the resistance. According to measurements by Zinov'eva,[4] 50% of the subcritical absorption goes to the Rayleigh maximum.

At a small overlap, when the estimate (12) is valid, the transmission coefficient (10) calculated in second order in ξ may turn out to be larger than unity, as is seen from the limiting expressions for τ (see (18) and (19) of Ref. 2). In this case we must consider Eq. (11) for Y. The integral term in this equation is of the order of $\mu/(\gamma+\tau)$. We then obtain for the order of magnitude of the transmission coefficient expression (10), in which μ is replaced by the smaller of μ and $\gamma+\tau$.

We take the opportunity to thank A. A. Abrikosov and A. F. Andreev for a discussion of the work.

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Occurrence of noncollinear magnetic structures in $DyCo_{5.3}$ near the compensation temperature in strong magnetic fields

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The influence of hexagonal anisotropy on the occurrence of noncollinear magnetic structures, induced by an external magnetic field, is investigated in the intermetallic compound $DyCo_{5.3}$ near the compensation temperature (124 K). Experimental data on the magnetization and magnetostriction, obtained in strong pulsed magnetic fields up to 280 kOe, are compared with the theoretical results of A. K. Zvezdin and A. F. Popkov, [Fiz. Met. Metalloved. **49**, No. 8 (1980)]. It is shown that at low temperatures, the hexagonal anisotropy strongly influences the form of the field dependences of the magnetization and magnetostriction, leading to the appearance of wavelike singularities in the noncollinear phase and also to the occurrence of phase transitions of the first kind. Experimental and theoretical magnetic phase diagrams are constructed for fields applied along the easy and hard directions in the basal plane. The causes of qualitative differences between theory and experiment, such as the presence of appreciable hysteresis in the experimental field dependence of the magnetostriction, are discussed. The molecular field exerted on the Dy sublattice by the Co sublattice is determined experimentally to be $H_M = (950 \pm 50)$kOe.

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Noncollinear magnetic structures induced by an external field in ferrimagnets have been well studied, theoretically and experimentally, principally on crystals that have cubic or uniaxial magnetocrystalline anisotropy.[1] It has been shown that the anisotropy may strongly influence the phase state of a ferrimagnet placed in an external field, and that this leads in a number of cases to qualitative differences from the isotropic model, such as the occurrence of phase transitions of the first kind, the appearance of new lines on the magnetic phase diagrams, etc. Singularities due to the occurrence of noncollinear magnetic structures and to the presence of crystalline anisotropy express themselves in the field and temperature dependences of the magnetization, the magnetostriction, and other magnetic characteristics of the ferrimagnet.

At present, for ferrimagnets that possess hexagonal anisotropy in a plane of easy magnetization, there is only the theoretical analysis given in the paper of Zvezdin and Popkov[2] for the noncollinear magnetic structures that originate in an external field. In this paper, magnetic phase diagrams are constructed for an external field directed along the easy and hard axes in the basal plane, together with the temperature dependences of the angles between the magnetic moments of the sublattices and the crystallographic axes for various values of the external field.

Suitable objects for experimental investigation of field induced noncollinear magnetic structures in hexagonal ferrimagnets are the intermetallic compounds $DyCo_5$ and $TbCo_3$, which possess anisotropy of the "easy plane" type at temperatures below room temperature. The presence in these compounds of rare-earth atoms with nonvanishing orbital moments leads to appreciable anisotropy in the basal plane at low temperatures, including the magnetic compensation temperatures (120–150 K). This leads us to expect in them a strong influence of the hexagonal anisotropy on the occurrence of field-induced noncollinear magnetic structures.

