Magnetic anisotropy of alloys of terbium with yttrium and gadolinium

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The nature of the magnetic anisotropy of terbium-yttrium and terbium-gadolinium alloys is investigated. The single-ion magnetic anisotropy constant K_2^0 at 4.2 K and the magnetic anisotropy constant in the basal plane K_6^6 of these alloys are measured in the temperature interval 78–190 K. Anomalies are observed in the concentration dependence of K_2^0 in Tb_xY_{1-x} alloys in the interval $x = 0.3$–0.5, and a nonlinear concentration dependence of K_2^0 is observed in the Tb_xGd_{1-x} alloys. An analysis of the experimental data indicates predominance of the single-ion crystal anisotropy and the presence of a smaller contribution due to anisotropic exchange. It is established that the dependence of K_6^6 on the relative magnetization and on the concentration can be described by the single-ion mechanism of the interaction of the orbital angular momentum with the crystal lattice field.

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INTRODUCTION

The gigantic magnetic anisotropy of rare-earth metals (REM) is presently attributed to two competing mechanisms: the interaction of the orbital angular momentum of the 4*f* subshell of the rare earth ion with the crystal-lattice field (single-ion model), or anisotropic indirect two-ion exchange interaction.[1-3] The relative role of these mechanism is not clear to this day, and the published data lead to contradictory conclusions.[2-4] Further theoretical and experimental investigations of the magnetic anisotropy of REM alloys are therefore necessary.

The purpose of the present study was to determine the nature of the magnetic anisotropy of alloys of terbium with yttrium and gadolinium, in which the magnetic anisotropies of the components differ greatly. Terbium has a gigantic magnetic anisotropy,[5-6] whereas the magnetic anisotropy of gadolinium is smaller by two orders of magnitude.[7] This difference is due to the singularities of the electronic structures of terbium and gadolinium. Whereas the trivalent gadolinium ion is in the *S* state ($L=0$) and has a spherical 4*f* electron shell, the trivalent terbium ion, which has one more 4*f* electron, has an oblate 4*f* electron shell because an additional electron is added to the spherical 4*f* subshell of the gadolinium ion, resulting in an orbital angular momentum $L=3$.

As for yttrium, it is a Pauli paramagnet and assumes in REM alloys the role of an ideal magnetic solvent[8] because the external electron shells of yttrium and the REM are similar, while the crystal-lattice constants of yttrium and heavy REM are quite close. Alloys of heavy REM with each other and with yttrium have hcp lattices.[9]

Results of studies of the anisotropy of the paramagnetic Curie points in terbium-yttrium and terbium-gadolinium alloys were reported earlier.[10,11] These data, however, are insufficient for a final elucidation of the nature of the magnetic anisotropy in alloys, because the magnetic anisotropy can differ greatly in the paramagnetic and magnetically ordered states.

EXPERIMENTAL PROCEDURE

The technology of growing single crystals of the alloys Tb_xY_{1-x} and Tb_xGd_{1-x} and of the control of their quality were described in earlier papers.[10-12] The uniaxial magnetic anisotropy constants were determined by us from the magnetization curves measured at 4.2 K along the hexagonal *c* axis (the difficult magnetization axis) and is the basal plane along the easy-magnetization axis. The magnetization was measured with a vibration magnetometer in a superconducting solenoid in magnetic fields up to 70 kOe, and in the case of some samples in a pulsed magnetic field up to 150–200 kOe, using a previously described procedure.[13] The magnetic-anisotropy constant in the basal plane was measured by the torque method with an anisometer whose design was similar to that proposed by Bryukhatov and Kirenskiĭ.[14]

To measure the magnetization in the superconducting solenoid, the samples were cut in the form of rectangular rods measuring $1\times1\times2$ mm. The samples used in the torque measurements were disks of 4 mm diameter and 1 mm thickness. After cutting, the samples were chemically etched and annealed. The single-crystal samples were oriented along the crystallographic directions by the Laue method using the URS-60 apparatus. The orientation accuracy was not worse than ±3°. The error in the measurement of the magnetization with the vibration magnetometer was 3%, in pulsed fields 8%, and in torque determination 3%.

