"Kinematic" soft mode in metamagnets in the absence of phase transitions

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In the single-phase region in a metamagnet in a magnetic field, one of the frequencies of the spin-wave spectrum vanishes. The effect is not a consequence of the "softening" of the system which usually occurs at a phase transition.

Although ideas regarding a possible explanation of the metamagnetic behavior of antiferromagnets[1)] on the basis of a nonequilibrium Landau thermodynamic potential containing exchange terms have been around since the first studies by Dzyaloshinskiĭ,[1] the concept of metamagnetism has been based essentially completely on representations regarding anisotropic interactions which are anomalously strong in comparison with exchange interactions.[3,4] The important possibilities in using an exchange thermodynamic potential to explain certain properties of antiferromagnets which are not metamagnetic were also pointed out by Borovik-Romanov,[5] who used a Landau exchange potential to describe the reorienation of the antiferromagnetic vector near the Néel temperature.

The basis for a thermodynamic description of the behavior of antiferromagnets, including those exhibiting metamagnetic properties, is an extremely simple, rational, complete exchange basis of invariants[6] containing three functions of components of the multicomponent order parameter:

$$\bar{\mathbf{L}}^2,\ \bar{\mathbf{M}}^2,\ (\bar{\mathbf{L}}\bar{\mathbf{M}})^2 \qquad (1)$$

(as usual, $\bar{\mathbf{M}} = \bar{\mathbf{M}}_1 + \bar{\mathbf{M}}_2$, $\bar{\mathbf{L}} = \bar{\mathbf{M}}_1 - \bar{\mathbf{M}}_2$, $\bar{\mathbf{M}}_1$ and $\bar{\mathbf{M}}_2$ are the sublattice magnetizations). In particular, a very simple nonequilbrium Landau thermodynamic potential corresponds to this basis and is valid at least near the Neél point (and perhaps over a broad temperature range):

$$\Phi = A_1\bar{\mathbf{L}}^2 + A_2\bar{\mathbf{L}}^4 + B_1\bar{\mathbf{M}}^2 + B_2\bar{\mathbf{M}}^4 + D_1(\bar{\mathbf{L}}\bar{\mathbf{M}})^2 + D_2\bar{\mathbf{M}}^2\bar{\mathbf{L}}^2 - \mathbf{M}\mathbf{H}. \tag{2}$$

We can use this potential to examine the situation in which $|\bar{\mathbf{L}}|$ and $|\bar{\mathbf{M}}|$ are comparable in magnitude [to describe metamagnetic behavior we would need $D_1 < 0$, and $D = D_1 + D_2 > 0$; this situation corresponds to the case in which the parallel susceptibility ($\chi_{\parallel}$) is greater than the perpendicular susceptibility ($\chi_{\perp}$)]; this situation might occur in, for example, $FeCO_3$ near the Néel point.[7] At $D > 0$ we have $\bar{\mathbf{L}}\|\bar{\mathbf{M}}\|\bar{\mathbf{H}}$, and expression (2) for $\Phi = \Phi(\bar{\mathbf{M}},\bar{\mathbf{L}})$ satisfies the requirement of structural stability.[8,9] This circumstance means that the qualitative results found from the potential written above are independent of the addition to this potential of any possible terms, with any signs, constructed as combinations of the exchange invariants given above, (1) [at $B_1 > 0$, structural stability is preserved even if the term $B_2\bar{\mathbf{M}}^4$ is omitted; the exclusion of any other terms from (2) makes this potential structurally unstable].

Figure 1 is a phase diagram of an exchange metamagnet in a magnetic field containing a line of second-order transitions, OT (the equation of this line is $H^2 = 2|A_1|B_1^2D^{-1} + 16A_1^2B_1B_2D^{-2} + 16|A_1|^3B_2^2D^{-3}$, the tricritical point T (the coordinates of this point are $H_T = 2^{5/2}B_1^{3/2}A_2^{1/2}|\Delta||D^2 + 3\Delta|^{-3/2}$, $A_{1T} = 2A_2B_1D\,|D^2 + 3\Delta|^{-1}$) and a line of first-order transitions, TE ($\Delta = 4A_2B_2 - D^2$). The region in which the phases exist is bounded by the lines showing the loss of stability, $PT\,A_1 = D^{-1}[2B_1 + 3|\Delta|^{-1/3}A_2^{1/3}(1/2(H))^{2/3}]$ and $QT(H^2 = 4B_1^2D^{-1}|A_1| + 16B_1B_2A_1^2D^{-2} + 16B_2^2|A_1|^3D^{-3})$.

