THEORY OF INTERMEDIATE STATES OF AN ANTIFERROMAGNET DURING A FIRST-ORDER PHASE TRANSITION IN AN EXTERNAL MAGNETIC FIELD

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As is well known, the antiferromagnetism (AF) vector $\vec{\ell}$ is rotated through 90° in antiferromagnets with magnetic anisotropy of the easy-axis type situated in sufficiently strong external magnetic fields. The change of direction of $\vec{\ell}$ as a function of the magnetic-anisotropy properties can proceed either via a gradual rotation of jumpwise [1]. The latter occurs apparently in MnF_2 [2]. We consider one case of rotation of $\vec{\ell}$, corresponding to a first-order phase transition.

If the sample is ellipsoidal in shape, then considerations analogous to those advanced by Landau [3] in the analysis of the intermediate state of superconductors of the first kind show that the body should break up into domains, with phases in one of which the vector $\vec{\ell}$ is parallel to the principal axis (ℓ phase) and in the other the vector $\vec{\ell}$ is perpendicular to this axis ($\ell_\parallel$ phase) and in the other the vector $\vec{\ell}$ is perpendicular to this axis ($\ell_\perp$ phase). The phase-equilibrium condition is constancy of the magnetic field acting on the magnetic moments of the sublattices in the sample. Following [1], we denote this field by H_s

$$H_s = \sqrt{(2\delta + \beta' - \beta + b\pi\mu M_0)(\beta + \beta')}.$$

Calculations made within the framework of the phenomenological theory of AF show that the lowest surface energy is possessed by plane interphase boundaries parallel to the principal axis. The arrangement of the boundaries is determined by the anisotropy in the basal plane. Rotation of $\vec{\ell}$ in an interphase boundary is determined by the formula

$$\cos 2\theta = -\mathrm{th}\,\frac{x}{x_0}, \qquad x_0 = \sqrt{\frac{(\alpha - \alpha_{12})\,\delta}{\beta(\beta - \beta')}}, \tag{1}$$

where θ is the angle between $\vec{\ell}$ and the principal axis, x_0 has the meaning of the thickness of the boundary, β and β' are the anisotropy constants, α and α_{12}' are the constants of the inhomogeneous exchange interaction, and δ the constant of homogeneous exchange interaction.

The AF energy is taken to be

$$W = \int\left\{\frac{1}{2}\alpha\left(\frac{\partial \mathbf{M}_1}{\partial x_i}\frac{\partial \mathbf{M}_1}{\partial x_i} + \frac{\partial \mathbf{M}_2}{\partial x_i}\frac{\partial \mathbf{M}_2}{\partial x_i}\right) + \alpha_{12}\frac{\partial \mathbf{M}_1}{\partial x_i}\frac{\partial \mathbf{M}_2}{\partial x_i} + \delta\,\mathbf{M}_1\mathbf{M}_2 + \right.$$
$$\left. + \frac{1}{2}\beta(M_{1z}^2 + M_{2z}^2) + \beta' M_{1z}M_{2z} - (\mathbf{M}_1 + \mathbf{M}_2, \mathbf{H}_0) + \frac{\mathbf{h}^2}{8\pi}\right\} dr, \tag{2}$$

where $\vec{M}_{1,2}$ are the magnetic moments of the sublattices ($M_1 = M_2 = M_0$) and H_0 is the external magnetic field that would exist in the space in the absence of the body.

Recognizing that $\delta \simeq 1/2\chi_\perp$, $\beta \sim \beta' \sim 1$, $\alpha \sim \alpha_{12} \sim a^2/\chi_\perp$ (a is the lattice constant and $\chi_\perp$ is the static magnetic susceptibility in the direction perpendicular to the principal axis, we obtain $x_0 \simeq (a/\chi_\perp)$. Assuming $\chi_\perp \simeq 10^{-3}$, we get $x_0 \simeq 10^{-5}$ cm.

If $H_0 < H_s$, then there can exist boundaries in which the vector $\vec{\ell}$ is turned through 180°. This rotation of $\vec{\ell}$ is described by the formula

$$\cos\theta = -\text{th}\,\frac{x}{x_1}, \quad x_1 = \sqrt{\frac{2M_0^2(a - a_{12})\delta}{H_s^2 - H_0^2}} \,. \tag{3}$$

The energy per unit surface of the boundary between the phases $\ell_{\parallel}$ and $\ell_{\perp}$ is equal to

$$\sigma = M_0^2 \sqrt{(a - a_{12})\,\beta(\beta - \beta')\delta^{-1}} \sim M_0^2 a \,. \tag{4}$$

Knowledge of the surface energy makes it possible to estimate the dimensions and structure of the domains. Let us consider for simplicity a plane-parallel plate whose surface is perpendicular to the external magnetic field. As shown by the estimates, in view of the relatively small value of the surface energy, the branching of the domains at the surface begins at a plate thickness of the order of several atomic layers. We shall therefore consider directly the simplest case of domain branching, when there are n wedges per domain on the surface. Accurate to coefficients on the order of unity, the energy of the plate can be represented in the form

$$W' = \text{const} + \sigma\ell_1\ell_2\ell_3 d^{-1} + \sigma n \ell_2 d\,\frac{\ell_3}{d} + MH_s\ell_2\frac{d^2}{n}\frac{\ell_3}{d}\,, \tag{5}$$

where d are the dimensions of the recurring domains, and $\ell_1 < \ell_2 < \ell_3$ are the dimensions of the plate. Recognizing that $M = \chi_{\perp} H_s$, we determine the values of d and n corresponding to the minimum of W'

$$n \approx \left(\frac{\ell_1 \chi_{\perp} H_s^2}{\sigma}\right)^{1/3}\left(\frac{\ell_1}{a}\right)^{1/3}, \quad d \approx \left(\frac{\sigma\ell_1^2}{\chi_{\perp}H_s^2}\right)^{1/3}. \tag{6}$$

Equating the normal components of the induction inside and outside the plate, we obtain an expression for the relative fraction ρ of the substance in the phase $\ell_{\perp}$:

$$\rho = \frac{H_e - \mu_{\parallel} H_s}{(\mu_{\perp} - \mu_{\parallel})H_s}\,, \tag{7}$$

where H_e is the magnetic field at the far distance from the plate, and $\mu_{\parallel}$ is the magnetic permeability of the $\ell_{\parallel}$ phase in the easy-axis direction. We see that domains exist when $\mu\ H_s \leq H_e \leq \mu_{\perp} H_s$.

We present an expression for the effective magnetic susceptibility of the plate. If the average magnetization of the plate is represented in the form $M_{av} = \chi_{av} H_e$, then $\chi_{av} = (\chi_{\parallel}/\mu_{\parallel})$ if $H_e \leq \mu_{\parallel} H_s$, $\chi_{av} = 1/4\pi$ if $\mu_{\parallel} H_s \leq H_e \leq \mu_{\perp} H_s$, and $\chi_{av} = (\chi_{\perp}/\mu_{\perp})$ if $\mu_{\perp} H_s < H_e$.

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