Journal of Physics F: Metal Physics

Susceptibility, magnetisation and critical behaviour of a magnetic superconductor:Y_9Co_7

To cite this article: A Kolodziejczyk and C Sulkowski 1985 *J. Phys. F: Met. Phys.* **15** 1151

J. Phys. F: Met. Phys. 15 (1985) 1151–1163. Printed in Great Britain

Susceptibility, magnetisation and critical behaviour of a magnetic superconductor: Y_9Co_7

A Kołodziejczyk† and C Sułkowski‡

† Department of Solid State Physics, University of Mining and Metallurgy AGH, Al Mickiewicza 30, 30–059 Cracow, Poland

‡ Institute for Low Temperature and Structure Research, Polish Academy of Sciences, Prochnika 95, 53–529 Wrocław, Poland

Received 8 May 1984, in final form 19 September 1984

Abstract. We present detailed measurements of the AC susceptibility and magnetisation as functions of temperature and magnetic field for the magnetic superconductor Y_9Co_7 and compare them with the mean-field theories and the self-consistent renormalisation theory of spin fluctuations. We have also determined the critical exponents β and γ from the asymptotic relations for the critical behaviour of the magnetisation and susceptibility. We have found further evidence that the weak itinerant ferromagnetism of the intermetallic compound Y_9Co_7 is of double character with two groups of Co magnetic behaviour. Comparing the magnetisation data with the theory we have extended the zero-field magnetisation curve up to 0 K, finding further evidence of the coexistence of ferromagnetism and superconductivity.

1. Introduction

The problem of the magnetism of the intermetallic compound Y_4Co_3 (Berthet-Colominas *et al* 1968), later found to be the phase Y_9Co_7 (Sarkissian *et al* 1982, Grover *et al* 1982), was revived at the beginning of the eighties (Gratz *et al* 1980) when it was suggested that there exist itinerant magnetic moments on some cobalt positions and more local magnetic moments on the other cobalt positions, in contrast to a prediction that the compound should be a Pauli paramagnet. More interest has arisen since the discovery of superconductivity (Kołodziejczyk *et al* 1980) with the transition temperature $T_S = 2$ K. The compound was later established as a new type of coexistence of very weak itinerant ferromagnetism (with Curie temperature $T_C = 4.5$ K) and superconductivity (Kołodziejczyk *et al* 1980, Sarkissian 1982a, b, Huang *et al* 1983, Lewicki *et al* 1983, Sułkowski *et al* 1983, Kołodziejczyk 1983a, b, Sarkissian and Beille 1983). A large number of experiments have now been performed (for a review see, e.g., Sarkissian 1982a, b, Kołodziejczyk 1983a, b and references cited therein) but more detailed information on the origins of the magnetism and superconductivity of the compound are needed.

The important discovery that there are three non-equivalent cobalt sites in the unit cell of Y_9Co_7 is a result of NMR spin–echo measurements (Figiel *et al* 1981, Lewicki *et al* 1983, Wada *et al* 1983, Takigawa *et al* 1983) and also of magnetoresistance measurements (Sarkissian 1982a, b, Sarkissian and Grover 1982, Cheng *et al* 1982, Sułkowski *et al* 1983) and specific heat measurements (Cheng *et al* 1982, Sarkissian 1982b, Lewicki *et al* 1983). Two groups of NMR spin–echo lines were observed: the first exhibited a small but finite hyperfine field and the second had almost zero hyperfine field. Thus, two different types of Co magnetic behaviour have been suggested as a result of the three non-equivalent Co positions. However, the magnetic behaviour of the compound is generally very similar to that of other typical, weak itinerant ferromagnets.

Spin fluctuations also play a large role in the temperature dependences of the resistivity and susceptibility above T_C (Kołodziejczyk and Spałek 1984) and in the magnetisation below T_C (Yamaguchi *et al* 1983). Sarkissian and Beille (1983) suggested that the spin fluctuations interact strongly and result from the low-dimensional character of the magnetic correlations.

We have undertaken AC susceptibility and magnetisation measurements close to and below the Curie temperature with as small temperature steps as possible in order to compare the data with the theories available and to study the critical behaviour.

The gap in the magnetisation data of the Arrott plots between rather high-magnetic-field data (Gratz *et al* 1980, van der Liet *et al* 1982, Yamaguchi *et al* 1983, Sarkissian and Beille 1983) and very low-magnetic-field data (Sarkissian 1982a) was another motivation for these measurements. Moreover, it is very important to be able to reconstruct the zero-field magnetisation ($M(0, T)$) curve at temperatures as low as possible in order to determine the temperature interval for the coexistence of magnetism and superconductivity in the compound.

2. Experimental procedure

Our Y_9Co_7 samples were arc-melted and chill-cast and then annealed at 850 K for one week then at 750 K for three weeks. They were prepared from yttrium of purity 99.99% with respect to other rare-earth metals (Rare Earth Product) and specpure cobalt (Johnson–Mathey). Metallographic observations showed some evidence that a second phase exists in the samples, but this is likely to be the intermetallic compound Y_8Co_5 which is non-magnetic and non-superconducting (Sarkissian *et al* 1982). The x-ray powder diffraction pattern was very similar to that of our previous samples and to the samples of other authors. The local deviation of the atomic ratio 9:7 as measured by a microprobe was less than 1 at.%. Therefore the Y_9Co_7 seemed to be quite homogeneous.

