The contribution of phonons to the heat flux is appreciable, but it is independent of magnetic field because the phonons are scattered by the electrons, for which the relaxation time is much less than the cyclotron period at all fields.

In order to analyze the data further, it is necessary to assume some model for the magnon thermal conductivity and see if it describes consistently the magnetic-field and temperature dependence.

The thermal conductivity of the magnon gas is

$$\kappa_m = \tfrac{1}{3}\sum c v^2 \tau_m, \qquad (1)$$

where c is the specific heat, v the group velocity, and τ_m the lifetime of a magnon mode. If we take some average over frequency for τ_m (where the average, $\bar{\tau}_m$, may be temperature dependent) then[2]

$$\kappa_m = \frac{k_B^{7/2} T^{5/2}}{3\pi^2 \hbar^2 D^{1/2}} \bar{\tau}_m \int_0^{+\infty} \frac{(x+y)^2 x^{3/2} e^{x+y}}{(e^{x+y}-1)^2} dx, \qquad (2)$$

where $x = \hbar\omega/k_B T$, $y = g\beta B_{\text{eff}}/k_B T$, and $D = \hbar\omega/q^2$ is the exchange stiffness for the alloy. If we denote the integral by $J(y)$ in Eq. (2), then $J(y)/J(0) = J(y)/13.1$ represents the fraction of the magnon thermal conductivity that remains at a given B_{eff} and T as compared with the magnon thermal conductivity at that temperature at $B_{\text{eff}} = 0$. If τ_m varies slowly with frequency, this model should work. By using $B_{\text{eff}} = B_E = (13/45)M_s$ (MKS units), where M_s is the saturation magnetization, we automatically take into account the long-range dipole-dipole energy of the magnons[6,7] and its effect on both the specific heat and velocity in Eq. (1)[8] for longitudinal fields.

By subtracting the experimental curve at $B_E = 5.94$ T from that at 0.781 T (Fig. 1) and using Eq. (2), κ_m can be calculated for $B_{\text{eff}} = 0$. As a consistency check, the thermal conductivity at $B_E = 3.3$ T is calculated by Eq. (2) and is plotted as the dashed curve in Fig. 1. It agrees very well with the data taken at that field and is evidence that Eq. (2) is applicable. Since the results are calculated separately at each temperature, we do not use the constants in front of the integral.

At $B_{\text{eff}} = 0$ we find $\kappa_m \propto T^{2.1}$ (Fig. 2). According to Eq. (2), therefore, $\bar{\tau}_m \propto T^{-0.4}$. We can calculate $\bar{\tau}_m$ from Eq. (2) and the value[9] $D = 3.83 \times 10^{-40}$ J m^2. At 4 K we get $\bar{\tau}_m = 1.75 \times 10^{-10}$ sec. Since the expression under the integral in Eq. (2) is peaked at $\hbar\omega = 3.2 k_B T$, we associate the calculated lifetime with that frequency and hence derive an $\omega^{-0.4} \simeq \omega^{-1/2}$ dependence for the lifetime. A better model may be obtained by putting this dependence back into the original integral and recalculating. We get

$$\kappa_m = \frac{b k_B^3 T^2}{3\pi^2 \hbar^{3/2} D^{1/2}} \int_0^{+\infty} \frac{e^{x+y}(x+y)^{3/2} x^{3/2}}{(e^{x+y}-1)^2} dx, \qquad (3)$$

where $\tau_m = b\omega^{-1/2}$. If we now use the same procedure to calculate κ_m as before, we get (as we would hope) essentially the same results, although the temperature dependence is now closer to the predicted T^2 than to $T^{2.1}$.

