MAGNETIC AND MAGNETOSTRICTION PROPERTIES OF AN ERBIUM SINGLE CRYSTAL IN THE PARAMAGNETIC REGION

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Submitted to JETP editor July 1, 1966

J. Exptl. Theoret. Phys. (U.S.S.R.) 51, 1634–1638 (December, 1966)

The magnetization, magnetostriction, and torque of an erbium single crystal were measured in pulsed magnetic fields up to 150 kOe. In the paramagnetic region (between 90 and 300° K), the magnetostriction of erbium was very high and anisotropic. The magnetostriction was positive along the hexagonal axis and negative perpendicular to it. The value of the magnetostriction in a field of 150 kOe reached 240×10^{-6} at 220° K (150° K higher than the point of transition to a magnetically ordered state). It is shown that the temperature dependence of the magnetostriction is wholly due to the temperature dependence of the paramagnetic magnetization.

1. Rare-earth metals dysprosium, terbium, holmium, erbium, thulium have anisotropic magnetic susceptibility in the paramagnetic region.[1-4] For example, at 100° K, the paramagnetic susceptibility of erbium, measured along the hexagonal axis (χ_c), is twice as large as the susceptibility in the basal plane (χ_a); at room temperature, the anisotropy is considerably greater. The susceptibility anisotropy is responsible for the different values of the paramagnetic Curie point Θ_p or erbium along different directions ($\Theta_{pc} = 61.7°$ K, $\Theta_{pa} = 32.5°$ K), while the Curie constant C, related to the effective magnetic moment of the atoms, is the same for different directions in a crystal. We have shown earlier[5] that polycrystalline samples of terbium, dysprosium, and holmium, have a relatively large positive magnetostriction in the paramagnetic region in strong magnetic fields while the magnetostriction of polycrystalline erbium is considerably smaller and negative. The present paper reports the results of our measurements of the magnetostriction, magnetization, and torque of an erbium single crystal.

2. The erbium single crystal was grown by V. E. Kolesnichenko in the Laboratory for Rare Metals at the Baĭkov Metallurgy Institute, using the directional recrystallization method. The crystallographic axes were determined by x-ray diffraction. The magnetostriction and magnetization were measured on rods, 5 mm long and of 1 mm^2 cross section, cut along the hexagonal axis and in the basal plane. The measurements of the torque were carried out on a small sphere of 1.5 mm diameter.

The magnetization, torque, and magnetostriction were measured in pulsed fields of up to 150 kOe using external piezoelectric pickups. The description of the method of measuring the magnetostriction in pulsed fields is given in [6]. The magnetization was determined by a ponderomotive method: a sample was placed in an inhomogeneous pulsed field and a bimorphous piezoelectric pickup was used to measure the force acting on the sample in this field. The torque curves of a crystal were determined in a pulsed field using a piezoelectric pickup to measure torsional deformations in a coil consisting of two sections (Helmholtz-type coils). The method of measuring the torque will be described in detail elsewhere.

3. Figure 1 shows the field dependences of the magnetization of an erbium crystal, recorded along the hexagonal axis of the crystal and in its basal plane. It is evident that the magnetization varies linearly with the field (except in the region which is in the direct vicinity of the transition point of erbium to a magnetically ordered state, $\Theta_2 = 83°$ K). This departure from linearity may be due to paramagnetic saturation effects or to the influence of the nonisothermal nature of magnetization processes in pulsed fields (the influence of the magnetocaloric effect).

Figure 2 gives the temperature dependences of the susceptibility and the reciprocal of the susceptibility along and at right-angles to the hexagonal axis, calculated from the results given in Fig. 1. (from the magnetization in weak fields). It is evident that the susceptibility obeys the Curie–Weiss law. The paramagnetic Curie points $\Theta_{pc} = 60$

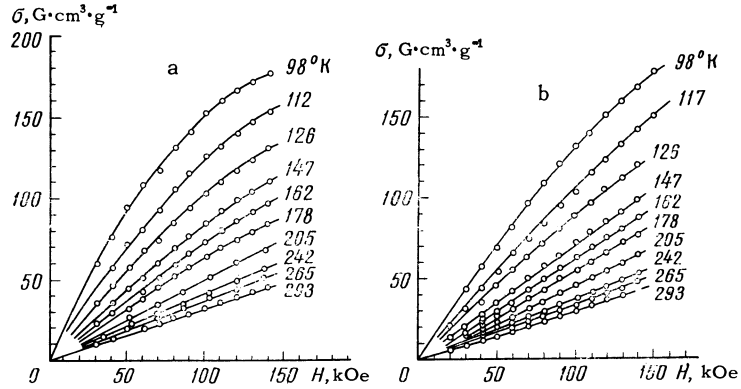

FIG. 1. Dependence of the magnetization of an erbium single crystal on the field: a) along the hexagonal axis; b) in the basal plane.

