SOVIET PHYSICS JETP VOLUME 15, NUMBER 2 AUGUST, 1962

EFFECT OF HELICOIDAL MAGNETIC STRUCTURE ON THE MAGNETOSTRICTION OF DYSPROSIUM

K. P. BELOV and S. A. NIKITIN

Moscow State University

Submitted to JETP editor September 14, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **42**, 403-407 (February, 1962)

A very complex dependence of magnetostriction on field and temperature is observed in dysprosium in the temperature range from 120 to 190° K. The complication of this dependence is due to the fact that in the temperature range indicated, there is, apart from the magnetostriction corresponding to rotation of the magnetic moments of the layers in the basal plane, a magnetostriction accompanying the destruction of the helicoidal magnetic structure. In addition, there is a large paraprocess magnetostriction in the region of the Curie point Θ_2, which is produced by exchange forces between atoms located in neighboring basal planes.

1. It has been established by magnetic[1] and neutron diffraction[2] studies that dysprosium has a helicoidal magnetic structure: the magnetic moments of the atoms lying in the basal plane of the hexagonal crystal are parallel to one another, but there is a certain angle α_0 between the magnetic moments of neighboring layers. It follows from a consideration of the magnetization curves of Dy[1] that forces act between the planes, in each of which the magnetic moments are parallel, which are overcome by relatively weak fields, not exceeding 11,000 Oe. However, the Curie temperature of dysprosium corresponds to an effective field several orders of magnitude greater than this value. It can be deduced from an analysis of the experimental material collected that the interaction between the layers of atoms lying in neighboring basal planes is weak, while there is a strong positive exchange interaction force within the layers. The latter brings about the parallel alignment of the magnetic moments of atoms lying in one and the same basal plane (ferromagnetism). The nature of the interaction between the layers, as a result of which the helicoidal structure arises, is not completely clear at present. As Enz suggested,[3] the interaction between the layers is the sum of two exchange interactions: one positive between neighboring layers and one negative between next nearest layers. However, the magnetic interaction between atoms lying in different layers cannot be left out of account. The measurement of magnetostriction is an effective method of studying the character of the interactions in a crystal which have an influence on its magnetic structure, since magnetostriction is a direct result of this interaction (the deformation of the lattice produced by magnetic or exchange forces). In this article we give experimental data on the magnetostriction of dysprosium.

2. On cooling a crystal of Dy below the Curie point Θ_2* the free energy F_p which the crystal had in the paramagnetic state is increased by the free energy F_{ex} of the exchange interaction within the layer, the free energy of magnetic anisotropy F_a (in the layer) and the free energy of interaction of neighboring layers F_n. As a result of the dependence of each of these energies on the deformation, the lattice deforms, and a spontaneous magnetostriction occurs which can be calculated from the condition

$$\partial(F_p + F_{ex} + F_a + F_n)/\partial A_{ik} = 0,$$

where A_{ik} are the components of the deformation tensor. We can separate from the total spontaneous magnetostriction of the crystal the spontaneous magnetostriction due to the exchange and magnetic forces within the layer, and also the magnetostriction resulting from the interaction between the layers, which can also in principle be produced not only by exchange but also by magnetic forces.

We showed earlier[4] that a very large anisotropic magnetostriction is observed at temperatures where dysprosium is in the ferromagnetic state (below Θ_1). This is also observed in the tempera-

---

*There are two magnetic transitions in Dy: Θ_1 is the temperture at which the helicoidal magnetic structure appears and Θ_2 is the temperature at which the ferromagnetism in the basal planes is destroyed and with it the helicoidal magnetic structure (Θ_1 = 85°K, while Θ_2 = 177°K).

