

Transport Properties of Nearly Magnetic Alloys and Metals*

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Abstract

We give an elementary review of how simple spin fluctuation models can account for the distinctive transport properties of nearly magnetic alloys and metals. The principal systems considered are dilute alloys such as *PdNi* in which host and impurity have somewhat similar electronic structure but with the impurity more nearly magnetic than the host. Similar effects occurring in pure metals or concentrated alloys are also mentioned.

1. Introduction

In contrast to Ni, which is ferromagnetic, the metals Pd and Pt below Ni in the periodic table (see Fig. 1) are 'nearly ferromagnetic', i.e. they possess no spontaneous magnetic moment but their magnetic susceptibility χ is enhanced relative to the Pauli susceptibility of a non-interacting electron gas. Thus in Pd and Pt the average occupation of the two spin bands is the same, but interactions between d electrons induce transient parallel spin alignments over microscopic regions of the crystal. The nearer the system is to the ferromagnetic instability, the greater is the spatial and temporal persistence of these spin fluctuations. When a dilute concentration of Ni impurities is added to Pd or Pt, the spin fluctuations are enhanced in the vicinity of the impurity to form local spin fluctuations (LSF). As would be expected, if the Ni concentration is increased sufficiently the alloys become ferromagnetic.

In this review of spin fluctuation effects on transport properties, we mention systems such as pure Pd in which 'uniform' spin fluctuations occur, but we concentrate mainly on alloys with LSF, taking *PdNi* as the chief example. Only single impurity effects, i.e. very dilute alloys, are considered. The basis of the alloy models we describe is the Wolff (1961) model. This model is appropriate when both impurity and host are transition metals with similar electronic structure, so that no localized virtual bound state is formed at the impurity and the residual resistivity is relatively small. Magnetic scattering from spin fluctuations in these alloys produces a resistivity which *increases* with temperature, as illustrated for *RhFe* in Fig. 2. Alloys such as *PdNi*, *RhFe* and *IrFe* showing this behaviour are sometimes referred to as Coles alloys.

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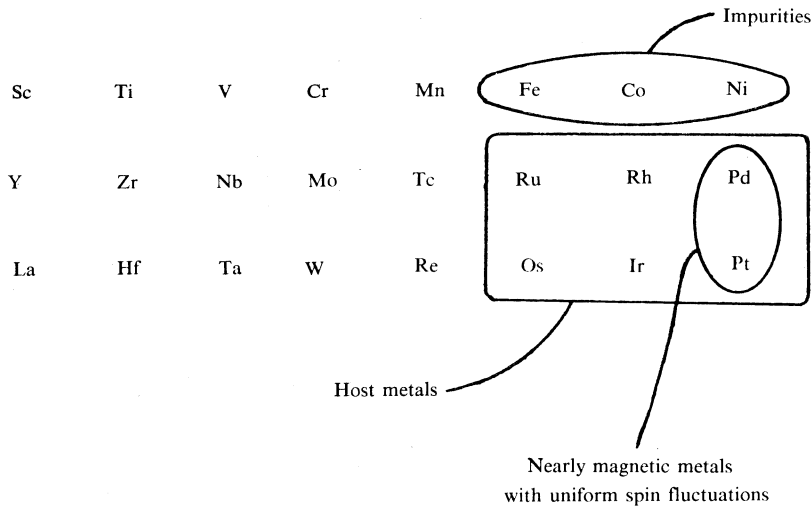


Fig. 1. Transition metals in the periodic table, indicating metals and alloys which show the spin fluctuation effects discussed in text.

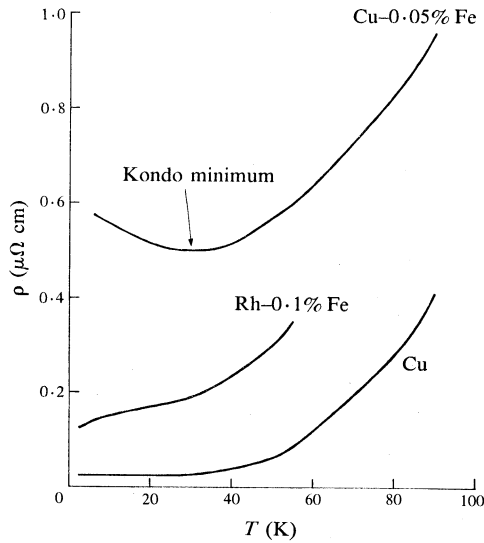


Fig. 2. Electrical resistivity ρ for a Coles alloy such as $RhFe$ (Coles 1964) compared with that for a Kondo alloy such as $CuFe$ (Domenicali and Christenson 1961).

In contrast, in the usual Kondo alloys such as $CuFe$, an impurity with an unfilled d or other magnetic shell forms a virtual bound state when placed in a host of different electronic structure, a process described by the Anderson (1961) model. The resulting strong scattering of conduction electrons by the virtual bound state gives rise to a large residual resistivity, as illustrated in Fig. 2 for $CuFe$, and the resistivity due to the magnetic impurities *decreases* as temperature increases. This decreasing contribution, when combined with the usual resistivity component due to scattering by phonons, gives rise to the characteristic Kondo resistivity minimum.