EXPERIMENTAL RESULTS

Figures 1a and 1b show the magnetization curves of the alloys Tb_xY_{1-x} and Tb_xGd_{1-x}, measured with a vibration magnetometer at a temperature 4.2 K. The magnetization along the *b* axis saturates rapidly, but is relatively small along the *c* axis, which is the difficult magnetization axis. A linear growth of the magnetization σ is observed for all the Tb_xY_{1-x} alloys, and a nonlinear $\sigma(H)$ dependence is obtained for the Tb_xGd_{1-x} alloys at a high gadolinium concentration (curve 5 of Fig. 1b).

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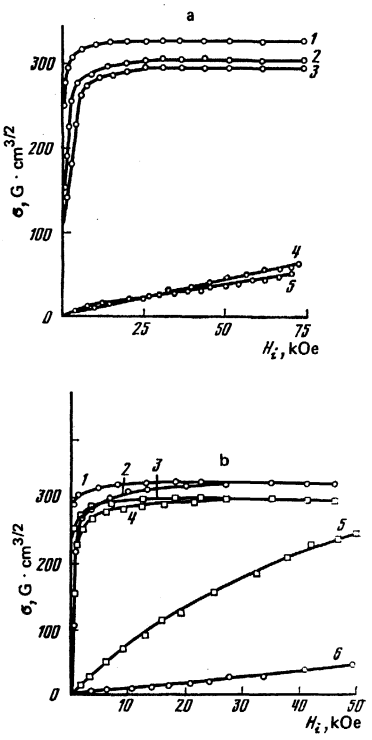

FIG. 1. Dependence of magnetization on the true magnetic field: a) for the alloys Tb_xY_{1-x} along the b axis, curves 1) $x=1$, 2) $x=0.91$, 3) $x=0.835$, and along the c axis, 4) $x=1$, 5) $x=0.835$; b) for the alloys Tb_xGd_{1-x}, curves 1) $x=0.94$, $H\|b$, 2) $x=0.94$, $H\|a$, 3) $x=0.09$, $H\|b$, 4) $x=0.09$, $H\|a$, 5) $x=0.09$, $H\|c$, 6) $x=0.94$, $H\|c$.

Figure 2 shows, for the alloys Tb_xY_{1-x} and Tb_xGd_{1-x}, the concentration dependences of the specific absolute saturation magnetization σ_0 and of the magnetization in a field along the c axis at 4.2 K in magnetic fields 50 and 70 kOe; the value of σ_0 was determined from the magnetization curves measured at 4.2 K along the b axis (easy magnetization axis), by extrapolating the $\sigma=(1/H)$ curve to $H\to\infty$. The magnetic moment μ_0 per terbium atom in the Tb_xY_{1-x} alloys exceeds noticeably the magnetic moment of the free trivalent terbium ion, owing to the polarization of the conduction electrons on

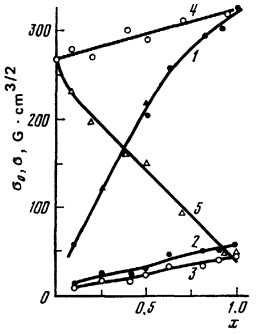

FIG. 2. Concentration dependence of the absolute-saturation magnetization σ_0 and of the magnetization σ in a field along the c axis at 4.2 K. For the alloys Tb_xY_{1-x}: 1—for σ_0; ● — measurement in static magnetic fields, ▲—in pulsed fields; 2, 3, —magnetization along the c axis at 70 and 50 kOe, respectively. For the alloys Tb_xGd_{1-x}: 4—for σ_0, 5—magnetization along the c axis at 50 kOe.

account of the s–f interaction (for example, in these alloys $\mu_0=9.45\mu_B$ at $x=0.835$ and $\mu_0=9.9\mu_B$ at $x=0.1$). The average magnetic moment per rare-earth ion in the Tb_xGd_{1-x} alloys decreases monotonically (within the limit of errors) with decreasing terbium concentration:

x:	1	0.94	0.7	0.5	0.39	0.09	0
μ_0/μ_B:	9.3	9.2	8.8	8.2	8.5	7.8	7.5

The free energy of a single-domain ferromagnet, with account taken of the magnetic anisotropy, can be written in the case of a hexagonal crystal lattice in the form

$$\mathcal{F}_A=K_1\sin^2\theta+K_2\sin^4\theta+K_3\sin^6\theta+K_6^6\sin^6\theta\cos 6\varphi-HI_s\cos\theta, \quad (1)$$

where θ is the angle between the vector of the spontaneous magnetization I_s and the hexagonal c axis, K_i are the magnetic-anisotropy constants, and φ is the angle between the magnetization projection and the a axis.