The specimen for which the temperature dependences of the susceptibility and the magnetisation were measured has its transition temperature to the superconducting state at $T_S = (2.02 \pm 0.05)$ K, as measured by the standard four-probe AC resistance technique. T_S is the temperature at which the resistance is half that in the normal state (figure 1). The resistance ratio is $R_{300\,K}/R_{4.2\,K} = 9.2$. The slope of the upper critical field near T_S is very similar to that of our previous samples (Sułkowski *et al* 1983) and is approximately 0.21 T K^{-1}.

In-phase AC susceptibility measurements (figure 1) were carried out for a needle-like sample of mass $m = 0.0425$ g by the conventional mutual inductance technique from 1.55 K up to 19.5 K with temperature steps of 0.05 K and stabilisation better than 0.02 K. The amplitude of the AC magnetic field was ~0.1 Oe (RMS) and an operating frequency of 323 Hz was used. The vertical component of the earth's field was cancelled. The error of each experimental point ranged from approximately 0.5% at liquid-helium temperature to approximately 2% at the highest temperatures.

For a rod-shaped specimen of mass $m = 0.2173$ g of the same sample, the magnetisation was measured as a function of the temperature and the magnetic field by a standard ballistic method using a superconducting coil, from 4.365 K down to 1.57 K with temperature steps of 0.2 K, and in magnetic fields from ~2.5 Oe to ~6.0 kOe. The

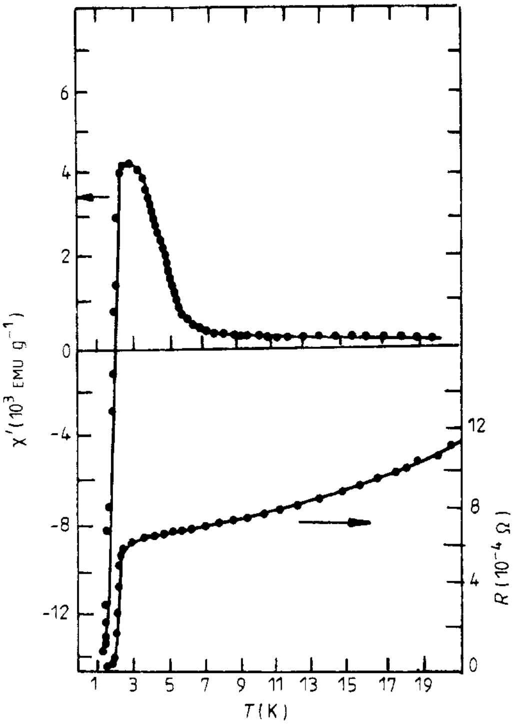

Figure 1. The AC susceptibility χ' and the AC resistance R of the compound Y_9Co_7.

temperature stabilisation was better than 0.02 K and the fluctuations of the applied magnetic fields were less than 0.1%. The error for each experimental point of the magnetisation was about 2%.

3. Results and analysis

From the Landau theory of second-order phase transitions, for the Heisenberg model treated in the mean-field approximation, the magnetic isotherms of the field and temperature dependences of the magnetisation are

$$M(H, T)^2 = M(0,0)^2[A(T)(1 - T/T_C) + B(T)H/M(H, T)] \tag{1}$$

where $A(T)$ and $B(T)$ are model-dependent functions. This expression is in general only applicable near T_C (see, e.g., the review of Brommer 1982 and references cited therein).

The Landau theory for the Stoner model of single-particle excitations yields, in the mean-field approach, the field and temperature dependences of the magnetisation; in the limiting case of very weak itinerant ferromagnetism these take the form (Edwards and Wohlfarth 1968)

$$M(H, T)^2 = M(0,0)^2[1 - (T/T_C)^2 + 2\chi_0 H/M(H, T)]. \tag{2}$$

This expression is valid for the temperature range $0\ K < T < T_F$, the so called effective degeneracy temperature.

From equation (2) we obtain the temperature dependence of the zero-field magnetisation $M(0, T)$ as

$$(M(0, T)/M(0, 0))^2 = 1 - (T/T_C)^2 \tag{3}$$

and the zero-field differential susceptibility χ' in the form

$$\begin{aligned} \chi' &= \chi_0[1-(T/T_C)^2]^{-1} \qquad && T < T_C \\ \chi' &= 2\chi_0[(T/T_C)^2 - 1]^{-1} \qquad && T_F \gg T > T_C. \end{aligned} \tag{4}$$

The empirical relation for magnetic isotherms was proposed by Arrott and Noakes (1967) in the form

$$(M(H, T)/M_1)^{1/\beta} = |(T_C - T)/T_1| + (H/M(H, T))^{1/\gamma} \tag{5}$$

which is composed of three asymptotic relations for the singularities in the critical behaviour of the magnetisation and susceptibility in the limits as $T \to T_C$ and $H \to 0$. These asymptotic relations are

$$\lim_{H\to 0} M(H, T) \equiv M(0, T) = [(T_C - T)/T_2]^\beta \qquad T < T_C, \tag{6}$$

$$\lim_{H\to 0} H/M(H, T) \equiv 1/\chi' = [(T - T_C)/T_1]^\gamma \qquad T > T_C \tag{7}$$

$$H/M(H, T) = (M(H, T)/M_1)^{\gamma/\beta} \qquad T = T_C \tag{8}$$

where β and γ are the critical exponents and $T_2 = M_1^{1/\beta} T_1$. In the mean-field approach the critical exponents are $\beta = 0.5$ and $\gamma = 1.0$. Therefore, plots of $M(H, T)^2$ against $H/M(H, T)$ give a series of parallel straight lines at each temperature below T_F for equation (2), but only near T_C for equation (5).