Although a complete description of the Kondo effect in terms of group renormalization theory is complex, the behaviour near the low temperature limit can be understood in terms of an LSF model (Nozières 1974). We do not consider Anderson-model spin fluctuation alloys, but note that a Wolff-model spin fluctuation alloy would show behaviour similar to that of a Kondo alloy if a virtual bound state develops at the impurity site, since the additional scattering due to the spin fluctuations as T increases would push the scattering off resonance and decrease the resistivity as T increases (Kaiser and Doniach 1970).

After introducing the spin fluctuation models in Section 2, we discuss in successive sections their application to electrical resistivity, thermal resistivity and thermopower. Many of the particular systems whose behaviour appears to be explained by the spin fluctuation models are mentioned in Section 6.

2. Theoretical Models

(a) Two-band Model

The Fermi surface of palladium consists of two distinct sheets, one containing about 0.3 heavy holes per atom and the other a similar number of lighter electrons. As a very simple model to represent Pd, and also perhaps other transition metals, we use the two-band model of Mills and Lederer (1966), in which the heavy d holes provide the principal contribution to the magnetic properties of the metal while the lighter electrons from the other sheet provide the principal contribution to the conductivity. To make the calculations tractable each band is taken as spherical: the phenomenological parameters of the LSF model are then assumed to be appropriate averages over the Fermi surfaces. This two-band model is still taken as applicable when a dilute concentration of Ni impurities is added, the main difference being that the d-band spin fluctuations are enhanced in the impurity cell. In this model, the mechanism by which the spin fluctuations affect the transport properties is scattering of conduction electrons via the s-d exchange interaction J . This scattering gives rise to a temperature-dependent magnetic scattering component which is calculated in the Born approximation.

(b) One-band Model

For metals such as Rh and Ir, d-like electrons are thought to play a major role in contributing to conductivity (see e.g. Cheng *et al.* 1979). Rivier and Zlatić (1972) and Fischer (1974) have pointed out that for these hosts there is an alternative method of calculating how LSF affect the transport properties. These authors ignore any difference in character between the electrons and start from an isotropic one-band Wolff model in which the same electrons are responsible for magnetic properties and for conductivity. The self-energy of the d-like conduction electrons due to scattering by LSF and by a non-magnetic potential V at the impurity site can be calculated, taking the spin fluctuations as confined to the impurity cell and the scattering as isotropic. The t -matrix and transport properties can then be evaluated, with no limitation on the strength of the coupling between conduction electrons and LSF. The model used for the LSF spectral density is essentially the same as that for the two-band model described in the next subsection (with uniform spin fluctuations in the host taken as absent).

(c) *Spin Fluctuation Spectral Density*

To calculate the effect of spin fluctuations on transport properties we need a model for the spin fluctuations which allows us to calculate their spectral density. The magnetic properties of a metal are determined by the generalized susceptibility $\chi(\mathbf{q}, \omega)$, the response function giving the magnetization $\mathbf{M}(\mathbf{q}, \omega)$ arising from an applied magnetic field $\mathbf{H}(\mathbf{q}, \omega)$ of wavevector $\mathbf{q}$ and angular frequency ω :

$$\mathbf{M}(\mathbf{q}, \omega) = \chi(\mathbf{q}, \omega) \mathbf{H}(\mathbf{q}, \omega). \quad (1)$$

The interaction between electrons responsible for the spin fluctuations is the Coulomb repulsion U between opposite spin electrons, which favours parallel alignment (the Pauli exclusion principle keeps parallel spin electrons apart so they do not feel the Coulomb repulsion to the same extent). Taking the interaction as a contact attraction between an electron and hole of opposite spin, the susceptibility for a uniform electron band can be calculated in the random phase approximation (RPA) to give (Izuyama *et al.* 1963)

$$\chi(\mathbf{q}, \omega) = \frac{\chi_0(\mathbf{q}, \omega)}{1 - U\chi_0(\mathbf{q}, \omega)}, \quad (2)$$

where $\chi_0(\mathbf{q}, \omega)$ is the susceptibility of the non-interacting electron gas. In the static limit this equation gives the usual Stoner factor

$$\alpha_0 = (1 - U\chi_0)^{-1} \quad (3)$$

for the static susceptibility enhancement, χ_0 being the non-interacting Pauli susceptibility. The spectral density $A(\mathbf{q}, \omega)$ of the spin fluctuations is given by

$$A(\mathbf{q}, \omega) = 2 \operatorname{Im} \chi(\mathbf{q}, \omega). \quad (4)$$

When the susceptibility is enhanced, $A(\mathbf{q}, \omega)$ has large peaks at low energies, the energy of the peak increasing with q .