$\pm 3°$ K, $\Theta_{pa} = 35 \pm 3°$ K are in good agreement with the results of measurements in static magnetic fields.[2] The effective magnetic moment of erbium, determined from the value of the Curie constant, is, according to our data, $9.1 \pm 0.5 \mu_B$, which is close to the theoretical value $9.58 \mu_B$, calculated for the trivalent erbium ion in its ground state ($^4I_{15/2}$).

It follows from Fig. 2 that the magnetic susceptibility of erbium in the paramagnetic region is anisotropic. The susceptibility in the basal plane is less than that along the hexagonal axis. The susceptibility anisotropy is confirmed also by the measurements of the torque acting on the crystal in a magnetic field (Fig. 3). Our measurements showed that the torque curves could be described (with the exception of the region close to Θ_2) by a relationship valid for paramagnets:

$$L = {}^1/_2(\chi_c - \chi_a) H^2 \sin 2\varphi$$

(φ is the angle between the hexagonal axis and the direction of the field). The triangles in Fig. 2 represent the values of the susceptibility χ_a, found from the torque measurements, and of the susceptibility χ_c. It is evident that the susceptibilities

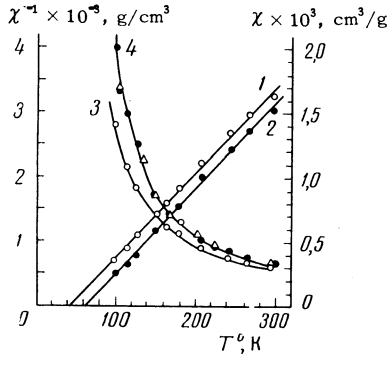

FIG. 2. Temperature dependence of the susceptibility and of the reciprocal of susceptibility of an erbium single crystal: 1) χ_a^{-1} (T); 2) χ_c^{-1} (T); 3) χ_a(T); 4) χ_c(T).

found by direct magnetic measurements and those deduced from the torque curves are equal within the experimental error.

4. Figure 4 shows the field dependences of the longitudinal magnetostriction, measured along and perpendicular to the hexagonal axis, in the temperature range 90–300° K, i.e., in the paramagnetic region. It is evident that the magnetostriction of erbium is very high and strongly anisotropic. The magnetostriction along the hexagonal axis is positive, and in the basal plane negative. At 220° K (150° K above the point Θ_2) in a field of 150 kOe, the magnetostriction along the hexagonal axis is 240×10^{-6}, and in the basal plane is 200×10^{-6}. The magnetostriction increases strongly on approach to the temperature Θ_2.

The observed strong temperature dependence of the magnetostriction of erbium in the paramagnetic region is in agreement with the temperature dependence of the magnetization in this region. Figure 5 shows the dependences of the magnetostriction in the basal plane and along the hexagonal axis on the square of the magnetization along these directions. It is evident that the points corresponding to different temperatures fit the same straight line. Thus, the magnetostriction is proportional to the square of the magnetization and the coefficient of proportionality is independent of temperature.

The fact that $\lambda_c > 0$ and $\lambda_a < 0$ explains why the paramagnetic magnetostriction of a polycrystalline erbium sample is considerably less than the magnetostriction of polycrystalline terbium and dysprosium samples and why it is negative. Our measurements have shown that the magnetostriction of terbium and dysprosium single crystals in the basal plane and along the hexagonal axis is positive. Therefore, the magnetostriction of polycrystals, which represents the average of the magnetostrictions of single crystals oriented along different directions, is less for erbium than for dysprosium and terbium.

5. The results reported show that, in the para-

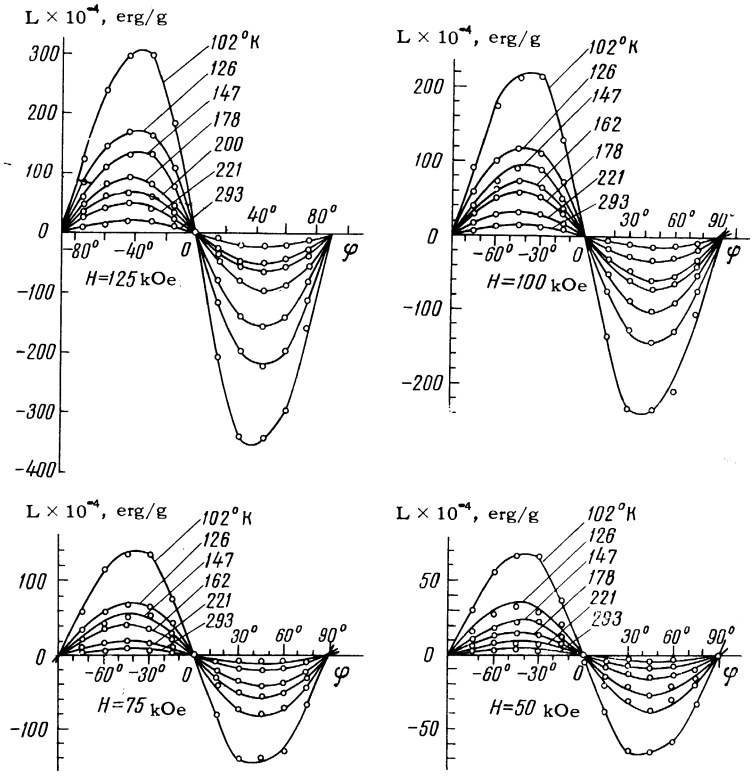

FIG. 3. Dependence of the torque, acting on an erbium single crystal in a magnetic field, on the angle between the direction of the field and the hexagonal axis of the crystal.

