Properties of the localized-spin-fluctuating system *Pt* Co. II. Resistivity and magnetoresistance*

Gwyn Williams†
School of Mathematical and Physical Sciences, University of Sussex, Brighton, United Kingdom and Department of Physics, University of Manitoba, Winnipeg R3T 2N2, Canada

G. A. Swallow‡
School of Mathematical and Physical Sciences, University of Sussex, Brighton, United Kingdom

J. W. Loram
School of Mathematical and Physical Sciences, University of Sussex, Brighton, United Kingdom

(Received 4 June 1974)

The results of measurements of the resistivity and magnetoresistance of a Pt–0.061-at.%-Co sample—the susceptibility and magnetization of which had been the subject of a previous investigation—are reported. These transport measurements were performed between 1.5 and 10 K in applied magnetic fields of 0, 10, 25, and 59 kOe. The zero-field electrical-resistivity data are well fitted by the modified localized-spin-fluctuation (lsf) expression: $\Delta\rho(T) = A + B \ln[(T^2 + \Theta^2)^{1/2}]$, and the lsf characteristic temperature Θ is estimated at 0.7 ± 0.1 K for the dilute *Pt* Co system. Except at the highest field and lowest temperatures, the remainder of these data are also well fitted by the above expression for the incremental resistivity, with T (in the presence of a magnetic field H) replaced by an effective temperature T_{eff} of the form $T_{\text{eff}}^2 = T^2 + (g\mu_B/k_B)^2 H^2$. The actual fitting scheme provides strong supporting evidence for the phenomenologically assumed form of T_{eff}, and yields a g value of 1.5 ± 0.1. The validity of the so-called Knapp plots has been investigated, and a generalized form applicable in a magnetic field suggested, $\Delta\rho(H, T) \propto \mu_{\text{eff}}^2(T_{\text{eff}})$.

INTRODUCTION

The transport properties of dilute *Pt*Co show strong qualitative resemblance to those of *Rh*Fe.[1] Resistivity measurements[2] on a Pt–0.07-at.%-Co specimen have revealed a strong positive logarithmic temperature dependence in the incremental resistivity $\Delta\rho(T)$ between 1 and 10 K, while the magnetoresistance[3] of this same sample was found to be positive. These data have previously been discussed[2] in terms of the following approaches: (i) The first is based on the modification[4] of the conventional Kondo[5] "ln$T$" term by the phase shift δ_v induced by potential scattering; for $\delta_v > \frac{1}{4}\pi$ the sign of the ln$T$ term is reversed. (ii) The phenomenological 2-band model of Knapp.[6] In this latter model (in which low-effective-mass s electrons are assumed to dominate the conductivity) an antiferromagnetic local-moment–d-band coupling ($J_{d-\text{local}} < 0$) can result in spin compensation of such a moment by itinerant d electrons. The second-order incremental resistivity $\Delta\rho(T)$ arising from conduction electrons scattering from localized spins[7] is simply proportional to $J_{s-\text{local}}^2 S(S+1)$, with $J_{s-\text{local}}$ (in this context) being the s-electron–local-moment exchange coupling and S the spin of the impurity-moment–d-band complex.[8] Since S is decreasing due to compensation effects, so is $\Delta\rho(T)$.

Approach (i) seems as unlikely for *Pt*Co as it did for *Pd*Co (Ref. 9); viz., the impurity potential possesses substantial d-like symmetry and hence should be screened predominantly by the $l=2$ (d-like) component of the conduction band. With an effective host-impurity charge difference of 1, the d-electron phase shift is considerably smaller than $\frac{1}{4}\pi$; correspondingly, the (nonresonant) s-electron phase shift should also be smaller than $\frac{1}{4}\pi$. The two-band model, however, has met with more success; its principal achievement has been to phenomenologically relate[6] the incremental resistivity $\Delta\rho(T)$ to the effective impurity moment $\mu_{\text{eff}}(T)$ via the equation

$$\Delta\rho(T) \propto \mu_{\text{eff}}^2, \tag{1}$$

which has been shown by Knapp[6] to account for the data on both the *Ir*Fe and *Rh*Fe systems. More recently, Shen *et al.*[2] have shown that Eq. (1) also describes the *Pt*Co data below 5 K; they used NMR measurements on this system[10] to indirectly estimate $\mu_{\text{eff}}^2(T)$ from the relationship

$$\mu_{\text{eff}}^2(T) \propto T\Delta H, \tag{2}$$

where ΔH is the NMR linewidth. In addition they plot $T\Delta H$ [i.e., $\mu_{\text{eff}}^2(T)$] against temperature, and hence demonstrate the rapid decrease in this effective moment below 5 K. Additional evidence for an effective moment reduction has come from

nuclear orientation[11] and recent magnetization measurements,[12] both of which indicate a rapid suppression of $\mu_{\text{eff}}(T)$ in dilute *Pt*Co alloys below a characteristic temperature of about 1.6 K.