For dilute alloys containing impurities which are more nearly magnetic than the host, Lederer and Mills (1968) used a simple form of the Wolff model for transition metal impurities in which the intra-atomic Coulomb repulsion for d-band electrons was increased from U in the host to $U + \delta U$ in the impurity cell. Lederer and Mills derived an expression for the generalized susceptibility in the RPA analogous to equation (2), giving a local enhancement factor

$$\alpha = (1 - \delta U \bar{\chi})^{-1}, \quad (5)$$

where $\bar{\chi}$ is the average of $\chi(\mathbf{q}, 0)$ for the host over wavevector. If the host is unenhanced (i.e. $U = 0$), the effect of the non-magnetic potential V of the impurity on $\chi(\mathbf{q}, \omega)$ can also be included and shown to be small (Mills and Lederer 1967).

When the susceptibility enhancement at the impurity is much larger than that in the host (i.e. $\alpha \gg \alpha_0$), the spectral density $\bar{A}(\omega)$ of the LSF takes the universal shape (Kaiser and Doniach 1970)

$$\bar{A}(\omega) = \frac{a\hbar\omega}{\hbar^2\omega^2 + k_B^2 T_s^2}, \quad (6)$$

there being no q dependence for the LSF. This shape is plotted in Fig. 3: T_s is the spin fluctuation temperature, defined as the energy corresponding to the peak in the excitation spectrum. In the RPA, the magnitude of T_s is inversely proportional to the local enhancement α , i.e. the spectral peak is sharper for greater enhancements, as expected.

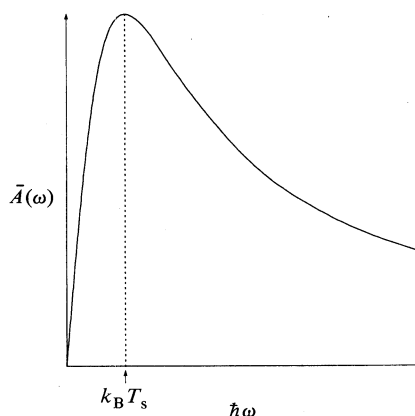


Fig. 3. Spectral density $\bar{A}(\omega)$ of LSF as a function of energy $\hbar\omega$, showing how the spectral peak defines the spin fluctuation temperature T_s (Kaiser and Doniach 1970).

The uniform and LSF spectra are essentially independent of temperature at low temperatures, but for $T > T_s$ in the RPA the sharp spectral peaks become blurred, especially if the enhancement is large (Kaiser and Doniach 1970).

For large enhancements, however, the RPA is inadequate and a renormalized theory is required, so T_s and a are treated as phenomenological parameters. Some support for the validity of this approach is provided by the perturbation calculations of Shiba (1976) for the Anderson model (for an unenhanced host) which go beyond the RPA: Shiba found that the shape of the LSF spectral density is still very similar to that of Fig. 3, but the peak fails to sharpen up and move to lower energies to the extent predicted in the RPA as the magnetic instability is approached. Recognizing this, Fischer (1978) suggested that LSF alloys such as *RhFe* with low values of T_s could be well past the RPA magnetic instability, i.e. could be *strongly* magnetic Wolff-model Kondo alloys rather than *nearly* magnetic alloys. Be that as it may, Nozière's (1974) demonstration that Kondo alloys give LSF model behaviour, at least at low temperatures, indicates that the LSF model with phenomenological parameters is still an appropriate framework to describe alloys such as *RhFe*. In fact, going beyond the RPA, the instability criterion $\delta U\bar{\chi} = 1$ loses its significance as a dividing line between magnetic and nearly magnetic behaviour and no sharp changes in physical properties are expected when the boundary is crossed.

3. Electrical Resistivity

(a) Two-band Model for Dilute Alloys (Low Temperatures)

The resistivity component due to exchange scattering of conduction electrons by LSF may be found by substituting the spectral density of equation (6) into the general expression for the resistivity due to scattering by Bose excitations

$$\rho = \rho_0 \beta \hbar \int_0^\infty d\omega \omega \bar{A}(\omega) \{\exp(\beta \hbar \omega) - 1\}^{-1} \{1 - \exp(-\beta \hbar \omega)\}^{-1}, \quad (7)$$

where $\beta = (k_B T)^{-1}$ and ρ_0 is a constant. This gives (Kaiser and Doniach 1970)

$$\rho_s/\rho_{s0} = (\pi T/2T_s) - \frac{1}{2} + (T_s/4\pi T) \psi'(1 + T_s/2\pi T), \quad (8)$$

where ρ_s/ρ_{s0} is the normalized resistivity due to LSF and $\psi'(x)$ is the trigamma function. This universal curve for the shape of the LSF resistivity component, starting as a T^2 law at low temperatures and changing to a linear law as T increases, is shown in Fig. 4; the shape of the curve agrees quite adequately with that of the temperature-dependent impurity resistivity component measured by Sarachik (1968) in dilute IrFe alloys.