From the condition that the free energy $\mathcal{F}_A$ be a minimum as a function of angle, we get

$$(2K_1+4K_2)-4K_2I/I_s=-HI_s^2/I, \quad (2)$$

where $I=I_s\cos\theta$ is the projection of the magnetic moment on the c axis. If the magnetic data are used to plot $-HI_s^2/I$ against I/I_s, then the slope of the line yields $-4K_2$, and the intercept on the ordinate axis is equal to $2K_1+4K_2$. The determination of the magnetic-anistropy constant from the magnetization curves measured along the difficult magnetization axis was used to determine the magnetic anisotropy constants of REM.[4,13] Quantum mechanical calculations have proved the validity of this method.[16]

This method can be used for the ferromagnetic Tb_xY_{1-x} alloys without restrictions, since these alloys contain magnetoactive ions of only one type—terbium. When magnetized along the c axis, the magnetic moments of the terbium ions in a single-domain sample are parallel to one another and their angle with the c axis is the same as that of the resultant magnetization. The same angle is made by the c axis and the magnetic moments of the terbium ions also in the antiferromagnetic Tb_xY_{1-x} alloys with helicoidal structure, except that the magnetic moments of neighboring basal planes are at some angle with one another.[17] In the experiment, a linear growth of the magnetization with increasing field is observed in both cases in fields up to 70 kOe. The magnetic-anisotropy constant determined for the antiferromagnetic Tb_xY_{1-x} alloys must be corrected to allow for the change of the energy of the exchange interaction between the layers when the antiferromagnetic helicoidal structure is destroyed. As a result, the magnetic anisotropy constant K_1^{eff} determined from the magnetization curves contains a contribution that takes into account the "helicoidality energy":

$$K_1^{\text{eff}}=K_1+H_{\text{cr}}I_s, \quad (3)$$

where H_{cr} is the critical magnetic field at which the helicoidal structure collapses.

A reduction of the magnetization curves in accord with Eq. (2) has shown that $|K_2|\ll|K_1|$ and can be disregarded in first-order approximation. This agrees with the results of Ref. 18, where it was shown that in pure terbium $|K_1/K_2|\sim 0.1$. It is seen from Fig. 3, which shows a plot of the constant K_1 of the Tb_xY_{1-x} alloys a against the terbium concentration, that the magnetic-

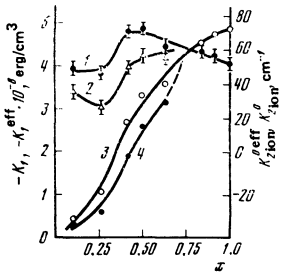

FIG. 3. Dependence of the magnetic-anisotropy constants on the terbium concentration for terbium-yttrium alloys: curves 1—for $K^0_{2\,\text{ion}}$, 2—for $K^{0\,\text{eff}}_{2\,\text{ion}}$, 3—for K_1, 4—K_1^{eff}. The dashed curve is the result of extrapolation to a concentration at which $H_{cr} = 0$.

anisotropy constant reaches the gigantic values (3–5) $\times 10^8$ erg/cm^3 in alloys with high terbium concentration ($x > 0.5$). The value of K_1 obtained for terbium by the method described above is quite close to the value $K_1 = -4.95 \cdot 10^8$ erg/cm^3 previously determined by Levitin and Ponomarev.[5]

The Tb_xY_{1-x} alloys with $x \leq 0.63$ have an antiferromagnetic helicoidal structure, so that the method based on Eq. (2) leads in this case to a determination of K_1^{eff} (curve 3 of Fig. 3). The values of K_1 (curve 4 of Fig. 3) were calculated for antiferromagnetic alloys with the aid of Eq. (3) and of the previously determined[19] values of H_{cr}. The most noticeable difference between K_1 and K_1^{eff} takes place in the region $x = 0.5$–0.8, where H_{cr} is quite large, 50–80 kOe. When the terbium content is decreased the absolute values of K_1 and K_1^{eff} are greatly reduced.

