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TWO-CURRENT CONDUCTION IN NICKEL

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Measurements on the low-temperature electrical resistivity of dilute nickel-based alloys give strong evidence that spin-↑ and spin-↓ electrons carry current in parallel, providing important implications for the interpretation of transport properties of pure as well as alloy ferromagnets.

Electrical-resistance results on Ni[1] have recently been interpreted by Herring[2] by a model in which no account is taken of the ferromagnetic nature of the metal. On the basis of measurements on Fe containing a number of dilute impurities, we have suggested[3] that there is strong evidence that in ferromagnetic metals spin-↑ and spin-↓ electrons carry current in parallel with different conductivities (at least at low temperatures). This model has a direct bearing on the interpretation of transport properties of pure as well as alloy ferromagnets.

We report in this Letter experiments on the electrical resistivity of Ni containing Co, Mn, Cr, and Ti as dilute impurities. The results confirm the two-current model and can lead to a better understanding of the scattering processes in Ni.

The model used can be summarized as follows. It is assumed that the conduction electrons of the two half-bands of opposite spin have different relaxation times $\tau_\uparrow$ and $\tau_\downarrow$. In addition there are spin-flip and electron-electron collision processes characterized by a relaxation time $\tau_{\uparrow\downarrow}$ which couple the Boltzmann equations for the two sorts of conduction electrons; these equations can then be written[4]

$$e\vec{E}\cdot\vec{v}\frac{\partial f_0}{\partial E} = -\frac{f_\uparrow - f_0}{\tau_\uparrow} - \frac{f_\uparrow - f_\downarrow}{\tau_{\uparrow\downarrow}},$$

$$eE\cdot\vec{v}\frac{\partial f_0}{\partial E} = -\frac{f_\downarrow - f_0}{\tau_\downarrow} - \frac{f_\downarrow - f_\uparrow}{\tau_{\uparrow\downarrow}} \qquad (1)$$

in the usual notation.[5] By solving the coupled system of equations, it can be shown[3] that the total resistivity is

$$\rho = \frac{\rho_\uparrow\rho_\downarrow + \rho_{\uparrow 0}(\rho_\uparrow + \rho_\downarrow)}{\rho_\uparrow + \rho_\downarrow + 4\rho_{\uparrow\downarrow}}, \qquad (2)$$

where $\rho_\uparrow = m/ne^2\tau_\uparrow$, $\rho_\downarrow = m/ne^2\tau_\downarrow$, and $\rho_{\uparrow\downarrow} = m/ne^2\tau_{\uparrow\downarrow}$.

We will further assume for $\rho_\uparrow$ and $\rho_\downarrow$ that the effects of the various scattering mechanisms add together by the quasi-Matthiessen rules:

$$\rho_\uparrow(T) = \rho_\uparrow^{\,0} + \rho_\uparrow^{\,i}(T),$$

$$\rho_\downarrow(T) = \rho_\downarrow^{\,0} + \rho_\downarrow^{\,i}(T), \qquad (3)$$

where $\rho_\uparrow^0, \rho_\downarrow^0$ are the temperature-independent scattering components due to the impurities while $\rho_\uparrow^i, \rho_\downarrow^i$ are the temperature-dependent parts of the scattering for the two half-bands. It will also be assumed that the temperature-independent part of $\rho_{\uparrow\downarrow}$ is zero.[6] We will concentrate attention on the low-temperature limit within these restrictions.

When

$$\rho_\uparrow^{\,0}, \rho_\downarrow^{\,0} \gg \rho_\uparrow^{\,i}, \rho_\downarrow^{\,i}, \rho_{\downarrow\uparrow}, \qquad (4)$$

the development of Eq. (2) gives

$$\rho = \rho_0 + \rho_i + \rho_i\frac{(\alpha-\mu)^2}{(1+\alpha)^2\mu} + \rho_{\uparrow\downarrow}\left(\frac{\alpha-1}{\alpha+1}\right)^2, \qquad (5)$$

where $\rho_0 = \rho_\uparrow^0\rho_\downarrow^0/(\rho_\uparrow^0 + \rho_\downarrow^0)$ is the residual resis-

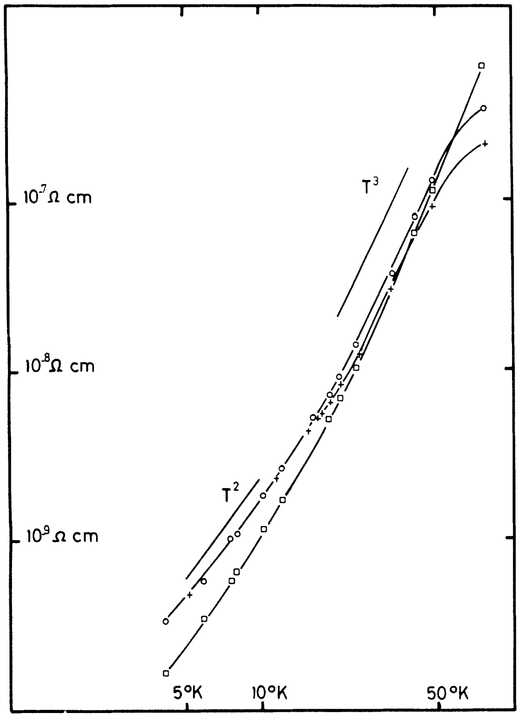

FIG. 1. Low-temperature resistivity variations. Squares: $\rho_i(T)$, ideal resistivity of pure Ni. Circles: deviation $\Delta\rho(T)$ for Ni:Cr with 1400 ppm Cr. Crosses: deviation $\Delta\rho(T)$ for Ni:Cr with 700 ppm Cr.

tivity, ρ_i is the ideal resistivity of the pure metal, $\alpha=\rho_\downarrow^0/\rho_\uparrow^0$, and $\mu=\rho_\downarrow^i/\rho_\uparrow^i$.