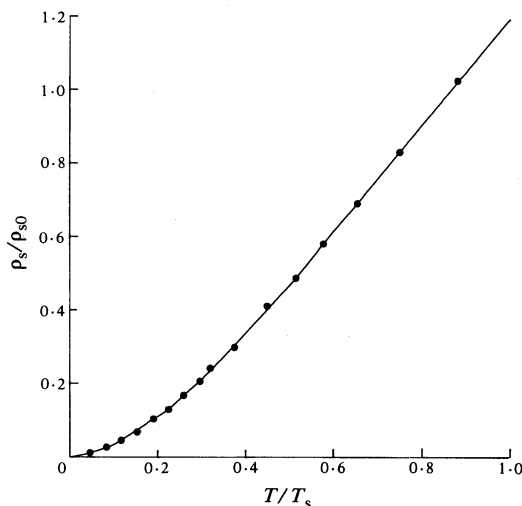


Fig. 4. Universal curve for the normalized LSF resistivity ρ_s/ρ_{s0} in the two-band model (Kaiser and Doniach 1970). This curve is compared with the temperature-dependent resistivity due to the impurities in a dilute Ir-0.5%Fe alloy (circles) (Sarachik 1968). Fitting parameters are $T_s = 28$ K and $\rho_{s0} = 0.11 \mu\Omega \text{ cm}$.

This LSF resistivity curve is analogous to the Bloch-Gruneisen law for the resistivity due to scattering by phonons. In fact, the linear T law is just the same as for phonons, and arises from the fact that when the whole excitation spectrum is excited, the number of bosons is proportional to the temperature. The differing T dependences at low temperatures for spin fluctuations and phonons arise from the differing spectral shapes and the phonon dispersion relation.

The magnetoresistance in this two-band LSF model was calculated by Schulz (1971), who found that the effect of an applied field on the enhancement factor α could increase or decrease the effective value of T_s .

(b) Two-band Model for Dilute Alloys (Higher Temperatures)

The resistivity due to spin fluctuations will follow a linear T law only if the spin fluctuation spectrum (and therefore T_s) is independent of temperature. In fact, as mentioned in Section 2c, the sharp peak blurs as T increases, leading to a reduction of the enhanced susceptibility and a reduction of resistivity below the linear T law.

A typical calculation of this effect within the RPA for a large local enhancement α is shown in Fig. 5 and compared with data for *IrFe*. If we use the RPA results that the susceptibility enhancement $\Delta\chi$ is proportional to α , and T_s is inversely proportional to α , we obtain for the LSF resistivity ρ_s for $T \gtrsim T_s$

$$\rho_s \sim T \Delta\chi. \quad (9)$$

This is just Knapp's phenomenological law relating the LSF resistivity and susceptibility $\Delta\chi$ in *IrFe* and *RhFe* (Knapp 1967).

Thus in these cases the two-band model appears capable of accounting qualitatively for the fall-off in resistivity below the linear law at higher temperatures, but clearly the RPA is at least quantitatively inadequate when the enhancement is large. We note that in *PdNi*, the local enhancement is smaller and T_s larger than in *IrFe* and *RhFe*, and the fall-off below the linear law has not yet been observed.

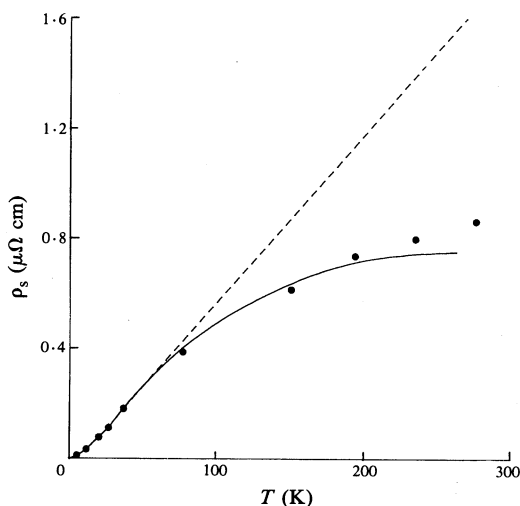


Fig. 5. A typical theoretical curve for the spin fluctuation resistivity (continuous curve) showing the decrease below the linear law caused by the temperature dependence of the spectral density (i.e. of T_s) for a local enhancement $\alpha = 80$ at $T = 0$ (Kaiser and Doniach 1970). Data (circles) for a dilute *Ir-0.5%Fe* alloy are also shown (Sarachik 1968).

(c) Deviations from Matthiessen's Rule

In the comparison between theory and experiment shown in Fig. 4 it was tacitly assumed that the various resistivity components are additive, i.e. that Matthiessen's rule is obeyed. This is not strictly correct. We should write the total resistivity of the alloy as

$$\rho = \rho_h + \rho_s + \rho_v + \Delta, \quad (10)$$

where ρ_h is the host resistivity, ρ_v is the temperature-independent resistivity due to potential scattering by the impurities, and Δ is the deviation from Matthiessen's rule (DMR).