One conceptual difficulty, however, in applying Knapp's approach to explain the positive logarithmic temperature dependence in $\Delta\rho(T)$ for systems like *Pt*Co, *Pt*Fe, (Ref. 13) and *Pd*Co (Ref. 9) lies in the fact that these are giant-moment systems, for which the *net* $J_{d\text{-local}}$ must therefore be positive. There are, of course, several contributions to $J_{d\text{-local}}$, the principal two being the "covalent admixture" and the "energy shift" components,[14,15] which produce positive and negative contributions, respectively. Clearly, in giant-moment systems the former must dominate, and it would further appear necessary to attribute the compensation effects to the energy-shift term alone. Some of the difficulties associated with this phenomenological two-band model can be avoided by using the concept of localized spin fluctuations (lsf),[16,17] the predictions of which substantiate those of the two-band model. More specifically the lsf model (with potential scattering included[18-22] predicts that

$$\Delta\rho(T)/c = A + B\ln[(T^2+\Theta^2)^{1/2}], \tag{3}$$

where A and B are constant, c is the impurity concentration, and Θ is the characteristic lsf temperature; furthermore, this model suggests that Eq. (1) should be valid when $\Delta\rho(T)$ varies approximately linearly with T.[17]

In this paper we present resistivity measurements on a Pt–0.061-at.%-Co alloy in the temperature range 1.5–10 K, and magnetoresistance data over the same temperature range and in applied fields of approximately 10, 25, and 58 kOe; the magnetic properties of this same sample had previously[23] been investigated over a comparable field and temperature range. Except at the highest fields and lowest temperatures used here the transport measurements are well represented by Eq. (3) when the latter has been phenomenologically modified to include the effects of an applied magnetic field.

EXPERIMENTAL DETAILS

For the magnetoresistance measurements a specimen approximately 0.2 cm wide and 6 cm long was cut from the same annealed Pt–0.061-at.%-Co foil that had been used to fabricate the magnetization specimen.[23] The magnetoresistance sample was bent into the form of a hairpin and mounted such that 5.7 cm experienced a longitudinal magnetic field and 0.3 cm a transverse field; such a geometry should not result in any complicated behavior since previous investigations[24] have shown that both the longitudinal and transverse magnoresistivity of polycrystalline paramagnetic magnetic alloys have the same dependence on field and temperature. With the above arrangement the sample current is predominantly parallel or antiparallel to the field direction, and the latter is estimated to vary by about 2 parts in 10^3 over the length of the sample. A four-probe technique, in which the specimen current was varied to balance a highly stable voltage, was used to measure the specimen resistance. This balanced condition was detected by a Keithley 149 millimicrovoltmeter to $\pm 10^{-9}$ V, and the sample voltage and current then estimated using Hewlett-Packard digital voltmeters. A resistance measurement accurate to 1 part in 10^4 was achieved in this way. Finally the area-to-length ratio of the specimen was estimated to within ±0.5%, thus allowing absolute values of the incremental resistivity $\Delta\rho(H,T)$ $[=\rho_{\text{alloy}}(H,T)-\rho_{\text{Pt}}(0,T)]$ to be determined to that accuracy. The pure Pt sample was prepared by cold rolling 99.999% pure Pt wire between Melinex sheets and was given the same etching and annealing treatment as the *Pt*Co specimen. Its resistance was determined in the above described manner; full details of its temperature dependence are given in Ref. 20. Both the measurement of the applied magnetic field and the temperature stabilization and measurement were performed in the same manner as with the magnetization investigation.[23]

RESULTS AND DISCUSSION

General features

The general features of the magnetoresistance are reproduced in Fig. 1, in which $\Delta\rho(H,T)$ is plotted against temperature (on a logarithmic scale) for $H=0$, 9.7, 24.8, and 58.5 kOe. This diagram indicates that in zero field $\Delta\rho(H=0,T)$ varies with temperature approximately as $\ln T$, although at the lowest temperature positive curvature away from this logarithmic dependence is observed. Such curvature is enhanced by the application of a magnetic field. The magnetoresistance is positive, and is not attributable to cyclotron-curvature effects since the Kohler term necessary to make the 60-kOe data fall below the zero-field results is about 0.04 $\mu\Omega$ cm, far in excess of the estimated value for this term in the *Pt*Fe system.[13] In Figs. 2 and 3 the low-temperature deviations of $\Delta\rho(H,T)$ from a $\ln T$ form are examined in more detail, with $\Delta\rho(H=0,T)$ and $\Delta\rho(H=25\text{ kOe},T)$ being plotted against T on a linear scale; such plots suggest $\Delta\rho(H,T)$ approaches a linear dependence on T at the lowest temperature reached.