Antiferromagnetism exists in the Tb_xGd_{1-x} alloys only at $x > 0.94$, and in this case $H_{cr} < 10^3$ Oe, as a result of which the anisotropy-constant correction that takes into account the energy lost to the collapse of the antiferromagnetic structure is quite small. The magnetic-anisotropy constants $K_2^0 = -\frac{2}{3}K_1$ calculated by the method described below and shown in Fig. 4 are noticeably nonlinear functions of the terbium concentration.

The mechanical torques L were measured in fields up to 22 kOe for the alloys Tb_xY_{1-x} and Tb_xGd_{1-x} in the temperature interval 78–190 K on disks whose planes coincided with the basal plane. Measurements of L as functions of the magnetic field have shown that the values L_∞ obtained by extrapolating $L = L(1/H)$ to $H \to \infty$ differ from the value of L at $H = 22$ kOe by not more than 5% in the most unfavorable case (at 78 K in alloys containing a large amount of terbium). The mechanical

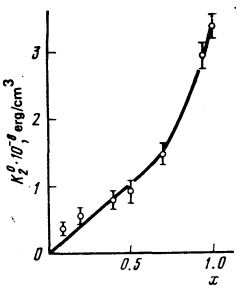

FIG. 4. Dependence of the magnetic anisotropy constant K_2^0 at 4.2 K on the terbium concentration for Tb_xGd_{1-x} alloys.

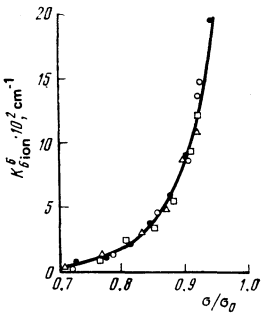

FIG. 5. Dependence of the magnetic anisotropy constant in the basal plane $K^6_{6\,\text{ion}}$ on the relative magnetization σ/σ_0 for Tb_xY_{1-x} alloys (the solid curve was calculated on the basis of the theory of Ref. 20): ○—$x = 1$, □—$x = 0.91$, △—$x = 0.835$, ●—$x = 0.63$.

torque is a periodic function of the angle between the field, which rotates in the basal plane, and the b axis (its period is 60°). It follows from (1) that the torque in the basal plane is

$$L(\varphi) = -\partial \mathcal{F}_A / \partial \varphi = 6K_6^6 \sin 6\varphi. \quad (4)$$

Expansion in a Fourier series made it possible to determine K_6^6 from the $L_\infty = L_\infty(\varphi)$ curves are shown in Figs. 5 and 6 as functions of the relative magnetization.

DISCUSSION OF RESULTS

The magnetic-anisotropy energy of a ferromagnet with helicoidal crystal lattice can be expressed by an expansion in Legendre polynomials

$$\mathcal{F}_A = K_2^0 P_2(\cos\theta) + K_4^0 P_4(\cos\theta) + K_6^6 \sin^6\theta \cos 6\varphi, \quad (5)$$

where K_n^0 is the anisotropy constant, $P_n(\cos\theta)$ is a Legendre polynomial, and θ is the polar angle between the magnetization vector and the c axis. The magnetic anisotropy constants K_i [in Eq. (1)] and K_j^0 [in Eq. (5)] are interrelated.[20] The use of the constants K_j^0 is preferable in a theoretical investigation of the magnetic anisotropy and in a comparison of theory with experiment, since the temperature dependences of the constants K_i and of the atomic constants are more complicated than that of K_j^0. On the other hand, K_i is easier to determine from experiment.

