Splitting of the longitudinal Néel transition in erbium in a c-axis magnetic field

1996 J. Phys.: Condens. Matter 8 361

(http://iopscience.iop.org/0953-8984/8/3/014)

J. Phys.: Condens. Matter **8** (1996) 361–366. Printed in the UK

Splitting of the longitudinal Néel transition in erbium in a *c*-axis magnetic field

Brian Watson and Naushad Ali

Department of Physics, Southern Illinois University, Carbondale, IL 62901, USA

Received 31 August 1995

Abstract. We have examined the magnetic phase diagram of single-crystal erbium in the temperature range between 60 K and 90 K and in applied magnetic fields along the *c*-axis up to 5.5 T using resistance versus temperature and magnetoresistance measurements. The H–T phase diagram for that region is presented. We have observed a splitting of the longitudinal Néel transition near 1.6 T. We have found a new phase with unknown structure in that portion of the phase diagram created by the splitting of the Néel transition. We have also found a multicritical point (P) at an applied field of 2.65 T and 71 K. A set of five magnetic phase lines appears to meet at this multicritical point.

In holmium, a splitting of the Néel transition is observed with the field applied normal to the *c*-axis [1, 2]. This supports the prediction by Schuab and Mukamel [3] that a field applied perpendicular to the spiral axis should introduce a new linearly polarized spin-density wave phase for rare earth metals with an $n = 4$ order parameter (erbium is most likely described by an $n = 2$ degrees of freedom order parameter as determined by Terki *et al* [4]). However, it has been observed that a field directed along the spiral axis in holmium also produces a splitting of the Néel transition [2, 5]. A field along the spiral axis does not reduce the symmetry and therefore should not introduce new magnetic phases. However, Plumer *et al* [6, 7] suggest that competition between single-ion anisotropies and the anisotropy induced by a magnetic field applied along the easy axis could produce a splitting of the Néel transition for erbium. This splitting of the longitudinal Néel temperature has been recently observed by Terki *et al* [8] in a measurement of $\mathrm{d}R/\mathrm{d}T$ of erbium. We have undertaken a series of experiments to verify that a field applied parallel to the *c*-axis will produce a splitting of the longitudinal Néel transition in erbium.

The *c*-axis erbium single crystal (12.0 mm $\times$ 1.1 mm $\times$ 1.6 mm; mass, 0.1781 g) was grown at Ames laboratory. Resistance measurements were performed using the temperature and magnetic field controls of a SQUID Magnetometer (Quantum Design, Inc., San Diego, CA), with a Keithley 220 programmable constant current source and Keithley 181 nanovoltmeter as external devices. The resistance measurements were carried out using the four-probe method. In order to construct our phase diagram, we performed 23 resistance versus temperature measurements at constant applied magnetic fields along the *c*-axis between 0.0 and 5.5 T. The interval between individual data points in a single resistance measurement is approximately 0.2 K. All of the measurements were taken with the temperature increasing at a constant rate of 1.5 K min^{-1}. We performed 23 magnetoresistance measurements at constant temperatures between 60 K and 90 K. The interval between individual data points in our magnetoresistance measurements is 200 G. The field was directed along the *c*-axis and all measurements were taken with field increasing.

We have used resistance measurements to construct the *c*-axis magnetic phase diagram of erbium between 60 K and 90 K and a maximum applied magnetic field of 5.5 T. By