The compound $DyCo_{5.3}$, which is the subject of study in

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the present paper, possesses a hexagonal structure of the $CaCu_5$ type (space group $P6/mmm$), in which some of the Dy atoms have been replaced by pairs ("dumbbells") of Co atoms.[3] The cobalt excess in this case made it possible to obtain a single-phase compound, whereas the alloy of the integral composition $DyCo_5$ contained a Dy_2Co_7 phase.[4] In a structure of the $CaCu_5$ type, the Co atoms occupy two (without allowance for replacement of rare-earth atoms) nonequivalent positions with, according to neutron-diffraction data, slightly different values of the magnetic moments.[5] We shall, however, following Refs. 5–7, neglect this difference and treat $DyCo_{5.3}$ as a ferrimagnet that consists of two (Dy and Co) magnetic sublattices.

In $DyCo_{5.3}$, as in other RCo_5 conpounds (R represents rare-earth elements), the decisive role in the formation of the magnetism is played by the exchange interaction within the Co sublattice; this produces the high Curie temperatures (of the order of 1000 K) of these magnets.[8] The exchange interaction within the rare-earth sublattice is small and needs to be considered only at temperatures of the order of 10–15 K. The R-Co interaction occupies an intermediate position and is about an order of magnitude weaker as compared with the Co-Co interaction.[9] Hence it follows that the rare-earth sublattice may be treated as a paramagnetic system of atoms, placed in an "external" molecular field exerted by the Co sublattice. Characteristic of all RCo_5 compounds are the huge, often comparable with the R-Co exchange interaction, values of the uniaxial anisotropy constants of the rare-earth and cobalt sublattices; these constants may be of different signs.[5-7] In $DyCo_{5.3}$, the negative anisotropy of the Dy sublattice leads to the result that at temperatures below 320 K, the magnetic moments of the Dy and Co sublattices lie in the basal plane, despite the fact that for the Co sublattice the favored orientation of the spins is along the hexagonal axis. The resultant anisotropy at low temperatures, according to our estimates, reaches 10^8 erg/cm^3; this prevents departure of the magnetic moments of the sublattices from the basal plane when the crystal is magnetized along any direction in this plane.

In the present paper, experimental data on induced noncollinear magnetic structures in $DyCo_{5.3}$, obtained from measurements of the magnetization and magnetostriction in pulsed magnetic fields up to 280 kOe over the temperature range 4.2–300 K, are compared with the theoretical results of Ref. 2.

SPECIMENS AND EXPERIMENTAL METHOD

Two single crystals of $DyCo_{5.3}$ were obtained in Ural State University from coarse grains of an ingot that was melted in an induction furnace in a helium atmosphere in an alundum crucible; they were kindly provided for the measurement by A. V. Andreev and A. V. Deryagin. An x-ray structural analysis made in the same place showed that the specimens are single-phase and that the misorientation of the subgrains in them does not exceed 3°. The single crystals were given the form of cubes, with surfaces perpendicular to principal crystallographic directions. The dimensions of the specimens were 1.5–2 mm.

The pulsed magnetic field was produced by discharge of a battery of condensers to a solenoid that was cooled by liquid nitrogen; the pulse duration was 7 msec. The value of the magnetic field was measured with accuracy ±5%. The temperature was determined over the range 20–300 K with a copper-constantan thermocouple, over the range 4.2–20 K with an Allen-Bradley thermometer, with accuracy ±1 K over the whole range of the measurements.

The magnetization measurements were made by an induction method.[10] The magnetostriction was measured with a piezoelectric gage attached to the specimen and previously calibrated against a nickel specimen. To eliminate the effect of indeterminacy of the initial magnetic state of the specimen, a longitudinal-transverse solenoid was used in the determination of the magnetostriction constant. In this solenoid the specimen was magnetized first along and then transversely to the measurement direction; this insured a possibility of simultaneous measurement of the longitudinal and of the transverse magnetostriction. The recording of the signal was accomplished by photographing the screen of an oscillograph. The absolute accuracy of the magnetization measurements was ±7%, the relative error of the field and temperature dependences 5%; for the magnetostriction measurements, the corresponding figures were ±15 and 5%.