In first-order approximation, which can be used for terbium and its alloys because $|K_1| \gg |K_2|$, the magnetic-anisotropy constant per ion $K^0_{2\,\text{ion}}$ is connected with the

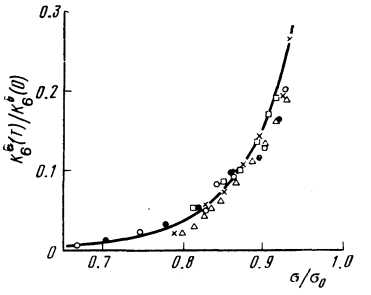

FIG. 6. Dependence of the relative constant of the magnetic anisotropy in the basal plane $K_6^6(T)/K_6^6(0)$ on the relative magnetization σ/σ_0 for the alloys Tb_xGd_{1-x}: ●—$x = 0.7$, □—$x = 0.5$, ○—$x = 0.39$, △—$x = 0.2$, ×—$x = 0.09$.

constant K_1 by the relation

$$K_{2\,\text{ion}}^0 = -\frac{2}{3} K_1 \frac{A}{Nx\rho}, \tag{6}$$

where A is the molecular weight, N is Avogadro's number, ρ is the density, and K_1 is expressed in erg/cm^3. For the alloys Tb_xY_{1-x} the values of $K_{2\,\text{ion}}^0$ calculated by us from Eq. (6) are shown in Fig. 3 (curve 1). It is seen that the plot of $K_{2\,\text{ion}}^0$ against the terbium concentration has a maximum in the region $x=0.4-0.5$. The concentration dependence of the anisotropy constant $K_{2\,\text{ion}}^{0\text{eff}}$, with account taken for the correction for the helicoidal-structure collapse energy (curve 2 in Fig. 3), has a minimum at $x<0.3$. These results cannot be explained on the basis of the simple single-ion theory,[21] according to which the contributions made to the magnetic anisotropy by the individual ions are additive, as a result of which the constant K_2^0 must be proportional to the terbium-ion concentration, while the magnetic-anisotropy constant per ion $K_{2\,\text{ion}}^0 \sim K_2^0/x$ should be a constant. According to the one-ion theory,[20,21] the magnetic-anisotropy constant K_2^0 is given by

$$K_2^0 = -\frac{\gamma 1.5}{2} e^2\langle r^2\rangle \frac{\alpha(2J)!}{2(2J-2)!}\eta x Z. \tag{7}$$

Here e is the electron charge, $\langle r^2\rangle$ is the mean squared radius of the $4f$ orbit, J is the quantum number, Z is the valence of the REM ion, and the factor $\eta = (1.633 - c/a)a^{-3}$ takes into account the deviation of the crystal structure from an ideal hexagonal one (c and a are the lattice parameters). Estimates made by us on the basis of measurements of Belovol, Finkel', and Sivokon'[9] of the lattice parameters in Tb_xY_{1-x} alloys have shown that the factor η changes monotonically from $1.11\cdot10^{-3}$ Å^{-3} for terbium to $1.26\cdot10^{-3}$ Å^{-3} for the alloy $Tb_{0.1}Y_{0.9}$, and allowance for this factor does not explain the anomalies on the plot of $K_{2\,\text{ion}}^0$ against the terbium concentration.

When the magnetic anisotropy constant of Tb_xGd_{1-x} alloys is determined it must be recognized that an external magnetic field applied along the c axis rotates the magnetic moments of the gadolinium and terbium ions through different angles, so that a noncollinear magnetic structure is produced. This leads to nonlinearity of the magnetization curve even in weak fields.

It follows from calculations[4,13] based on the molecular-field theory that the angles between the c axis and the magnetic moments of the gadolinium ions and the terbium ions, θ_{Gd} and θ_{Tb} are determined from the equations

$$I_{Tb-Gd} x\mu_{Tb}\sin(\theta_{Tb}-\theta_{Gd}) = H\sin\theta_{Gd}, \tag{8}$$

$$\mu_c = x\mu_{Tb}\cos\theta_{Tb} + (1-x)\mu_{Gd}\cos\theta_{Gd}, \tag{9}$$

where I_{Tb-Gd} is the integral of the exchange interaction between the terbium and gadolinium ions, μ_{Tb} and μ_{Gd} are their magnetic moments, and μ_c is the magnetic moment along the c axis per ion. From the experimental data for the paramagnetic Curie point we calculated $I_{Tb-Gd} = 1.52\cdot10^{25}$ G^2/erg. Assuming in accord with the experimental data that $\mu_{Tb}=9.3\mu_B$ and $\mu_{Gd}=7.5\mu_B$ and determining σ_c from the $\sigma(H)$ curves at $H\parallel c$, we found by simultaneously solving Eqs. (8) and (9) with a computer that the angles θ_{Tb} and θ_{Gd} differ greatly in the Tb_xGd_{1-x} alloys, as is seen from the results for the alloy $Tb_{0.2}Gd_{0.8}$ at 4.2 K:

