Study of the magnetic phase diagram of dysprosium by electromagnetic excitation of sound

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The field dependence of the efficiency of the electromagnetic-acoustic conversion in a dysprosium single crystal has been studied. The results are used to construct an H–T diagram for this metal in a magnetic field oriented along the twofold crystallographic *b* axis.

A restructuring of the spin subsystem of a magnetic material caused by an external magnetic field or by the temperature is manifested in many interactions, in particular, magnetoelastic interactions. These interactions can be studied by making use of the electromagnetic-acoustic conversion at the boundary of a magnetic material.[1] In this letter we are reporting a study of the field dependence of the efficiency of the electromagnetic-acoustic conversion in a Dy single crystal. As the temperature is raised in the absence of a magnetic field, this metal goes from an easy-plane ferromagnetic phase into a helicoidal antiferromagnetic phase at $T_1 = 85$ K; later, at $T_2 = 180$ K, it goes into a paramagnetic phase. At $T < T_1$ a magnetic field oriented in the *ab* basal plane causes a magnetization process of the customary type for a ferromagnet. The imposition of a magnetic field in the temperature interval $T_1 < T < T_2$ destroys the antiferromagnetic spiral. Studies of the effect of a magnetic field oriented along the twofold *a* axis on the magnetization,[2] conductivity,[3] and sound velocity[4] in Dy have shown that the destruction of the antiferromagnetic spiral is accompanied by the formation of an intermediate fan-shaped ferromagnetic phase.[5]

In the present experiments, the boundaries of the regions in which the various magnetic phases exist in Dy were determined in a magnetic field H oriented both along a and along the twofold b axis. The H–T diagram found for $\mathbf{H}\|a$ is essentially the same as that found in Refs. 2–4. The measurements with $\mathbf{H}\|\mathbf{b}$ are the first of their kind; the results are reported below.

The Dy single crystal was a parallelepiped whose faces ran parallel to the crystallographic axes c (the dimension along the sixfold axis was 0.435 cm), b (0.58 cm), and a (0.33 cm). The measurements were carried out by an echo technique. The sample was placed in a solenoidal inductance coil to which rf pulses with an amplitude of 2 kV, a length ~ 1 μs, and a modulated frequency of 10 MHz were applied. The external magnetic field H, with a strength up to 60 kOe, was applied in the basal plane along the b axis and parallel to the alternating magnetic field (h) produced by the coil ($h \approx 10^2$ Oe). The electromagnetic-acoustic interaction was caused by a magnetoelastic interaction in the skin layer of the metal. The elastic vibrations excited in the sample were detected by the same coil by virtue of the inverse electromagnetic-acoustic effect. The signal measured in this formulation of the experiment is proportional to the square amplitude of the excited sound or, equivalently, the conversion efficiency W (Ref. 6). The inductance coil around the sample was also used to record the field dependence of the magnetization of the sample, M, by the fluxmeter method. The temperature was monitored within 1° by a Cu–CuFe thermocouple.

Figure 1 shows the field dependence of W and M found in the ferromagnetic phase of Dy ($T < T_1$). The shape of the magnetization curves remains essentially the same as the temperature is increased. The field region in which sound is excited ($H < H_2$) shrinks as T_1 is approached. In fields corresponding to the inflection point on the $M(H)$ curve we observe a peak in the electromagnetic-acoustic interaction signal.

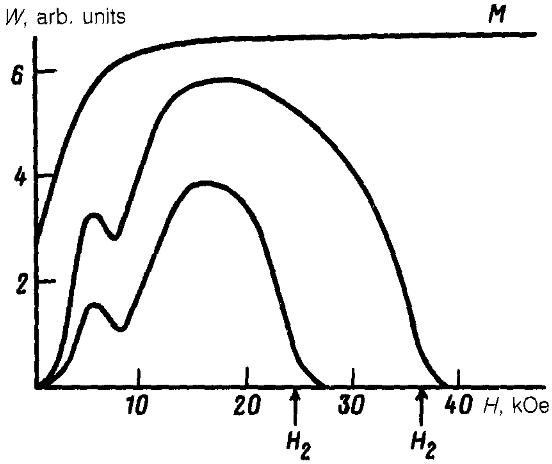

FIG. 1. Field dependence of the efficiency of the electromagnetic-acoustic interaction, W, and of the magnetization M in Dy at $T < T_1$. The $M(H)$ curve has been displaced along the ordinate.

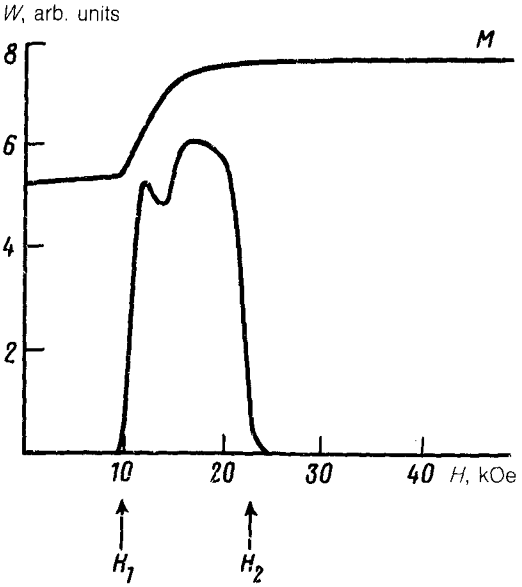

FIG. 2. Field dependence of the efficiency W and of the magnetization M in Dy at $T = 154$ K. The $M(H)$ curve has been displaced along the ordinate.