magnetic region, erbium exhibits a strong anisotropy of the magnetic and magnetostriction properties. Such anisotropy in the paramagnetic region can be understood on the basis of the following considerations.

The electronic structure of the erbium atom and of other rare-earth metals having a deep 4f-shell makes the spin–orbital reaction very strong compared with the crystal fields of the lattice and, therefore, in contrast to transition d-metals, the orbital moments are, in practice, not frozen in by the crystal field. This is confirmed by the fact that the magnetic moment of metallic erbium (per atom) is close to the value of the magnetic moment of a free trivalent erbium ion (i.e., it is governed by the total quantum number J and not by the spin quantum number S, as is the case for d-metals). On the other hand, the hexagonal symmetry of erbium gives rise to a strong anisotropy of the electrostatic crystal field. This field acts on the orbital moment and, through the spin–orbital interaction, it affects the spin moment of erbium, giving rise to a strong magnetic anisotropy. The magnetization-induced change in the orientation of the orbital moment of a rare-earth ion with respect to the crystallographic axes should perturb the electric field of the lattice, giving rise to a strong magnetostriction.

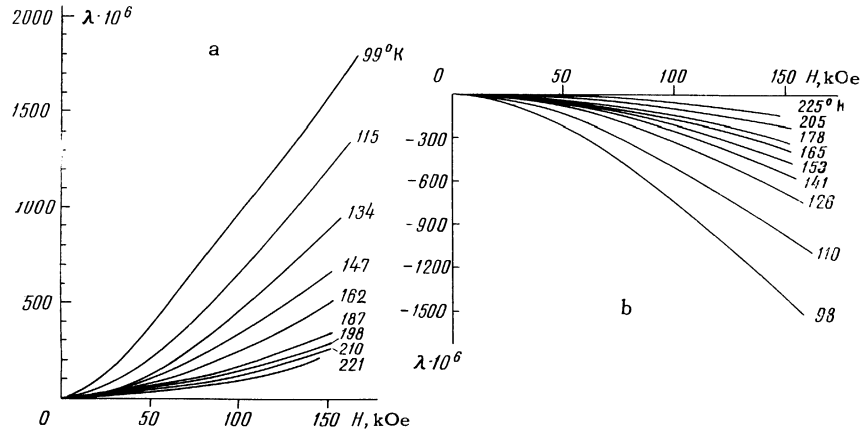

FIG. 4. Dependence of the longitudinal magnetostriction of an erbium single crystal on the field: a) along the hexagonal axis; b) in the basal plane.

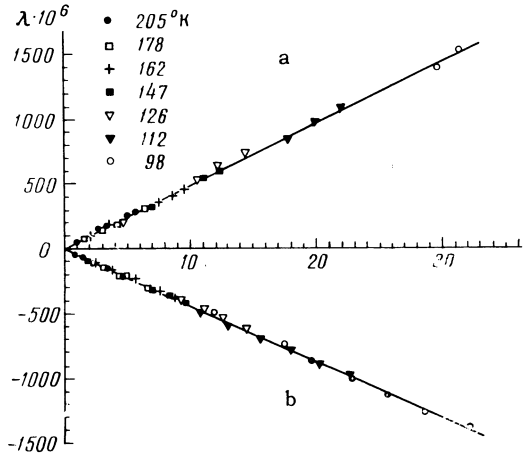

FIG. 5. Dependence of the longitudinal magnetostriction of erbium on the square of the specific magnetization [the abscissa gives $\sigma^2 \times 10^{-3}$ in $(G \cdot cm^3 \cdot g^{-1})^2$]: a) along the c-axis; b) in the basal plane.

The magnetic anisotropy and magnetostriction increase strongly when erbium is cooled below Θ_2, i.e., when the magnetic moments become ordered. The strong spin–orbit interaction also makes the exchange interaction anisotropic. The existence of an anisotropic term in the exchange interaction, taking place through conduction electrons in rare-earth ferromagnets, has recently been justified theoretically by Irkhin.[7]

The authors thank Professor E. M. Savitskiĭ, V. F. Terekhov, and V. E. Kolesnichenko for supplying an erbium single crystal.

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Translated by A. Tybulewicz
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