The self-consistent renormalisation theory of spin fluctuations of Moriya (1979) gives the formula for the zero-field magnetisation near T_C which competes with equations (3) and (6):

$$M(0, T)^2 \sim (T_C^{4/3} - T^{4/3}). \tag{9}$$

It is therefore very useful to elaborate our magnetic isotherms M^2 against H/M in order to obtain $M^2(0, T)$ from the extrapolation to $H = 0$ and then to compare this with equations (3), (6) and (9).

Figure 2 shows the conventional Arrott plots for Y_9Co_7. In the whole range of applied magnetic fields up to approximately 6.2 kOe the magnetic isotherms are not straight lines—they exhibit upward curvature. We are not able to prove definitely that spatial inhomogeneities of the magnetisation resulting from small spatially fluctuating local environments (Acker and Huguenin 1979, Brommer 1982, Wagner and Wohlfarth 1982) and/or spin fluctuations resulting from correlation effects (cf Moriya 1979) are the reasons for such Arrott plots, but the latter effect seems to be more important because only a small deviation from stoichiometry exists in Y_9Co_7 (cf the previous section). However, our purpose is to compare the magnetic isotherms as they are with the theoretical relations mentioned above.

One can distinguish three regions (marked in figure 2 as A, B and C) in which the Arrott plots are straight lines. The first region for low-field magnetisation data from 2.8 Oe to approximately 600 Oe is shown in inset (*a*) of figure 2. The magnetic isotherms in this region are almost straight and parallel lines, but only for sufficiently high magnetic fields (>200 Oe) which are higher when the temperature is lower (see the marks in inset (*a*) of figure 2). It is obvious that the Arrott plots for ferromagnetic materials bend towards zero in very low fields because of the domain structure. A good estimation of the lower limit of such fields is the coercive force which, for Y_9Co_7, ranges from approximately 4 Oe at 4.2 K to approximately 10 Oe at 1.57 K (see the hysteresis loops in inset (*b*) of figure 2). An additional decrease of the magnetisation in low fields comes from the negative diamagnetic contribution, which is more important at lower temperatures where the superconducting state exists.

The second region from approximately 600–2300 Oe is characterised by well defined straight and parallel lines for the magnetic isotherms (figure 2). The transition from the first to the second region is barely perceptible and only tiny changes in the slopes of the magnetic isotherms are observed (cf also figure 2 of Yamaguchi *et al* 1983). This is a further reason why we decided that the zero-field magnetisation $M(0, T)$ would be best determined from an extrapolation to $H=0$ of the Arrott plots between 200 and 2300 Oe, which are fairly good straight and parallel lines, especially at temperatures around 4 K, implying a reasonably well defined Curie temperature $T_C=(4.5 \pm 0.05)$ K at which $M(0, T_C)=0$. (The intercept of this magnetic isotherm with the M^2 axis would be zero.)

The transition from the second region to the third region (C) for magnetic fields higher than 2300 Oe is surprisingly sharp. Very similar behaviour may be observed in figure 2 of Yamaguchi *et al* (1983). The third region seems to show the beginning of a continuous decrease in the slopes of the magnetic isotherms (cf also figure 2 of Gratz *et al* 1980, figure 2 of Yamaguchi *et al* 1983 and figure 3 of Sarkissian and Beille 1983).

Figure 3 shows the square of the zero-field magnetisation, $M^2(0, T)$, as a function of temperature for the three regions of magnetic fields, according to relations (3), (6) and (9), in order to compare the experimental data with the theories.

In the first region (A) the T and $T^{4/3}$ dependences fit the magnetisation data within a broader temperature interval than the T^2 law. Moreover, there are two distinguishable regions of the T^2 law instead of the single region predicted by the theory (Edwards and Wohlfarth 1968).

In the second region (B) we are not able to differentiate between the three power laws at temperatures below T_C and down to ~ 3 K. This is apparently a more general conclusion than that of Yamaguchi *et al* (1983) where only the Moriya relation (9) was found to fit the zero-field magnetisation data below T_C, extrapolated from essentially the same magnetic fields as ours. Moreover, in this region only the T^2 law fits the data within the whole temperature interval below T_C, showing excellent agreement with the theory of single-particle excitations (Edwards and Wohlfarth 1968). Hence, one can extract the zero-field, zero-temperature magnetisation to be $M(0, 0)=0.383$ EMU g^{-1}, the Curie temperature to be $T_C=(4.47 \pm 0.03)$ K and the zero-field, zero-temperature differential susceptibility to be $\chi_0=1.84 \times 10^{-4}$ EMU g^{-1}. In addition, from equation (3.13) of Edwards and Wohlfarth (1968), one can calculate the parameter α $(=N(E_F)\mu_B^2\chi_0^{-1})$ to be 1.67×10^{-3}, where $N(E_F)=1.8$ states (eV atom spin)$^{-1}$ is the density of states calculated from the specific heat coefficient $\gamma=23.8$ erg mol^{-1} K^{-2} of Lewicki *et al* (1983). Thus the condition for the existence of a ferromagnetic ground state, $\alpha + 1 > 1$, is just fulfilled.

Finally, in the third region (C) the T^2 law is again the best one, and the other two relations are definitely poor. We suggest that the same behaviour should persist in higher magnetic fields because we have checked this for the 4.2 K magnetisation curve up to 32 kOe (cf Sarkissian and Beille 1983).