In addition, at 4.2 K measurements of the magnetization were made with a vibration magnetometer in a superconducting solinoid in fields up to 65 kOe (with absolute accuracy 2%). In the interval 78–300 K, the torque in the basal plane of the crystal, in a constant magnetic field of 22 kOe, was also measured. The results of the measurements on the two specimens agreed within the limits of the indicated accuracy.

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

Preliminary measurements in weak fields showed that the variation of the spontaneous magnetization of $DyCo_{5.3}$ with temperature is in satisfactory agreement, if the slightly different compositions of the specimens are taken into account, with the data of previous papers.[5,9,11] The magnetic compensation temperature, according to our measurements, is 124 K; the magnetization at 4.2 K is 1.11 μ_B per formula unit ($Dy_{0.85}Co_{5.15}$).

Before turning to an analysis of the experimental data in strong magnetic fields, we shall consider qualitatively, on the basis of the results of Ref. 2, what differences may be caused by hexagonal anisotropy of a ferrimagnet, as compared with an isotropic crystal.

In an isotropic two-sublattice ferrimagnet, a noncollinear magnetic structure originates at an external field

$$H_{cr}=A|M_1-M_2|, \quad (1)$$

where A is the parameter of exchange interaction between the sublattices, and where M_1 and M_2 are the magnetic moments of the sublattices. In fields less than

H_{cr}, there exists a collinear phase, in which the magnetic moments of the sublattices are antiparallel to each other and collinear with the field. On transition to the noncollinear phase (this transition in an isotropic ferrimagnet is a phase transition of the second kind), the moments of the sublattices depart from the field direction and become noncollinear with each other; the resultant magnetic moment remains parallel to the field. In the noncollinear phase, the magnetization increases linearly with the field; the susceptibility in this case is A^{-1}.[12] Since this value is larger than the susceptibility due to the paraprocess in the collinear phase, there should be a break on the field-dependence curves of the magnetization upon transition to the noncollinear phase. We note that this transition manifests itself strongly on the field-dependence curves of the magnetostriction. The latter, as is well known, is an even function of the magnetization and depends on the direction of the magnetic moments of the sublattices with respect to the crystallographic axes; in the noncollinear phase, the orientation of the sublattice moments changes greatly. At the same time, the magnetization is determined by the resultant magnetic moment and changes little.

Crystalline anisotropy (in particular, hexagonal), leads to the result that the critical field of the transition in the direction of easy magnetization increases as compared with the critical field for an isotropic ferrimagnet, since the anisotropy in this case impedes departure of the magnetic moments from the easy axis; whereas in a field parallel to the hard axis, it decreases, since the anisotropy promotes such a departure. It should be noted that because of the different energy of interaction of the magnetic moments of the sublattices with the field in the latter case, a noncollinear structure originates also in fields less than the anisotropy field.[1] In particular, near the compensation temperature a situation is possible in which the low-field noncollinear structure transforms directly to the high-field, avoiding an intermediate collinear phase.

The high degree of symmetry in the case of hexagonal anisotropy results in the existence of three equivalent axes of easy magnetization in the basal plane. Therefore in the demagnetized state, there can exist in the specimen six types of domains, oriented at angle 60° with one another, which must be taken into account in analysis of the experimental data. The presence of several easy and hard directions in the basal plane leads also to the result that in the noncollinear phase, during turning of the magnetic moments of the sublattices in this plane, they should lag at the easy directions and pass more rapidly through the hard directions. Then wavelike singularities appear on the field-dependence curves of the magnetization and magnetostriction. Near the compensation temperature, the magnetic moments of the sublattices may pass through the hard direction discontinuously; that is, a phase transition of the first kind occurs. For an external field applied along an easy direction, a jump of the magnetic moments may be observed on transition from the collinear phase to the noncollinear (then the moments of the sublattices are "thrown over" to the nearest easy axes, oriented at angle 60° to that along which the specimen is magnetized); along a hard direction, transitions of the first kind are possible only in the noncollinear phase (from the easy axes oriented at 30° to the field direction to the easy axis perpendicular to the field). The diagrams in the upper part of Fig. 1 explain this.