0953-8984/96/030361+06$19.50

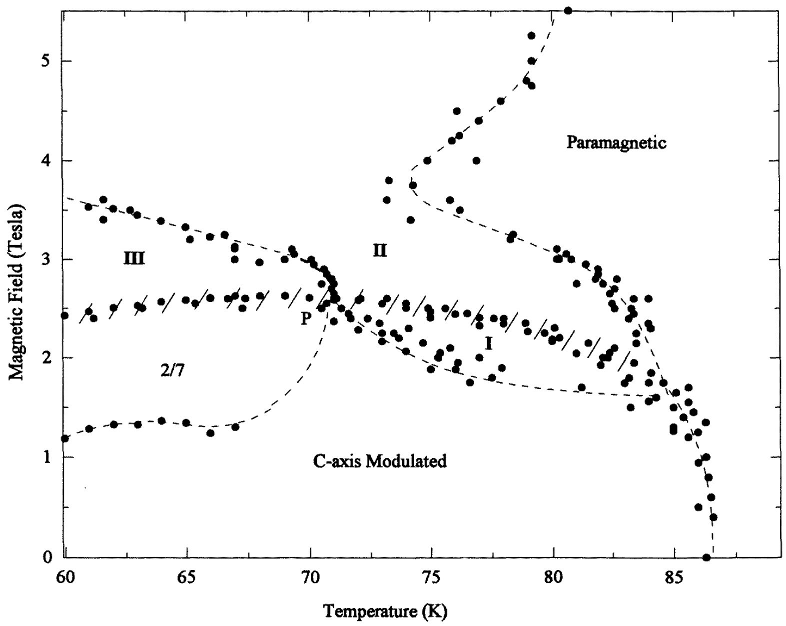

Figure 1. The c-axis H–T phase diagram of erbium in the region from 60 K to 90 K and 0.0 to 5.5 T. Transitions are marked by filled circles. Dashed lines have been added to suggest transition lines. Magnetic structures have been labelled using the results of Lin *et al* [9] and McMorrow *et al* [10]. Regions with unknown structure have been labelled with Roman numerals.

tabulating the temperature and magnetic field at which each transition occurred, we are able to construct the H–T phase diagram for erbium as shown in figure 1. We have used the results of the previous neutron scattering studies of Lin *et al* [9] and McMorrow *et al* [10] to provide information concerning the magnetic structure in areas of the phase diagram. Transitions are indicated by filled circles. Dashed lines have been added to suggest transition lines. As the field is increased the c-axis components of the magnetic moments eventually align in the direction of the applied field. This relatively large transition is the boundary between order and disorder and is indicated on the phase diagram in figure 1 by a diagonally hatched line. According to neutron scattering studies [9, 10] this hatched line in the phase diagram is the boundary between a phase with moments modulated longitudinally along the c-axis and a cone structure. The c-axis modulated, the paramagnetic and the 2/7 spin-slip structures have been identified using the neutron diffraction studies of Lin *et al* [9] and McMorrow *et al* [10]. The structure 2/7 indicates the c-axis modulation of this commensurate phase. The magnetic phases labelled with Roman numerals have not been identified. We have observed a splitting of the longitudinal Néel transition near 1.6 T that results in an enclosed region with an unknown magnetic structure. This new magnetic phase is indicated on the phase diagram by Roman numeral I. Above the order–disorder line, there are two other phases labelled by Roman numerals II and III, which have been labelled as ferromagnetic and incommensurate in previous phase diagrams [9, 10]. The magnetic structure in these regions is unknown and should be determined by further neutron diffraction studies.

In erbium, there is only a single longitudinal Néel transition up to a c-axis applied field of approximately 1.7 T. The c-axis resistance versus temperature with a constant applied