The main cause of these deviations from Matthiessen's rule is the destruction by approximately isotropic impurity scattering of the conduction electrons' ability to take advantage of the anisotropy of the scattering by phonons. Since scattering by LSF is also approximately isotropic, Δ in LSF alloys should be similar to that in non-magnetic alloys. For non-magnetic *PdTi* alloys, Williams and Weaver (1982) found an increase in Δ very roughly consistent with a T^5 law at low temperatures, with Δ saturating at values from 0.05 to 0.1 $\mu\Omega\text{cm}$ at about 40 K.

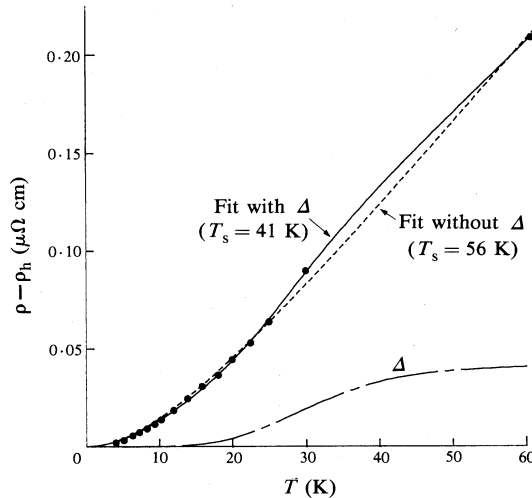


Fig. 6. Fits of the LSF universal curve of Fig. 4 to the resistivity of a dilute *Pd-1%Ni* alloy (circles), measured by Greig and Rowlands (1974), with and without the inclusion of the DMR term Δ . The fitted DMR term Δ is also shown.

Fig. 6 suggests that including a Δ term of this standard shape (with adjustable size and temperature scale) in the fitting for *PdNi* may give plausible results and lead to a somewhat different deduced value for the spin fluctuation temperature T_s , although clearly more data are required for any real conclusions. The DMR term is less important for *IrFe* and *RhFe* in which T_s is smaller.

(d) One-band Model

The alternative of a one-band model for calculating the effect of LSF on electrical resistivity of alloys with bands of similar d-like character (Rivier and Zlatić 1972; Fischer 1974) yields a resistivity shape remarkably similar to that given by the two-band model: the resistivity starts as T^2 and increases to the unitarity limit as T increases (Fig. 7).

The concave curvature of ρ_s to the T axis at higher temperatures is due in this model to a characteristic $\ln T$ dependence for scattering by a magnetic impurity and not to the temperature dependence of the LSF spectral density (which is neglected). Note that for a large non-magnetic impurity potential, the impurity state becomes distinct from the band, and the resistivity behaviour shows the change to high resistivity at $T = 0$ decreasing as T increases, which is reminiscent of Anderson LSF models.

The similarity of the resistivity shapes in the one- and two-band models indicates the general nature of the predicted LSF resistivity shape but precludes a choice between the models by comparison with experiment. Values of T_s deduced from fitting the one-band model, however, are about eight times larger than for the two-band model (Rivier and Zlatić 1972).

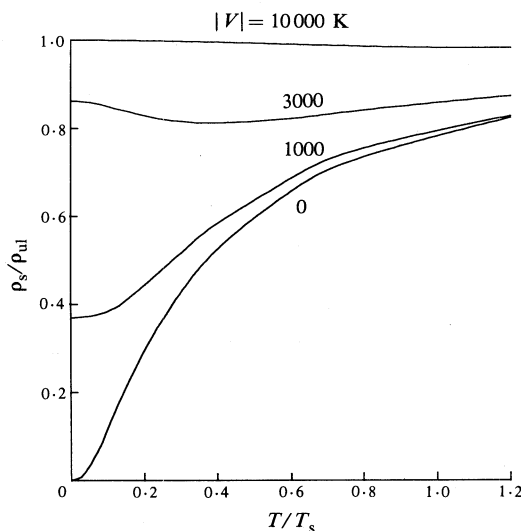


Fig. 7. The LSF impurity contribution ρ_s to resistivity for the one-band model, for different magnitudes of the shift V of the Wolff-model resonance relative to the Fermi level (Fischer 1974). Parameter values used were $T_s = 12$ K and $\Delta = 10^4$ K, where Δ is the width of the localized state, and ρ_{ul} represents the unitarity limit corresponding to maximum scattering by the impurity. Here $V = 0$ corresponds to the case of no non-magnetic scattering.