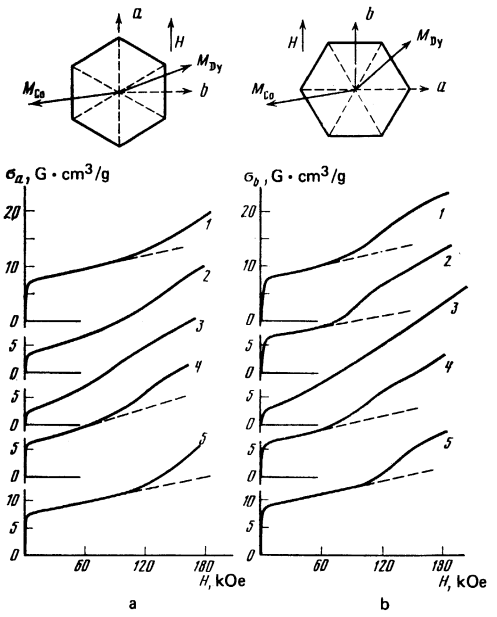

FIG. 1. Experimental field dependences of the magnetization of $DyCo_{5.3}$ near the compensation temperature. a) field directed along axis a: 1, 86 K; 2, 105 K; 3, 120 K; 4, 152 K; 5, 163 K. b) field directed along axis b: 1, 78 K; 2, 97 K; 3, 115 K; 4, 157 K; 5, 166 K. The dotted lines show magnetization curves without allowance for the occurrence of a non-collinear magnetic structure.

The lower part of Fig. 1 shows the experimental variation of the magnetization with the intensity of the magnetization with the intensity of the external field, for temperatures above and below the compensation point, in fields directed along an easy axis (a) and along a hard axis (b) in the basal plane. It is seen from the figure that after technical saturation of the specimen, there is a linear increase of the magnetization, caused primarily by the paraprocess in the Dy sublattice (Curves 1, 2, 4, and 5 in Fig. 1). With increase of the field, the character of the curves changes: the magnetization begins to increase considerably more rapidly on the whole; one notices alternating sections of rapid and slow increase of the magnetization ("waves"). At temperatures close to the compensation temperature (Curves 3 in Fig. 1), a considerable increase of magnetization occurs over the whole field interval. It is also seen that the transition to the region of large magnetization increase is of smooth character and that the determination of the critical transition field is subject to large error.

In order to confirm independently the presence of rotation of the magnetic moments of the sublattices in the basal plane, and in order to determine the critical fields more accurately, measurements were made of the magnetostriction along axis a in a field applied along crystal axes a (λ_{aa}) and b (λ_{ab}) (in the latter case, the field was directed perpendicular to the measurement

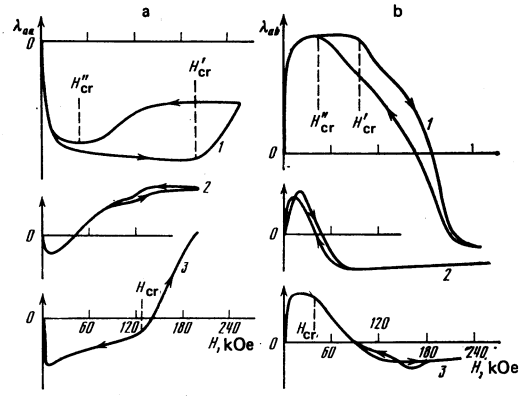

FIG. 2. Experimental field dependences of the longitudinal magnetostriction λ_{aa} and transverse magnetostriction λ_{ab} of $DyCo_{5.3}$ in a field applied along axes a and b respectively in the basal plane: 1, 4.2 K; 2, 124 K; 3, 162 K. The arrows show the direction of change of the external field; H'_{cr} is the critical field for transition to the noncollinear phase during increase, H''_{cr} during decrease of the external field.

