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The *b*-axis magnetic phase diagram of erbium

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Abstract. We have used resistance versus temperature and magnetoresistance measurements to construct the *b*-axis magnetic phase diagram of single-crystal erbium. The magnetic phase transitions are identified as slope changes in resistivity data at constant applied magnetic fields along the *b*-axis. At zero field we observe transitions at about 19 K (T_C), 22 K, 42 K, 48 K, 53 K ($T_{N\perp}$), and 87 K ($T_{N\parallel}$). The dependence of these transition temperatures as a function of applied magnetic fields ($\boldsymbol{H}$) allowed us to construct an $\boldsymbol{H}$–$\boldsymbol{T}$ phase diagram of single-crystal erbium along the *b*-axis. We observe that the zero-field 42 K and 87 K ($T_{N\parallel}$) transitions do not have significant magnetic field dependence whereas the zero-field transitions at 48 K and 53 K ($T_{N\perp}$) are highly field dependent. Recently, Jehan *et al* have constructed the *a*-axis magnetic phase diagram of erbium using neutron diffraction and magnetization measurements. We have utilized their data to provide information concerning the magnetic structure in some areas of our phase diagram.

1. Introduction

The magnetic structure of erbium has been studied in several neutron diffraction and x-ray scattering studies [1–3]. The magnetic structure of erbium in zero applied field was determined by Cable *et al* [2] to have three primary ordered states. Below the longitudinal Néel temperature at $T_{N\parallel} = 89$ K, erbium orders antiferromagnetically along the *c*-axis with a sinusoidal wavevector of approximately seven atomic planes. Below the basal plane Néel temperature $T_{N\perp} = 53$ K, the basal plane moments become ordered as well with the same modulation as the *c*-axis. Below the Curie temperature at $T_C = 18$ K, erbium orders ferromagnetically into a conical structure along the *c*-axis.

As the temperature is lowered below $T_{N\perp}$, the period of the *c*-axis wavevector increases from less than seven atomic layers to eight atomic layers. Also, the *c*-axis wavevector begins to lose its sinusoidal modulation and ‘square up’, until T_C is reached, when erbium attains an alternating cone structure. The magnetic structure in this intermediate region, between T_C and $T_{N\perp}$, has been described in a synchrotron x-ray scattering study by Gibbs *et al* [3]. In this study, they found that as the temperature is lowered the *c*-axis wavevector does not change continuously but rather locks in to rational values. These rational wavevectors follow the form $q = n(4n-1)^{-1}c^*$ where $n = 2, 3, 4, \ldots$, suggesting that at certain temperatures the magnetic structure of erbium is commensurate with the lattice. These commensurate structures have been described by Gibbs *et al* [3] using a spin-slip model first proposed for the rare-earth metals by Bohr *et al* [4]. In their model, the *c*-axis moments order antiferromagnetically into groups of four atomic planes either parallel or antiparallel to the *c*-axis. However, the rational wavevectors repeat after an odd number of atomic planes (7, 11, 15, 19, and 23 atomic planes). These periods may be explained if occasionally a

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Table 1. Magnetic phase transitions in erbium in zero applied magnetic field. The wavevectors $\boldsymbol{q}$ and the corresponding spin-slip structures are taken from Gibbs *et al* [3] and Cowley and Jensen [6]. Column three indicates the temperatures in our magnetization and ac susceptibility data [5] where we observe the respective structures.

q	Structure	Temperature
5/21	Ferromagnetic	$T_C = 18$ K
1/4	2(44)	18 K–25 K
6/23	2(444443)	25.5 K–28.5 K
5/19	2(44443)	29 K
4/15	2(4443)	32.5 K–35.5 K
3/11	2(443)	40 K
2/7	2(43)	49.5 K–52.5 K
		$T_{N\perp} = 53$ K
		$T_{N\parallel} = 89$ K

set of four atomic planes is replaced with a set of three atomic planes. This substitution is referred to as a spin-slip.