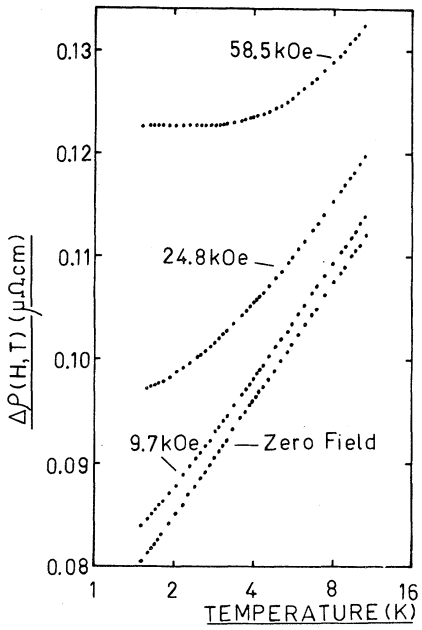

FIG. 1. Incremental resistivity $\Delta\rho(H, T)$ (in $\mu\Omega$ cm) plotted against temperature (in K) on a logarithmic scale, for zero applied field and in fields of 9.7, 24.8 and 58.5 kOe.

Details

Following the success of the lsf concept in explaining many of the properties of dilute systems based on second-transition-series hosts containing first-transition-series impurities, we have attempted a detailed fit of the transport data to lsf theory. The expression used in fitting these data is the result of a phenomenological modification[18-20] of the Kaiser-Doniach approach to include potential scattering at the impurity site, although more recent justification for the use of such an expression has been provided by Rivier and Zlatic.[21,22] The incremental impurity resistivity $\Delta\rho(T)$ is written as

$$\Delta\rho(T) = A + B\ln[(T^2+\Theta^2)^{1/2}]. \tag{4}$$

Here Θ measures the inverse lsf lifetime, while A and B are regarded as adjustable parameters obtained by fitting the data; however, according to the phase-shift model,[18-20] the *sign* for B is determined by the host-impurity charge difference z via

$$B \propto \cos[\pi z/(2l+1)], \tag{5}$$

where $2l+1$ is the orbital-degeneracy factor. For Co in Pt B is predicted to be positive.

In Fig. 4 the zero-field transport data are reproduced, with the solid line being a fit of Eq. (4) to these data; the fit is excellent, and B is positive as required by the phase shift analysis via Eq. (5). The values for A, B, and Θ are listed in Table I.

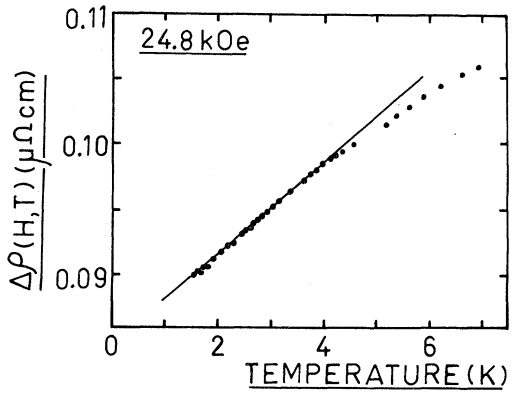

FIG. 3. Detailed plot of the incremental resistivity $\Delta\rho(H, T)$ (in $\mu\Omega$ cm), taken in a field of 24.8 kOe, plotted against temperature (in K).

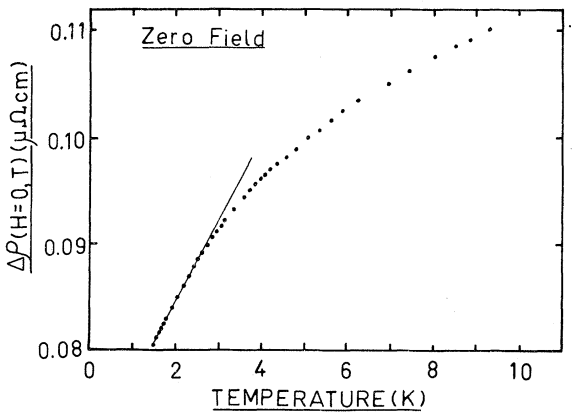

FIG. 2. Detailed plot of the incremental resistivity $\Delta\rho(T)$ (in $\mu\Omega$ cm), taken in zero applied field of 24.8 kOe, plotted against temperature (in K).