The log–log plot of the AC susceptibility as a function of temperature is shown in figure 4 in order to find which of the power laws (4) or (7) fits the experimental data and to determine the critical exponent γ. There are two distinguishable regions of the susceptibility

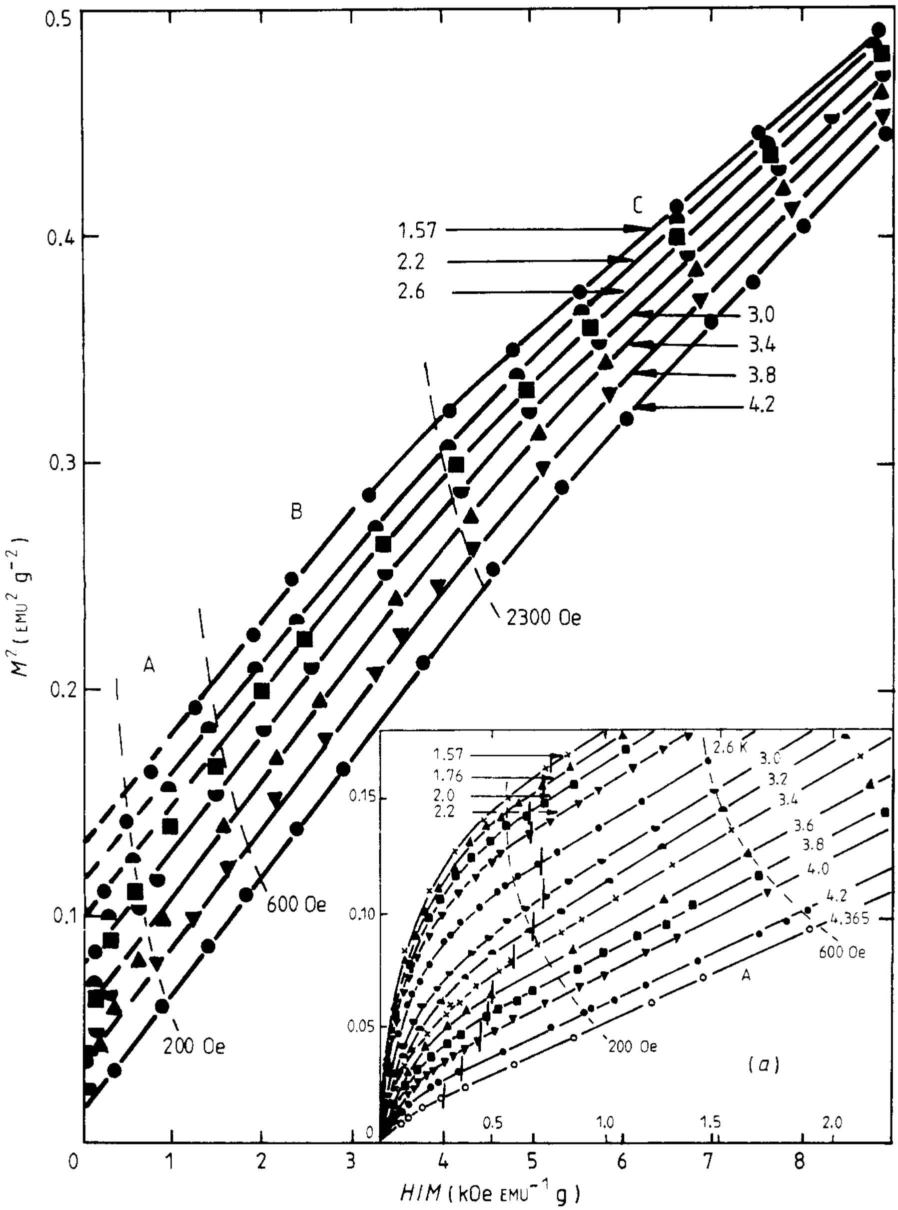

Figure 2. The magnetic field dependence of the magnetisation of the compound Y_9Co_7 at the given temperatures in the form of Arrott plots. The three distinguishable intervals of the magnetic field A, B and C are shown. The inset (*a*) shows the details of the first region (A) on an enlarged scale with the beginnings of the straight lines (cf the text) marked by the vertical bars. The inset (*b*) shows some representative hysteresis loops. All temperatures are in K.

power law above T_C. The first region with $\gamma = 1.12 \pm 0.05$ exists from just above T_C up to approximately 4.8 K and is almost in accord with relations (4) and (7). The second region with $\gamma = 2.02 \pm 0.05$ occurs from 4.8 K to approximately 8 K and is followed by the region