The magnetic phase transitions of erbium for low-field magnetization and ac susceptibility measurements [5] are shown in table 1. In this table we have adopted the notation of Gibbs *et al* [3] and Cowley and Jensen [6]. The notation (43) means that four magnetic moments are aligned parallel to the c-axis and three moments are antiparallel. Because the hexagonal close-packed structure contains two inequivalent sublattices, the structure is more accurately referred to as 2(43). Spin-slip structures with an odd number of quartets to triplets have a net ferrimagnetic moment. The ferrimagnetic structure 2(43) has a relatively large net c-axis moment with a spin-slip occurring every seven atomic planes. Spin-slip structures with a net magnetic moment, such as 2(43), lock in to rational wavevectors over a temperature range of approximately 3 K and appear as sharp peaks in the magnetization [5]. Alternatively, the structure 2(443) is difficult to identify in measurements of magnetization.

The magnetic structure in the antiferromagnetic phase between T_C and $T_{N\perp}$ was believed to be helical. However, it has been determined by Jensen (see [7, 8]) based on the results from neutron scattering studies, to be cycloidal. In this cycloidal structure, the magnetic moments trace out an ellipse in the a–c plane when they are drawn from a common origin. The b-axis component is relatively small and has a modulation different to that of the a- and c-axes.

2. Experimental method

The b-axis erbium single crystal ($11.2 \times 1.1 \times 1.6$ mm^3, mass $= 0.1640$ g) used in these experiments was grown at the Ames Laboratory. The resistance was measured by the four-probe method using the temperature and magnetic field control of a SQUID Magnetometer (Quantum Design), with a Keithley 220 programmable current source and Keithley 181 nanovoltmeter as external devices. The current was 60 mA, applied intermittently to avoid heating the sample. In constructing our b-axis magnetic phase diagram for erbium, we performed 35 resistance versus temperature measurements at various constant applied magnetic fields. The magnetic field is applied along the b-axis. The temperature range was from 10 K to 100 K to include the Curie temperature as well as the longitudinal Néel temperature. The interval between individual points in a single resistance measurement was 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 15 magnetoresistance measurements at various constant temperatures between 20 K and 90 K and applied magnetic fields up to 5.5 T. The interval between individual points in our magnetoresistance measurements was 200 G. All of the measurements were performed with the temperature or magnetic field increasing.

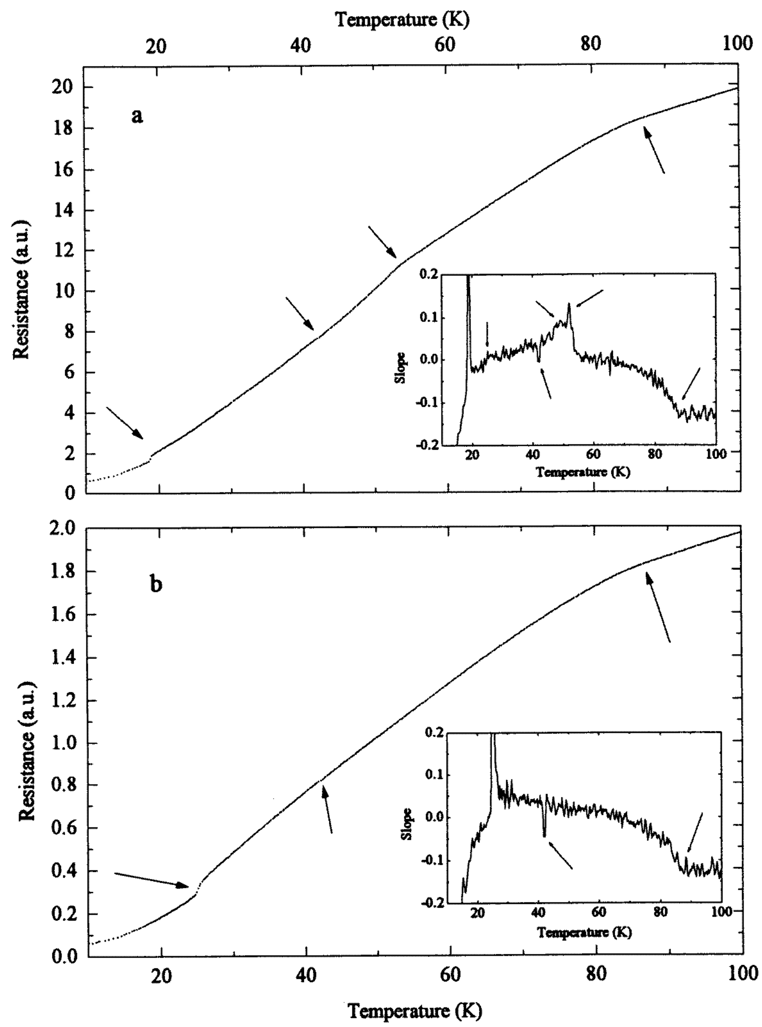

Figure 1. (a) The *b*-axis resistance versus temperature at a constant applied magnetic field of 1.00 T. The slope is included (inset). (b) The *b*-axis resistance versus temperature at a constant applied magnetic field of 5.25 T. The slope is included (inset).

