# Formation of front of antiferromagnet → (weak ferromagnet) transition in $DyFeO_3$ in field at which antiferromagnetic phase loses stability

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The formation of a transition front has been observed in the transition from the antiferromagnetic state to the weak ferromagnetic state in a field at which the antiferromagnetic phase loses stability in $DyFeO_3$. This front moves at a velocity far higher than that of the boundaries between phases. The instability line of the antiferromagnetic state on the $H$–$T$ phase diagram of $DyFeO_3$ has been determined.

A study has been made of the phase transition from the antiferromagnetic (AFM) state to the weak ferromagnetic (WFM) state in dysprosium orthoferrite under the condition that the external field which induces the phase transition reaches the level at which the AFM phase loses stability. The external field was oriented along the optic axis of the crystal, at an angle $\beta \approx 55°$ from the $c$ axis, in the $bc$ plane. It caused the phase transition $\Gamma_{14} \rightarrow \Gamma_4$. The process was studied by high-speed photography. The basic characteristics of the experimental apparatus are described in Ref. 1. The sample was in a static magnetic field $H_s \approx H_t + (1/2)\Delta H$, which leads to the formation of a strip domain structure of alternating domains of AFM and WFM phases. Here $H_t$ is the field at which the phase transition occurs, and $\Delta H \approx 4\pi(m_{\mathrm{WFM}} - m_{\mathrm{AFM}})$ is the interval in which an equilibrium intermediate state exists. After the formation of the equilibrium domain structure, a pulsed magnetic field $H_p$, with a pulse length of about 10 $\mu$s, was applied to the sample. The amplitude $H_p$ could be varied from 0 to 3.5 kOe.

At low values of $H_p$, the transition from the AFM + WFM two-phase state to a uniform WFM state occurred through the motion of phase boundaries and the collapse of the unfavored AFM domains. As $H_p$ was increased, and it reached a certain value, a rapidly moving transition front appeared in the sample. As this front traveled from one edge of the plate to the other, it erased the AFM phase (Fig. 1). The velocity of this front, $v_f$, reached 1 km/s and was nearly two orders of magnitude higher than the velocity of the phase boundaries in fields close to the front formation field.

We link the formation of the transition front observed in these experiments with the attainment of the field at which the AFM phase becomes unstable. The transition from the AFM state to the WFM state in a field equal to the lability field of the AFM phase, $H_{\mathrm{lab}}^{\mathrm{AFM}}$, should occur through a uniform rotation of spins. However, that course of the transition process would be expected only in uniform samples and in a uniform field. In real samples there are always composition variations, stresses, etc., which can cause variations in $H_{\mathrm{lab}}^{\mathrm{AFM}}$ over the crystal. In addition to the internal variations, one

  

