LONG-PERIOD MAGNETIC STRUCTURES IN THE RARE EARTHS

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The localized magnetic moments of the 4f-electrons in the heavy rare-earth metals Tb, Dy, Ho, Er and Tm all order in periodically modulated structures. The crystal structure of these metals is hexagonal closed-packed and the modulation vector **Q** is along the *c*-axis in all cases. The moments are ordered ferromagnetically in the hexagonal layers and change uniformly in magnitude and/or direction from one layer to the next. The basic arrangements of the moments in these systems were determined by neutron diffraction experiments by Koehler and his colleagues during the sixties [1], and their observations have been explained in detail as a result of the interplay between the long-ranged oscillatory RKKY-exchange coupling mediated by the conduction electrons and the magnetic anisotropy, which derives from the crystalline electric field acting on the 4f-electrons [1,2].

Tb, Dy, Ho are easy-planar magnets in which the moments order in a helical structure at T_N. At lower temperatures, Tb and Dy become basal-plane ferromagnets, whereas the ordered moments in Ho change into a cone-structure at low temperatures, with a small ferromagnetic component along the *c*-axis superimposed on the helical arrangement in the basal plane. In Er and Tm the *c*-axis is the easy axis, which implies that they order in a longitudinally polarized structure where, just below T_N, the *c*-component of the moments is sinusoidally modulated. In Tm there is a lock-in transition to a seven-layered structure and, in the low temperature limit, the *c*-component saturates, being positive for four layers followed by three layers in which it is negative. The tendency towards a minimization of the variation of the magnitudes of the moments, which becomes more pronounced the lower the temperature, results in the case of Er in a phase at lower temperatures in which one of the basal-plane components is non-zero, leading to an elliptic cycloidal structure. The neutron-diffraction results obtained in this phase were originally [3] interpreted as implying that both basal-plane components were ordered in a helix, but this is not the structure indicated by a Landau-expansion [2] and the observed refinement of the structure discussed below is incompatible with it. At the lowest temperatures the cycloid is replaced by a *c*-axis cone structure.

The observation of long-period structures commensurable with the lattice, which was made in the high-resolution synchrotron x-ray experiments on Ho [4] and Er [5] by Gibbs and coworkers, has renewed interest in the magnetic ordering in these systems. In the low-temperature limit of Ho, the ordering wave vector locks in to be $(1/6)\mathbf{c}^*$ [1], corresponding to a period of twelve hexagonal layers. The hexagonal anisotropy in Ho causes the helical component of the moments to bunch around the easy b-axes. In the twelve-layered structure the moments of the different layers bunch pairwise about successive easy directions making angles of about $\pm 5.8^\circ$ with the nearest b axis. As the temperature is increased, the ordering wave vector becomes longer and commensurable structures with different periods are derived from the twelve-layered structure by replacing one or more of the pairs in a period with a single layer where the basal-plane moment is along the easy axis, forming the so-called spin-slip structures [4]. The formation of the spin-slip structures was confirmed by high-resolution neutron diffraction experiments performed on large crystals on a triple-axis spectrometer, allowing the observation of peaks of up to 4 orders of magnitude smaller than the main ones [6]. The hexagonal-anisotropy energy and thus the bunching effect rapidly declines with increasing temperatures. The tendency towards the creation of commensurable spin-slip structures should therefore not be of much importance close to T_N. Nevertheless, Noakes *et al.* [7] have observed a commensurable phase with $\mathbf{Q} = (1/4)\mathbf{c}^*$ at a temperature of 96 K ($T_N = 132$ K) in an applied field.

In Er near 50 K, the ordering wave vector is $(2/7)\mathbf{c}^*$ and the commensurable (43)-structure comprises 4 planes with a positive component along the c-axis followed by 3 with a negative c-component. The length of the ordering vector decreases with decreasing temperature, and the longer period of the commensurable structures is achieved by replacing more and more of the blocks of length 3 with blocks of length 4 until, at around 20 K, all are of length 4. High-resolution neutron experiments [8] in combination with mean-field calculations largely confirmed this picture of the commensurable phases in Er, but in addition they showed that the different orientation of the hexagonal layers in the two sublattices of the hcp-structure influences the commensurable structures. Hence the (43)-structure actually turned out to be a (4343)-structure with a period of 14 layers instead of 7. The mean-field calculations showed that the reduced symmetry of the commensurable structures in Er is due to two-ion interactions with three-fold symmetry, leading to a non-planar distortion of the cycloidal structure. The trigonal coupling is also responsible for the lock-in at $\mathbf{Q} = (5/21)\mathbf{c}^*$ observed in the cone phase of Er. One period in this structure involves as many as 42 layers. A recent neutron experiment [9] on Ho has shown that the trigonal coupling is of the similar importance in this system as in Er.

In the presence of an external field, new structural effects appear, as seen in Ho [10] and Er [11,12] in a c-axis field. As the field applied perpendicular to the

c-axis of the helical structures is increased, the helix first distorts, giving rise to a moment along the field, and then undergoes a first order transition to a fan structure, in which the moments oscillate around the field direction. A further increase in the field reduces the opening angle of the fan which, in the absence of hexagonal anisotropy, goes continuously to zero. The hexagonal anisotropy causes the transition to the ferromagnet to be of first order or, if it large enough, eliminates the fan phase entirely. A detailed mean-field analysis of the transition between the (distorted) helix and the fan [13] has shown that long period combinations of the two structures, "the helifans", may appear as intermediate phases, in accordance with experimental findings in the case of Ho [14].

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