In the antiferromagnetic region (A), bounded by line OTE, in which megamagnetic properties are manifested, line OWM is a line on which the condition $|\bar{\mathbf{L}}| = |\bar{\mathbf{M}}|$ holds (such a line could also be derived theoretically if it is assumed that the anisotro-

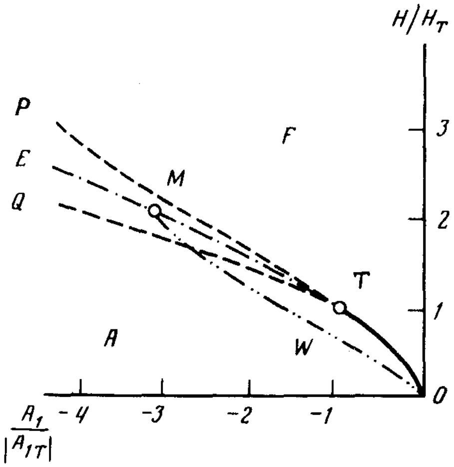

FIG. 1. Phase diagram of an exchange metamagnet. Line OTE separates phases A (the metamagnetic phase) and F (the paramagnetic phase). Line OT is a line of second-order phase transitions, and TE is a line of first-order phase transitions. Line OWM in the single-phase region A, a line on which the condition $\bar{\mathbf{L}}_0^2\bar{\mathbf{M}}_0^2$ holds, corresponds to a "kinematic" soft mode. On this line, one of the frequencies of the metamagnet vanishes.

py is large[4]). The physical meaning here is that the exchange field is precisely canceled by the external magnetic field at one of the sublattices.

The exchange thermodynamic equations describing the linear dynamics at all temperatures,[6,10]

$$\dot{\bar{m}} = \dot{\bar{M}} = \gamma_1 \left[\bar{M}_0 \times \frac{\partial \Delta\Phi}{\partial \bar{m}}\right] + \gamma_2 \left[\bar{L}_0 \times \frac{\partial \Delta\Phi}{\partial \bar{l}}\right]$$
$$\dot{\bar{l}} = \dot{\bar{L}} = \gamma_2 \left[\bar{L}_0 \times \frac{\partial \Delta\Phi}{\partial \bar{m}}\right] + \gamma_3 \left[M_0 \times \frac{\partial \Delta\Phi}{\partial \bar{l}}\right], \qquad (3)$$

correspond rigorously to an exchange antiferromagnet. Here $\bar{M}_0$ and $\bar{L}_0$ are the equilibrium values of the magnetizations of the sublattices, and $\bar{m}$ and $\bar{l}$ are small deviations of $\bar{M}$ and $\bar{L}$ from $\bar{M}_0$ and $\bar{L}_0$. Under the condition $\gamma_1 = \gamma_2 = \gamma_3$, these equations are the same as the linearized Landau-Lifshitz equations. If the anisotropic interactions are stronger than the exchange interactions, equations of the Landau-Lifshitz type cannot be used.[11]

For a potential of any form [including the one in which a slight anisotropy, $K_1 L_z^2 < 0$, which does not change the shape of the phase diagram, is added to (2)], Eqs. (3) lead to the secular equation

$$\omega^4 + R\omega^2 + \Delta_1 \Delta_2 = 0, \qquad (4)$$

where the quantity $\Delta_1 = (\gamma_2^2 \bar{L}_0^2 - \gamma_1\gamma_3 M_0^2)$ is related to the equations of motion, and Δ_2 is the determinant of the matrix which characterizes the stability of the corresponding phase. On the instability lines (including the line of second-order transitions), Δ_2 vanishes; according to (4), this result causes the frequency in one of the branches of the spectrum to vanish. This branch is usually referred to as the "soft" mode,[12] and it is a consequence of a softening of the system upon the phase transition. As can be seen from (4), however, in the case $\gamma_2^2 \bar{L}_0^2 - \gamma_1\gamma_3 \bar{M}_0^2 = 0$ there is a fundamentally different soft mode, a consequence of the kinematics of the magnetic subsystem. It may be called a "kinematic soft mode." Line *OWM*, which corresponds to the kinematic soft mode, on which the frequency vanishes for the Landau-Lifshitz equation, $\bar{M}_0^2 = \bar{L}_0^2$, $\gamma_1 = \gamma_2 = \gamma_3$, is drawn in Fig. 1 [the equation of this line is

$$H = 2(-A_1)^{3/2}(2B_2 + D)(2A_2 + D)^{-3/2} + 2B_1(-A_1)^{1/2}(2A_2 + D)^{-1/2}].$$

The presence of a kinematic soft mode naturally leads to fundamental features and anomalies in the magnetic and thermodynamic properties of metamagnetic systems in a magnetic field.

We wish to stress that the vanishing of the frequency on line *OWM* occurs at all values of the wave vector of the spin wave, $\bar{K}$.

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[1)]Metamagnets are antiferromagnets in which there is no flipping of sublattices when a magnetic field is imposed along the direction of the antiferromagnetism axis. In other words, the antiferromagnetism vector does not line up perpendicular to the field, in contrast with most antiferromagnets. At a certain critical field, the material switches directly from an antiferromagnetic state to a ferromagnetic state, without an intermediate angular phase (Ref. 2, for example).

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