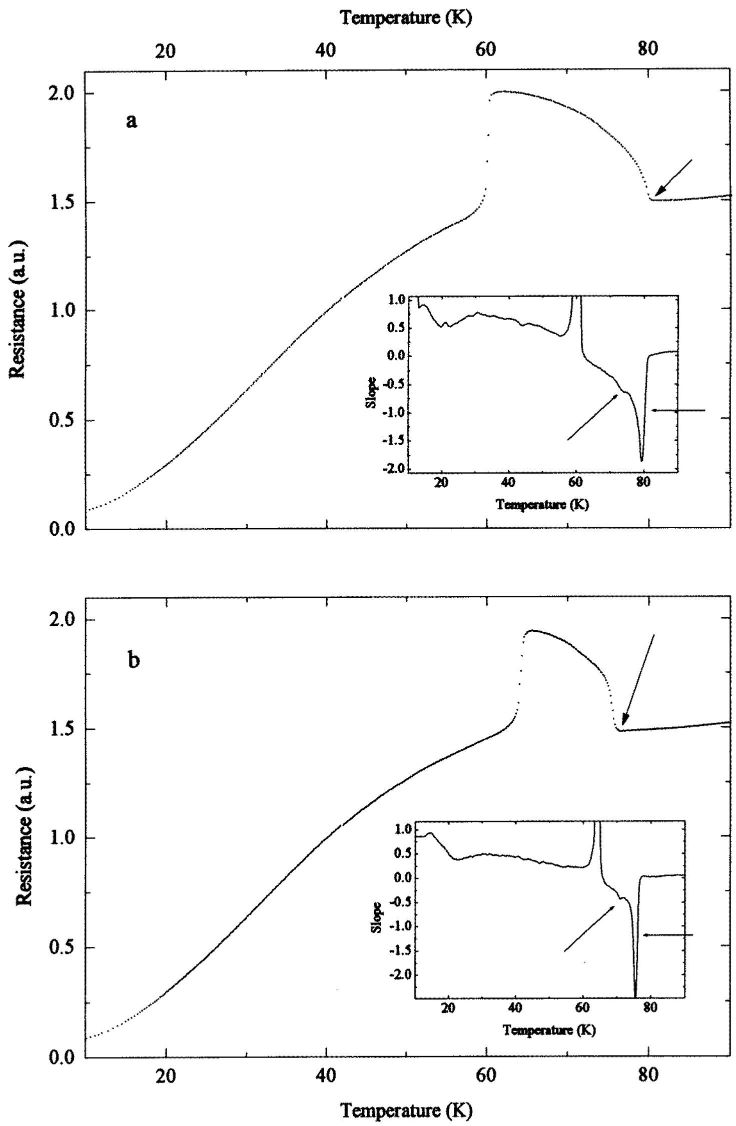

Figure 2. (a) The *c*-axis resistance versus temperature for a constant applied magnetic field of 2.30 T. The slope is included (inset). (b) The *c*-axis resistance versus temperature for a constant applied magnetic field of 2.50 T. The slope is included (inset).

field of 2.30 T is shown in figure 2(a). The inset of figure 2(a) is the slope of the resistance versus temperature measurement. By reviewing the slope, it is apparent that a transition is evident at 74.1 K as well as the longitudinal Néel transition at 80.1 K. This transition at 74.1 K is difficult to detect due to its proximity to the longitudinal Néel transition and we are unable to observe this transition below 1.7 T. However, by extrapolating from the data above 1.7 T, we can estimate that the splitting of the Néel transition occurs at approximately 1.6 T and 84 K. This is also the point at which the longitudinal Néel transition splits from the order–disorder line. The temperature at which this smaller transition occurs decreases as the

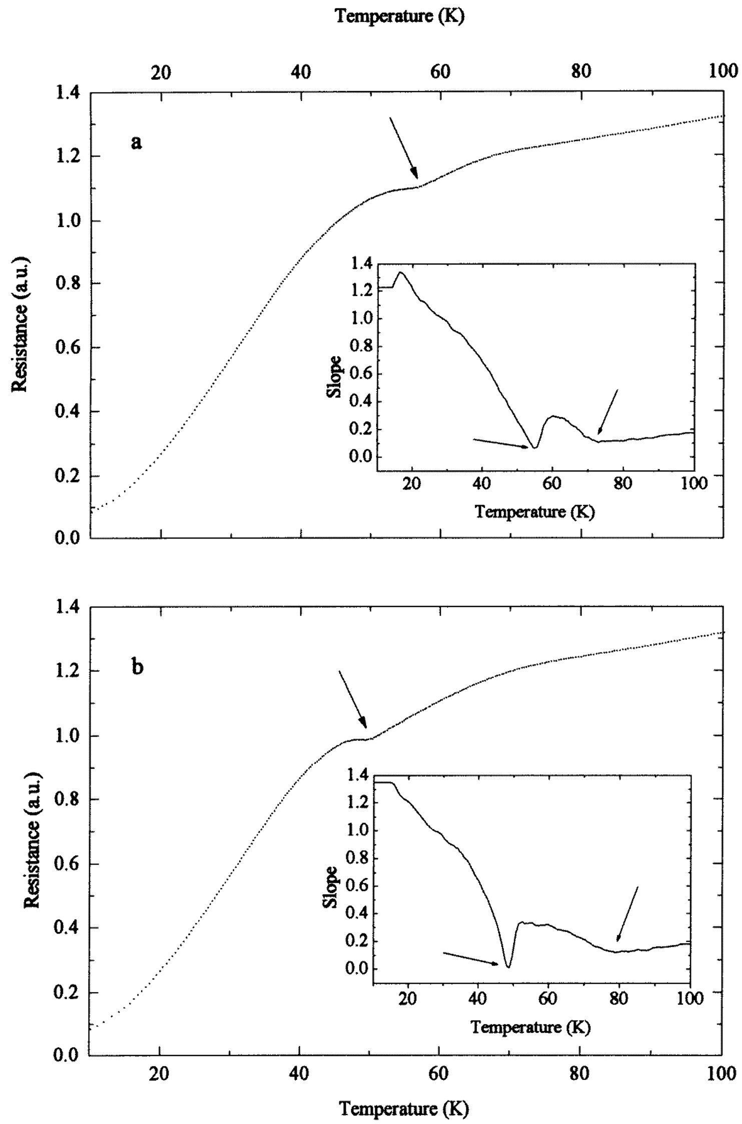

Figure 3. (a) The *c*-axis resistance versus temperature for a constant applied magnetic field of 3.80 T. The slope is included (inset). (b) The *c*-axis resistance versus temperature for a constant applied magnetic field of 4.80 T. The slope is included (inset).

