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ELSEVIER

Magnetic phase diagrams for three coupled magnetic moments

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Abstract

For three arbitrary coupled magnetic moments (sublattices), the stable magnetic structures have been determined. Three classes do exist: three (all), two and no equal coupling parameters, respectively. At any applied field, only one, collinear or non-collinear, structure is stable. Transitions are smooth: the magnetization curves show no jumps.

Keywords: Magnetic phase diagram; Non-collinear structures

In many lanthanide-transition metal (RT) compounds, the magnetic structures can be described, in a two-sublattice model, as a coupling between the total R-moment and the total T-moment [1]. In applied fields, non-collinear structures can be formed [2], corresponding, in the absence of crystalline anisotropy, to a linear dependence, $M = \mu_0 H / |n|$. In this way, for antiferromagnetic coupling, the molecular-field constant $n (< 0)$ can be measured directly. The influence of crystalline anisotropy is minimized by performing the experiments on an assembly of small, freely orientable, particles [3]. A two-sublattice model is not always adequate. For instance, in the case of two different R-moments on one sublattice, a three-sublattice model is necessary. Recently, $\text{RMn}_{6-x}\text{Cr}_x\text{Sn}_6$ was described [4] as a three-sublattice system, simplified because the Mn-atoms occupy two *equivalent* sublattices (the R-moments form the third one). In Ref. [5], a complete treatment is presented for three *inequivalent* coupled moments, with constant magnitude. Here, the method is explained and the main results are presented.

The (free) energy of a system of magnetic moments M_1 , M_2 , M_3 , placed in an external field $\mu_0 H$, coupled either ferro- ($n_{ij} > 0$) or antiferromagnetically ($n_{ij} < 0$) is given by

$$E = -(n_{12}M_1M_2 + n_{23}M_2M_3 + n_{13}M_1M_3) - \mu_0 H(M_1 + M_2 + M_3). \quad (1)$$

The possible stable structures are found by deriving the equilibrium conditions:

$$a_1M_1 - n_{12}M_2 - n_{13}M_3 = \mu_0 H, \quad (2a)$$

$$-n_{12}M_1 + a_2M_2 - n_{23}M_3 = \mu_0 H, \quad (2b)$$

$$-n_{13}M_1 - n_{23}M_2 + a_3M_3 = \mu_0 H. \quad (2c)$$

The coefficients a_j and the determinant D of the coefficient matrix of this set of equations should be non-negative, mathematically in order to have an energy minimum, from a physical point of view, because the effective field acting on a moment M_j should be oriented along M_j , i.e. equals a_jM_j with positive a_j . For a non-collinear state, D must vanish, since non-zero components perpendicular to H should exist. Moreover, considering a fixed moment M_1 and variable moments M_2 and M_3 , we find that the corresponding minor (subdeterminant) $m_{11} = a_2a_3 - n_{23}^2$, should also be non-negative. Using $m_{12} = a_3n_{12} + n_{13}n_{23}$ (cycl), we can derive

$$m_{11}M_2 = (a_3 + n_{23})\mu_0 H + m_{12}M_1. \quad (4)$$

An analogous relation holds for M_3 (exchange indices 2 and 3). Hence, by addition:

$$m_{11}M_t = (a_2 + a_3 + 2n_{23})\mu_0 H + (m_{11} + m_{12} + m_{13})M_1. \quad (5)$$

For vanishing field, these equations reveal that either all minors have non-zero values (collinear structure) or all minors do vanish (non-collinear structure). In the latter case:

$$a_1 = -n_{12}n_{13}/n_{23}; \quad a_2 = -n_{12}n_{23}/n_{13}; \quad a_3 = -n_{13}n_{23}/n_{12}. \quad (6)$$

Since a_j should be positive (all j), a non-collinear zero-field phase can only exist in case all molecular field constants are negative (antiferromagnetic) or in case only one such constant is negative, the other two being positive (ferromagnetic).

For non-zero fields, we may exchange, in Eqs. (2a)–(2c), the first colon and the right hand side. Then, analogously, we find that a non-collinear solution may exist provided the sum $m_{11} + m_{12} + m_{13}$ vanishes. Looking in more detail, we find a natural classification of the coupled systems. Suppose, for instance, that m_{11} vanishes. Then,

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