ture range $\Theta_1 - \Theta_2$ (see below). This magnetostriction arises as a result of the existence of a spontaneous magnetostriction brought about by the magnetic anisotropy energy (within a layer) and it must change in magnitude with the processes of rotation of the magnetic moment of the layer in the basal plane. This magnetostriction decreases monotonically with increasing temperature, so that the magnetostriction produced by other forms of spontaneous magnetostriction can be observed on approaching Θ_2. An x-ray diffraction study of Dy has shown[5] that the hexagonal lattice parameter a_0, determined by the distance between atoms within a layer, in which the magnetic moments are parallel, does not change anomalously on passing through Θ_2. This indicates that the spontaneous magnetostriction as a result of exchange forces within a layer is small. On the other hand, the parameter c_0, determined by the distance between the layers, increases anomalously on passing through Θ_2, showing that there is a large spontaneous magnetostriction resulting from interaction between the layers. A study of the magnetic properties of single crystals of Dy[1] showed that the magnetic field which is necessary to turn the magnetic moment of a layer out of the basal plane is many orders of magnitude greater than the magnetic field required to rotate it in the basal plane. We can therefore assume, in analyzing the magnetization processes in polycrystalline Dy in the fields we used, that the magnetic moment does not pass out of the basal plane in the magnetization processes.

3. Measurements of magnetostriction were made using wire strain gauges with a 7 mm base. One gauge was fixed to the specimen and the other was a compensator fixed to a thin quartz plate pressed against the specimen. The gauges were connected in opposite arms of a Wheatstone bridge. The resistances of the working and compensating gauges did not differ by more than 0.1%. The specimen was attached to a large copper block so that the heat produced by the magnetocaloric effect was led away rapidly. Readings were taken after the specimen had returned to the temperature it had before the magnetic field was turned on. The gauges were made of wire which did not have a noticeable galvanomagnetic effect. The specimens in the form of 11 mm diameter disks of thickness 1.5 mm were cut out of a polycrystalline Dy ingot and did not have any heat treatment afterwards. The specimens contained less than 0.5% metallic impurities.

4. When the helicoidal structure of dysprosium is destroyed by a magnetic field, the angle α_0 changes from several tens of degrees to zero.[2] This must be accompanied by a noticeable change in the energy of interaction between the layers and a corresponding change in spontaneous magnetostriction. We were able to observe this effect in Dy. Figure 1 shows the isotherms of the transverse, and Fig. 2 of the longitudinal magnetostriction of Dy. The temperature dependence of the critical field in Dy, above which the helicoidal structure is destroyed, is shown in Fig. 3 (curve 2) according to the data of Behrendt et al.[1] It can be seen from Figs. 1, 2 and 3 that at fields less than the critical, $\lambda_\perp$ is negative and $\lambda_\parallel$ is positive. This magnetostriction accompanies rotation of the magnetic moments of the layers in the basal planes, with the magnetic anisotropy forces in the layers predominating. This rotation only leads to a small "deformation" of the helicoidal structure

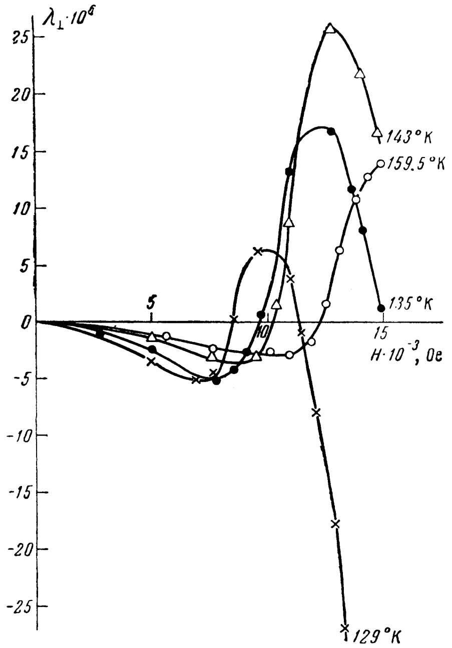

FIG. 1. Isotherms of the transverse magnetostriction of dysprosium.