The electrical resistivity for this sample

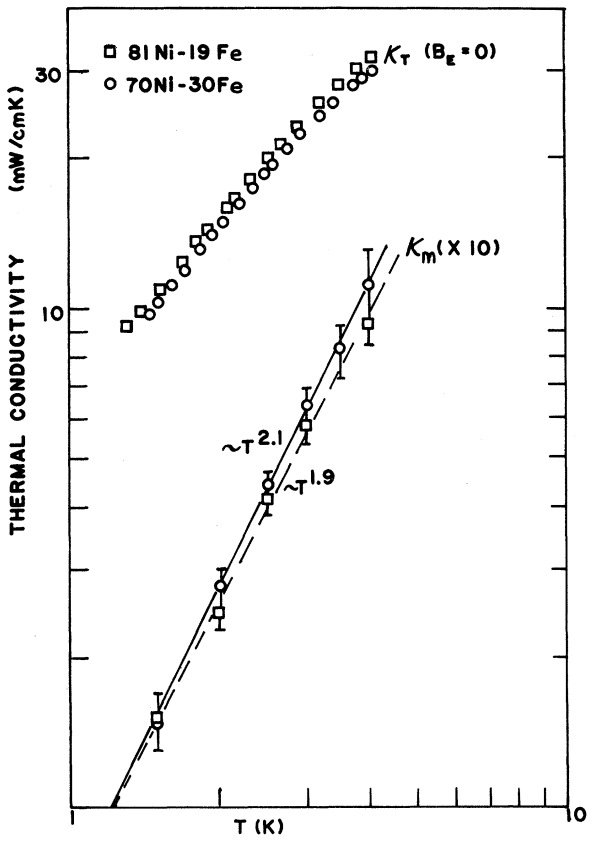

FIG. 2. The calculated magnon thermal conductivity at $B_{\text{eff}}=0$ for both nickel-iron alloys and the total thermal conductivity at $B_E=0$. The points were calculated by linear interpolation from the raw data and are only taken at half-degree steps.

shows a marked peak at about 0.1 T which probably occurs when the domains in the sample start rotating. This peak has been observed in other Permalloys.[5] However, the thermal conductivity data that we use were all taken at or above 0.781 T, in a region where the magnetoresistance is well behaved and only very slowly varying, with $\rho \approx 4.24\times10^{-8}$ Ω m. Therefore, the Wiedemann-Franz law can be used easily to correct for the electronic change in the thermal conduction above saturation.

The thermal conductivity was also measured for 81Ni-19Fe and the results (Fig. 2) are remarkably similar to that of the other alloy. Using[9] $D=4.04\times10^{-40}$ J m^2 the magnon conductivity varies as $T^{1.9}$, and is equal to that of the other alloy to within 10% over the temperature range studied. Above saturation, $\rho \approx 4.32\times10^{-8}$ Ω m.

The lifetime deduced from Eq. (2) and the constant b from Eq. (3) again give consistent results, and b is the same for the two alloys to within the errors of measurement. The value $b=(21\pm2)\times10^{-5}$ sec$^{1/2}$ predicts $\tau_m=3.5\times10^{-10}$ sec at 57.8 GHz as compared with 6.2×10^{-10} sec measured at that frequency by linewidth of spin-wave resonance (SWR).[9] This can be considered good agreement in light of the uncertainties involved in the extrapolation.

In the s-d exchange model,[10] magnons are scattered by the conduction electrons through an s-d exchange integral J_{sd}. At low temperatures this gives $\tau_m \propto \omega^{-1/2}$. The value is predicted to be about 10^{-10} sec for thermal magnons at 10 K in agreement with our experimental value. However, there is considerable uncertainty in the value of J_{sd} and the predicted lifetime could differ considerably from that value. If a momentum gap exists between spin-up and spin-down s electrons at the Fermi surface, then magnons with less than that momentum cannot be scattered by the s-d exchange. Note, however, that the magnons excited in the thermal conductivity measurements are typically an order of magnitude higher in energy than magnons excited by SWR. Therefore, this momentum gap is less likely to be important. In addition, it seems probable that the "smearing" of the bands that occurs on alloying will reduce the size of the gap as compared with the pure metal.

Other mechanisms are often considered in the damping of magnons in metals but they can be ruled out for various reasons. The lifetime for magnon-impurity scattering varies as $\omega^{-2.5}$, yielding a magnon thermal conductivity that is virtually independent of temperature.[11] Eddy-current damping of the magnons gives $\tau_m \propto \omega^{1/2}$ and hence $\kappa_m \propto T^3$, as compared with our measured T^2. Moreover, the lifetime predicted is a factor of 10 too large. Inhomogeneous broadening should also be relatively unimportant since our bulk samples were homogenized for 48 h near their melting point and are quite uniform. In addition, the grain size (0.1-0.5 mm) is large compared with the mean free path ($\Lambda \simeq 2000$ Å) of the magnons, and boundary scattering is negligible.