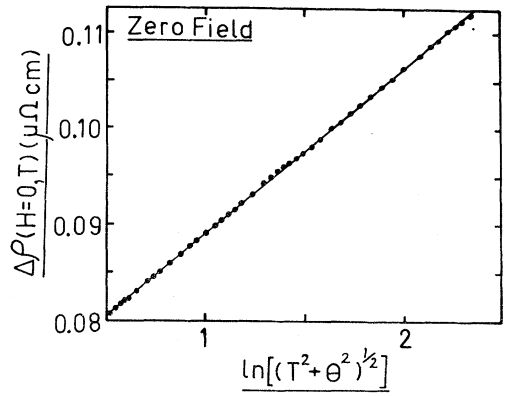

FIG. 4. Zero-field incremental resistivity $\Delta\rho(T)$ (in $\mu\Omega$ cm) plotted against $\ln[(T^2+\Theta^2)^{1/2}]$. The solid line is a fit to Eq. (4) using the parameters listed in Table I.

An attempt was then made to fit the data taken in a field of 9.7 kOe, and, consequently, possible modifications of Eq. (4) to take into account the effects of an applied magnetic field were examined. As already discussed in a previous paper on the magnetization data,[23] the effect of such a field is to reduce the spin fluctuation rate by stabilizing spin fluctuations at the impurity sites, thus forcing the impurity closer to the static Hartree-Fock instability. This would appear to be equivalent to reducing the characteristic lsf temperature Θ, but such a reduction would lead via Eq. (4) to a negative magnetoresistance in lsf systems for which B is positive, and a positive magnetoresistance when B is negative, contradicting the experimentally observed variations. It was thus decided to use the concept of an effective temperature by writing

$$\Delta\rho(T) = A + B\ln[(T_{\rm eff}^2 + \Theta^2)^{1/2}], \tag{6}$$

where, as originally suggested by Suhl[25] in examining interaction effects in the Kondo problem, and discussed in relation to the magnetization data,

$$T_{\rm eff}^2 = T^2 + (g\mu_B/k_B)^2 H^2. \tag{7}$$

In fitting Eq. (6) to the experimental data, the coefficient B was fixed at the value determined from the zero-field data, but A was regarded as further adjustable so as to allow for the effect of the usual positive Kohler term due to cyclotron-curvature effects. For convenience $T_{\rm eff}^2 + \Theta^2$ was replaced by $T^2 + \alpha^2$, with α being allowed to vary *without restriction* to produce the best fit.[26] This latter procedure was followed in an attempt to provide a firmer foundation for the use of Eq. (7); viz., it was our intention to fit Eq. (6) to data taken in various fields, allowing α to vary freely, and then show that α^2 did indeed scale as H^2, as suggested in Eq. (7).

In Fig. 5 the transport data taken in a field of 9.7 kOe are displayed, the solid line being the fit of Eq. (6) to these data using the values for A, B, and α listed in Table I. The fit is again very good. Figures 6 and 7 incorporate the data taken in fields of 24.8 and 58.5 kOe, respectively, with the solid

TABLE I. Values for the parameters of Eq. (6) used to fit the data.

Field H (k0e)	A ($\mu\Omega$ cm)	B ($\mu\Omega$ cm)	θ; α (K)
0	0.0721	0.004 26	0.7 ± 0.1
9.7	0.0740	0.004 26	1.0 ± 0.1
24.8	0.0793	0.004 26	2.4 ± 0.1
58.5	0.0900	0.004 26	5.7 ± 0.1

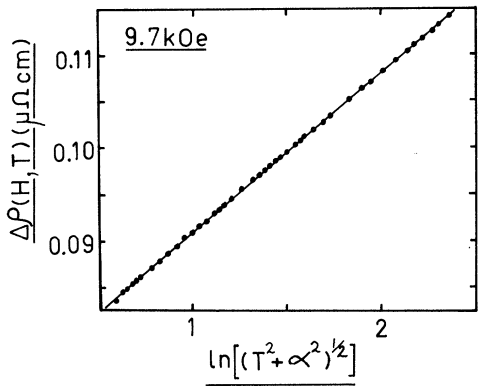

FIG. 5. Incremental resistivity $\Delta\rho(H,T)$ (in $\mu\Omega$ cm) taken in a field of 9.7 kOe plotted against $\ln[(T^2+\alpha^2)^{1/2}]$. The solid line is a fit to Eq. (6) using the parameters listed in Table I.

lines representing the appropriate fits using the listed values for A, B, and α. While the fit of the 24.8-kOe data is very good, it is clear from Fig. 7 that at the highest fields used in this investigation Eq. (6) reproduces only those data taken above about 5 K. Below this temperature systematic deviations from the fitted curves occur, with the measured value for $\Delta\rho(H = 58.5$ kOe, $T)$ becoming progressively larger than the calculated value as the temperature is reduced.

