of the relative magnitudes of d-orbital and d-spin hyperfine interactions in dilute paramagnetic alloys.

We wish to thank D. C. Barham for his experimental assistance.

*Work supported by the U. S. Atomic Energy Commission.

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Electron Transport and Lorenz Number in Iron*

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(Received 6 July 1970)

Measurements of the electrical and thermal resistivity in longitudinally saturated ⟨111⟩ iron crystals provide evidence that the temperature-dependent transport is dominated by electron-electron scattering from 0.28 to 20°K. The ideal Lorenz number is nearly constant below 40°K and has a value of 1.09×10^{-8} W Ω/deg^2 from 40 to 6°K and a value of 1.16×10^{-8} W Ω/deg^2 below 6°K.

We have measured both the electrical and thermal resistivity of iron single crystals in the range 2 to 77°K. In addition, electrical resistivity has been measured down to a temperature of 0.28°K. Measurements have been carried out in zero magnetic fields and in applied longitudinal magnetic fields up to values sufficient to saturate the specimen as a single domain along the measuring length. Specimens with both ⟨100⟩ and ⟨111⟩ axial orientations have been used with ratios $R(295°K)/R(4.2°K)$ between 700 and 2000. The data reported here are limited mainly to the ⟨111⟩ axial orientation in the single-domain saturated state.

Our measurements have indicated that the single-domain ⟨111⟩ crystals give the most reproducible results on the temperature dependence of electrical and thermal resistivity. Measurements in the multidomain state show large magnetic contributions which alter substantially both the magnitude and temperature dependence of the transport and make the interpretation of results complex.

Herring[1] has given a theoretical analysis which suggests that for transition metals with complex Fermi surfaces and in which electron-electron scattering dominates the temperature-dependent transport at low temperature, the ideal Lorenz number ($L_i=\rho_i/W_iT$) should reach a constant value at low temperature equal to 1.58×10^{-8} W Ω/deg^2. (This number is the corrected number; see Erratum, Ref. 1.) ρ_i and W_i are the intrinsic electrical and thermal resistivities, respectively. White and Tainsh[2] have reported data on nickel which tend to support this prediction for a magnetic transition metal. A number of experiments[3,4] on nonmagnetic transition metals also provide evidence that this prediction may have general validity although the exact value of the Lorenz number may depend somewhat on the particular metal.[5]

The data reported here for single-domain longitudinally saturated ⟨111⟩ iron crystals appear to indicate that Herring's prediction may

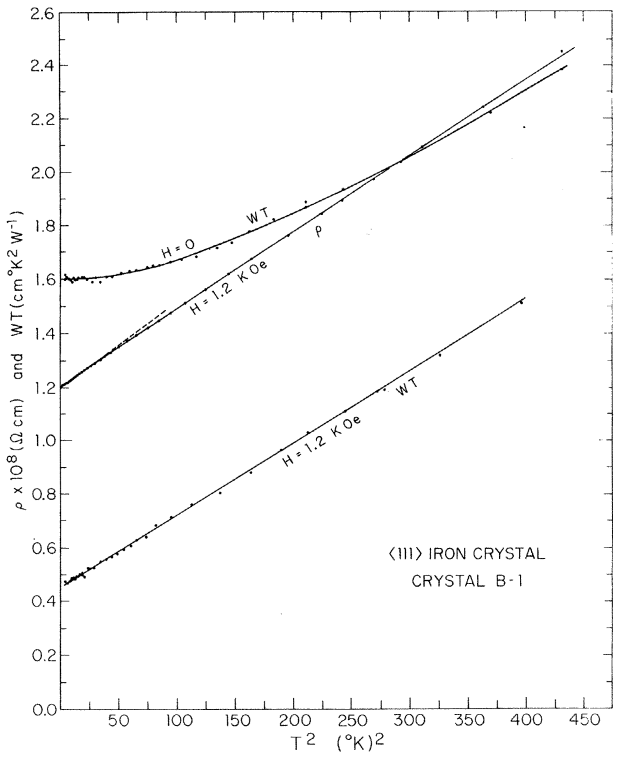

FIG. 1. Electrical resistivity ρ and thermal resistivity times temperature WT vs T^2. Lower two curves are for the single-domain longitudinally saturated state. Upper curve shows WT for the $\tilde{H}=0$ multidomain state.