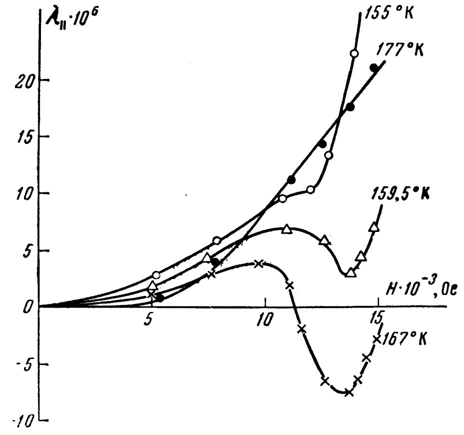

FIG. 2. Isotherms of the longitudinal magnetostriction of dysprosium.

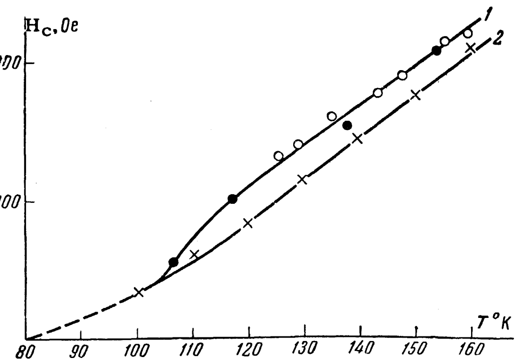

FIG. 3. The temperature dependence of the critical field in dysprosium: curve 1 – from our measurements, curve 2 – from the data of [1].

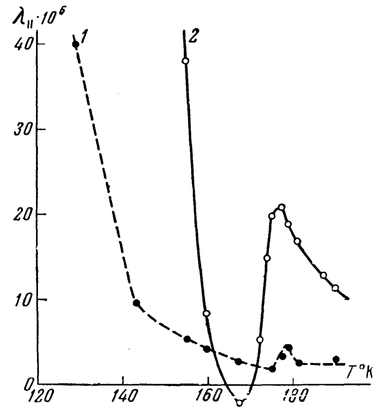

FIG. 4. The temperature dependence of the longitudinal magnetostriction of dysprosium: curve 1 – 7500 Oe, 2 – 15000 Oe.

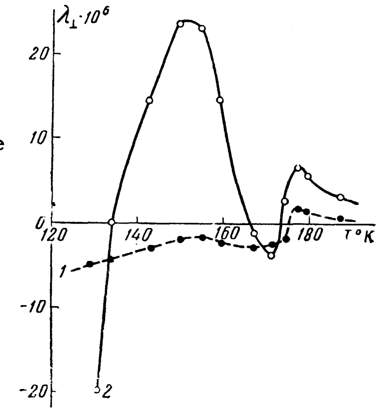

FIG. 5. The temperature dependence of the transverse magnetostriction of dysprosium: curve 1 – 7500 Oe, 2 – 15000 Oe.

$(H < H_c)$. When the field increases up to the critical, H_c, destruction of the helicoidal structure occurs, the interaction energy between the layers changes and, consequently, the spontaneous magnetostriction produced by the interaction between the layers changes. It follows from Figs. 1 and 2 that positive components then appear in $\lambda_{\perp}$ and negative in $\lambda_{\parallel}$, as a result of which the signs of $\lambda_{\perp}$ and $\lambda_{\parallel}$ change over. $\lambda_{\parallel}$ and $\lambda_{\perp}$ return to their former signs in stronger fields, when the helicoidal structure is destroyed $(H \gg H_c,\ \alpha_0 = 0)$, since the magnetostriction accompanying the process of rotation of the magnetic moments of the layers against the magnetic anisotropy forces in the basal planes becomes evident (as occurred in fields $H < H_c$, and also in the ferromagnetic region, i.e., for $T < \Theta_1$[4]).