The results recorded in the antiferromagnetic phase of Dy (Fig. 2) differ from the results which we just described in that in weak fields, up to a threshold H_1, there is no change in the magnetic moment, and there is no excitation of sound. The sound is excited only in a limited field interval $H_1 < H < H_2$. In the temperature interval $T_1 < T < T_2$, we observe a peak in the electromagnetic-acoustic interaction signal near H_1, as in the low-temperature region.

The experimental data found in the ferromagnetic phase of Dy can be interpreted in the following way. The imposition of a magnetic field oriented along the b axis in the basal plane is accompanied by displacements of domain walls and spin reorientations. The initial region of the $W(H)$ curve and the peak on this curve in weak fields are consequences of magnetoelastic processes involving a displacement of domain walls. It follows from the $M(H)$ curve that the displacement processes terminate at $H < 10$ kOe. In strong fields, the $W(H)$ curve is determined exclusively by spin-flip processes. The absence of sound excitation at $H > H_2(T)$ indicates that the spin-flip transition has been completed and that the magnetic moments have been aligned with the direction of the field H.

In the interval $T_1 < T < T_2$, the temperature dependence of the critical fields H_1 and H_2 cannot be explained in terms of an easy-plane anisotropy, since the constant K_6 is very small at these temperatures. The curves of $W(H)$ and $M(H)$ imply that the antiferromagnetic spiral is destroyed in two steps. The order in which the magnetic states arise is as follows: In fields $H < H_1(T)$, the antiferromagnetic spiral is retained; in the field $H_1(T)$, this spiral is destroyed, and a fan-shaped ferromagnetic phase is formed. This phase persists up to $H_2(T)$. At $H_2(T)$, the angle over which the fan is spread out vanishes, and $H > H_2(T)$ the Dy is a collinear ferromagnet.

To construct the phase diagram of Dy, we calculated the internal magnetic field in the sample, H^{int}, with the help of the temperature dependence of the saturation magnetization M_s (Ref. 7). We calculated the demagnetizing factor for the sample, $D = 1.9$, for the magnetic field at the center of the plane-parallel faces on which the sound waves were excited and detected.[1] The curves of the critical magnetic fields shown in the coordinates H^{int}–T in Fig. 3 are the boundaries of the regions in which the various magnetic phases exist in the case $\mathbf{H}\|\mathbf{b}$. The curve $H_1(T)$ is the boundary of the helicoidal antiferromagnetic phase in the temperature interval 85–180 K. The $H_2(T)$ curve separates the angular and collinear ferromagnetic phases.

The origin of the angular phases is different in the intervals $T < T_1$ and $T_1 < T < T_2$. In the low-temperature region, the existence of an angular phase is a consequence of the easy-plane anisotropy. The phase interface in this region was calculated with the help of data on the temperature dependence of the easy-plane anisotropy constant,[8] as $H(T) = 36K_6(T)M_s(T)$. The calculated curve is the solid line in Fig. 3; the agreement with experiment is seen to be good.

At temperatures $T_1 < T < T_2$ the $H_2(T)$ curve is the boundary between the fan and collinear phases. From the theory of Ref. 5, which uses only two exchange integrals and which ignores the anisotropy in the basal plane, we have a ratio $H_2(T)/H_1(T) \approx 2$. The curves calculated on this basis are also shown in Fig. 3; again in this region we see a good agreement with experiment. In the temperature interval 90–120

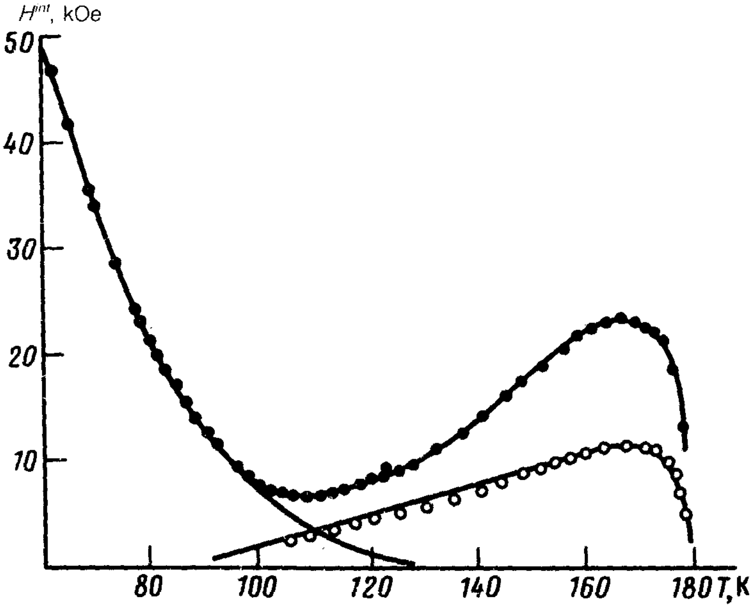

FIG. 3. Magnetic phase diagram of Dy in a field $\mathbf{H}\|\mathbf{b}$.

K the value of $H_2(T)$ appears to be affected by both the easy-plane anisotropy and the existence of a ferromagnetic fan structure. It can be shown that in this case the critical field $H_2(T)$ is the sum of the magnetic fields corresponding to each of these factors.

In conclusion we wish to stress that these measurements demonstrate that the method of electromagnetic excitation of sound is a simple and effective tool for constructing magnetic phase diagrams and for determining the magnetic anisotropy constants of magnetic materials.

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