H, kOe:	4	10	16.8	22.8	30.5	37.8	44.5	50.5
θ_{Gd}, deg:	85.5	79.6	74.0	67	60.8	55.1	44.9	43.1
θ_{Tb}, deg:	86.3	81.7	77.5	71.5	66.7	61.8	56.1	50.7

The magnetic anisotropy constants for these alloys were determined by solving an equation that follows from the calculations of the magnetization curves by the molecular-field theory[4,13]

$$\frac{3}{2}K_2^0 + \frac{5}{8}K_4^0 + \frac{35}{16}K_6^0\frac{\sin 4\theta_{Tb}}{\sin 2\theta_{Tb}} = H\frac{x\mu_{Tb}\sin\theta_{Tb} + (1-x)\mu_{Gd}\sin\theta_{Gd}}{\sin 2\theta_{Tb}}. \tag{10}$$

The calculations have shown that $K_2^0 \gg K_4^0$, and the dependence of K_2^0 on the terbium concentration is nonlinear (see Fig. 4).

Using the theory of Irkhin and Karpenko,[1] we express the magnetic-anisotropy constant of the disordered binary alloy Tb_xGd_{1-x} in the form

$$K = xK_{Tb}^{cr} + x^2K_{Tb}^{exch} + x(1-x)K_{Tb-Gd}^{exch}, \tag{11}$$

and for the Tb_xY_{1-x} alloys in the form

$$K = xK_{Tb}^{cr} + x^2K_{Tb}^{exch}, \tag{12}$$

where K_{Tb}^{cr} is the single-ion anisotropy constant governed by the crystal-field mechanism, and K_{Tb}^{exch} and K_{Tb-Gd}^{exch} are the constants of the anisotropic exchange between the terbium ions and between terbium and gadolinium. We have neglected here the quantities[7] K_{Gd}^{cr} and K_{Tb}^{exch}.

We estimate now the contributions made to the magnetic anisotropy by the different mechanisms. According to our experimental data, the magnetic-anisotropy constant per ion in pure terbium is $K_{2\,\text{ion}}^0 = 52$ cm^{-1}, while in dilute $Tb_{0.1}Y_{0.9}$ alloys $K_{2\,\text{ion}}^0 = 35$ cm^{-1} and in $Tb_{0.09}Gd_{0.91}$ $K_{2\,\text{ion}}^0 = 65$ cm^{-1}. If the anisotropy were due only to anisotropic exchange, then upon dilution of terbium by yttrium or by gadolinium one should expect in these alloys $K_{2\,\text{ion}}^0 \sim 5$ cm^{-1}, which differs by one order of magnitude from the experimental values. This indicates that the predominant contribution to the anisotropy is changed very little when the terbium is diluted by yttrium or gadolinium. This contribution, as follows from (11), is the single-ion anisotropy due to the interaction of the angular momentum of the terbium ion with the crystal field of the lattice, inasmuch as the constant that characterizes this anisotropy per ion, $K_{Tb\,\text{ion}}^{cr}$, should remain constant in these alloys.

Allowance for the change of the lattice parameters introduces only a small correction [see Eq. (7)], inasmuch as the parameters of the lattices of Tb, Gd, and Y are close to one another (for example, in the alloys Tb_xGd_{1-x} the factor η in (7) changes from 0.893×10^{-3} to 1.12×10^{-3} Å^{-3}).

Nonetheless, to explain the bending of the $K_2^0(x)$ plot of the Tb_xGd_{1-x} alloys (see Fig. 4), as well as the difference between the values of $K_{2\,\text{ion}}^0$ in dilute alloys and in pure terbium, we must assume also the presence of anisotropic exchange, which makes a noticeable contribution not only on account of the constant K_{Tb}^{exch} but also near the equiatomic compositions on account of the constant K_{Tb-Gd}^{exch}.