3. Results and discussion

The *b*-axis resistance versus temperature for a constant applied magnetic field of 1.00 T is shown in figure 1(a). The Curie temperature is 18.8 K. The longitudinal Néel temperature is

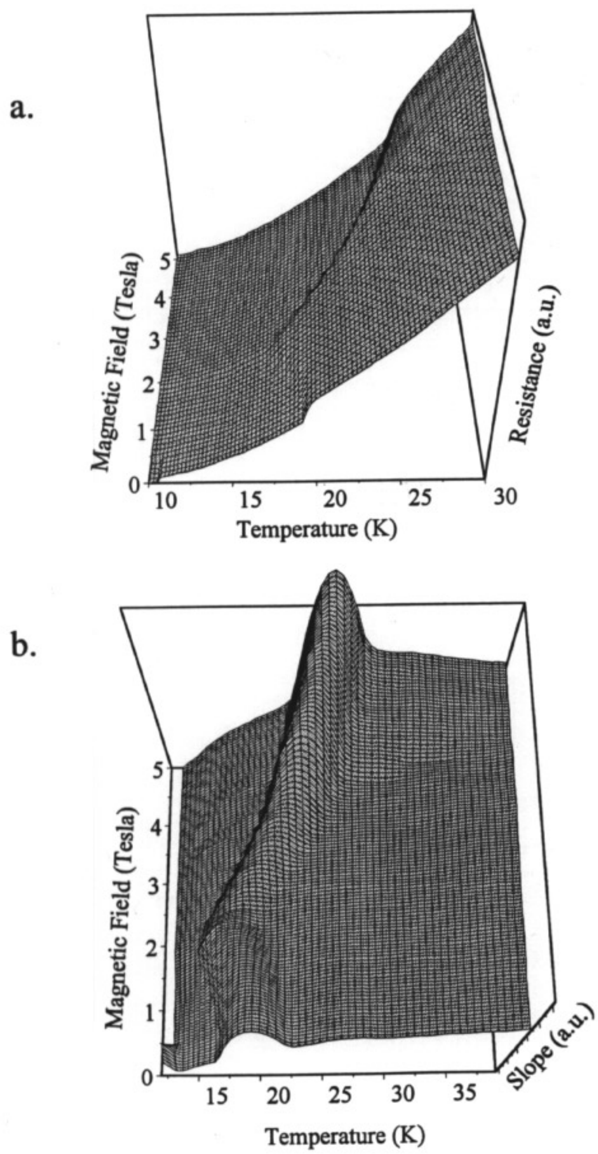

Figure 2. (a) The 3-D *b*-axis magnetic phase diagram of erbium from 10 K to 30 K created by compiling individual resistance versus temperature measurements. (b) The 3-D *b*-axis magnetic phase diagram of erbium between 10 K to 40 K created by compiling the slopes of individual resistance versus temperature measurements.

87.9 K. There is a double peak in the slope (see the inset). The first peak corresponds to the 2(43) spin-slip structure at 47.1 K. The second peak is the basal plane Néel temperature at 52.9 K. There is a small discontinuity at 42.0 K that is visible in the resistance measurement and also in the slope that corresponds to the 2(443) spin-slip structure. There is also a peak in the slope at 25.3 K that corresponds to a transition to the (44) structure (see [1]). As the *b*-axis applied field is increased, the general form of the resistance measurement does not change substantially.

The resistance versus temperature for a constant applied magnetic field of 5.25 T is shown in figure 1(b). The Curie and longitudinal Néel transitions occur at 25.0 K and 87.1 K, respectively. We are unable to observe the basal plane Néel transition and the 2(43) spin-slip transition at this applied field. However, the transition at 42.2 K is still evident at 5.25 T. This is contrary to the results of the previous study by Jehan *et al* [1] which indicate that this spin-slip structure does not exist above the applied field of approximately 3.5 T. This spin-slip structure has a zero net magnetic moment and should be destabilized by the applied magnetic field [1]. Therefore we do not understand the transition at 42 K above about 3 T.