also hold fairly well for iron in the low-temperature region. If electron-electron scattering dominates the temperature dependence of resistivity, then ρ_i and W_iT would be expected to vary as T^2 at temperatures of less than 20°K where electron-phonon and interband s-d exchange scattering are no longer important. Figure 1 shows the quantities ρ and WT plotted as a function of T^2 for a ⟨111⟩-axial iron crystal in the range 2 to 20°K. The lower pair of curves represents data taken in the saturated single-domain state obtained by applying a longitudinal field of 1200 Oe. The upper curve shows data on the thermal resistivity measured on the same crystal in the multidomain state with the applied field equal to zero. The electrical resistivity of the multidomain state is not included in Fig. 1 but shows an even greater deviation from a T^2 behavior as well as a large contribution from transverse magnetoresistance. Figure 2 shows both the ideal Lorenz number L_i and the total Lorenz number corresponding to the single-domain curves of Fig. 1. For the single domain state, L_i reaches a nearly constant value of 1.09×10^{-8} W Ω/deg² below 40°K. This value

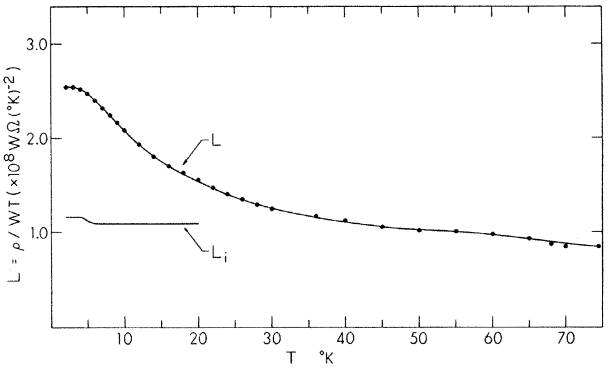

FIG. 2. Curves show the total Lorenz number L and the ideal Lorenz number L_i as a function of temperature below 70°K.

increases to 1.16×10^{-8} W Ω/deg² below 6°K because of a break in slope at approximately 6°K observed in the electrical resistance data. Such a break is not discernible in the thermal-conductivity data, although the data show more scatter due to the small size of the crystals which presents a much more severe experimental problem in the thermal than in the electrical measurement. Such a break is similar to the one observed by White and Tainsh[2] in nickel. The value of the slope below 6°K in the electrical resistance is also confirmed by more detailed measurements below 4°K and these will be discussed below. The total Lorenz number for the single-domain state approaches the value 2.55×10^{-8} W Ω/deg² which is slightly above the Sommerfeld value of 2.44×10^{-8} W Ω/deg². One would therefore conclude that within the accuracy of these experiments electron-electron scattering probably dominates the temperature-dependent transport in the single-domain longitudinally magnetized state at low temperatures and that intraband electron-magnon scattering is not sufficient to produce any strong deviation in the ideal Lorenz number below 20°K. The total Lorenz number falls to an unusually low value at high temperatures and is still decreasing up to 70°K as shown in Fig. 2. Between 20 and 70°K the thermal resistivity rises substantially faster than the electrical resistivity and, of course, produces a corresponding decrease in the Lorenz number. Electron-magnon scattering of s electrons into d holes[6] is expected to make an increasing contribution in this range of temperature and may account for this behavior.