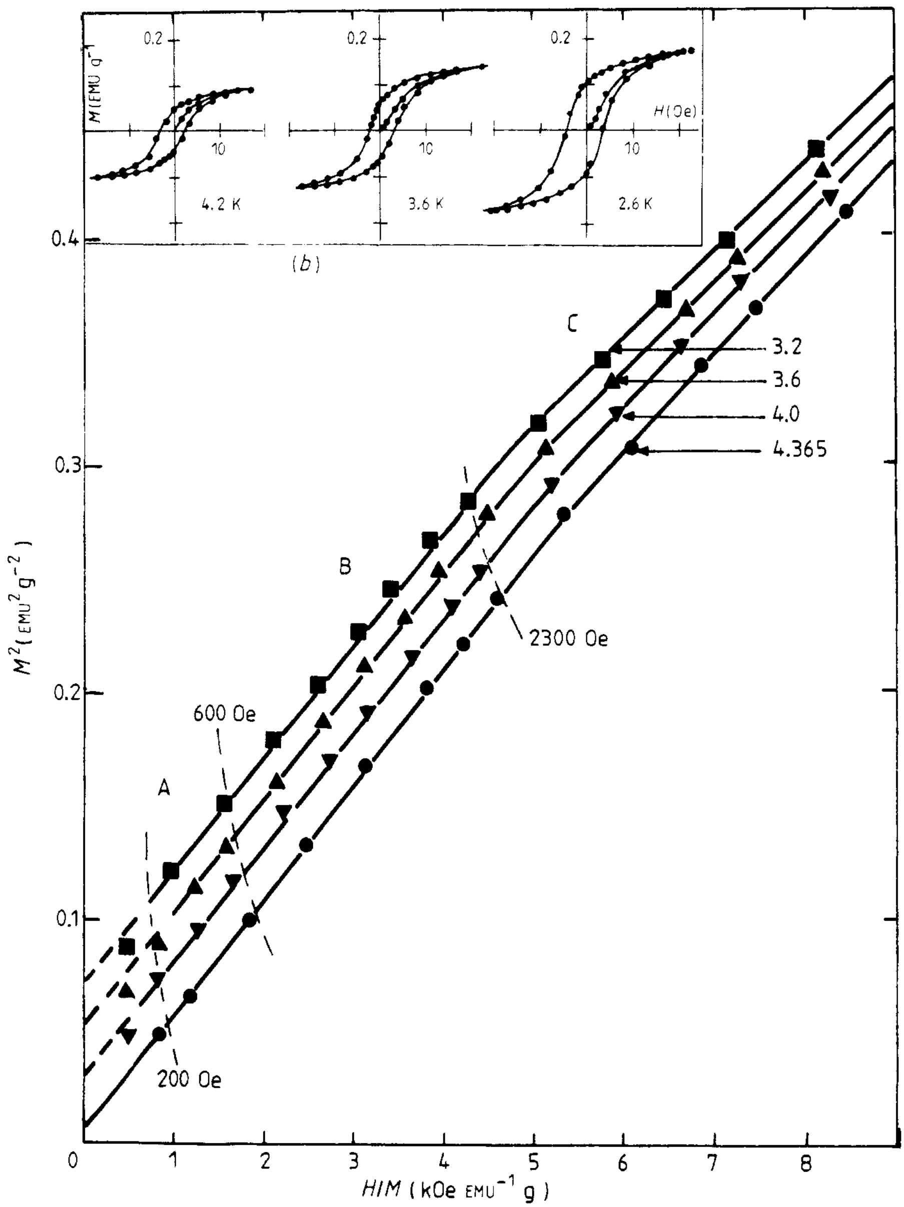

Figure 2(*b*).

where the Curie–Weiss law exists (cf Kołodziejczyk and Spałek 1984).

On the basis of such an analysis of the experimental data we can conclude that up to approximately 2300 Oe the single-particle excitation model for a very weak itinerant ferromagnet fits the data within the whole temperature range from 1.57 K to T_C. Very pronounced effects of the spin fluctuations ($M^2(0, T) \sim T^{4/3}$) and the critical fluctuations ($M^2(0, T) \sim T$), in the ordinary sense of the mean-field approach, are observed up to approximately 3 K and especially at lower magnetic fields (see the upper and middle parts

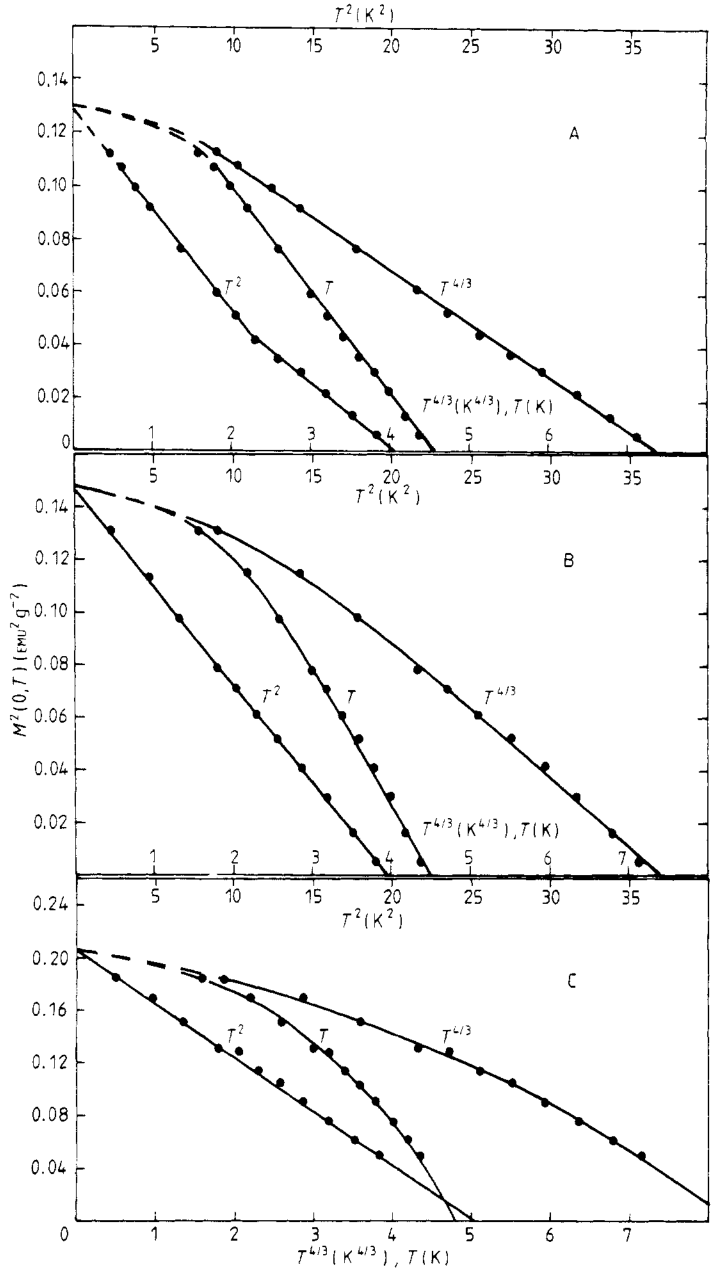

Figure 3. The square of the extrapolated zero-field magnetisation plotted against T^2, T and $T^{4/3}$ according to relations (3), (6) and (9) for the three distinguishable intervals of the applied magnetic field A, B and C (cf figure 2). Note the upper scale for the T^2 dependence.

of figure 3). At magnetic fields higher than approximately 2300 Oe the magnetisation obeys only the single-particle excitation model.

