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Magnetization of single-crystal erbium

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We present the results of magnetization and ac-susceptibility measurements on single-crystal erbium along all three crystal axes. We observe antiferromagnetic ordering of the *c* axis and the basal-plane-moment components at 89 and 53 K, respectively. In addition, we observe anomalies at 51, 40, 34, 29, and 27 K. These anomalies in magnetization and ac-susceptibility data correspond to the commensurate spin-slip structures observed by Gibbs *et al.* in x-ray synchrotron scattering studies. In addition, we find that the basal-plane ordering at $T_{N_\perp}=53$ K takes place before any spin-slip transition appears as the temperature is lowered.

Erbium crystallizes into a hcp structure with two layers per chemical unit cell and a magnetic moment of $9\mu_B$ per atom. Neutron-diffraction studies by Cable *et al.*,[1] Habenschuss *et al.*,[2] and Atoji[3] have identified three distinct magnetically ordered states in erbium. The *c*-axis-moment component orders below $T_{N_\parallel}=84$ K in a sinusoidally modulated structure with the wave vector parallel to the *c* axis and a periodicity of approximately seven atomic layers. A spiral ordering of the basal-plane moment appears below $T_{N_\perp}=53$ K having the same periodicity as that of the *c*-axis-moment ordering. A "squared up" alternating cone structure of the *c*-axis moment is observed as the temperature is lowered to 22 K. Below $T_C=18$ K, the *c*-axis moment orders ferromagnetically into a conical structure. The ac-susceptibility measurements on polycrystalline and single-crystal erbium by Taylor, Gerstein, and Spedding[4] and Astrom *et al.*[4] reveal anomalies at 27 and 34 K in addition to those at $T_{N_\parallel}$, $T_{N_\perp}$, and T_C.

More recently, Gibbs *et al.*[5] have studied the magnetic structure of erbium using synchrotron x-ray scattering. In their study, the *c* axis of erbium exhibits a sequence of lock-in transitions to rational wave vectors. Gibbs *et al.*[5] observed lock-in behavior at $\tau_m=\frac{2}{7}$ (51.6–48.5 K), $\frac{3}{11}$ (41 K), $\frac{4}{15}$ (34.5–31.5 K), $\frac{5}{19}$ (29 K), $\frac{6}{23}$ (26.5–23 K), $\frac{1}{4}$ (23–18 K), and $\frac{5}{21}$ (below 18 K). These commensurate structures have been described by Gibbs *et al.*[6] and Bohr *et al.*[7] using a spin-slip model.

Based on the work of Gibbs *et al.*,[5] we undertook the task of observing the lock-in transitions through magnetization measurements on a single crystal of erbium. In this paper we present the temperature dependence of the magnetization and the ac susceptibility of a single crystal of erbium in all three crystal axes (*a*, *b*, and *c* directions).

The erbium single crystal ($4.4\times3.3\times5.0$ mm^3, mass $=0.6404$ g) was grown at Ames laboratory. The temperature dependence of the magnetization in the range from 5 to 100 K in a magnetic field of 50 G applied along the *a*, *b*, and *c* axes was carried out in a superconducting quantum interference device (SQUID) magnetometer (Quantum Design, Inc., San Diego, CA). The ac susceptibility in an alternating field of approximately 1.5 G was measured using the mutual-inductance method.

The magnetization (M) and ac susceptibility (χ_{ac}) as a function of temperature are presented in Figs. 1 and 2 for the *a* and *c* crystal axes. As the temperature is decreased, the *c*-axis moments order in a sinusoidal modulation of approximately seven atomic layers below $T_{N_\parallel}=89$ K. As the temperature is further decreased, a small peak appears

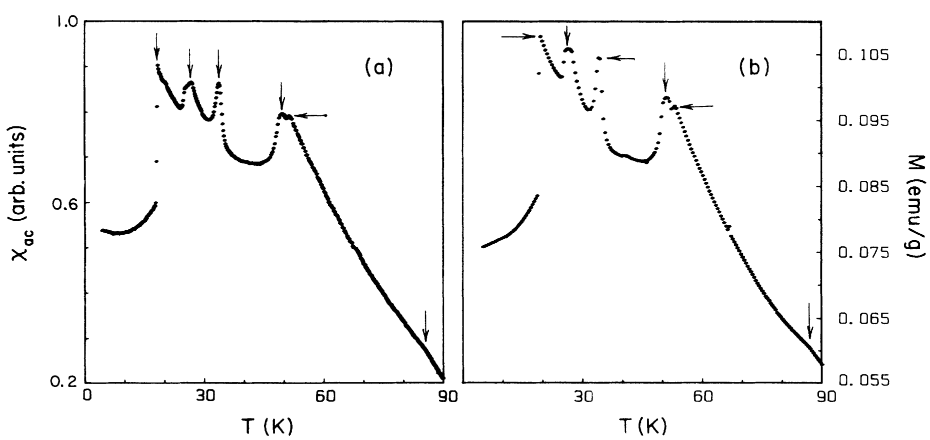

FIG. 1. (a) ac susceptibility (χ_{ac}, in arbitrary units) of a single crystal of Er in the temperature range from 4–90 K measured along the *a* axis; (b) magnetization (M) of single-crystal Er measured along the *a* axis in an applied field of 50 G. The anomalies are indicated by arrows.