By compiling individual resistance versus temperature measurements at constant applied fields, we are able to present the *b*-axis magnetic phase diagram in 3-D format shown in figure 2(a). Resistance values are plotted along the z-axis. Temperature and magnetic field are plotted along the x- and y-axes, respectively. We are able to observe the relatively large ferromagnetic transition. The Curie temperature decreases with applied magnetic field until 1.8 T is reached, at which point it begins to increase. This inflection point has been observed previously by Jehan *et al* [1] as the boundary between two ferromagnetic structures: the 5/21 cone structure and the 1/4 fan structure. In the cone phase, the basal plane moments are ordered helically. Conversely, in the fan structure, the basal plane moments are arranged with a large component along the direction of applied field and a small component transverse to the field. The transition line between these two structures is also visible in figure 2(a) at 1.8 T.

Figure 2(b) is the 3-D magnetic phase diagram of erbium between 10 K and 40 K created by compiling the slopes of individual resistance versus temperature measurements. Once more, the magnetic field dependence of the ferromagnetic transition is illustrated. In addition, the extension of the basal plane Néel transition line is visible at approximately 4 T above the Curie temperature.

Figure 3 is the 3-D magnetic phase diagram of erbium between 10 K and 100 K created by compiling the slopes of individual resistance versus temperature measurements. The slope of each resistance measurement with respect to temperature is plotted along the z-axis. Temperature and magnetic field are plotted along the x- and y-axes, respectively. The 2(443) spin-slip transition and the longitudinal Néel transition are observed at 42 K and 87 K, respectively, independently of the applied field. The basal plane Néel transition is observed at 53 K, in zero applied field, and this transition temperature decreases as magnetic field is applied along the *b*-axis.

We have performed 35 resistance versus temperature measurements at various constant applied magnetic fields up to 5.5 T and 15 magnetoresistance measurements at various constant temperatures between 20 K and 90 K. By tabulating the temperature and the *b*-axis applied magnetic field at which each transition occurred, we have been able to construct the *b*-axis magnetic phase diagram presented in figure 4. Filled circles represent transitions. Solid lines have been added to connect the data points as a visual guide. We have labelled regions of the phase diagram with their proposed structure and/or *c*-axis wavevector. These structures were obtained by comparing our phase diagram with the previous neutron scattering study by Jehan *et al* [1]. Phase transition boundaries have been identified by interpolating from transition temperatures in zero field. From the phase diagram, it is apparent that the 2(43) spin-slip transition temperature and the basal plane Néel transition temperature decreases with increasing applied *b*-axis magnetic field until they converge with the Curie transition line. We have also observed in our phase diagram (figure 4) a transition to the magnetic phase (44). This phase is consistent with the neutron scattering work of Jehan *et al*. In the previous *a*-axis phase diagram of Jehan *et al* [1], they observed additional magnetic phases around 30 K in zero applied field. We also observe a transition around 30 K, although it is not included in our phase diagram since we are unable to consistently identify these transition temperatures in our resistance data.

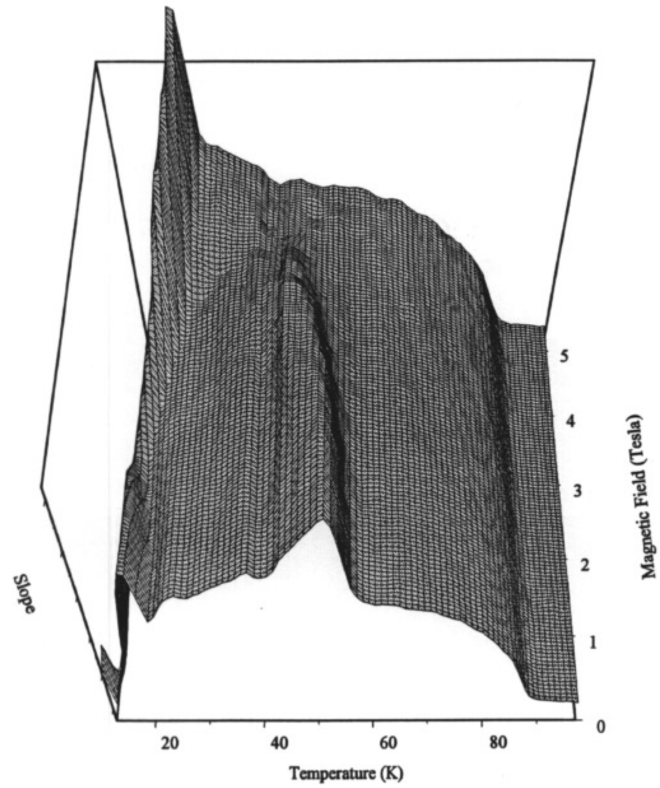

Figure 3. The 3-D *b*-axis magnetic phase diagram of erbium between 10 K and 100 K created by compiling the slopes of individual resistance versus temperature measurements.