In accord with the theoretical investigations[22] that have established the connection between the magnetic ordering in REM and the topology of the Fermi surface, it can be assumed that the anomalous concentration dependence of the magnetic-anisotropy constants in Tb_xY_{1-x} alloys is due to a realignment of the electronic structure when the terbium is alloyed with the yttrium; this is indicated also by experimental data on the electric, magnetic, and magnetostriction properties, as well as by the paramagnetic Curie points.[10] In this case one should expect a change of the contribution made to the magnetic anisotropy by the anisotropic exchange [the constant K_{Tb}^{exch} in Eq. (12)], which depends on the properties of the conduction electrons.[23]

The dependence of the magnetic-anisotropy constant in the basal plane on the relative magnetization (see Fig. 5) for ferromagnetic Tb_xY_{1-x} alloys is satisfactorily described by the theoretical formula that follows from the single-ion with account taken of the finite spin and of the quantization effects[20]:

$$[K_6^6(T)]_{ion}=\frac{AK_6^6(T)}{\rho Nx}=[K_6^6(0)]_{ion}\mathcal{L}_6\left(S,\frac{\sigma}{\sigma_0}\right), \qquad (13)$$

where $K_6^6(T)$ and $[K_6^6(T)]_{ion}$ are the anisotropy constants in the basal plane per unit volume and per ion, respectively, $K_6^6(0)$ are their values at $T=0$ K, $\mathcal{L}_6$ is a function of the spin S and of the relative magnetization $\sigma(T)/\sigma_0$, which is tabulated in Ref. 20. The value $[K_6^6(0)]_{ion}$ calculated by the theoretical formula (13) at $T=0$ K from the experimental data shown in Fig. 5 is equal to 0.52 cm^{-1} for the Tb_xY_{1-x} alloys.

When comparing the experimental data on K_6^6 of Tb_xGd_{1-x} alloys with the theory it must be recognized that it is necessary to substitute in (13) the magnetization of the terbium sublattice, and not the total magnetization.

The temperature dependences of the terbium and gadolinium sublattices are described in the molecular-field theory by Brillouin functions. Starting from the values of the exchange integrals obtained by us from the paramagnetic Curie points,

$$I_{Tb-Tb}=1.01\cdot10^{25}\,G^2/erg,\ I_{Tb-Gd}=1.52\cdot10^{25}\,G^2/erg,$$
$$I_{Gd-Gd}=2.28\cdot10^{25}\,G^2/erg,$$

we calculated the magnetizations of the terbium and gadolinium sublattices with the aid of the equations that follow from the molecular-field theory. The dependence of the relative magnetic-anisotropy constant in the basal plane on the relative magnetization of the terbium sublattice is in good agreement with the theoretical equation (13) (see Fig. 6).

We present below the values of K_6^6 in the Tb_xGd_{1-x} alloys at 77.8 and 0 K:

x:	1	0.7	0.5	0.39	0.3	0.2	0.09
$K_6^6\cdot10^{-5}$, erg/cm^3:	9.2	6.6	5.5	3.5	2.9	1.3	0.72
$K_6^6(0)\cdot10^{-5}$, erg/cm^3:	35	25	21	14	11	5.1	2.8

Analysis of the experimental data shows that the constant $K_6^6(T)$ measured at the given temperatures and the value of $K_6^6(0)$ extrapolated in accord with (13) to 0 K increase in proportion to the terbium concentration, in agreement with the single-ion mechanism of the crystal field. The mean value $[K_6^6(0)]_{ion}$ calculated per terbium ion amounts to 0.56 cm^{-1} in the Tb_xGd_{1-x} alloys.

Thus, the results of the present investigation have shown that the concentration dependence of the uniaxial magnetic-anisotropy constant in alloys of terbium with ytttrium and gadolinium is determined mainly by the single-ion mechanism of the interaction of the orbital angular momentum with the crystal field of the lattice, while the anisotropic exchange and the change of the electron structure make an additional contribution to the uniaxial magnetic anisotropy. The temperature dependence of the magnetic-anisotropy constant K_6^6 in the basal plane is satisfactorily described by the single-ion theory when account is taken of the finite value of the spin and of quantization effects.