We have measured the resistivity of a number of dilute alloys Ni:X as a function of temperature and concentration; the results can be expressed in terms of the deviation from Matthiessen's rule,[7]

$$\Delta\rho(T)=\rho(T)-\rho_0-\rho_i(T). \tag{6}$$

Typically, $\Delta\rho(T)\gtrsim\rho_i(T)$ for low T. $\Delta\rho(T)$ saturates at higher temperatures. As an example, the results for two Ni:Cr alloys are given in Fig. 1.

We find at low temperatures the following results:

(i) As predicted by Eq. (5), $\Delta\rho$ is independent of the concentration of the impurity in the concentration range where the impurity resistivity dominates but where interaction effects between impurities are still negligible.

(ii) The analysis of $\Delta\rho(T)$ shows clearly a contribution varying as T^2 (particularly strong in Ni:Co and Ni:Mn); this we identify with $\rho_{\uparrow\downarrow}(T)=AT^2$.

By analyzing the data as in Eq. (5) into a term proportional[8] to $\rho_i(T)$ and a term proportional to T^2, we have determined the values α_I of α for each impurity I and the values of μ and A. The latter parameters appeared to be independent of the nature and concentration of the impurity and hence to be characteristic of the host metal. Between the set of values α_I, μ and the set $1/\alpha_I$, $1/\mu$, which is a solution as well, we have retained the set consistent with the structure of the impurities. The results were the following: $\alpha_{\rm Ti}=3.4$, $\alpha_{\rm Cr}=0.38$, $\alpha_{\rm Mn}=16$, $\alpha_{\rm Co}=30$, $\mu=2.3$, and $A=5\times10^{-11}$ Ω cm °K^{-2}. High-temperature measurements were reasonably consistent with these values of the parameters.[9]

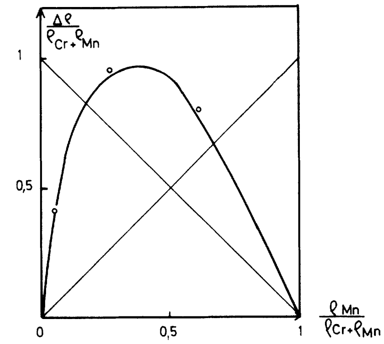

FIG. 2. The deviation $\Delta\rho$ in the residual resistance of Ni containing Cr and Mn impurities as a function of the relative concentrations of Cr and Mn. $\rho_{\rm Cr},\rho_{\rm Mn}$ are the corresponding residual resistances when Cr or Mn is present alone at the same concentration, $\Delta\rho=\rho-\rho_{\rm Cr}-\rho_{\rm Mn}$.

As a further check on the model, alloys containing Cr and Mn impurities simultaneously were made up with varying relative concentrations. The model predicts the simple relation for the residual resistances of such alloys:

$$\rho=\rho_1+\rho_2+\frac{\rho_1\rho_2(\alpha_1-\alpha_2)^2}{(1+\alpha_1)^2\alpha_2\rho_1+(1+\alpha_2)^2\alpha_1\rho_2}, \tag{7}$$

where ρ_1,ρ_2 are the residual resistivities of the impurities when present one at a time, and α_1, α_2 are the $\rho_\downarrow/\rho_\uparrow$ ratios for the two impurities. In Fig. 2, the experimental 4°K resistivities for the ternary alloys are compared with the curve calculated from Eq. (7) using the $\alpha_{\rm Cr}$, $\alpha_{\rm Mn}$ given above. The model has thus been shown to be consistent.

The series of values of $\rho_\uparrow^0,\rho_\downarrow^0$ as shown in Fig. 3 can clearly be associated with the magnetic behavior of the different impurities; in particular the peak in $\rho_\uparrow^0$ near Ni:Cr corresponds to a bound state crossing the spin-$\uparrow$ Fermi level.[10,12]

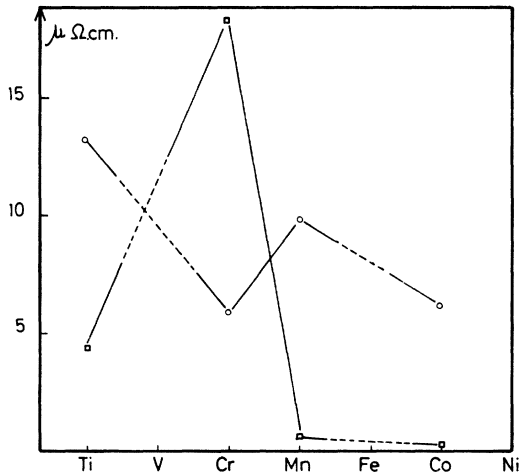

FIG. 3 Residual resistivities $\rho_\uparrow^0$ and $\rho_\downarrow^0$ per percent concentration of Ti, Cr, Mn, and Co impurities in Ni. Squares: $\rho_\uparrow^0$. Circles: $\rho_\downarrow^0$.

The value of μ is lower than might be expected a priori[13]; further work may well show it to be temperature dependent.

The physical origin of $\rho_{\uparrow\downarrow}$ is not simple electron-electron collisions[14]; it may arise from spin-wave-electron interactions or spin-orbit coupling.

These results have direct implications on measurements on pure ferromagnetic metals. Even a small concentration of impurity can lead to a low-temperature resistivity contribution varying first as T^2 and then saturating; the size of this contribution will depend on the nature and concentration of the dominant impurity, which will also affect the magnetoresistance correction. The two-current character of the conduction in ferromagnetic metals also means that care must be taken in comparing their transport properties with those of paramagnetic transition metals.

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