It was established mainly from the NMR spin–echo measurements (Lewicki *et al* 1983, Wada *et al* 1983, Takigawa *et al* 1983) that the itinerant-electron ferromagnetism in

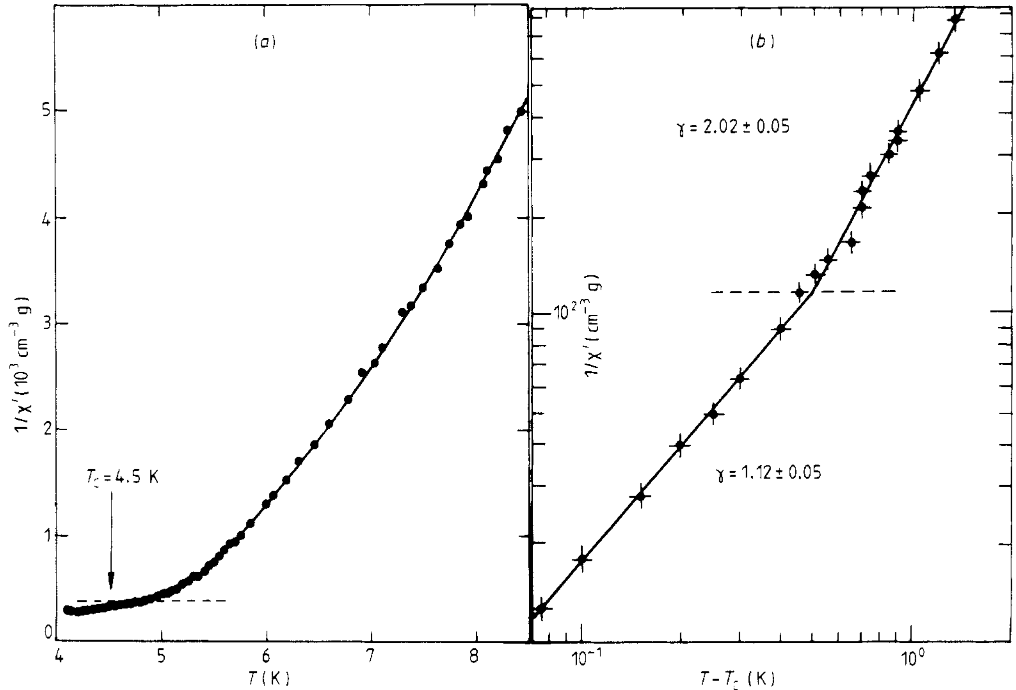

Figure 4. (*a*) The reciprocal AC susceptibility against the temperature and (*b*) the log–log plot of the same data. The broken lines separate two temperature regions of the critical exponent γ.

the compound Y_9Co_7 is of double character, consisting of a larger magnetic moment on the b-type Co atoms ($0.1\mu_B$ per atom) with some more local behaviour and a very small 'pure' itinerant magnetic moment on the d-type and h-type Co atoms (for the structure see, e.g., Lemaire *et al* 1969, Grover *et al* 1982).

We therefore suggest that the first, more local component of the total magnetic moment experiences pronounced spin fluctuations especially in low magnetic fields. The second component results from the single-particle excitations, most likely inside an almost filled 3d cobalt–4d yttrium hybridised band which may be magnetised by a weak molecular field of the first component and is very susceptible in higher applied magnetic fields.

A similar conclusion concerning the double character of the magnetism in Y_9Co_7 may be drawn from an analysis of the critical behaviour of the magnetisation and the susceptibility near T_C.

4. Critical behaviour

In order to examine the critical fluctuations near the Curie temperature and to determine the critical exponents β and γ we can make use of relation (5) together with the asymptotic relations (6), (7) and (8). We expect that the critical exponents β and γ will be slightly different from the respective mean-field values 0.5 and 1.0 (cf the value of γ in the previous section).

Near T_C we can use relation (5) for the magnetic isotherms with the linear temperature term $(T_C - T)/T_1$ as the simplest and most general relation. Even if we take into account the other temperature terms, for instance those in relations (1), (2) or (9), it turns out that they contribute less than 5% to the magnetic isotherms near T_C.

Our purpose is to find values of β and γ such that the Arrott plots are straight and parallel lines from 200 Oe up to the highest magnetic fields, i.e. 6200 Oe.

Because there are four unknown parameters (β, γ, T_1 and M_1) and since the Curie temperature is essentially unknown (we only have an estimate of the Curie temperature, $T_C = 4.45$ K, from the data in figures 2 and 3), the fitting procedure has to be done step by step.

First, from equation (7) and the AC susceptibility data we have obtained the parameters γ and T_1 by the linear regression method within the temperature range of approximately 4.2–4.9 K as $\gamma = 1.12 \pm 0.05$ and $T_1 = (6.9 \pm 0.1) \times 10^{-3}$ EMU (cf figure 4). In addition, we have checked that a value of the Curie temperature is hard to fix in this step because almost the same quality of fits has been obtained for each Curie temperature chosen within the temperature range 4.2–4.6 K.

