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SEQUENCES OF MAGNETIC PHASES IN ANISOTROPIC SYSTEMS WITH CUBIC SYMMETRY

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Abstract. – The infinite-range magnetization equation is solved for a three-component spin system involving cubic anisotropy. Applying the Landau theory it is found that only one ordered phase is possible for a given set of coefficients in the Landau expansion.

Very recently, the completeness of this picture has been challenged. Studying the two component vector model with cubic symmetry in the framework of Landau theory, Galam and Birman have shown that including sixth-and eighth degree terms in the free-energy expansion gives rise to an additional symmetry breaking, into a phase with an order parameter continuously rotating in the $XY$-plane as a function of the temperature [1-5].

An analysis of the types of phases arising in the three component system of cubic symmetry with terms up to eighth order, was carried out within the framework of Landau theory by Gufan and Sakhnenko [6-8]. They pointed out the existence of five phases which we denote by symbols, listing the non-vanishing magnetization components and specifying equalities among them, when they exist. These five phases are: $(X)$, $(X=Y)$, $(XY)$, $(X=Y=Z)$, $(X=Y,Z)$. The cubic symmetry is not totally broken in any of the above five phases.

As an example we mention that higher order anisotropic effective Hamiltonians are relevant to the ferroelectric transitions in rare-earth molybdates [9].

In the present paper we examine the three-component spin system with cubic anisotropy containing terms up to tenth order. We apply the microscopic mean-field theory [10-12].

2. Solution of the magnetization equation for the various phases

The Hamiltonian for any anisotropic spin system with cubic symmetry can be written in terms of the three invariants

\[
\begin{align*}
I_1 &= S_x^2 + S_y^2 + S_z^2 = S^2; \\
I_2 &= S_x^2S_y^2 + S_y^2S_z^2 + S_z^2S_x^2; \\
I_3 &= S_x^2S_y^2S_z^2.
\end{align*}
\]

Retaining terms up to tenth order in the Hamiltonian we obtain

\[
H = aS^2 + bS^4 + cS^6 + dS^8 + fS^{10} + e(S)I_2 + g(S)I_3 + h(S)I_2^2 + nI_2I_3.
\]

Depending on the degree of the Hamiltonian one finds different sets of feasible phases.

For a sixth degree spin Hamiltonian the following four phases are feasible:

\[(X = Y = Z), (X = Y, Z), (X = Y) \text{ and } (X).\]

Adding the eighth degree terms we find that one new phase – $(XY)$ is introduced.

Tenth degree anisotropic terms introduce the sixth, lowest symmetry phase – $(XYZ)$.

3. Phase sequences for different choices of the Hamiltonian parameters

We concentrate on generating non-reentrant sequences involving second order transitions among all the phases which can arise as a consequence of the competition between the different anisotropic terms in the Hamiltonian.

The sixth order Hamiltonian contains two types of anisotropic terms, one of which has an $S$ dependent coefficient. Thus, one might expect the opportunity for competition, giving rise to different phases at different temperatures. The longest continuous sequence that one might anticipate is $(X = Y = Z) \rightarrow (X = Y, Z) \rightarrow (X = Y) \lor (Z) \rightarrow (X = Y, Z) \rightarrow (X = Y = Z)$.

An extensive analysis suggests that no choice of Hamiltonian parameters can give rise to either one of these sequences as the equilibrium solution.
For the eighth order Hamiltonian the longest non-reentrant sequence involves the phases \((X), (XY), (X = Y), (X = Y, Z)\) and \((X = Y = Z)\).

Assuming that the highest temperature ordered phase is \((X) (e_0 > 0)\) the longest possible sequence of continuous phase transitions will be of the form

\[
(X) \rightarrow (XY) \rightarrow (X = Y) \rightarrow (X = Y, Z) \rightarrow (X = Y = Z).
\]

An example of this sequence of phases, for the choice of Hamiltonian parameters \(a = -15, b = 1, c = 0, d = 0, e_0 = 2.37 \times 10^{-3}, e_1 = -0.255, h = 1, g(S) = 0\) is presented in figure 1.

Introducing the tenth order terms in the spin Hamiltonian we obtain sequences incorporating the \((XYZ)\) phase, in which a complete breaking of the cubic symmetry is achieved. One such sequence is of the form

\[
(X) \rightarrow (XY) \rightarrow (XYZ) \rightarrow (X = Y = Z).
\]

An example of this sequence, for the set of parameters \(f = 0, e_0 = 7.28 \times 10^{-4}, e_1 = -9.29 \times 10^{-3}, h_0 = -4.63 \times 10^{-2}, h_1 = 0.681, g(S) = -2S^2h(S), n = 1\) is presented in figure 2.

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