Figure 8 establishes the field dependence of the parameter α; this figure verifies the dependence suggested prior to Eq. (7), viz., that α has the form

$$\alpha^2 = \Theta^2 + (g\mu_B/k_B)^2 H^2, \tag{8}$$

where the lsf temperature Θ is determined from the zero-field data to be 0.7 ± 0.1 K. The slope of Fig. 8 yields a value for the g factor; here we obtain

$$g = 1.5 \pm 0.1.$$

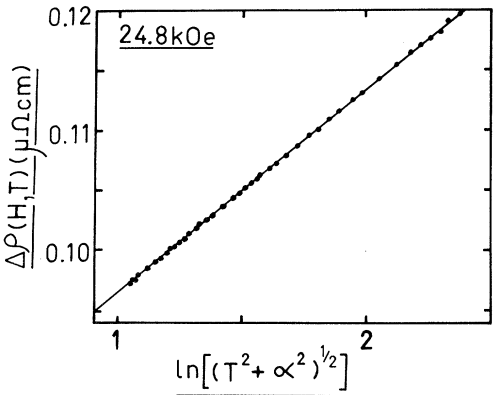

FIG. 6. Incremental resistivity $\Delta\rho(H,T)$ (in $\mu\Omega$ cm) taken at 24.8 kOe plotted against $\ln[(T^2+\alpha^2)^{1/2}]$. The solid line is a fit to Eq. (6) using the listed parameters.

The estimated lsf temperature Θ for *Pt*Co is thus about twice that for *Pt*Fe,[20] which thus agrees with the established trend in Pd-based alloys; viz., the characteristic temperature for *Pd*Co is higher than that for *Pd*Fe (although by substantially more than a factor of 2). Further, the characteristic lsf temperature for Co in Pt is higher than that for Co in Pd, again in agreement with the previously established pattern[27,28] for first-row transitional impurities in these hosts.

The g value, however, remains puzzling, not in view of the fact that it is different from 2, but in that it is less than 2. Like *Pd*Fe, *Pd*Co, and *Pt*Fe, *Pt*Co is a giant-moment system, from which it is inferred that the net d-band–local-moment coupling ($J_{d\text{-local}}$) is positive. For such systems it is usual to write[8,13,29]

$$g_{\text{eff}} \simeq g_s + 2\chi J_{d\text{-local}}/g_e \mu_B, \tag{9}$$

where g_s and g_e are the impurity and electron splitting factors, respectively; the use of $J_{d\text{-local}}$ in Eq. (9) results from the fact that in these hosts the dominant contribution to the susceptibility comes from the d band. With $J_{d\text{-local}} > 0$ one expects $g_{\text{eff}} > 2$; indeed, magnetoresistance measurements on dilute *Pd*Fe, *Pd*Co, and *Pt*Fe alloys appear to confirm this. However, in these latter three systems the magnetoresistance is negative, and is well described by a straightforward second-order perturbation-theory calculation[7] based on the s-d model, this latter model also serving as the basis for Eq. (9). In contrast, *Pt*Co exhibits a positive magnetoresistance, indicating the dominance of the spin-fluctuation aspect of the impurity d-spin polarization dynamics over its field-oriented properties as described by the s-d model. Such a situation could invalidate the simplified calculation of g_{eff} based on the s-d model, as represented by

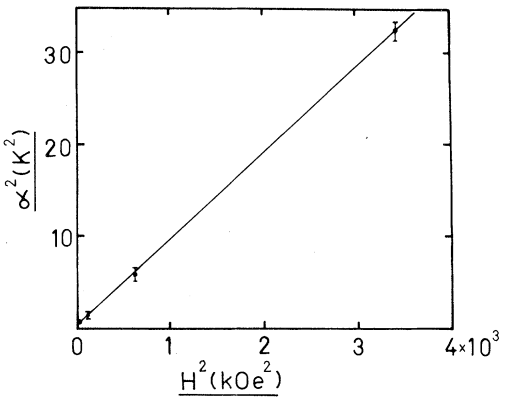

FIG. 8. Plot of α^2 (in K^2), derived from fitting the data in Figs. 4 and 7, plotted against the square of the applied field H (in kOe). The line drawn corresponds to a "g value" of 1.5.

Eq. (9). The possibility that g_s—the impurity splitting factor—is different from 2.0 due to incomplete quenching of the impurity orbital angular momentum has also been considered. Calculations of such effects by Hirst,[30] however, indicate that for a $3d^7$ configuration subject to a cubic crystal field the impurity splitting factor is not reduced below 2.0 for either sign of the coefficient C_4 of the fourth-order crystal-field term. Impurity g values which are less than 2.0 have been observed for some impurities in exchange-enhanced hosts[31]; these impurities, however, usually have localized f electrons, and the explanations offered for the negative g shift specifically involve the f-electron nature of the impurity moment, and thus do not apply to the system considered here.