Measurements on 67Ni-33Cu failed to show any magnetic-field dependence of the thermal conductivity above saturation. From this, using Eq. (2) and the value[12] $D=2.03\times10^{-40}$ J m^2, we can set $\tau_m < 3\times10^{-11}$ sec. This probably indicates that the magnons are strongly scattered by the magnetic disturbances on the copper sites. It is well known that the nickel atoms near the copper sites have reduced magnetic moments,[13] increasing the size of the defect. In addition, clusters have been

observed in these alloys, clouds of greater or lesser than average magnetization. These may be due to some metallurgical process like precipitation[14] or may be due simply to statistical fluctuations.[15] Furthermore, in Ni-Cu "soft," resonant, localized magnon states may be available at very low energies into which the magnons may be easily scattered.[16] All of these factors can reduce the magnon lifetime and thus our upper limit seems reasonable. Unfortunately, existing papers on SWR in these alloys do not report a linewidth.[12]

These are the first observations of magnon thermal conduction in transition metals. At 4 K the magnons contribute only about 3% of the total conductivity, but since our samples are alloys, the change of the electronic and phonon conductivities with magnetic field is much less than that. Thus we have been able to draw several conclusions about the behavior of the magnons in these metals. The results for the Ni-Fe alloys indicate that the magnons are scattered with $\tau_m \propto \omega^{-1/2}$. The only mechanism which gives this frequency dependence and predicts the correct order of magnitude for τ_m is s-d exchange scattering by electrons.

[1]S. A. Friedberg and E. D. Harris, in *Proceedings of the Eighth International Conference on Low Temperature Physics, Washington, D. C., 1962,* edited by R. O. Davies (Butterworths, London, 1963), p. 302; B. Luthi, J. Phys. Chem. Solids 23, 35 (1962).
[2]D. C. McCollum, R. L. Wild, and J. Callaway, Phys. Rev. 136, A426 (1964).
[3]J. E. Rives and D. Walton, Phys. Lett. 27A, 609 (1968).
[4]G. S. Nikolskii and V. V. Eremenko, Phys. Status Solidi 18, K123 (1966).
[5]L. Berger and D. Rivier, Helv. Phys. Acta 35, 715 (1962).
[6]T. Holstein and H. Primakoff, Phys. Rev. 58, 1098 (1940).
[7]S. H. Charap, Phys. Rev. Lett. 13, 237 (1964).
[8]W. B. Yelon and L. Berger, to be published.
[9]M. H. Seavey, Phys. Rev. 170, 560 (1968).
[10]E. A. Turov, Izv. Akad. Nauk SSSR, Ser. Fiz. 19, 462 (1955) [Bull. Acad. Sci. USSR, Phys. Ser. 19, 414 (1955)]; A. H. Mitchell, Phys. Rev. 105, 1439 (1957).
[11]P. Erdos, Phys. Rev. 139, A1249 (1965).
[12]H. Nose, J. Phys. Soc. Jap. 16, 2473 (1961).
[13]J. W. Cable, E. O. Wollan, and H. R. Child, Phys. Rev. Lett. 22, 1256 (1969).
[14]S. C. Moss, Phys. Rev. Lett. 23, 381 (1969).
[15]J. P. Perrier, B. Tissier, and R. Tournier, Phys. Rev. Lett. 24, 313 (1970).
[16]Y. A. Izyumov and M. V. Medvedev, Zh. Eksp. Teor. Fiz. 49, 1887 (1965) [Sov. Phys. JETP 22, 1289 (1966)].

Reaction Q Values from Near-Threshold Neutron Spectra*

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A thick-target time-of-flight technique has been employed to measure neutron energies for (p,n) resonance levels near threshold in medium-weight nuclei. Combining the results with proton energy measurements of these resonances, the following ground state (p,n) Q values have been deduced: ^{41}K, -1203.8 ± 0.5 keV; ^{45}Sc, -2843.6 ± 4.0 keV; ^{51}V, -1533.7 ± 1.5 keV; and ^{57}Fe, -1618.2 ± 2.0 keV.

Parks et al.[1] have shown by a direct measurement of proton energy, and an indirect measurement of neutron energy, that the first compound nuclear resonance to be reached in the reaction $^{40}\mathrm{Ar}(p,n)^{40}\mathrm{K}$ lies 3 keV above the true reaction threshold. Johnson, Trail, and Galonsky[2] comment upon this case but point out that there is little other direct evidence for "resonance errors" in Q-value determinations from (p,n) threshold measurements, although the possibility of such errors has long been recognized.[3,4] In fact, Parks et al. state that Johnson, Trail, and Galonsky misinterpreted the Duke results. Thus, even for the reaction $^{40}\mathrm{Ar}(p,n)$ adequate data does not exist for demonstrating a resonance error in Q-value determination from a thick-target threshold measurement. We wish to report a direct measurement of both proton and neutron energies for the reaction $^{41}\mathrm{K}(p,n)^{41}\mathrm{Ca}$ which shows that for this reaction a sub-