Detailed measurements of the electrical resistivity in the single-domain longitudinally saturated state of ⟨111⟩-axial crystals down to 0.28°K also tend to confirm this conclusion. Fig-

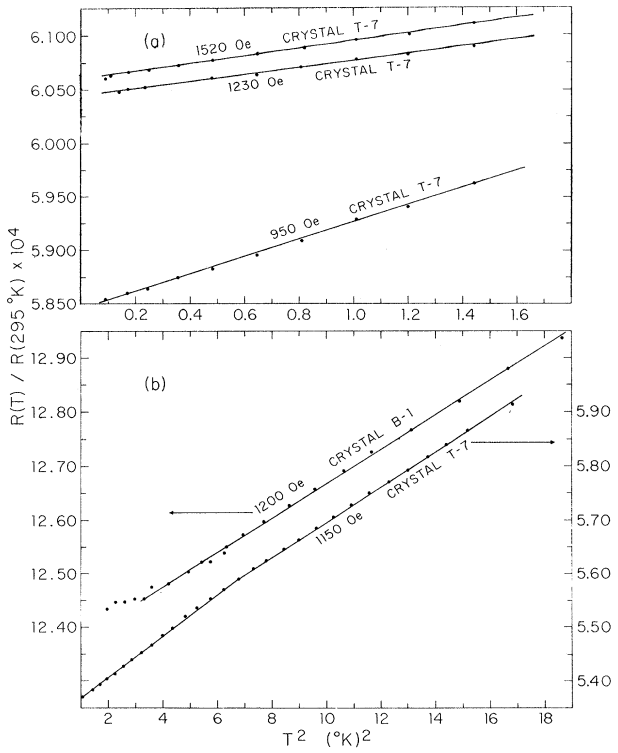

FIG. 3. Electrical resistivity of ⟨111⟩-axial iron crystals in the longitudinally saturated state as a function of T^2. (a) Temperature range 0.28-1.2°K; (b) Temperature range 1.1-4.2°K.

ure 3 shows the electrical resistance of ⟨111⟩ axial crystals measured in the temperature ranges 0.28-1.2°K and 1.0-4.2°K and plotted as a function of T^2. The set of curves shown in Fig. 3(a) show measurements on the same ⟨111⟩ axial crystal at three different longitudinal magnetic fields. The temperature dependence shows a T^2 functional dependence in all cases, but shows a considerably larger slope at 950 Oe than at 1230 and 1520 Oe, where the slope appears to have reached a field-independent value of 3.3×10^{-6} deg^{-2}. Measurements on the same crystal in the range 1.0-4.2°K are shown in the lower curve of Fig. 3(b) for an applied longitudinal field of 1150 Oe. This curve shows an apparent break in slope around 2.5°K which could be interpreted as an increasing T^2 behavior below 2.5°K. However, the slope above 2.5°K is equal to 3.3×10^{-6} deg^{-2}, in agreement with the slopes measured below 1°K for slightly higher magnetic fields.

The upper curve in Fig. 3(b) shows data on a second ⟨111⟩-axial crystal in a longitudinal field of 1200 Oe. This is also the crystal used for the electrical and thermal data shown in Fig. 1. The slope for this case is 3.2×10^{-6} deg^{-2} and when converted to units of Ω cm/deg^2 is the value used to draw the line in the low-temperature section of the electrical resistivity curve of Fig. 1. The two ⟨111⟩ crystals therefore give reasonable consistency in the value of the slope below 4.2°K and there is good evidence that this same value of the slope extends down to 0.28°K. No break in slope was seen in the upper curve of Fig. 3(b) although the data show considerably more scatter below 2.5°K as a result, in part, of the fact that different experimental setups were used for the two measurements. From this group of experiments we conclude that the longitudinally saturated ⟨111⟩ crystals show a T^2 dependence from 4.2°K down to 0.28°K with a constant slope approximately equal to 3.3×10^{-6} deg^{-2} or, in terms of resistivity,

$$\rho_i \approx 31\times10^{-12}T^2.$$

This coefficient has been obtained using three different experimental setups and two different crystals so that it appears to be a reasonably reproducible number.

