Domain Structure in the Region of the Metamagnetic Transition

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On the basis of a general method developed by the authors[5] for the investigation of inhomogeneous states in the vicinity of first-order phase transitions in antiferromagnetic structures, it is predicted that a transition domain structure should exist in the metamagnetic transition region. The transition from the antiferro- to the ferromagnetic state should involve a shift of the domain walls parallel to the crystal axis. The nature of the transition structure walls depends on the initial antiferromagnetic state. Uniaxial (Neel) metamagnetic substances and helicoidal structures of rare-earth metals are considered. The difference between the metastable transition structure and the ferromagnetic-domain structure stabilized by "closing" of the magnetic flux of the sample is discussed.

1. Recently reported experiments on neutron depolarization in the region of the metamagnetic transition (MMT) in $FeCl_2$[1] raise the hope of explaining in the nearest future the character of the MMT in different magnetic structures. The presence of a MMT is a common property of magnetically-uniaxial antiferromagnetic structures in which the anisotropy field H_A exceeds the effective field of the sublattice exchange coupling[2].

It is obvious that were the MMT to proceed via uniform rotation of the sublattice magnetizations, the hysteresis loop would have a width $2H_A$[3] and would be stretched out at $H_A \leq 2H_E$, or else a displacement of the hysteresis loop would be observed. No such broad hysteresis was observed in either[1] or[3], and it is natural to attribute its "narrowing" to the appearance, in the MMT region, of a special type of domain structure, which is thus responsible for the neutron depolarization in[1]. We present below a calculation of such a domain structure for uniaxial and magnetically planar (helicoidal) metamagnets. The latter case turns out to be somewhat more complicated, but can also be analyzed in a sufficiently general form.

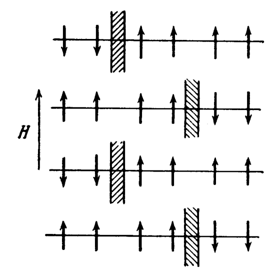
2. Without loss of generality, we choose for geometric clarity a layered Landau antiferromagnet[2]. The magnetic moments M_j of the sublattices are antiparallel for neighboring atomic planes in the absence of a magnetic field H. When considering the magnetic inhomogeneities, we can neglect the inhomogeneity of the energy of exchange interaction between the sublattices in comparison with the inhomogeneity of the much larger intrasublattice energy. The thermodynamic potential

$$\Phi = \int dV \left\{ A_j \left(\frac{\partial M_{1i}}{\partial x_j}\frac{\partial M_{1i}}{\partial x_j} + \frac{\partial M_{2i}}{\partial x_j}\frac{\partial M_{2i}}{\partial x_j} \right) + K(\sin^2\theta_1 + \sin^2\theta_2) + B\mathbf{M}_1\mathbf{M}_2 - \mathbf{MH}(\cos\theta_1 + \cos\theta_2) \right\} \qquad (1)$$

is written out for a concrete domain wall normal to the atomic ferromagnetic planes, θ_j are the angles between M_j and the z axis, and $\mathbf{H} \parallel z$. We can show in simple manner that the domain-wall sections parallel to the atomic planes are not displaced in the MMT region. We introduce the notation

$$x/\delta = \xi, \quad \delta = \sqrt{A/K}, \quad \gamma_0 = 4\sqrt{AK}, \quad MH/K = h, \quad BM^2/K = \alpha, \quad BM = H_E \qquad (2)$$

The first term in (1) is of the form $(d\theta_1/d\xi)^2$



Nucleus of ferromagnetic phase (the arrows indicate the magnetization directions).

$+ (d\theta_2/d\xi)^2$, and the second is $+\alpha\cos(\theta_1 - \theta_2)$. At H = 0, the Euler equations agree with the condition $\theta_2(\xi) = \pi + \theta_1(\xi)$ for the compensation of the magnetic moment, from which it follows that the 180° antiferromagnetic wall under consideration consists of 180° "Bloch walls" in each atomic plane. The polarizations of the walls in the neighboring planes are antiparallel. When H is turned on the system becomes magnetized as a result of the rotation of M_j. The changes of the distribution of M_j can be described by an effective displacement of the planar "Bloch walls" by $\pm\xi_0$. The compensation condition is replaced by the more general condition

$$\theta_2(\xi - \xi_0) = \pi + \theta_1(\xi + \xi_0). \qquad (3)$$

We investigate the Euler equation

$$-2\theta_1'' + \alpha\sin(\theta_1 - \theta_2) + \sin 2\theta_1 + h\sin\theta_1 = 0 \qquad (4)$$

in the limiting cases of small $H \ll H_E$ and near the MMT.