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[1]V. P. Karpenko and Yu. P. Irkhin, Zh. Eksp. Teor. Fiz. **64**, 756 (1973) [Sov. Phys. JETP **37**, 383 (1973)].
[2]V. G. Demidov, R. Z. Levitin, and O. D. Chistyakov, Zh. Eksp. Teor. Fiz. **71**, 2381 (1976) [Sov. Phys. JETP **44**, 1256 (1976)].
[3]P. Boutron, Phys. Rev. **9**, 2971 (1974).
[4]H. Fujii, Y. Hashimoto, A. Mishima, N. Shohata, and T. Okamoto, J. Phys. Soc. Jpn. **41**, 1179 (1976).
[5]R. Z. Levitin and B. K. Ponomarev, Zh. Eksp. Teor. Fiz. **53**, 1978 (1967) [Sov. Phys. JETP **26**, 1121 (1967)].
[6]J. Rhyne and A. Clark, J. Appl. Phys. **38**, 1379 (1967).
[7]C. Graham, J. Phys. Soc. Jpn. **17**, 1310 (1967).
[8]K. P. Belov and S. A. Nikitin, in: Ferromagnetizm (Ferromagnetism), K. P. Belov and Yu. D. Tret'yakov, eds., Moscow State Univ. Press, 1975, p. 92.
[9]V. S. Belovol, V. A. Finkel', and V. E. Sivokon', Zh. Eksp. Teor. Fiz. **69**, 1734 (1975) [Sov. Phys. JETP **42**, 880 (1975)].
[10]K. P. Belov, S. A. Nikitin, N. A. Sheludko, V. P. Posyado, and G. E. Chuprikov, Zh. Eksp. Teor. Fiz. **73**, 270 (1977) [Sov. Phys. JETP **46**, 140 (1977)].
[11]S. A. Nikitin, N. A. Sheludko, V. P. Posyado, and G. E. Chuprikov, Zh. Eksp. Teor. Fiz. **73**, 1001 (1977) [Sov. Phys. JETP **46**, 530 (1977)].
[12]K. P. Belov, S. A. Nikitin, V. P. Posyado, and G. E. Chuprikov, Zh. Eksp. Teor. Fiz. **71**, 2204 (1976) [Sov. Phys. JETP **44**, 1162 (1976)].
[13]R. Z. Levitin, E. M. Savitskiĭ, V. F. Terekhova, O. D. Chuprikov, and V. L. Yakovenko, Zh. Eksp. Teor. Fiz. **62**, 1858 (1972) [Sov. Phys. JETP **35**, 968 (1972)].
[14]N. L. Bryukhatov and L. V. Kirenskiĭ, Zh. Eksp Teor. Fiz. **8**, 198 (1938).
[15]W. Sucksmith and I. Thompson, Proc. Roy. Soc. **225**, 362 (1954).
[16]A. A. Kazakov, Teor. Mat. Fiz. **30**, 415 (1977).
[17]H. Child, W. Koehler, E. Wollan, and J. Cable, Phys. Rev. **138**, 1655 (1965).
[18]J. Feron, C. R. Acad. Sci., Paris **269**, 611 (1969).
[19]S. A. Nikitin and N. P. Arutyunyan, Zh. Eksp. Teor. Fiz. **75**, 2179 (1978) [Sov. Phys. JETP **48**, 1098 (1978)].
[20]A. A. Kazakov, in: Fizika metallov i ikh soedinenii (Physics Metals and Their Compounds), Urals State Univ. Sverdlovsk, No. 2, 1974, p. 187.
[21]T. Kasuya, Magnetism, ed. by Rado and Suhl **2B**, Academic

Press, 1966, p. 216.
[22]I. E. Dzyaloshinskiĭ, Zh. Eksp. Teor. Fiz. **47**, 336 (1964) [Sov. Phys. JETP **20**, 223 (1964)].
[23]Yu. P. Irkhin, V. V. Druzhinin, and A. A. Kazakov, Zh. Eksp. Teor. Fiz. **54**, 1183 (1968) [Sov. Phys. JETP **27**, 633 (1968)].

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