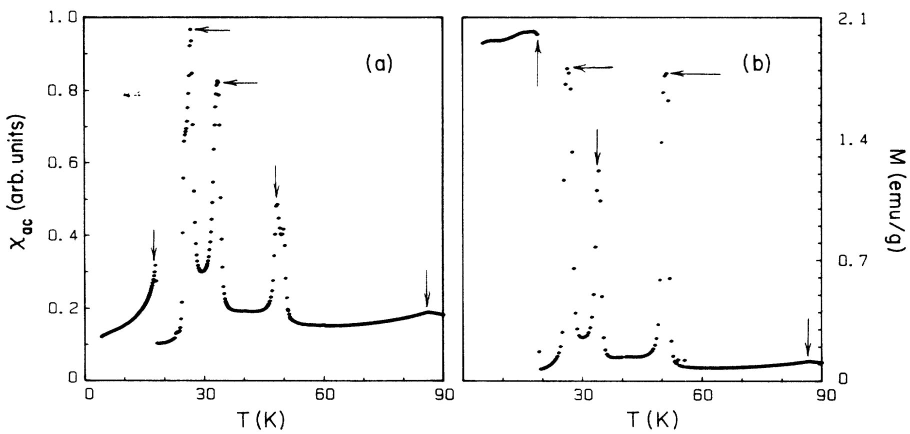

FIG. 2. (a) ac susceptibility (χ_{ac}, in arbitrary units) of a single crystal of Er in the temperature range from 4–90 K measured along the c axis; (b) magnetization (M) of single-crystal Er measured along the c axis in an applied field of 50 G. The anomalies are indicated by arrows.

at $T_{N_\perp}=52.7$ K (Figs. 1 and 2) corresponding to the ordering of the basal-plane moments in a spiral modulation of identical period. Decreasing the temperature further, one observes sharp peaks in M and χ_{ac} at 51, 34, and 27 K (Figs. 1 and 2). Below 18.5 K, erbium has a conical ferromagnetic structure. In addition to the anomalies described above, there are anomalies in M and χ_{ac} at 40 and 29 K, as shown in Figs. 3 and 4.

At this point, we would like to compare the magnetic structure of erbium as determined by Gibbs *et al.*[5] using x-ray synchrotron and neutron scattering with that of our magnetic measurements. Gibbs *et al.*[5] observe a series of lock-in transitions to rational wave vectors as the temperature is decreased below 52 K. They describe the c-axis commensurate structures in erbium in terms of spin slips. The spin-slip description for the c-axis modulation of erbium is as follows. The basic unit consists of four adjacent basal planes (quartet) with the c-axis moment either parallel or antiparallel to the c axis. By associating one less plane of moments to a quartet, one forms a triplet corresponding to a single spin slip. In this scheme for spin-slip structures, Gibbs *et al.*[5] adopt a notation $\cdot p$ where the dot ($\cdot$) represents a triplet and the integer p represents the number of quartets. It is interesting that only lock-in transitions to simply commensurate structures ($\cdot p$) have been observed. Higher-order commensurate structures, for example, of the form $\cdot p \cdot q$ with $p \neq q$, have not been observed. It is also worth noting (Gibbs *et al.*[5]) that the structures with an odd ratio of quartets to triplets ($\cdot 1$, $\cdot 3$, $\cdot 5$) posses a net ferromagnetic component. These ferrimagnetic structures might be expected to result in large changes of the magnetization. Spin-slip structures with an even ratio of quartets to triplets, in contrast, should give a smaller change.

In Table I the fundamental lock-in wave vectors (τ_m) and the corresponding spin-slip structures are taken from the work of Gibbs *et al.*[5] The temperatures at which we observe anomalies in the magnetization and ac-susceptibility data are provided in column 3 of Table I. We note that the spiral ordering of the basal-plane moments in erbium happens at $T_{N_\perp}=53$ K, above the commensurate spin-slip transition at $T=51$ K, to the $\cdot 1$ structure. This suggests that the $T_{N_\perp}=53$ K transition is incommensurate and it is only at $T=51$ K that a lock-in transition appears to the $\cdot 1$ structure over a small temperature range. As the temperature is decreased, we observe

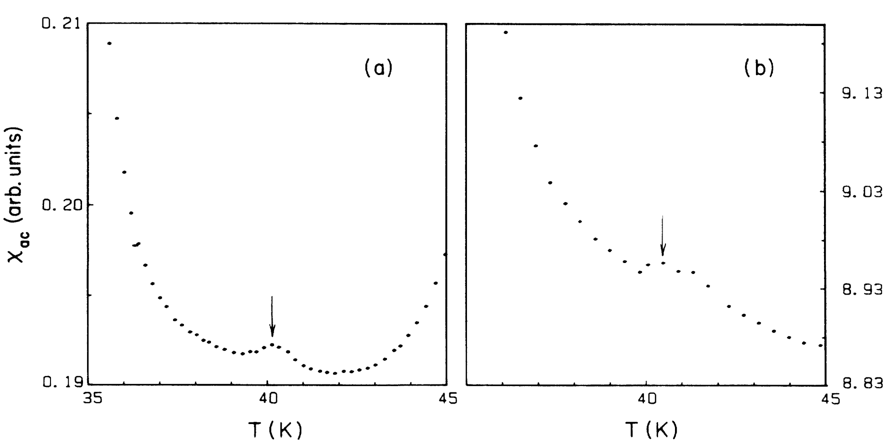

FIG. 3. (a) ac susceptibility (χ_{ac}, in arbitrary units) of single-crystal Er near 40 K; (b) magnetization (M) of single-crystal Er near 40 K. The arrows indicate the anomaly near 40 K.