3. Small $H \ll H_E$, $\xi_0 \ll 1$. From (4) we obtain $2\xi_0 = h/\alpha$, and the magnetization curve is linear, as it should be for a reversible "wall" displacement. The magnetization distribution is given by $\cos\theta_{1,2} \mp \tanh(\xi \mp \xi_0)$.

4. The MMT region. In fields $H \approx H_E$, the value of ξ_0 increases rapidly and this leads to a sharp decrease of θ_2 in the region of variation of θ_1 and vice versa. Equation (4) takes the form

$$-2\theta_1'' + \sin 2\theta_1 - (\alpha - h)\sin\theta_1 = O(\theta_2) \qquad (5)$$

and as $h \to \alpha - 0$ ($H \to H_E - 0$) we obtain in the limit the solution $\xi_0 \to \infty$ and $\cos\theta_1 = -\tanh(\xi - \xi_0)$. Thus, the 180° antiferromagnetic wall has split into two walls between the ferro- and antiferromagnetic phases. A ferromagnetic phase has appeared in the gap. The energy of such "metamagnetic" walls (MMW) is equal to the sum of the energies of the planar "Bloch walls," or $\gamma_0/2$ per unit area (see the figure). Let us estimate the MMW energy for $H_E = 10$ kOe, $K = 10^7$ erg/cm^3, $A = 10^{-7}$ erg/cm^2. We obtain $\gamma_0 \sim 0.1$ erg/cm^2 and a wall width $\sim 10^{-6}$ cm.

We can consider analogously MMT in a system of ferromagnetic filaments with antiferromagnetic coupling between the filaments (for example, Eu_3O_4 [4]). It is obvious that the MMT domains should be much smaller than the domains produced upon "flipping of the sublattices" and predicted in[5], owing to the larger jump of the magnetization at the MMT point[1)]. It is therefore more probable to observe in the MMT scattering of radiation passing in any direction, since a noticeable scattering anisotropy is possible at the "flipping" point; the character of the anisotropy should be determined by the domain structure.

It is of interest to apply our analysis to MMT in rare-earth ferromagnets, say with a helicoidal structure. The strong magnetic anisotropy ($K_1 \sim 5 \times 10^8$ erg/cm^3) retains the magnetic moments in the basal plane. At the MMT point there can arise a ferromagnetic-phase nucleus separated by a domain wall from the helicoidal phase. Such a wall can be considered in each monatomic plane to be a flat "Neel wall," and its energy is of the order of $\gamma_{REM} \sim \sqrt{AM^2}$, where A is the exchange parameter of the interaction inside the layer and M is the saturation magnetization ($\gamma_{REM} \sim 10$ erg/cm^2). In cases when the MMT field is $H_E \ll 4\pi M$, a branched domain structure can arise at the MMT point, similar to the structure that should be observed in a hexagonal "magnetoplanar" ferromagnet. In a thin plane whose hexagonal axis lies in the plane of the plate it is possible to have a domain structure that differs little from the Kittel structure[2], for which the estimated period is $d \sim \sqrt{\gamma_{REM}/M} \sim 10^{-3}$ cm.

We note that, just as in the preceding case, the role of the MMT nuclei is played only by the walls parallel to the hexagonal axis. Walls perpendicular to the hexagonal axis have an activation energy approximately equal to the anisotropy energy K_6^6 of the basal plane. In the case of a Landau antiferromagnet, the activation energy of such MMW is $\sim K_1$.

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1) It is important to note that the domain structure in non-ferromagnets is unstable. The absence of "antiphases" makes closing of the magnetic flux lines impossible. Calculations of the "equilibrium" period of the domain structure of the type described in [6] can therefore not give a correct result.

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