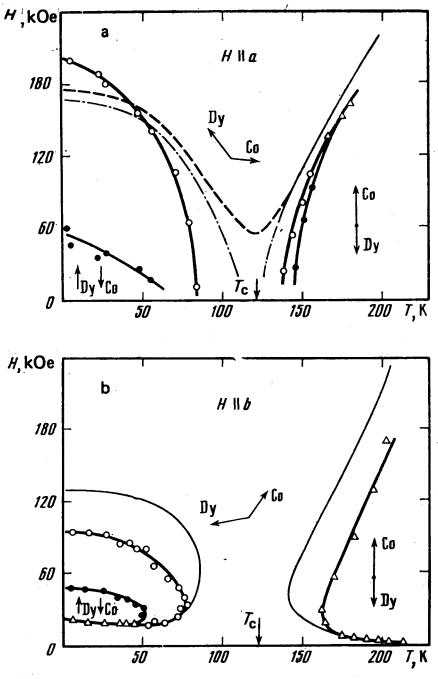

FIG. 3. Experimental and theoretical phase diagrams of $DyCo_{5.3}$ in a field directed along the easy axis a and along the hard axis b in the basal plane: o, experimental critical field (H'_{cr}) and anisotropy field during increase of the external field; •, critical field (H''_{cr}) during decrease of the external field; △, the critical fields coincide. The heavy lines are experimental phase diagrams; the thin solid lines are theoretical lines of phase transitions of the second kind; the dotted lines are theoretical lines of loss of stability of the collinear phase, the dashed-dotted of the noncollinear (high-field) phase.

direction). Characteristic field dependences of λ_{aa} and λ_{ab} are shown in Fig. 2. It is seen from the figure that singularities due to the occurrence of a noncollinear phase and influenced by hexagonal anisotropy show up considerably more clearly on the field-dependence curves of the magnetostriction than on those of the magnetization. Consider the curves at 4.2 K in an increasing magnetic field (Curves 1 in Fig. 2; the direction of the field is shown by the arrow). In weak fields (up to 25 kOe), the change of magnetostriction along axis *a* is caused by domain processes; along axis *b*, both by displacement of domain boundaries and by rotation of the magnetic moments along the hard axis. On further increase of the field (in the noncollinear phase), saturation is observed for both directions (the slight linear drop of the magnetostriction is due, as was shown by measurements that we made on YCo_3, primarily to isotropic magnetostriction of the paraprocess in the Co sublattice). In fields exceeding a certain critical value H'_{cr}, there is an abrupt change of character of the field dependence of the magnetostriction (along axis *b*, for example, it changes sign), resulting from appreciable departure of the magnetic moments of the sublattices from the direction of the field. Along axis *b* in the noncollinear phase ($H > H'_{cr}$), there are also seen wavelike anomalies, similar to those observed on the field-dependence curves of the magnetization.

With increase of temperature, the critical fields of the transition decrease; near the magnetic compensation temperature, no saturation is observed (Curves 2 in Fig. 2). On further increase of the temperature, a transition from the collinear phase to the noncollinear is again detected; the wavelike anomalies become less pronounced (Curves 3 in Fig. 2). At high temperatures, a noticeable role is played by isotropic magnetostriction of the paraprocess; this leads to a linear increase of magnetostriction with increase of field in the collinear phase (Curve 3, Fig. 2a).

The magnetostriction measurements revealed still another peculiarity that was scarcely noticeable on the field-dependence curves of the magnetization; namely, appreciable hysteresis, that is a noncoincidence of the values of the strain during an increase and a subsequent decrease of the external field.[1)] Correspondingly, the critical fields of the transition were strongly dependent on the past history of the magnetic state of the specimen. The hysteretic phenomena decrease with rise of temperature and disappear completely at temperatures above 170 K.