Figure 9, in which $\Delta\rho(H,T)$ is plotted against $\ln[(T^2+\alpha^2)^{1/2}]$, summarizes all the zero-field and magnetoresistance data. If Eq. (6) provides the

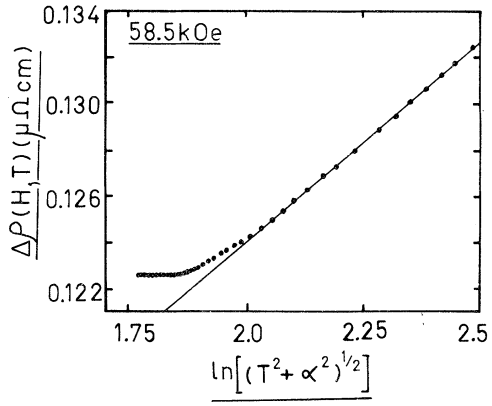

FIG. 7. Incremental resistivity $\Delta\rho(H,T)$ (in $\mu\Omega$ cm) at 58.5 kOe plotted against $\ln[(T^2+\alpha^2)^{1/2}]$. The solid line is a fit to Eq. (6) using the listed parameters.

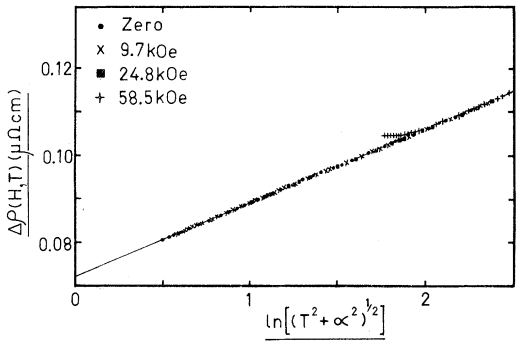

FIG. 9. Universal plot of the incremental resistivity $\Delta\rho(H,T)$, taken at the various applied fields, plotted against $\ln[(T^2+\alpha^2)^{1/2}]$. The data taken in different fields have been shifted (the Kohler term) so that they scale as $\ln[(T^2+\alpha^2)^{1/2}]$.

TABLE II. Estimates of the Kohler term.

Field H (k0e)	A ($\mu\Omega$ cm)	$\Delta\rho$ (Kohler) ($\mu\Omega$ cm)
0	0.0721	0.0
9.7	0.0740	0.0019
24.8	0.0793	0.0072
58.5	0.0900	0.0179

correct description of these data—and the previous analysis indicates that this is indeed the case—then, *once allowance has been made for the Kohler term*, $\Delta\rho(H,T)$ should be a universal function of $\ln[(T_{\text{eff}}^2+\Theta^2)^{1/2}]$ (neglecting the previously mentioned difficulties encountered at the highest field and lowest temperatures). Figure 9 demonstrates that this is the case, and further allows estimates of the Kohler terms to be made; the latter are simply the *constant* shifts applied to data taken at particular fixed fields in order that they match up with the zero-field results. The Kohler terms so estimated are listed in Table II; they appear comparable in magnitude with the corresponding values estimated for similar concentrations of Fe and Co in Pd,[8] and Fe in Pt.[13] In addition, the previous discussion suggests that within experimental error these terms are temperature independent over the range of measurement. In Fig. 10 the Kohler terms are plotted against applied magnetic field; above 10 kOe a linear dependence on field is followed, although below 10 kOe a more rapid dependence is indicated.

Our final point concerns the applicability of the Knapp plots. As mentioned in the Introduction, Shen *et al.*[2] have demonstrated that below 5 K their data on the *Pt*Co system follows the relationship

$$\Delta\rho(T) \propto T\Delta H \tag{10}$$

(where ΔH was obtained in a field of 8 kOe), which

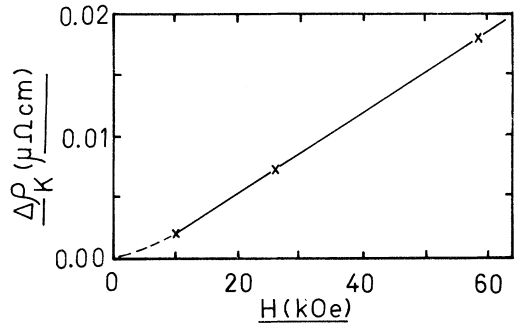

FIG. 10. Kohler term $\Delta\rho_K$ (in $\mu\Omega$ cm), derived as explained in the text, plotted against the applied field H (in kOe).