field is increased. Figure 2(b) shows the resistance versus temperature for a constant applied *c*-axis magnetic field of 2.50 T. The Néel transition is easily observed on the resistance plot at 75.6 K. The smaller transition can be observed on the slope (inset of figure 2(b)) at 71.3 K.

The transition that corresponds to the Néel splitting, discussed in the previous paragraph, crosses the order–disorder line at 71 K and 2.65 T and continues to decrease in temperature with higher field. This multicritical point has been labelled on the phase diagram by the letter P. Figure 3(a) and (b) shows the resistance versus temperature at the applied fields of

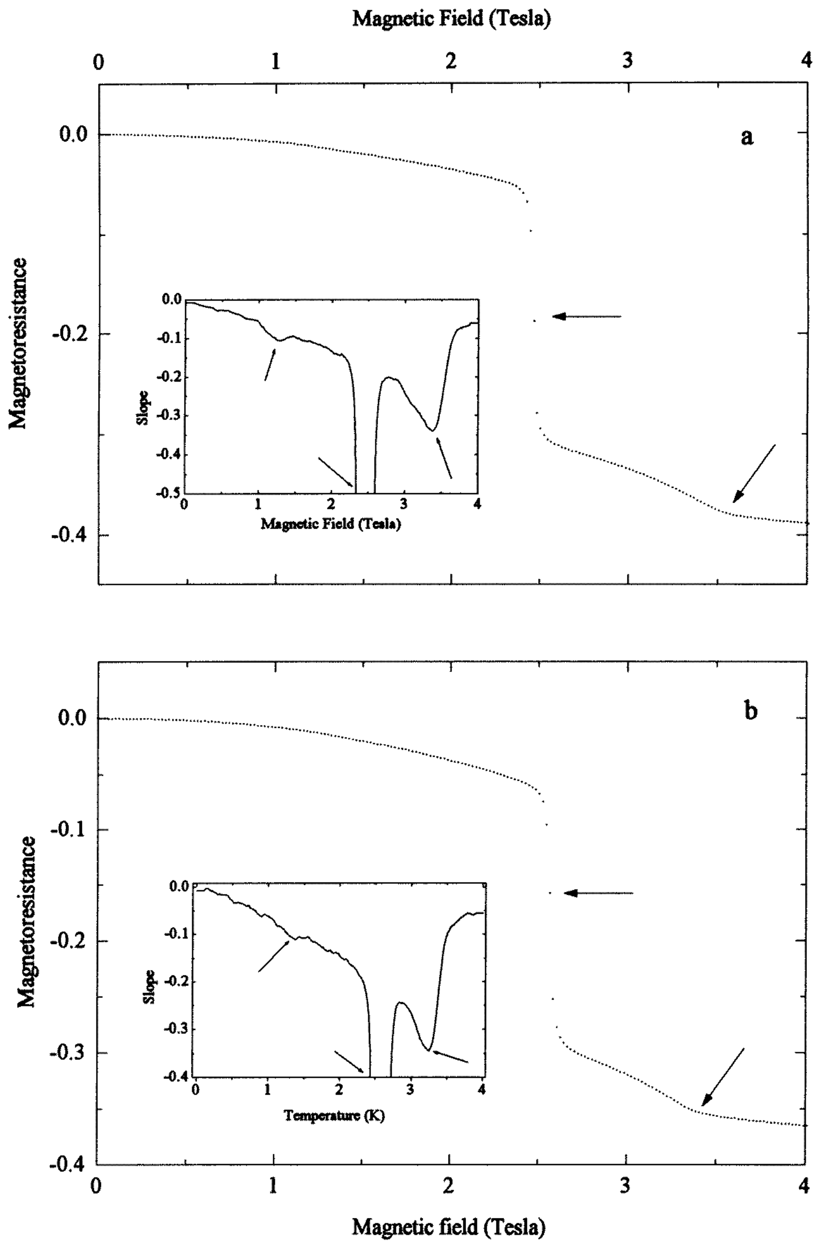

Figure 4. (a) The *c*-axis magnetoresistance at a constant temperature of 61 K. The slope is included (inset). (b) The *c*-axis magnetoresistance at a constant temperature of 64 K. The slope is included (inset).

