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To cite this version:

W. Fairbairn. DOMAIN STRUCTURE IN HELICAL MAGNETS. Journal de Physique Colloques, 1988, 49 (C8), pp.C8-1945-C8-1946. <10.1051/jphyscol:19888880>. <jpa-00229146>

HAL Id: jpa-00229146
https://hal.archives-ouvertes.fr/jpa-00229146
Submitted on 1 Jan 1988

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DOMAINE STRUCTURE IN HELICAL MAGNETS

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Abstract. – For a helical magnet the axis of the helix is a hard axis in most materials but the moments are never constrained so completely. Without that restriction the moments have two degrees of freedom. The two appropriate equations of motion are derived and it is shown in the continuum approximation that within a domain a modulated structure is predicted for the variation of the out-of-plane angle, as found experimentally. The domain walls are probably similar in width to those in which the moments are constrained.

The spirally-ordered phases of magnetic materials (helimagnets) consist usually of layers of similarly ordered magnetic moments, the moments in consecutive layers being rotated relative to each other through the same angle. These rotations are around a direction normal to the layers and this defines the axis of the helical structure. The angle of turn can be either right-handed or left-handed so that there exist two possible types of helical magnetic ordering, corresponding to the two chiralities [1]. Many of the heavier rare earth metals have ordered phases of this type: one of these is holmium, for which the ordered phase exists in the temperature range from 18 K to 133 K. There are other materials such as MnP which exhibit a similar spiral magnetic ordering.

A dominant feature of many of these materials is a strong interaction which encourages the moments to lie within the planar layers mentioned above. This produces a hard axis (with a corresponding easy-plane) which for the rare earth metals is the c-axis of the hexagonal structure. Previous discussions [2, 3] have assumed in the main that this interaction is so strong that a model with that fixed constraint (i.e. all moments are perpendicular to the hard axis) is appropriate. However this is not always so and in this paper we consider a model which includes the possibility of the moments tilting out of the easy plane.

Introduce as the two degrees of freedom which identify the orientation of a localized moment at its site the two angles (θ, φ) referred to spherical polar axes with the c-axis as the axis of reference for the angle θ. All the moments within one of the planar layers have the same orientation so that the angles (θ, φ) are functions only of the plane in which the moment lies. The model is, therefore, equivalent to that for a one-dimensional chain of spins with Hamiltonian

\[ H = \sum_j \left\{ \sum_n J(n) S_j S_{j+n} + A S_j^2 \right\} \]  

where \( J(n) \) are the equivalent exchange interactions representing the sum of the RKKY interactions between the individual moments in planes \( n \) lattice spacings apart and \( A > 0 \) represents the single-site hard axis interaction. The interactions \( J(n) \) are of long range and need to be so to encourage the spiral structure. The magnitude of the spins \( S_j \) is \( S \), which is related to the total electronic spin \( J \) on a site through the de Gennes factor: \( S = (g-1)J \).

Using the equations of motion for the spins

\[ \dot{S} = i[H, S] \]

together with the continuum approximation we obtain two differential equations for the two variables (θ, φ).

If terms are retained up to third derivative in θ and fourth derivative in φ these are

\[ \dot{\theta}/S = C_2 u' \sin \theta + 2S_1 u' \cos \theta \]
\[ + \frac{1}{3} S_3 u'' \cos \theta - \frac{1}{3} S_5 (\theta')^3 \cos \theta \]
\[ - S_5 \theta' u' \sin \theta - \frac{1}{6} S_5 u'' \sin \theta \]
\[ - \frac{1}{24} C_6 (u')^3 \sin \theta + \frac{1}{3} C_4 \theta'' u' \cos \theta \]
\[ - \frac{1}{2} C_4 (\theta')^2 u' \sin \theta + \frac{1}{12} C_4 u'' \sin \theta \]

and

\[ \dot{\phi}/S = 2(A + C_0) \cos \theta \]
\[ - S_3 \theta' u' \cos \theta \cot \theta \]
\[ - \frac{1}{3} S_3 u'' \cos \theta - \frac{1}{4} C_4 (u')^2 \cos \theta \]
\[ + C_2 \theta'' \cos \theta \cot \theta - C_2 (\theta')^2 \cos \theta \]

where \( u \) has been written for \( \partial \phi / \partial z \), dots denote time derivatives and dashes space (z) derivatives, with \( z \) being measured in units of inter-layer spacing (equivalent to c/2 for the hcp lattice). The coefficients \( C_r(u) \) and \( S_r(u) \) are defined by