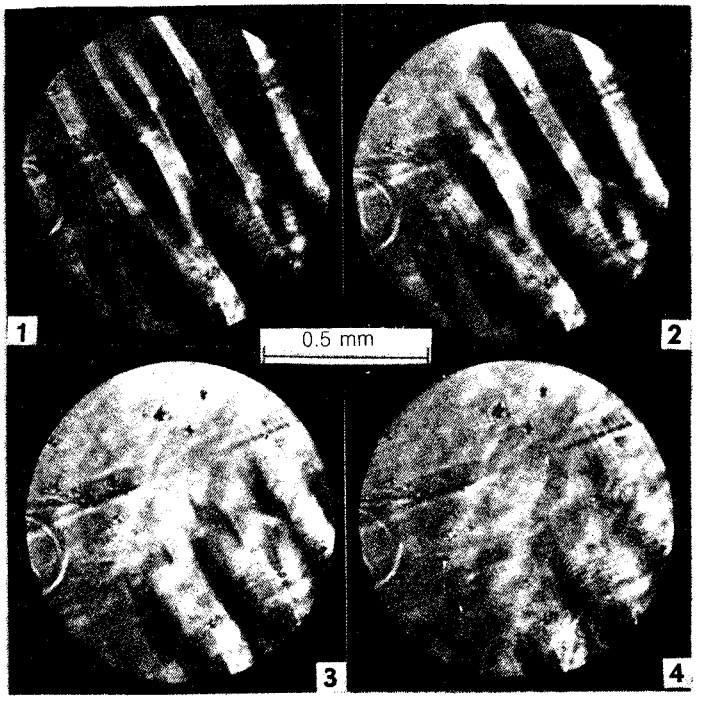


FIG. 1. Transition from an AFM + WFM two-phase state to a uniform WFM state in $DyFeO_3$ in the field at which the AFM phase becomes unstable ($T = 34.5$ K, $H_s = 2.3$ kOe, $H_p \simeq 3$ kOe). 1—The pulsed field is applied at $t = 0$; 2—at 3 $\mu$s; 3—at 3.5 $\mu$s; 4—at 4 $\mu$s. The velocity of the phase boundaries is $v \approx 14$ m/s; the velocity of the transition front is $v_f \approx 400$ m/s.

must also consider the nonuniformity of the pulsed field, produced by two plane coils. Because of the variations in $H_{\text{lab}}^{\text{AFM}}$ and $H_p$ over the sample, the state in which the AFM phase becomes unstable will be reached at different times at different points in the crystal as the external field is increased. Consequently, the AFM→WFM transition will also occur at different times at different points in the crystal, so a phase front will form and move through the crystal as the external field increases. In this case the phase front is a surface in the sample on each point of which the value of $H_{\text{lab}}^{\text{AFM}}$ has been reached at the given instant.

To test this suggestion, we carried out experiments to observe the formation of a phase front in pulsed fields while the field was increased at various rates $dH/dt$. It was found that the field $H_1$, at which the phase front appeared, and the field $H_2$, at which the phase front disappeared after traversing the entire sample, are indeed independent of $dH/dt$. On the other hand, the time required for the transit of the sample by the phase front and, corresponding by the velocity of this front, are different in fields with different values of $dH/dt$ and are determined by the time over which $H_p$ rises from $H_1$ to $H_2$.

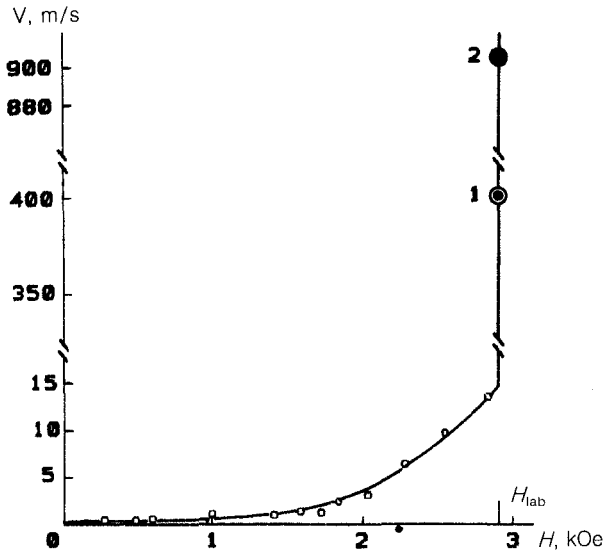


FIG. 2. □—Velocity of the phase boundary versus the direction of the driving pulsed field; ◉—velocity of the transition front at two rates of increase of the pulsed field. 1) $dH/dt \approx 200$ Oe/$\mu$s; 2) $dH/dt \approx 450$ Oe/$\mu$s. The sample temperature was $T = 34.5$ K.

Figure 2 shows the velocity of the phase boundary as a function of the strength of the pulsed driving field. Shown for comparison here are the velocities of the transition front for two pulsed fields, with different rates of increase, $dH/dt$. It is clear from this figure that the velocity of the phase boundary tends toward a constant value as $H \to H_{lab}^{AFM}$. The velocity of the phase boundary depends on $dH/dt$ and can take on the values shown by the points on the vertical line in Fig. 2. The values of $v_f$ which were reached were still not high enough that we would expect the appearance of nonlinear processes which would influence the velocity and shape of the front. One would expect to see effects of nonlinear processes on the kinetics of the phase transition at the field at which the AFM phase becomes unstable, at which the rise time of the pulsed field becomes comparable to the relaxation times of the spin system.