4. Summary

We have used resistance versus temperature and magnetoresistance measurements to construct the *b*-axis magnetic phase diagram of single-crystal erbium presented in figure 4. By noting the similarities between our phase diagram and the previous neutron scattering study by Jehan *et al* [1], we have labelled the 5/21 and 1/4 ferromagnetic and (44) structures as seen in figure 4. We have used individual resistance versus temperature measurements to produce the *b*-axis magnetic phase diagram in a 3-D format. We have also created the *b*-axis phase diagram using the slope of individual resistance versus temperature measurements in order to further clarify the various transitions. We observe a transition near 25 K that corresponds to a transition to the (44) structure. We have found that the Curie transition temperature has an inflection point at 1.8 T. This inflection point is the boundary between the 5/21 ferromagnetic cone and 1/4 ferromagnetic fan structures. We have found that the longitudinal Néel temperature at 87 K is independent of the *b*-axis applied magnetic field. The 2(43) spin-slip transition and the basal plane Néel transition are highly dependent on the applied field and decrease in temperature until they meet the Curie transition line at 3.0 T and 3.6 T, respectively. We observe a transition at about 42 K for fields even above 3 T. These data points are included in figure 4 with a question mark. We do not understand the existence of these data points particularly in light of neutron scattering studies by Jehan *et al* [1]. This part of the phase diagram needs to be studied further.

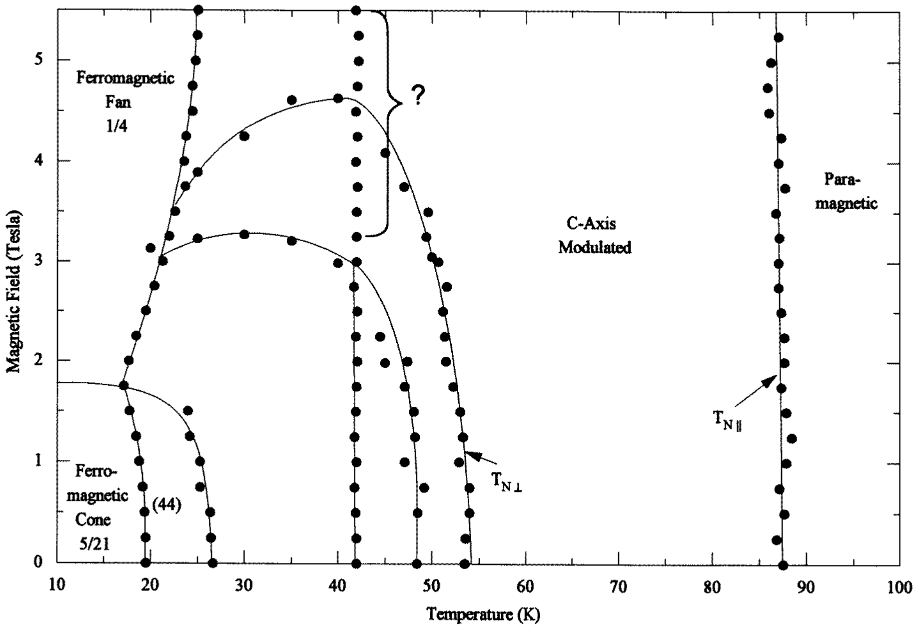

Figure 4. The *b*-axis magnetic phase diagram of erbium between 10 K and 100 K up to 5.5 T. Filled circles represent transitions. Dashed lines are used to suggest transition lines. The ferromagnetic structures and the (44) structure have been labelled using the results of a neutron scattering study by Jehan *et al* [1].

In conclusion, we have established a basic H–T phase diagram for *b*-axis erbium using resistance and magnetoresistance measurements. Details of the magnetic structure in the various parts of the phase diagram need to be determined by further studies such as neutron scattering.

Acknowledgment

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