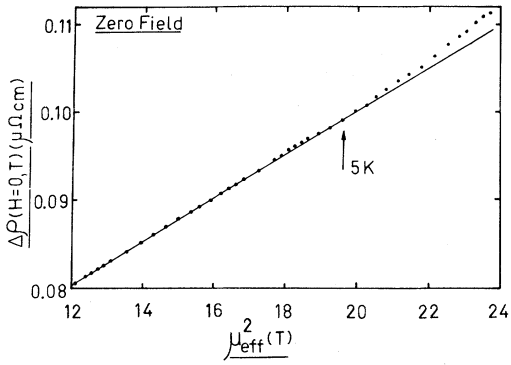

FIG. 11. Zero-field Knapp plot of the incremental resistivity $\Delta\rho(T)$ (in $\mu\Omega$ cm) against the square of the effective moment $\mu_{\text{eff}}(T)$ (in Bohr magnetons per impurity).

is confirmed here in Fig. 11. In this figure the zero-field resistivity data $\Delta\rho(T)$ are plotted against $\mu_{\text{eff}}^2(T)$, the latter being obtained from Fig. 2 of Ref. 23 by way of the susceptibility data. The range of validity of Eq. (1) is seen to extend beyond $\mu_{\text{eff}}^2(T) \simeq 20$, which, from Fig. 2 of Ref. 23, corresponds to a temperature of 5 K. Kaiser and Doniach[17] have predicted that the Knapp plots [Eq. (1)] should be valid in that temperature region where $\Delta\rho(T)$ varies linearly with temperature; however, an inspection of Fig. 2 reveals that experimentally such a linear dependence of $\Delta\rho(T)$ in *Pt*Co persists only to about 2.5 K, above which $\Delta\rho(T)$ increases more slowly (approximately as $\ln T$). This suggests that Knapp's phenomenological relationship may be valid over a wider temperature range than at first thought. Equation (1) has also been applied to the data taken in an applied field. In Fig. 12 the 24.8-kOe data are reproduced in the

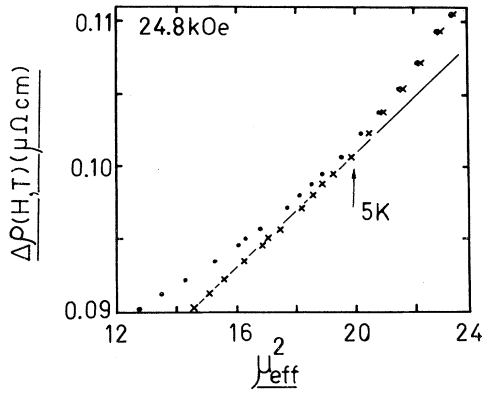

FIG. 12. Knapp plot at 24.8 kOe, showing $\Delta\rho(H,T)$ (in $\mu\Omega$ cm) plotted against the square of the effective moment μ_{eff} (in Bohr magnetons per impurity). The circles are $\mu_{\text{eff}}(T)$, the crosses $\mu_{\text{eff}}(T_{\text{eff}})$, where T_{eff} is calculated as explained in the text.

form $\Delta\rho(H=24.8\ \text{kOe}, T)$ vs $\mu^2_{\text{eff}}(T)$; these data, shown as circles, clearly do not follow Eq. (1), as they exhibit considerable curvature over the entire range examined. However, it has already been demonstrated that in an applied magnetic field it is necessary to introduce an effective temperature T_{eff}, given by Eq. (7), in order to describe such data. Correspondingly the Knapp plot appropriate to data taken in an applied field H is one in which $\Delta\rho(H, T)$ is plotted against $\mu^2_{\text{eff}}(T_{\text{eff}})$ rather than $\mu^2_{\text{eff}}(T)$. The crosses in Fig. 12 represent just such a plot, which utilizes the T_{eff} calculated from Eq. (7) using $g=1.5$. As can be seen from this figure, the more general relationship

$$\Delta\rho(H, T) \propto \mu^2_{\text{eff}}(T_{\text{eff}}) \tag{11}$$

holds for the *Pt*Co data up to 5 K; above this temperature the deviations from Eq. (11) are similar to those observed for the zero-field data. Although it is not reproduced here, we find that the data taken at 9.7 kOe can similarly be represented by Eq. (11) below 5 K, but the data taken at 58.5 kOe has not been plotted in the form suggested by Eq. (11) since these data do not follow Eq. (6) at the lower temperatures, where the Knapp plots for data taken in lower fields enjoy some success.