Next, we have taken into account equation (8) and the magnetisation against magnetic field data at $T = 4.365$ K and $T = 4.47$ K (the latter are not shown in figure 2) as the temperatures nearest to T_C. We have obtained the ratio $\gamma/\beta = 2.38 \pm 0.04$ and the parameter $M_1 = (1.2 \pm 0.3) \times 10^{-2}$ EMU. Moreover, we have checked that M_1 is a nearly constant parameter up to approximately 3 K and that it increases very slowly with decreasing temperature in accord with relation (1).

In turn, we have explored equation (5), the most general equation, having a good estimate of all the parameters β, γ, T_1 and M_1, and making use of a two-parameter fitting procedure for β and T_1 with γ and M_1 as constants and choosing a few reasonable values of T_C around $T = 4.5$ K. The calculations were performed for the whole interval of magnetic fields and separately for low magnetic fields from approximately 200–800 Oe, resulting in only a very small difference between the two. We were able to fix the Curie temperatures as $T_C = (4.5 \pm 0.05)$ K. Moreover, we have ascertained that T_1 can also be kept at a constant value with good accuracy ($T_1 = (6.0 \pm 0.3) \times 10^{-3}$ EMU) for all the temperatures considered because it is only slightly sensitive to the temperature, decreasing by approximately 10% when the temperature decreases to 1.57 K. We have thus managed to follow the change with temperature of the critical exponent β. It transpired that the critical exponent β increased very slowly with decreasing temperature and in fact it took a constant value of $\beta = 0.48 \pm 0.01$ over a very wide temperature interval below T_C and down to at least 3.0 K. The parameter does not depend much on the region of magnetic fields from which it was calculated and is essentially the same for the low and high ranges of magnetic fields within an uncertainty of ± 0.01. Moreover, the same tendency for T_1 and β is displayed if the parameter γ is changed within its limits of accuracy from $\gamma = 1.05$ to $\gamma = 1.17$. Then, the respective values of β obtained were 0.45 and 0.5. Thus, we can never get the mean-field values of $\beta = 0.5$ and $\gamma = 1.0$ simultaneously.

Finally, we have taken advantage of equation (6). The extrapolated zero-field magnetisation values $M(0, T)$ for the magnetic isotherms with the correct powers $1/\beta$ and $1/\gamma$ evaluated from the previous three steps of the calculation are shown in figure 5. Here the best critical exponents have been fitted: $\beta = 0.47 \pm 0.01$ down to 3.0 K and $\beta = 0.48 \pm 0.01$ down to 1.57 K. We have thus obtained the critical exponents β and γ in a self-consistent manner from relations (5), (6), (7) and (8), which improves the accuracy of the results.

We would like to stress that the critical region for Y_9Co_7 is very broad near the Curie temperature, $T_C = 4.5$ K; it stretches from approximately 4.9 K to at least 3 K or even to the lowest temperature 1.57 K. This is why the hysteresis behaviour of Y_9Co_7

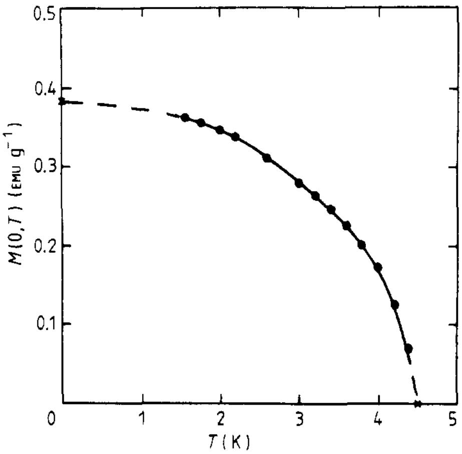

Figure 5. The temperature dependence of the zero-field magnetisation which is the extrapolated value for $H \to 0$ from the second region (B) of the applied magnetic fields. The points marked $\times$ indicate the best-fit values of $M(0, 0)$ and T_C from the T^2 law as is shown in the middle part of figure 3.

above T_C (the unpublished discussion after the paper of Sarkissian and Beille 1983) could be possible. It might also be another reason, in addition to the small magnetic moment, why it is so hard to observe a well defined region of small-angle critical scattering of neutrons around T_C (Sarkissian 1982a).

Now we can compare our critical exponents with some values predicted theoretically. First, the values of $\beta = 0.48$ and $\gamma = 1.12$ mean that for Y_9Co_7 the mean-field approach may be treated as a reasonably good first theoretical approximation. However, a comparison with renormalisation group theory (see, e.g., Wilson 1979) gives us new information. Such values of β and γ indicate that the dimension, n (>3), of the magnetic order parameter (magnetisation) and the dimension, d ($3 < d < 4$), of space might play a role in the critical behaviour. One reason why this is so might come from the double magnetic behaviour of the compound.

Thus the small but apparent deviations of the values of β and γ from the mean-field ones may perhaps be explained by a small magnetic contribution from a less concentrated magnetic phase with a more pronounced dependence of the critical behaviour on the dimensionalities (n and d respectively) of the order parameter and of space. The only such phase in the intermetallic compound Y_9Co_7 would be the b-type cobalt sublattice because the concentration per unit cell of those cobalt atoms is only $x_1 = 0.14$ in comparison with the concentration $x_2 = 0.86$ of the second group of the d- and h-type cobalt atoms.

Therefore we have calculated the effective values, β_{eff} and γ_{eff}, of the critical exponents which are defined as

$$\beta_{\text{eff}} = x_1\beta_1 + x_2\beta_2 \qquad \gamma_{\text{eff}} = x_1\gamma_1 + x_2\gamma_2 \tag{10}$$

where β_i and γ_i for $i = 1$ and 2 are the critical exponents β and γ of the first and second groups of cobalt atoms. Of course we have to assume that the majority magnetic phase of the second group of cobalt atoms obeying the mean-field theory has $\beta_2 = 0.5$ and $\gamma_2 = 1.0$. Then the critical exponents of the minority magnetic phase with more local behaviour would be $\beta_1 = 0.36$ and $\gamma_1 = 2.0$.