We have no satisfactory explanation for the apparent break in slope observed below 2.5°K and extending to 1.1°K in the one crystal. If we fit the data showing the break by a smooth curve using a least-squares computer program, we obtain an expression

$$R(T)/R(295^\circ\mathrm{K}) = 5.3\times10^{4} + 5.5\times10^{-6}T + 2.4\times10^{-6}T^2,$$

which shows a strong linear term as would be expected since the T^2 plot shows a downward curvature as temperature increases. Previous results of the temperature dependence in the range 1.0-4.2°K reported by our laboratory[7] showed strong linear coefficients in both the flux-closed and partially saturated state of ⟨100⟩ and ⟨111⟩ crystals. We used procedures which we throught controlled the domain structure during the temperature run so that meaningful values of the slope could be obtained. However, it appears that in addition to the difficulty of controlling domain structure, there are large contributions to both the magnitude of the slope and the power of the temperature when measurements are made in either the $\vec{M}=0$ state or in fields below saturation. These are connected in some way with the domain structure and may enter through the large changes in magnetoconductivity that occur in the multidomain state due to the

large ratio ρ_T/ρ_L which occurs in these high-purity crystals. ρ_T and ρ_L are the transverse and longitudinal magnetoresistivity, respectively. The details of the contributions to the magnetoresistance in the multidomain region due to domain reorientation have been analyzed by Shumate, Coleman, and Fivaz.[8]

The present results coupled with our experiments on the multidomain crystals would lead us to conclude that the intrinsic temperature dependence of the electrical resistivity in single-domain longitudinally magnetized iron crystals is proportional to T^2 from 20°K down to 0.28°K. Additional features such as breaks in slope or the appearance of linear temperature terms are likely to be associated in some way with the presence of domain structure. We cannot completely rule out the presence of magnetic contributions to the temperature dependence, but the present behavior of the single-domain state does not seem to be significantly different from nonmagnetic transition metals.

The results obtained here are strikingly similar to the numbers obtained by White and Tainsh[2] for nickel and are listed below along with their values for comparison. Below 4°K, for iron,

$$\rho_i \approx 31\times10^{-12}T^2, \quad W_i \approx 27\times10^{-4}T,$$

$$L_i = 1.16\times10^{-8}\ \text{W}\ \Omega/\text{deg}^2;$$

for nickel,

$$\rho_i \approx 34\times10^{-12}T^2, \quad W_i \approx 34\times10^{-4}T,$$

$$L_i = 1.0\times10^{-8}\ \text{W}\ \Omega/\text{deg}^2.$$

From 5 to 20°K, for iron,

$$\rho_i \approx 29\times10^{-12}T^2, \quad W_i \approx 27\times10^{-4}T,$$

$$L_i = 1.09\times10^{-8}\ \text{W}\ \Omega/\text{deg}^2;$$

for nickel,

$$\rho_i \approx 26\times10^{-12}T^2, \quad W_i \approx 25\times10^{-4}T,$$

$$L_i = 1.0\times10^{-8}\ \text{W}\ \Omega/\text{deg}^2.$$

The authors would like to acknowledge useful discussions with Professor John E. Christopher and Professor Leo M. Falicov. Mr. Phillip Sommer and Mr. Werner Frewer have made valuable contributions in the construction of the apparatus.

*Work supported by the U. S. Atomic Energy Commission.

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Negative Magnetoresistance and Magnetically Controlled Switching in Fe_3O_4 Single Crystals*

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The negative magnetoresistance in Fe_3O_4 crystals at 77°K was found to saturate at about 9 kG and to increase with increasing electric field. The magnetoresistance data are explained in terms of spin disorder scattering. In the presence of a magnetic field the switching in this material can be advanced if voltage pulses are applied, and delayed if current pulses are applied. These findings are shown to be in quantitative agreement with the magnetoresistance data and the expectations from Joule self-heating.

Of the transition-metal oxides,[1] Fe_3O_4 is the only material that exhibits a transition from insulator to metal as well as having a net magnetic moment per unit cell. It is thus expected that the coupling between the electronic and magnetic properties in this material can bring about some new effects and provide an "extra handle" for the study of the insulator-to-metal transition.[2] In this Letter we will focus our attention on an effect that is a result of the combination of the relatively large negative magnetoresistance, associated with the ferrimagnetic nature of the ma-