The temperature dependence of the field at which a positive component of striction starts to appear in $\lambda_{\perp}$ is shown in Fig. 3 (curve 1, full circles), i.e., the magnetostriction accompanying the destruction of the helicoidal structure. On the same curve are shown the critical fields (open circles), determined as the magnetic fields at which a sharp decrease in the electrical resistance in a field starts to occur in Dy (the galvanomagnetic effect accompanying the destruction of the helicoidal structure), according to our work.[6] Curve 1 in Fig. 3 is close to curve 2, which represents the temperature dependence of the critical field in a single crystal.[1] The lack of complete agreement between curves 1 and 2 occurs because we carried out the experiments on polycrystalline material and the effect of the demagnetizing factor was not taken into account.

5. The temperature dependences of $\lambda_{\parallel}$ and $\lambda_{\perp}$ for dysprosium between 120 and 190°K are shown in Figs. 4 and 5. It can be seen that $\lambda_{\parallel} > 0$ and $\lambda_{\perp} < 0$ in the range 120 — 130° K, since the magnetostriction due to the existence of magnetic anisotropy energy predominates here (the process of rotation of the magnetic moment in the basal planes); we studied this previously at lower temperatures[4] and it was shown that this magnetostriction is very large $(\lambda \approx 10^{-3})$. Superposition onto it of the magnetostriction due to destruction of the helicoidal structure produces the maxima and minima on the curves of Figs. 4 and 5 in the temperature range 130 — 167° K; however, these maxima and minima only appear for fields $H > H_c$. It can further be seen from Figs. 4 and 5 that there are maxima of the same (positive) sign of $\lambda_{\parallel}$ and $\lambda_{\perp}$ in the immediate neighborhood of the Curie point $(\Theta_2 = 177°\,K)$, which indicates that we are mainly concerned here with a volume magnetostriction produced by the paraprocess. This magnetostriction is very large in Dy, of the same order of magnitude as in the invar alloys. We assume that it is produced by exchange forces acting between the layers along the c_0 axis. There is a "porous" structure along this axis, consisting of layers with a weak exchange interaction which is strongly dependent on the distance between the layers. Although it exists, magnetostriction by the paraprocess in Dy produced by exchange forces within a layer is small. This view is confirmed by the results of measurements of the temperature dependence of the lattice param-

eters of Dy. Banister et al.[5] showed that there is a large negative anomaly in the lattice parameter along the c_0 axis (which agrees with the sign of the paraprocess magnetostriction) on passing through the Θ_2 point, while no noticeable change in the parameter a_0 was found. The form of the dependence of the paraprocess magnetostriction on H at $\Theta_2 = 177°K$ is shown in Fig. 2

Finally, it is noteworthy that the magnitudes of the maxima of $\lambda_{||}$ and $\lambda_{\perp}$ at Θ_2 are not equal to one another, indicating the existence of a complicated magnetostrictive deformation of the Dy lattice in the region of Θ_2. It is well known that in cubic ferromagnets the spontaneous deformation of the lattice due to exchange forces has a volume (isotropic) nature. The situation will be more complicated in the hexagonal Dy lattice. It is quite possible that in hexagonal crystals, especially with a layered magnetic structure, the spontaneous magnetostriction due to exchange forces can be anisotropic, and this may lead to the different magnitudes and signs of $\lambda_{||}$ and $\lambda_{\perp}$ near Θ_2.

We thank A. S. Borovik-Romanov for discussion of the results.

---

[1] Behrendt, Legvold, and Spedding, Phys. Rev. **109**, 1544 (1958).

[2] Wilkinson, Koehler, Wollan, and Cable, J. Appl. Phys. **32**, 49 (1961); suppl. to No. 3.

[3] U. Enz, J. Appl. Phys. **32**, 22 (1961); suppl. to No. 3.

[4] Belov, Levitin, Nikitin, and Ped'ko, JETP **40**, 1562 (1961), Soviet Phys. JETP **13**, 1096 (1961).

[5] Banister, Legvold, and Spedding, Phys. Rev. **94**, 1140 (1954).

[6] K. P. Belov and S. A. Nikitin, FMM **13**, 1 (1962).

Translated by R. Berman
64