5. Conclusions

(i) We were able to improve the analysis of our detailed magnetisation and susceptibility measurements and to find a further argument in favour of the double character of the magnetic behaviour of Y_9Co_7, namely the very weak itinerant-electron behaviour which may be described by the single-particle excitation model, and the more local behaviour with pronounced spin fluctuations.

(ii) We were also able to calculate the critical exponents for the magnetisation ($\beta=0.48$) and the susceptibility ($\gamma=1.12$) in a self-consistent manner from all the asymptotic relations for the singularity in the critical behaviour of the magnetisation and the susceptibility in the limits as $T\rightarrow T_C$ and $H\rightarrow 0$.

(iii) From the fact that the critical exponent β is almost independent of the temperature within a very wide region below T_C, we can conclude that the intermetallic compound Y_9Co_7 exhibits critical fluctuations far below the Curie temperature, most likely because of the very weak ferromagnetism of the compound.

(iv) From the comparison of the calculated critical exponents with the theory we have found further evidence for the existence of two magnetic phases in Y_9Co_7.

(v) We have managed to reconstruct the zero-field magnetisation curve down to 0 K (see figure 5) even if superconductivity sets in below 2 K. In this sense we have found an argument for the coexistence of weak ferromagnetism and superconductivity in a rather wider temperature interval than that in the well known re-entrant ferromagnetic superconductors of rare-earth ternary compounds.

Acknowledgments

We would like to thank Mr Z Kakol for his help in the numerical elaboration of the data. We are greatly indebted to Professor G Kozłowski for his encouragement and interest in this work. One of us (AK) thanks the Physics Institute of Polish Academy of Sciences in Warsaw for financial support. We also thank both the referees for their comments which helped us to improve this paper.

References

Acker F and Huguenin R 1979 *J. Magn. Magn. Mater.* **12** 58
Arrott A and Noakes J E 1967 *Phys. Rev. Lett.* **19** 786
Berthet-Colominas C, Laforest J, Lemaire R, Pauthenet R and Schweizer J 1968 *Cobalt* **39** 97
Brommer P E 1982 *Physica* B **113** 391
Cheng W, Creuzet G, Garoche P, Campbell I A and Gratz E 1982 *J. Phys. F: Met. Phys.* **12** 475
Edwards D M and Wohlfarth E P 1968 *Proc. R. Soc.* A **303** 127
Figiel H, Gratz E and Kapusta Cz 1981 *J. Magn. Magn. Mater.* **23** 123
Gratz E, Kirchmayr R, Sechovsky V and Wohlfarth E P 1980 *J. Magn. Magn. Mater.* **21** 191
Grover A K, Coles B R, Sarkissian B V B and Stone H E N 1982 *J. Less-Common Met.* **86** 29
Huang C Y, Olsen C E, Fuler W W, Huang J H and Wolf S A 1983 *Solid State Commun.* **45** 795
Kołodziejczyk A 1983a *Proc. Int. Conf. on Cryogenic Fundamentals (ICCF 83), Cracow–Wrocław* ed. G Kozłowski in print
—— 1983b *Proc. Int. Conf. on Magnetism of Rare-Earth and Actinides, Bucharest* ed. E Burzo and M Rogalski (Bucharest: Central Institute of Physics) p 171
Kołodziejczyk A, Sarkissian B V B and Coles B R 1980 *J. Phys. F: Met. Phys.* **10** L333
Kołodziejczyk A and Spałek J 1984 *J. Phys. F: Met. Phys.* **14** 1277

Lemaire R, Schweizer J and Yakintos J 1969 *Acta Crystallogr.* B **25** 710
Lewicki A, Tarnawski Z, Kapusta Cz, Kołodziejczyk A, Figiel H, Chmist J, Lalowicz Z and Śniadower L 1983 *J. Magn. Magn. Mater.* **36** 297
van der Liet A, Frings P H, Menovsky A, Franse J J M, Mydosh J A and Nieuwenhuys G J 1982 *J. Phys. F: Met. Phys.* **12** L153
Moriya T 1979 *J. Magn. Magn. Mater.* **14** 1
Sarkissian B V B 1982a *Proc. 4th Conf. on Superconductivity in d- and f-Band Metals, Karlsruhe* p 311
—— 1982b *J. Appl. Phys.* **53** 8071
Sarkissian B V B and Beille J 1983 *Proc. 29th Ann. MMM Conf., Pittsburgh* (*J. Appl. Phys.* to be published)
Sarkissian B V B and Grover A K 1982 *J. Phys. F: Met. Phys.* **12** L107
Sarkissian B V B, Grover A K and Coles B R 1982 *Physica* B **109–110** 2041
Sułkowski C, Rogacki K, Kołodziejczyk A, Kozłowski G and Chmist J 1983 *J. Phys. F: Met. Phys.* **13** 2147
Takigawa M, Yasuoka H, Yamaguchi Y and Ogawa S 1983 *J. Phys. Soc. Japan.* **52** 3318
Wada S, Kohara T, Asayama K, Kitaoka Y, Kohori Y and Ishikawa N 1983 *Solid State Commun.* **48** 5
Wagner D and Wohlfarth E P 1982 *Physica* B **112** 1
Wilson K G 1979 *Sci. Am.* **241** 140
Yamaguchi Y, Nishihara Y and Ogawa S 1983 *J. Magn. Magn. Mater.* **31–34** 513