Surface spin-flop and the antiferromagnetic spin-flop transition*

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The role of the surface spin-flop state in the antiferromagnetic spin-flop phase transition in MnF_2 is examined. Demagnetizing and Lorentz fields are included in the analysis. It is shown that the surface spin-flop state is equivalent to an ordinary spin-flop domain residing at the surface of the crystal, and that the mechanism for bypassing the energy barrier between the bulk antiferromagnetic and spin-flop phases is domain formation.

In a previous paper,[1] Mills predicted a surface spin-flop (SSF) state for a uniaxial antiferromagnet in an applied field H_0, parallel to the "easy axis" and of magnitude $H_s < H_0 < H_3$. $H_s = (H_E H_A)^{1/2}$, where H_E and H_A are, respectively, the exchange and anisotropy fields. $H_3 = (2H_E H_A - H_A^2)^{1/2}$ is the field at which the bulk antiferromagnetic (AF) and spin-flop (SF) states have equal free energy. Keffer and Chow (KC) showed[2] that the depth of penetration of the SSF state increases with increasing H_0. Since as $H_0 \rightarrow H_3$ "the SSF regions catastrophically expand into three dimensions and encompass the entire material," they suggested that the SSF state bypasses the energy barrier between the AF and SF phases.

One might hope to study the SSF state experimentally, measuring, for example, its thickness in fields near H_3. With this in mind, we evaluated the KC expressions[3] for the case of MnF_2, in which $H_A = 7.87$ kOe and $H_E = 550$ kOe. In Fig. 1 we have plotted, for several values of $H_3 - H_0$, the angle between the z axis and spin in successive layers from the surface. It is seen that an experimentally detectable number of layers in the SSF state occurs only for values of H_0 extremely close to H_3.

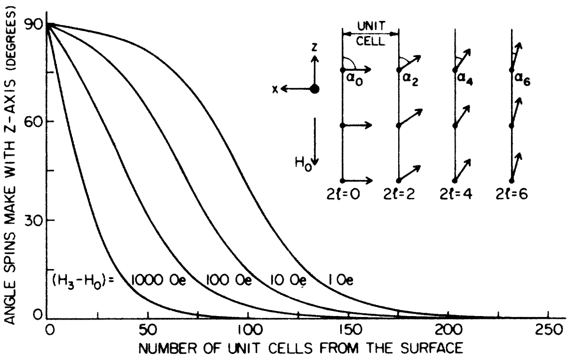

FIG. 1. KC prediction for the penetration of the SSF state in MnF_2 shown for several values of $H_3 - H_0$. As schematically depicted in the insert, "up sublattice" spins in the $2l$th layer from the surface are oriented at angle α_{2l} with respect to the z axis.

In a physically realizable sample the effects of demagnetizing and Lorentz fields must be considered. As shown in Fig. 2, H_3 is dependent on sample shape, and may be expressed as $H_3' = H_D(1 + \frac{1}{2}N_z\chi)$. N_z is the demagnetizing factor along z; χ is the susceptibility in the SF state;

$$H_D = [(2H_E H_A - H_A^2)(1 - \tfrac{4}{3}\pi\chi)]^{1/2}$$

is the field at which SF domains form,[4] and is independent of sample shape. For samples with $N_z = 0$ (e.g., needles or thin slabs with $\vec{c} \parallel \vec{H}_0$ in the plane), $H_3' = H_D$, while for all other shapes $H_3' > H_D$. Therefore, the catastrophic penetration of the SSF state into the sample, which would have been complete only at H_3', is interrupted at $H_0 = H_D$ by the formation of the domain state and the resultant screening of the inter-

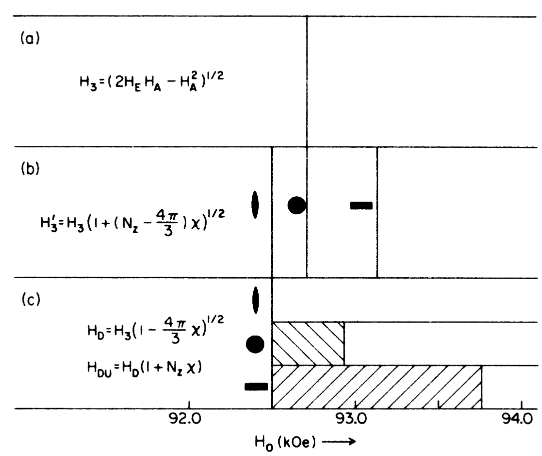

FIG. 2. Evaluated for the case of MnF_2 are (a) H_3, neglecting demagnetization and Lorentz fields; (b) H_3, including demagnetization and Lorentz fields shown for three representative sample shapes (needle, sphere, disk); and (c) the domain region for the sample shapes in (b).

nal field. The upper boundary of the domain region *is* shape dependent and may be expressed as $H_{DU} = H_D(1 + N_z\chi)$.

For some sample shapes (e.g., disks perpendicular to H_0), H_{DU} is larger than

$$H_4 = [2H_E H_A + H_A^2 - (\tfrac{4}{3}\pi - N_\perp)2M_s H_A]^{1/2} ,$$

the field at which AF magnons are calculated to reach zero frequency.[5] This is due to screening of the internal field by the domains.

It may be noticed that the SSF layer closely resembles an SF domain, except that it has only one "domain wall." In fact, the KC treatment is an extension of a standard domain wall calculation.[6] If the value derived in Ref. 4 for the anisotropy energy density is inserted into Eq. (9.25) of Ref. 6, one obtains Eq. (6) of KC with $H_0 = H_3$. Equation (8) of KC and Eq. (9.31) of Ref. 6, which describe, respectively, the spin orientations in an SSF wall and a domain wall, become identical. Since the SSF layer is bounded on one side by an ordinary domain wall, and on the other side by a surface layer of negligible energy, the demagnetization energy required to stabilize its wall energy is half that required by an SF domain. Hence, the SSF layer is half the thickness of an SF domain.

Our picture of the phase transition is, therefore, somewhat modified from the KC description. The SSF layer thickens with increasing H_0 until at $H_0 = H_D$ domain formation becomes energetically favorable. As H_0 is increased above H_D, the widths of both the SSF layer and of the SF domains increase until at $H_0 = H_{DU}$ the entire crystal has flopped. In downgoing field, the process is simply reversed, the first AF domain forming at $H_0 = H_{DU}$, etc. Thus, we conclude that the energy barrier between the bulk AF and SF states is bypassed by domain formation.

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[1] D. L. Mills, Phys. Rev. Lett. 20, 18 (1968).

[2] F. Keffer and H. Chow, Phys. Rev. Lett. 31, 1061 (1973).

[3] In order to obtain "infinite penetration" at $H_0 = H_3$, it is necessary to add a small correction term, $-2(H_A/H_E)^3$, to the KC expression for a^2.

[4] A. R. King and D. Paquette, Phys. Rev. Lett. 30, 662 (1973).

[5] J. P. Kotthaus, thesis (University of California, Santa Barbara, 1972) (unpublished).

[6] See, for example, S. Chikazumi, *Physics of Magnetism* (Wiley, New York, 1964), Chap. 9.