This method of studying the kinetics of the phase transition in pulsed fields with short $H_p$ rise times has been used to determine the lability field line $H_{lab}^{AFM}(T)$ on the $H$–$T$ phase diagram of $DyFeO_3$ (Fig. 3). The experimental points on the line of the phase transitions $\Gamma_{14} \leftrightarrow \Gamma_4$ in this diagram were determined from visual observation of the appearance of the WFM phase in static fields. The points on the instability line of the AFM phase were found from observations of the formation of the phase boundary in pulsed fields. Each of these points corresponds to the average value of $H_{lab}^{AFM} = (1/2)(H_1 + H_2)$, averaged over the sample, for the given temperature. Working from the thermodynamic potential[2,3]

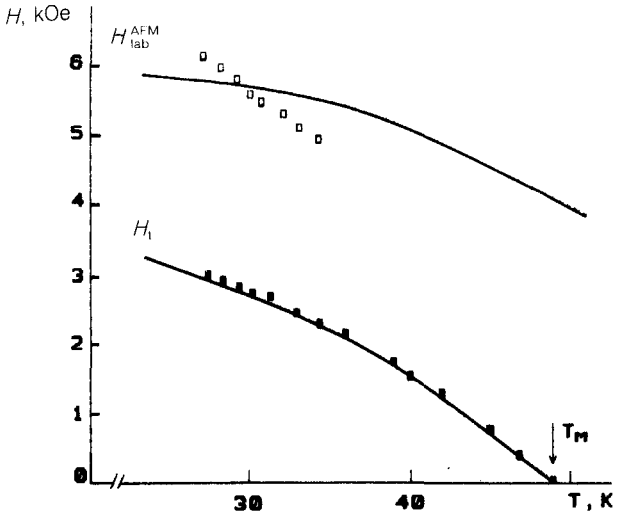


FIG. 3. The $H$–$T$ phase diagram of $DyFeO_3$ at $H = (0,H_y,H_z)$ for $\beta \approx 55°$, where $\beta$ is the angle between **H** and the $c$ axis, $H_t$ is the field of the AFM↔WFM phase transition, and $H_{\text{lab}}^{\text{AFM}}$ is the field at which the AFM phase becomes unstable. Points—Experimental; lines—theoretical. The Morin temperature of the crystal is $T_M \approx 49$ K.

$$\Phi = \Phi_0 + [K_2 - \frac{1}{2}\chi_\perp (1+\eta_y)^2 H_y^2]\cos 2\varphi + K_4 \cos 4\varphi - m_z^0 H_z \cos\varphi \qquad (1)$$

we calculated the lines $H_t(T)$ and $H_{\text{lab}}^{\text{AFM}}(T)$, which are shown in Fig. 3. The line of the phase transitions AFM↔WFM was calculated from the expression

$$H_t = \frac{4(K_2 - 4K_4)}{m_z^0 \cos\beta} \frac{\{1 - [1 - K_2(1-\kappa)/(K_2 - 4K_4)]^{1/2}\}}{(1-\kappa)}$$

$$\kappa = 8\chi_\perp (K_2 - 4K_4)\left(\frac{1+\eta_y}{m_z^0}\right)^2 \operatorname{tg}^2\beta \,, \qquad (2)$$

and the line $H_{\text{lab}}^{\text{AFM}}(T)$ was found through a numerical solution of the equation $(d^2\Phi/d\varphi^2)|_{\varphi=\varphi_0} = 0$. In this calculation we used the constants found in Ref. 4.

We see a good agreement between the calculated $H_t(T)$ line and the experimental points. The experimental and theoretical values of $H_{\text{lab}}^{\text{AFM}}$ do not agree as well, possibly because of uncontrollable deviations of the pulsed field from the selected orientation in a nonuniform way over the sample; such deviations were ignored in the calculation. The experimental values of $H_t$, determined in a more uniform steady-state field, on the other hand, should agree better with the calculations.

We note in conlcusion that this interpretation of the formation of a transition

front is also supported by the circumstance that a phase front does not form when the direction of the pulsed field is reversed at amplitudes $H_p$ up to 3.5 kOe. When the direction of the pulsed field is changed, we would expect the transition front to appear when the field at which the WFM phase becomes unstable is reached. The absolute value of $H_{\text{lab}}^{\text{WFM}}$, on the other hand, is far higher than $H_{\text{lab}}^{\text{AFM}}$. The theoretical $H_{\text{lab}}^{\text{WFM}}(T)$ line on the $H$–$T$ phase diagram runs 15 kOe below the $H_t(T)$ line in the temperature range studied, while the difference $H_{\text{lab}}^{\text{AFM}} - H_t$ is only 3 kOe.

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