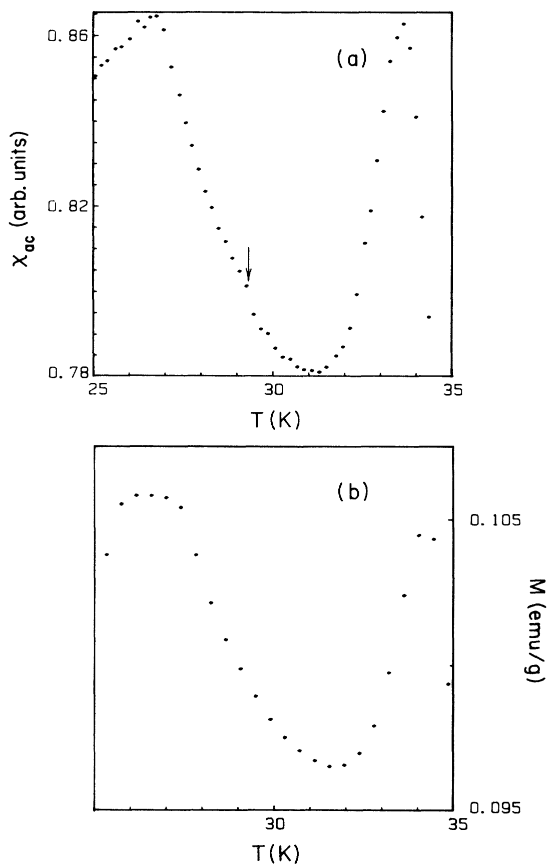

FIG. 4. (a) ac susceptibility (χ_{ac}, in arbitrary units) of single-crystal Er near 29 K. The anomaly is indicated by an arrow; (b) magnetization (M) of single-crystal Er near 30 K. No anomaly is seen in the magnetization (possibly due to an insufficient number of data points).

a small broad peak in M and χ_{ac} at 40 K corresponding to the $\cdot 2 \cdot 2$ structure. The peak in M and χ_{ac} at 34 K corresponds to the $\cdot 3$ structure. We observe a very small broad peak at 29 K (Fig. 4) in χ_{ac}, but not in M (possibly due to the lack of a sufficient number of data points in M) corresponding to the $\cdot 4 \cdot 4$ spin-slip structure. The peak at 27 K corresponds to the $\cdot 5$ structure and below $T=25$ K (Fig. 1), erbium locks into a squared up structure at $\tau_m = \frac{1}{4}$ and finally below 18 K, erbium forms a conical ferromagnetic structure in the c axis with a lock-in wave vector of $\tau_m = \frac{5}{21}$.

TABLE I. Commensurate spin-slip structures in single-crystal erbium. τ_m and corresponding spin-slip structure are taken from Gibbs *et al.*[5] Column three shows the anomaly temperature in our magnetization and ac-susceptibility data corresponding to the respective spin-slip structures.

τ_m	Spin-slip structure	Anomaly in magnetization
		$T_{N_\parallel}=89$ K
		$T_{N_\perp}=53$ K
$\frac{2}{7}$	$\cdot 1$	51 K
$\frac{3}{11}$	$\cdot 2 \cdot 2$	40 K
$\frac{4}{15}$	$\cdot 3$	34 K
$\frac{5}{19}$	$\cdot 4 \cdot 4$	29 K
$\frac{6}{23}$	$\cdot 5$	27 K
$\frac{1}{4}$	2	25–18 K
$\frac{5}{21}$		$T_c=18$ K

In describing the commensurate structures of erbium, it was found to be sufficient to consider the c-axis spin slip.[5] However, from the magnetization and ac susceptibility data in the basal plane (particularly the peaks at 27, 34, and 51 K) it would seem reasonable to ascertain that the basal-plane spin-slips have the same periodicity as that of the c-axis spin-slip structures. In conclusion, we have observed anomalies in the magnetization and ac susceptibility of single-crystal erbium corresponding to all the simply commensurate spin-slip structures observed by Gibbs *et al.*[5] in x-ray synchrotron scattering study. We find that the ferrimagnetic structures did indeed give large changes in the magnetization, and the structures ($\cdot 2$ and $\cdot 4$) that are not ferrimagnetic give much smaller changes in the magnetization. We find also that the basal-plane ordering $T_{N_\perp}=53$ K takes place before any commensurate spin-slip transition appears as the temperature of erbium is decreased.

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