(e) Pure Metals and Concentrated Alloys

The spectral density $A(\mathbf{q}, \omega)$ for *uniform* spin fluctuations has a peak whose location is strongly q dependent, but the linearity in ω still gives a T^2 resistivity law at low temperatures and the general linear T law for bosons is again obtained as T increases. Thus the predicted resistivity shape is very similar to the universal curve for local spin fluctuations (Kaiser and Doniach 1970). Detailed calculations by Jullien *et al.* (1974) show that the resistivity tends to the spin-disorder limit at high temperatures (where conduction electrons scatter off the independent d or f electron spins), with or without a peak at intermediate temperatures. Fig. 8 shows the fits obtained for Pd and Pu, although the possible inadequacy of the RPA, and the alternative explanation of the high temperature resistivity of Pd in terms of electron-phonon scattering (Pinski *et al.* 1981), should be kept in mind.

4. Thermal Resistivity

At low temperatures, inelastic scattering mechanisms such as that due to spin fluctuations can cause 'vertical processes', i.e. scattering of an electron from above to below the Fermi level without changing its direction significantly. These vertical processes contribute to thermal but not to electrical resistivity, in contrast to the

'horizontal processes' in which the direction rather than the energy of the conduction electron is changed, which contribute to both resistivities. Thus the thermal resistivity W is enhanced by the presence of vertical processes and the Lorenz number $L = \rho/WT$ is reduced below its classical value L_0 .

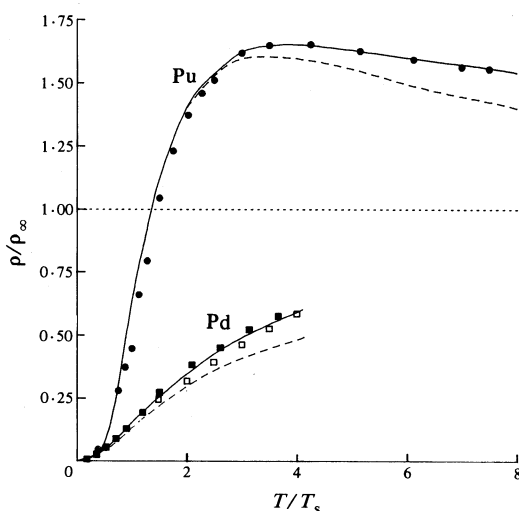


Fig. 8. Experimental electrical resistivities of Pd (squares) and Pu (circles) with detailed fits made by Jullien *et al.* (1974) using the two-band uniform spin fluctuation model. The dashed curves give the spin fluctuation resistivity ρ_s ; the continuous curves give the total resistivity including an electron-phonon term; ρ_∞ is the resistivity in the spin-disorder limit. Fitting parameters are $T_s = 200$ K, $\rho_\infty = 47 \mu\Omega \text{ cm}$ for Pd, and $T_s = 28$ K, $\rho_\infty = 95 \mu\Omega \text{ cm}$ for Pu.

Fig. 9 shows the universal curves for the thermal resistivity contribution of LSF in the two-band model. The curve for horizontal processes is the analogue of the universal electrical resistivity curve in Fig. 4, while the additional thermal resistivity component from vertical processes causes the reduction in the LSF scattering Lorenz number L_s below T_s shown in Fig. 10.

The one-band calculation of Fischer (1974) implies a deviation in Lorenz number from L_0 for $T \sim 0.25T_s$ (usually a decrease) but gives $L_s \rightarrow L_0$ as $T \rightarrow 0$. This of course would be expected due to the presence in the one-band model of non-magnetic impurity scattering (which dominates as $T \rightarrow 0$ and which shows classical Lorenz number behaviour). However, the one-band model still appears to give $L_s \rightarrow L_0$ as $T \rightarrow 0$ for the case $V = 0$ which, in contrast to the two-band model, implies that even the temperature-dependent magnetic scattering reverts to classical behaviour as $T \rightarrow 0$.

In both Pd and dilute PdNi alloys Schriempf *et al.* (1969) found that L_s for spin fluctuation scattering was roughly constant from 2 to 15 K and between $0.35L_0$ and $0.5L_0$; this result is more consistent with the two-band model than with the one-band model. Unfortunately there appear to be no thermal resistivity data for IrFe or RhFe.

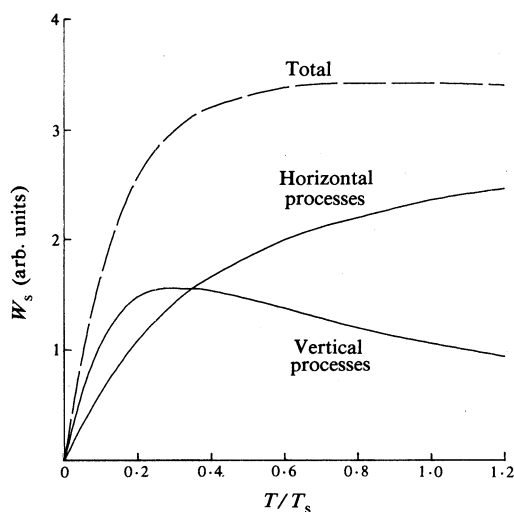


Fig. 9. Universal curves for the thermal resistivity due to scattering by LSF in the two-band model, for the horizontal and vertical components of scattering (Kaiser 1971). The size of the two contributions, and therefore the shape of the total thermal resistivity W_s , is a complicated function of susceptibility averages.