The variation of the critical transition fields and of the anisotropy fields (the *H-T* diagram) is shown in Fig. 3, where the light circles show the critical fields during increase, the dark during decrease, of the external field. It is seen from the figure that near the compensation temperature (T_c), the collinear phase is absent for both directions; the critical fields increase with distance from the compensation point.

For the field dependences of the magnetostriction λ_{aa} and λ_{ab} at 4.2, 124, and 162 K, and also for the magnetic phase diagrams along axes *a* and *b*, the corresponding theoretical relations were plotted. Following Ref. 2, we write the free energy of $DyCo_{5.3}$ in the form

$$F = -HM_{Co}\cos\varphi_{Co} - \int_0^{H_{eff}} M_{Dy}(x)\,dx \mp \frac{1}{6}K_{6Dy}\cos 6\varphi_{Dy} \mp \frac{1}{6}K_{6Co}\cos 6\varphi_{Co}, \quad (2)$$

where $H_{eff} = |\mathbf{H} + \mathbf{H}_m| = (H_M^2 + H^2 - 2HH_M\cos\varphi_{Co})^{1/2}$,

$H_M = AM_{Co}$ is the molecular field exerted on the Dy sublattice by the Co sublattice, M_{Co} and M_{Dy} are the moments of the sublattices and K_{6Dy} and K_{6Co} are the constants of hexagonal anisotropy of the Dy and Co sublattices. The upper and lower signs in (2) correspond to fields applied along axes a and b. Since only the resultant anisotropy constant $K_6 = K_{6Dy} + K_{6Co}$ has been determined experimentally, and since the temperature dependence of K_{6Dy} and K_{6Co} is unknown, it is impossible to separate the contributions of the individual sublattices to the resultant anisotropy.[2)] For this reason, we were forced to neglect the difference between φ_{Dy} and φ_{Co} in the last two terms of formula (2). We remark that this assumption is incorrect only when there is appreciable turning of the magnetic moments of the sublattices and in strong fields (larger than 200 kOe), where the degree of noncollinearity of the sublattices reaches 10–12°.

On minimizing (2) with respect to the angle φ_{Co} under the assumption made, we get the following equation, valid in the noncollinear phase:

$$HM_{Co}[1-AM_{Dy}/H_{eff}]+2K_6\cos\varphi_{Co}(4\cos^2\varphi_{Co}-1)(3-4\cos^2\varphi_{Co})=0, \quad (3)$$

from which we can determine the variation of the angle of rotation of the Co sublattice with the external field.

$$\varphi_{Co}=\varphi_{Co}(H). \quad (4)$$

The parameters that occur in equation (3) were specified as follows. Values of the magnetic moment of the Co sublattice as a function of temperature were taken from Ref. 9; with allowance for the fact that our specimens had a slightly different structural formula, we took $M_{Co} = 8.2\ \mu_B$ at 4.2 K. The magnetic moment of the Dy sublattice was found as the sum (below the compensation point) or difference (above the compensation point) of the spontaneous moment of $DyCo_{5.3}$ and the magnetic moment of the Co sublattice. As has already been mentioned, the value of the intersublattice exchange interaction in an isotropic ferrimagnet can be found from measurements of the susceptibility in the noncollinear phase. In the presence of hexagonal anisotropy, as is easy to show, the susceptibility in the noncollinear phase at the compensation temperature should be A^{-1} in a field applied along either the a or the b axis, if the angle of "bending under" of the magnetic moments of the sublattices is not too large. Actually, it follows from our measurements of the magnetization at 124 K that the susceptibility in both cases, within the limits of accuracy of the experiment, is the same and equal to $(0.92\pm0.07)\times10^{-3}$; hence $H_M = (950\pm50)$ kOe. We note that this value of the molecular field agrees well with the value $H_M \approx 900$ kOe obtained[5] on the basis of an analysis of the temperature variation of the spontaneous magnetization of $DyCo_{5.2}$ in the spin-reorientation range, and that it disagrees with the value $H_M = 1570$ kOe determined from Mössbauer measurements.[9] The anisotropy constant K_6 was determined at low temperatures from measurements of the anisotropy field when the crystal was magnetized along the hard direction ($K_6 = (42\pm7)\times10^4$ erg/cm^3 at 4.2 K), and at high temperatures from torque curves in the basal plane. On the basis of experimental magnetization data, allowance was also made for the dependence of the values of the magnetic moments on the external field.