3.80 T and 4.80 T respectively. Two transitions are indicated in figure 3(a). The transition at 55.3 K is the continuation of the splitting of the longitudinal Néel transition above the order–disorder line. The second transition is the longitudinal Néel temperature and is clearly seen on the slope (inset) at a temperature of 73.3 K. These transitions continue to have a strong field dependence. As the c-axis applied field is increased, the temperature interval between these two transitions also increases. Figure 3(b) shows the resistance versus temperature for an applied field of 4.8 T. The two transitions occur at 49.1 K and 78.6 K respectively. Above 2 T, the Néel transition decreases in temperature, until approximately 3.75 T where it begins to increase in temperature. The point where this reversal occurs can be seen on the phase diagram in figure 1 at about $H \simeq 3.8$ T and $T \simeq 73$ K. The strange profile in figure 1 between phase II and the paramagnetic phase suggests that there may be another phase transition line joining at the point at $H \simeq 3.8$ T and $T \simeq 73$ K. We have looked for such a transition line but have not observed it in our studies yet.

The magnetoresistance at a constant temperature of 61.0 K is shown in figure 4(a). The large transition at 2.47 T is the order–disorder transition. The second transition at 3.53 T is the continuation of the longitudinal Néel splitting as observed previously. These transitions can also be observed on the slope (inset). The resistance versus c-axis applied field at a constant temperature of 64.0 K is shown in figure 4(b). The two transitions have moved closer together in temperature and eventually will merge at 71 K at the multicritical point (P) on the phase diagram in figure 1. There is also a much smaller transition indicated in figure 4(a) and (b), at the magnetic fields of 1.30 and 1.38 T respectively, that corresponds to the boundary between the 2/7 phase and the incommensurate phase. Although this transition is difficult to observe in magnetoresistance measurements, it has been observed previously by Lin *et al* [9].

We have used resistance and magnetoresistance measurements to construct the c-axis magnetic phase diagram of erbium between 60 K and 90 K and up to an applied magnetic field of 5.5 T presented in figure 1. We have found a multicritical point at an applied field of 2.65 T and 71 K. We have observed a splitting of the longitudinal Néel transition that results in an enclosed region in the H–T phase diagram with an unknown magnetic structure. The c-axis modulated, the paramagnetic and the 2/7 spin-slip structures have been identified using the results of neutron studies by Lin *et al* [9] and McMorrow *et al* [10]. The magnetic phases labelled with Roman numerals are not known. A new magnetic phase has been created by the splitting of the Néel transition and is indicated on the phase diagram by Roman numeral I. Above the order–disorder line, there are two other phases labelled by Roman numerals II and III, which have been labelled as ferromagnetic and incommensurate in the previous phase diagrams of Lin *et al* [9] and McMorrow *et al* [10]. The magnetic structure in these regions is unknown and should be determined by further neutron diffraction studies.

References

[1] Steinitz M O, Kahrizi M and Tindall D A 1987 *Phys. Rev.* B **36** 783
[2] Willis F, Ali N, Steinitz M O, Kahrizi M and Tindall D A 1990 *J. Appl. Phys.* **67** 5277
[3] Schuab B and Mukamel D 1985 *Phys. Rev.* B **32** 6385
[4] Terki F, Gandit P and Chaussy J 1992 *Phys. Rev.* B **46** 922
[5] Steinitz M O, Kahrizi M, Tindall D A and Ali N 1989 *Phys. Rev.* B **40** 763
[6] Plumer M L and Caille A 1992 *Phys. Rev.* B **45** 12 326
[7] Plumer M L, Caille A and Hood K 1989 *Phys. Rev.* B **39** 4489
[8] Terki F, Gandit Ph and Chaussy J 1994 *Physica* B **194–196** 295
[9] Lin H, Collins M F, Holden T M and Wei W 1992 *Phys. Rev.* B **45** 12 873
[10] McMorrow D F, Jehan D A, Cowley R A, Eccleston R S and McIntyre G J 1992 *J. Phys.: Condens. Matter* **4** 8599