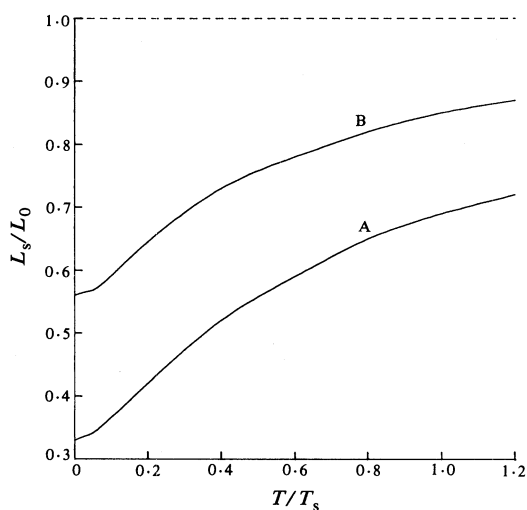


Fig. 10. Lorenz number $L_s = \rho_s / W_s T$ for scattering by LSF in the two-band model relative to the classical Lorenz number L_0 . Curve A is for the relative component sizes shown in Fig. 9, while curve B is the upper bound for the model (Kaiser 1971).

5. Thermopower

Because there is essentially no dependence on electron energy of the scattering rate due to spin fluctuations in the two-band model, no giant peaks in the diffusion thermopower can be produced (Kaiser 1976)—unless possibly higher order processes are considered as in the work of Neilsen and Taylor (1968) for electron-phonon

scattering. Iglesias-Sicardi *et al.* (1978) found that including Umklapp processes and Fermi surface distortion could produce non-linear thermopowers, but the presence or absence of spin fluctuations made no significant difference at all. In the one-band model, however, the interplay of potential and spin-fluctuation scattering does lead to giant diffusion thermopower peaks, as shown in Fig. 11. There is also a possibility of a spin-fluctuation drag thermopower component S_{sd} (Kaiser 1976) in analogy to phonon drag S_g . Although this term would be expected to be rather small in magnitude, the large peaks in the *PdNi* thermopower (Foiles and Schindler 1968) show a strong increase with impurity concentration, suggesting a drag rather than a diffusion effect. Experiments were therefore devised to distinguish the two effects (Kaiser *et al.* 1980).

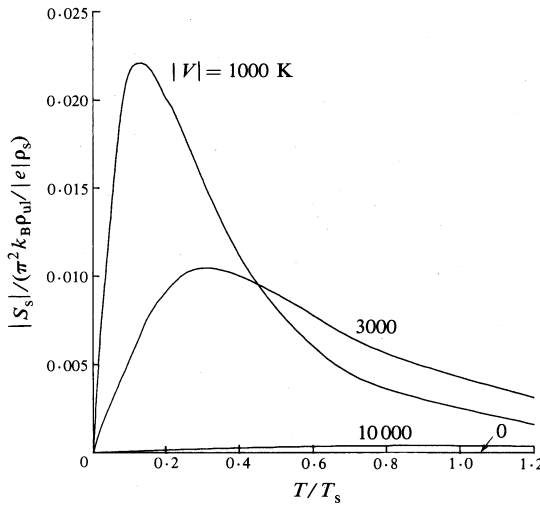


Fig. 11. The LSF contribution S_s to the diffusion thermopower for the one-band model, for V values as shown and $T_s = 12$ K, $A = 10^4$ K (as in Fig. 7 for resistivity).

The total thermopower of an alloy is given by

$$S = S_d + S_g + S_{sd}. \quad (11)$$

The diffusion component S_d is given by the usual rule

$$S_d = (W_i/W)S_i + (W_h/W)S_h, \quad (12)$$

where W_i and W_h are the thermal resistivity components due to the impurity and host respectively, S_i and S_h are the characteristic thermopowers for the impurity and host, and W is the total thermal resistivity. By varying the balance of scattering W_i/W_h in a way which could be estimated, two tests were performed. In the first test, the thermopower of a second less concentrated but more pure *PdNi* alloy was predicted using equations (11) and (12): the purity and concentration effects nearly cancel for the diffusion term but the drag term scales with Ni concentration, as shown in Fig. 12. In the second test, Pt was added in increasing amounts to a *PdNi* alloy to decrease W_i/W for the Ni impurities without greatly affecting the spin fluctuation

spectrum, so a diffusion peak would progressively disappear while a drag peak would not be greatly affected. Perhaps surprisingly decisive for thermopower measurements, the results disposed of the drag hypothesis.