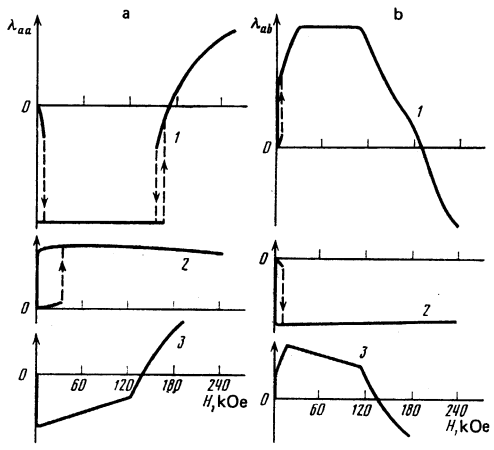

FIG. 4. Theoretical field dependence of the magnetostriction; the magnetostriction behavior shown is that for the maximum possible hysteresis. The notation is the same as in Fig. 2.

From Eq. (4), by use of the formula for the values of the magnetostriction of a hexagonal crystal in the basal plane,[13]

$$\lambda_{aa}={}^1/_2\lambda^{1,2}(T)\cos2\varphi_{Dy}, \quad \lambda_{ab}=-\lambda_{aa} \quad (5)$$

(here $\lambda^{1,2}$ is the magnetostriction constant responsible for the strain of the crystal in the basal plane), one can plot the theoretical $\lambda_{aa}(H)$ and $\lambda_{ab}(H)$ relations. In writing formula (5), we have assumed that at low temperatures the magnetostriction is caused principally by the Dy sublattice (see below). The angle φ_{Co} was found from the relation[2]

$$\sin\varphi_{Dy} = -\frac{H_M}{H_{eff}}\sin\varphi_{Co}. \quad (6)$$

The theoretical field-dependence curves of the magnetostriction are given in Fig. 4. In the calculation it was assumed that in the initial state, the specimen is demagnetized and the magnetic moments are uniformly distributed among the three easy axis in the basal plane; the isotropic paraprocess magnetostriction was also taken into account. In Fig. 4, phase transitions of the first kind are shown dotted (with allowance for the maximum possible hysteresis); increase and decrease of the field are denoted by arrows.

It is evident from a comparison of Figs. 2 and 4 that the theory describes a number of peculiarities that are observed on the experimental curves, such as the abrupt change of the field dependence of the magnetostriction on transition to the noncollinear phase and the change of sign of the magnetostriction. On the theoretical curve there are wavelike sections (Curve 1, Fig. 4b) coinciding qualitatively with the experimental. The difference between theory and experiment reduces chiefly to the presence of appreciable hysteresis in the experimental relations and will be discussed below.