SUMMARY

Electrical-resistivity measurements, carried out between 1.5 and 10 K in applied fields of 0, 10, 25, and 50 kOe on a Pt–0.061-at.%-Co sample, are well represented (except at the highest field and lowest temperatures) by the modified expression

$$\Delta\rho(H, T) = A + B\ln[(T^2_{\text{eff}} + \Theta^2)^{1/2}],$$

with the lsf temperature Θ estimated at 0.7 ± 0.1 K for this system. These transport data not only provide strong evidence supporting the phenomenological form assumed for T_{eff}, but also suggest a modified Knapp relationship in an applied field, viz., $\Delta\rho(H, T) \propto \mu^2_{\text{eff}}(T_{\text{eff}})$.

---

*This work was supported in part by the Air Force Materials Laboratory (AFSC) through the European Office of Aerospace Research (OAR), United States Air Force, under Contract No. F61052-68-C-0011.

†Work at the University of Manitoba was also partially supported by the Defence Research Board under Grant No. 9510-100.

‡Present address: Material Science Division, Berkely Nuclear Laboratories, United Kingdom.

[1]B. R. Coles, Phys. Lett. 8, 243 (1963).

[2]L. Shen, D. S. Schreiber, and A. J. Arko, Phys. Rev. 179, 512 (1969).

[3]L. Shen, D. S. Schreiber, and A. J. Arko, J. Appl. Phys. 40, 1478 (1969).

[4]K. Fischer, Phys. Rev. 158, 613 (1967).

[5]J. Kondo, Prog. Theor. Phys. 32, 37 (1964).

[6]G. S. Knapp, Phys. Lett. A25, 114 (1967).

[7]K. Yosida, Phys. Rev. 107, 396 (1957).

[8]A. D. C. Grassie, G. A. Swallow, Gwyn Williams, and J. W. Loram, Phys. Rev. B 3, 4154 (1971).

[9]J. W. Loram, Gwyn Williams, and G. A. Swallow, Phys. Rev. B 3, 3060 (1971).

[10]L. D. Graham and D. S. Schreiber, J. Appl. Phys. 39, 963 (1968).

[11]J. C. Gallop and I. A. Campbell, Solid State Commun. 6, 831 (1968).

[12]B. Tissier and R. Tournier, Solid State Commun. 11, 895 (1972).

[13]G. A. Swallow, Gwyn Williams, A. D. C. Grassie, and J. W. Loram, J. Phys. F 1, 511 (1971).

[14]P. W. Anderson, Phys. Rev. 124, 41 (1961).

[15]T. Moriya, Prog. Theor. Phys. 34, 329 (1965); T. Moriya, in *Proceedings of the International School of Physics "Enrico Fermi", Course XXXVII, 1966* (Academic, New York, 1967).

[16]P. Lederer and D. L. Mills, Phys. Rev. 165, 837 (1968).

[17]A. B. Kaiser and S. Doniach, Int. J. Magn. 1, 11 (1970).

[18]H. Nagasawa, Solid State Commun. 10, 33 (1972).

[19]J. Souletie, J. Low Temp. Phys. 7, 141 (1972).

[20]J. W. Loram, R. J. White, and A. D. C. Grassie, Phys. Rev. B 5, 3659 (1972).

[21]N. Rivier and V. Zlatic, J. Phys. F 2, L87 (1972).

[22]N. Rivier and V. Zlatic, J. Phys. F 2, L99 (1972).

[23]G. A. Swallow, Gwyn Williams, and A. D. C. Grassie, preceding paper, Phys. Rev. B 11, 337 (1975).

[24]Y. Muto, K. Noto, and F. T. Hedgcock, Can. J. Phys. 42, 15 (1964).

[25]H. Suhl, Phys. Rev. Lett. 20, 656 (1968).

[26]One could write Eq. (6) as

$$\Delta\rho(T) = A + B\ln\{[T^2 + (g\mu_B/k_B)^2 H^2 + \Theta^2]^{1/2}\},$$

and so as far as the present analysis is concerned there is no difference between introducing an effective temperature T_{eff}, given by $T^2_{\text{eff}} = T^2 + (g\mu_B/k_B)^2 H^2$, or Θ_{eff}, given by $\Theta^2_{\text{eff}} = \Theta^2 + (g\mu_B/k_B)^2 H^2$. All the present analysis does show is that the form of the magnetic field modification of Eq. (6) is correct.

[27]F. C. C. Kao and Gwyn Williams, Phys. Rev. B 7, 267 (1973).

[28]R. M. Roshko and Gwyn Williams, Phys. Rev. B 9, 4945 (1974).

[29]M. Peter, J. Dupraz, and H. Cottet, Helv. Phys. Acta 40, 301 (1967).

[30]L. L. Hirst, Z. Phys. 241, 9 (1971).

[31]See, for example, R. H. Taylor and B. R. Coles, J. Phys. F 4, 303 (1974), and references listed therein.