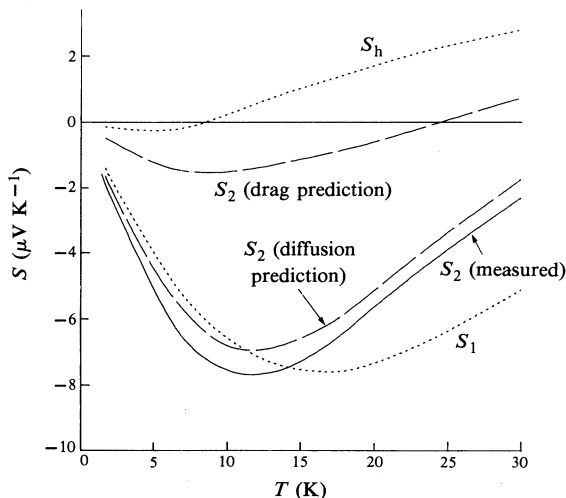


Fig. 12. Measured thermopower S_2 of a second $PdNi$ sample, compared with predictions assuming diffusion and drag mechanisms. Here S_1 is the thermopower of the first sample and S_h the thermopower of Pd used for the predictions (Kaiser *et al.* 1980).

It appears therefore, that the large thermopower peaks in $PdNi$ (and also in $IrFe$ and $RhFe$) are a diffusion effect arising from a mechanism similar to that in the one-band model. Even if the contribution of the Pd d-hole bands to the electrical and thermal conductivity is rather small, the same is not necessarily true for the diffusion thermopower, especially since the electron band contribution is very small.

6. Conclusions

The distinguishing feature of the uniform spin fluctuation or Wolff-model LSF systems that we have considered is a spin fluctuation resistivity component which increases as T^2 at the lowest temperatures with a slower T dependence as T increases. We now list many of the systems to which these models have been applied, giving references to papers on the resistivity (usually the latest paper if there are more than one).

(a) Uniform Spin Fluctuation Systems

The two-band uniform (i.e. spatially extended) spin fluctuation model appears to offer an explanation of the resistivity of the transition metals Pd (Jullien *et al.* 1974) and Pt (Mackliet *et al.* 1970), and of the compounds Ni_3Al and Ni_3Ga (Fluitman *et al.* 1973). The resistivities of the exchange-enhanced actinide metals Np and Pu also show typical spin fluctuation behaviour arising from 5f band fluctuations (Jullien *et al.* 1974), as do many actinide-based compounds: UAl_2 , UAl_3 , UAl_4 , USn_3 , UGe_3 , USi_3 , UGa_3 , UIn_3 , $PuZn_2$, $PuRh_2$, $PuAl_2$, $PuRu_2$, $PuIr_2$, $NpRh_3$ (Brodsky 1974).

It has been suggested (Jullien and Coqblin 1976) that because of the lack of temperature dependence in the static susceptibilities of Pu and Np, and the compounds UAl_2 , UAl_4 , USn_3 , PuRh_2 , PuAl_2 , PuZn_2 and NpRh_3 , the spin fluctuations in these materials could be antiferromagnetic rather than ferromagnetic. The resistivity is similar in each case, but because the peak in susceptibility $\chi(\mathbf{q}, 0)$ in the antiferromagnetic case occurs at a nonzero q value rather than $q = 0$ the static susceptibility $\chi(0, 0)$ may show less T dependence than in the ferromagnetic case.

(b) LSF Systems

The two-band LSF model appears appropriate for the resistivities of dilute PdNi alloys (Greig and Rowlands 1974), especially in view of the thermal resistivity observations mentioned in Section 4, although the thermopower appears to have a large one-band contribution. This picture should also apply for other dilute alloys with Pd or Pt hosts: (Pd, Pt)Ni (Greig and Rowlands 1974), (Pd, Rh)Ni (Purwins *et al.* 1972), PdCo (Loram *et al.* 1971), PdV (Kao *et al.* 1973), PtNi (Mackliet *et al.* 1970), PtFe (Loram *et al.* 1972) and PtCo (Williams *et al.* 1975).

The LSF model has been invoked to explain the resistivity of α -Ce with magnetic impurities, possibly β -Ce clusters (Brodsky and Friddle 1973). The dilute alloy PdPu (Nellis and Brodsky 1971) presents an interesting case: this alloy shows a Wolff-model type of LSF resistivity (*increasing* as T increases), yet has a large temperature-independent scattering component due to the dissimilarity of the electronic structures of Pd and Pu (which would suggest that the Anderson model with an LSF resistivity *decreasing* with T should have been more appropriate).

Contributions from the one-band Wolff-model LSF scattering mechanism (and possibly also from the two-band mechanism) are likely to be present in Rh and Ir based dilute alloys: RhFe (Rusby 1974), (Rh, Ru)Fe (Knapp and Sarachik 1969), RhMn and possibly RhCo (Coles *et al.* 1971), IrFe, (Ir, Os)Fe and (Ir, Pt)Fe (Sarachik 1968), and also in RuFe (Kao and Williams 1974). The LSF model should still be applicable (at least at low temperatures) even if some of these alloys are considered as Wolff-type Kondo alloys with strongly magnetic impurities, as discussed in Section 2c.

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