UNIAXIAL MAGNETIC ANISOTROPY OF DYSPROSIUM AND TERBIUM

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The magnetization and torque of Dy and Tb single crystals were measured in pulsed magnetic fields up to 150 kOe. It is shown that in the magnetically ordered state a field of 150 kOe is insufficient for saturating the metals along the direction of hard magnetization. At 100°K the first uniaxial anisotropy constants of Dy and Tb are approximately equal to 3×10^8 erg/cm^3, which is greater by two orders of magnitude than the anisotropy constants of ferromagnets of the iron group.

ONE of the most interesting properties of Dy and Tb, as well as of other rare-earth ferromagnets, is the huge magnetic anisotropy compared to the ferromagnets of the iron group. Although up until now there has been no direct measurement of the magnetic anisotropy of Dy and Tb, its size can be judged by the fact that the magnetization of Dy in the difficult direction (the c axis of the crystal) is not saturated in fields up to 20 kOe.

We have measured the torque and magnetization curves of single crystals of Dy and Tb in pulsed magnetic fields up to 150 kOe. The method was described in[2,3]. The measurements were made in the temperature interval 100–300°K. Above a temperature $\Theta_2 = 178°$K, Dy is paramagnetic, and below this temperature it becomes a helicoidal antiferromagnet. The critical field for destruction of the helicoidal structure is about 10 kOe in the basal plane.

Terbium is paramagnetic above $\Theta_2 = 230°$K, has a helicoidal antiferromagnetic structure between this temperature and $\Theta_1 = 219°$, and becomes ferromagnetic below 219°K. The critical field for destruction of the helicoidal structure in Tb is not greater than 200 Oe.

Figure 1 shows magnetization versus field for the axis of hard magnetization (c axis) and in the plane of easy magnetization (the basal plane) for monocrystals of Dy and Tb. The curves taken in the basal plane are characteristic of ferromagnets in fields greater than the saturation field—a sharp rise in relatively weak fields followed by a small increase in magnetization due to the paraprocess. The magnetization along the c axis has a different field dependence—it gradually increases with increasing field and in fields up to 150 kOe shows no tendency to saturate; moreover the magnetization in the c direction is markedly less than in the basal plane.

Figure 2 shows curves of the torque acting on monocrystals of Dy and Tb in different fields as a function of the angle φ between the direction of the magnetic field and the basal plane. It is seen that the torque in fields of the order of 100 kOe suddenly changes sign at $\varphi = \pi/2$. This is not because the field actually deflects the magnetization vector from the basal plane, but because when the sign of the projection of the field on the basal plane changes, the direction of the magnetization in the basal plane also reverses.

In relatively weak fields (on the order of 50 kOe) the torque curves for Dy and Tb are different: the torque of Dy sharply decreases in absolute magnitude at $\varphi < \pi/2$ and remains small in a certain interval of values of the angle φ near $\pi/2$. This is explained by the transition of Dy from the ferromagnetic to the helicoidal antiferromagnetic state when the projection of the field in the basal plane becomes less than the field for destruction of the helicoidal structure. From the measurements of magnetization and torque it follows that the effective magnetic anisotropy field of Dy and Tb exceeds 150 kOe.

On the basis of the results of these measurements we estimated the values of the first uniaxial anisotropy constant for Dy and Tb. They are given in the table, in which also appear the values for the first uniaxial anisotropy constant of Gd and Co from[4,5]. Our data do not permit calculation of the second uniaxial anisotropy constant of Dy and Tb; it is evidently of the same order of magnitude as the first.

Our results show that the magnetic anisotropy is

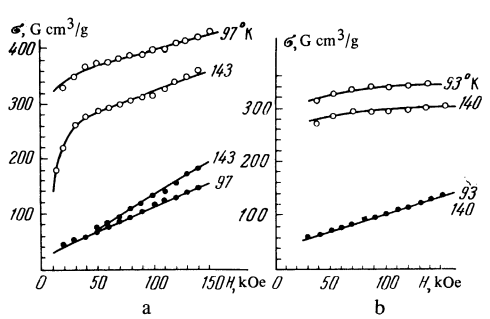

FIG. 1. Dependence of magnetization on field: a–for Dy, b–for Tb, in the basal plane (open points) and along the c axis (solid points).

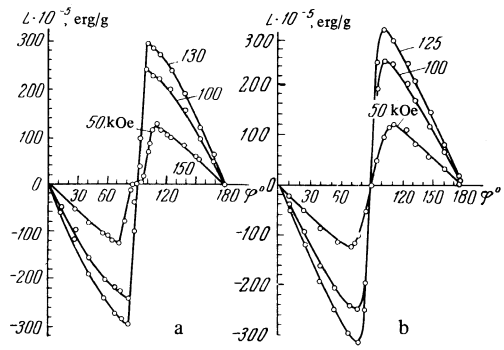

FIG. 2. Dependence of torque on the angle between the direction of the field and the basal plane: a–for Dy, T = 116 K; b–for Tb, T = 105 K.

Uniaxial anisotropy constants of Dy, Tb, Gd, and Co (angle reckoned from the basal plane)

Element	Temperature of measurement, °K	$K_1 \times 10^{-6}$, erg/cm^3	Temperature of magnetic ordering, K
Tb	105	+270±110	230
Dy	116	+190±80	179
Gd [5]	115	—0,5	290
Co [4]	73	—12	1388

very large in Dy and Tb, the ions of which have a nonzero orbital momentum. In Gd, the ions of which have zero orbital momentum, the anisotropy is two orders of magnitude smaller.[5] This says that the basic contribution to the magnetic anisotropy energy of rare-earth ferromagnets is from the interaction of the orbital momentum with the crystal lattice. The mechanism of this interaction is still not completely clear. The coupling of the orbital momentum with the crystal lattice can be effected via: a) an electrostatic interaction between the intracrystalline field and the anisotropic charge cloud of the 4f electrons (single-ion model)[8] and b) an anisotropic indirect exchange interaction between the orbital momenta of the ions via conduction electrons (anisotropic exchange).[6-8] If the orbital momentum of the ferromagnetic rare-earth ion differs from zero, the charge cloud of the 4f electrons is spatially anisotropic, and the axis of symmetry of the cloud, which coincides with the direction of the orbital momentum of the ion, is oriented along the direction of easy magnetization in the crystal. During magnetization along the difficult direction, the magnetic moments of the ions try to orient themselves along the field. Since in heavy rare-earth metals the coupling between the spin and orbital momenta of the ion (spin-orbit interaction) is markedly stronger than the interaction of the orbital momentum with the crystalline field, the process of magnetization along the hard direction is accomplished by a change in the spatial orientation of the orbital momentum of the ion, and consequently, also of the anisotropic charge cloud of the 4f electrons. This leads to a big change in the energy of interaction of the spatially anisotropic 4f-electron charge cloud with the crystalline environment. Theoretical calculations[6-8] show that the energy of single-ion anisotropy and the energy of anisotropic indirect exchange are of the same order of magnitude as the anisotropy energy observed experimentally in Dy and Tb.

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