\[ C_r(u) = \sum n^r J(n) \cos nu; \]
\[ S_r(u) = \sum n^r J(n) \sin nu. \]
If static solutions of these equations are considered then $\dot{\theta} = \dot{\phi} = 0$, and $\theta = \frac{\pi}{2}$, $u' = 0$ satisfies the equations. This shows that two chiral ordered states with turn angle $u = \pm \gamma$ and moments lying in the easy plane ($\theta = \frac{\pi}{2}$) are allowed and the turn angle is given by

$$S_1(\gamma) \equiv \sum_n nJ(n) \sin n\gamma = 0.$$ 

If two such domains of opposite chirality co-exist then the region between them forms a planar domain wall in which the turn angle changes from $u = +\gamma$ to $u = -\gamma$, with the moments always lying in the easy plane. Such a domain wall can be compared in structure with that of a Néel wall in a ferromagnetic material. The properties of these walls has been discussed [2] and the particular case of holmium metal treated in detail.

When the single-ion potential is not sufficiently strong to confine the moments to the easy plane the structure of both the ordered regions and the domain walls is more complicated. First consider a single domain in which the turn angle remains constant but the moments are allowed to deviate out of the easy plane. The angle $\theta$ is no longer equal to $\pi/2$ at all sites and its derivatives are non-zero although expected to be small. From equations (2) and (3) which determine the ordered state, and retaining only terms in $\theta$ up to the second derivative, the single condition for the spatial variation of $\theta$ within such a domain with $u = +\gamma$ (or $u = -\gamma$) is

$$C_2(\gamma) \sin \theta \quad + 2(A + C_0(\gamma)) \sin \theta = 0,$$

which is a second-order differential equation for $\sin \theta$. This equation is the appropriate (i.e. with $u = \pm \gamma$) static restriction of (2) and (3). The solution depends on temperature because the coefficients are defined in terms of $J(n)$, $A$ and $\gamma$ which vary with temperature. This temperature-dependent modulation has been demonstrated and analysed recently [4] for the helimagnetic phase of Ho. For Holmium metal at 50 K the appropriate values of the parameters are

$$J(1) = -0.101 \quad J(2) = -0.035$$
$$J(3) = +0.026 \quad J(4) = +0.022$$
$$J(5) = -0.010 \quad A \ldots = +0.050$$

with other $J(n)$ being zero. For the corresponding value of $\gamma$, which is $\pi/5$, the coefficients $C_2$ and $2(A + C_0)$ are both negative so that $\sin \theta$ varies periodically within the domain and this spatial period is approximately $2\pi/0.7 \sim 9$ lattice spacings. The experimentally predicted value is 8 lattice spacings ([4], Fig. 6).

The co-existence of two chiral domains in which $\theta$ is not constrained to have the value $\pi/2$ implies the existence of a domain wall within which both $u$ and $\theta$ vary. In this case the full equations (2) and (3) must be used. The value of $u$ changes from $+\gamma$ to $-\gamma$ across the wall, but $\theta$ could vary in many ways. For small variations of the moments out of the easy plane the wall is similar to those discussed previously [2]. However a further type of structure within the wall is possible and is the analogue of the Bloch wall in a ferromagnet. In such a wall the value of $\theta$ changes from $\pi/2$ to $-\pi/2$ on passing through zero the magnetic moments lie along the hard axis so that the cost in energy is high and the width of such walls is likely to be small. Nevertheless the relationship between the modulation of the deviation from the easy plane of the magnetic moments within a domain and the chirality of the domain could result in the formation of such walls being favoured.

The two simultaneous static differential equations for $\theta$ and $u$, as for the walls with $\theta$ kept constant and equal to $\pi/2$ [2], are highly non-linear equations and not simple to solve numerically, mainly because of the singularities caused by the vanishing of coefficients ($C_2$) as $u$ varies from $+\gamma$ to $-\gamma$ across the wall. Calculations indicate that walls are little different in width from those considered previously. However with the information now available [4] on the structure of the helically-ordered domains it is likely that those walls which do exist in any multi-domain specimen are of this latter type. The hard-axis single-ion potential is not sufficiently strong to inhibit out-of-plane orientations of the magnetic moments. It is known that the sixfold symmetry of the hcp structure will produce minor modification to the predicted ordering with constant turn angle within each domain [5, 6]. However these small perturbations to the turn angle $\gamma$ should not affect the general structure of the domains and walls which has been described.