In order to find the theoretical critical fields in phase transitions of the second kind, we used the formula

$$H_{cr} = \frac{1}{2}\frac{A|M_{Co}-M_{Dy}|}{1-A\chi} + \left[\frac{A^2(M_{Co}-M_{Dy})^2}{4(1-A\chi)^2} + \frac{6K_6A}{1-A\chi}\right]^{1/2}, \quad (7)$$

in which the susceptibility $\chi(T)$ of $DyCo_{5.3}$ in the collinear phase was determined experimentally (within the

limits of accuracy of the experiment, the susceptibility was independent of the external field). For phase transitions of the first kind, the lines of loss of stability of the collinear and noncollinear phases were determined from the equations[3)]

$$dF/d\varphi_{Co}=0, \quad d^2F/d\varphi_{Co}^2=0 . \tag{8}$$

Theoretical magnetic phase diagrams of $DyCo_{5.3}$ are shown in Fig. 3. The thin solid lines correspond to phase transitions of the second kind; the dotted lines show the critical fields during increase, the dashed-dotted during decrease of the external field for phase transitions of the first kind. Transitions of the first kind that occur in the noncollinear phase in a field applied along the hard direction, as well as those that occur during technical magnetization of the specimen, are not shown. It is seen from Fig. 3 that there is partial agreement of the theoretical and experimental phase diagrams. For a field applied along the axis *a*, the phase transitions of the first kind predicted by theory are observed at low temperatures. For a field applied along the axis *b*, both the theoretical and the experimental diagrams have the "throat" form characteristic of hard directions. Agreement of the experimental data with the theoretical shows up also in the fact that the critical fields of the transition along the axis *a* are larger than along the axis *b*, for each fixed temperature.

The greatest discrepancies between the theoretical and experimental phase diagrams occur at low temperatures and near the compensation temperature. Without discussing the quantitative differences, which can be explained to some degree by inaccuracy in the choice of the parameters in the calculation, we shall consider the qualitative differences between the theoretical and experimental results. First, appreciable hysteresis is observed experimentally in a field directed along the hard axis, whereas theoretically along this direction the transition from the collinear phase to the noncollinear should be of the second kind, and the occurrence of hysteresis is in principal impossible. Second, along the easy direction the collinear phase is absent within the interval 85–135 K; according to theory, it is unobservable within a considerably narrower temperature interval (110–135 K). To the qualitative differences may be added the fact that the experimentally observed hysteresis along the axis *a* exceeds the calculated by an order of magnitude (Curve 1 in Figs. 2a and 4a).

The appearance of hysteresis under the real conditions of performance of the experiment may be caused by a number of accompanying phenomena: heating of the specimen in the pulsed magnetic field; induction of Foucault currents in a metallic specimen; magnetic viscosity; production of uniaxial stresses during the measurement of the magnetostriction with a piezoelectric gauge. We shall consider these effects in somewhat more detail. Heating of the specimen, if it were appreciable, would lead not only to a difference between the critical fields of the transition during increase and decrease of the field, but also to a noticeable decrease of the value of the magnetostriction during decrease of the field; this does not occur.[4)] Effects due to magnetic viscosity or eddy currents, and all others dependent on the time derivative of the external field, can be isolated by varying the conditions of magnetization of the specimen. A special experiment showed that when the rate of increase of the field was varied almost by two orders of magnitude, no dependence of the values of the strain on the rate of change of the field was detected. Presence of uniaxial stresses should give different anisotropy fields in measurement of the magnetization (a free specimen) and of the magnetostriction (a stress specimen); this is not observed experimentally (within the limits of error of the measurements).

Thus the influence of the phenomena considered either is small or should lead to qualitative effects that are not observed experimentally. We note that in the similar compound $TbCo_{5.1}$, such hysteretic effects are practically not observed, although the hexagonal anisotropy in this compound is considerably larger than in $DyCo_{5.3}$.

It is possible that the presence of such hysteresis can be explained by taking into account the dependence of the constant of hexagonal anisotropy on the external field. According to the single-ion theory,[15] at low temperatures this constant is proportional to the twenty-first power of the magnetization and, even for a small paraprocess, can depend strongly on the external field at 4.2 K. There is still another possible explanation of the hysteretic phenomena observed along the axis *b*. We determined the anisotropy constant by supposing that at low temperatures, on increase of the field the low-field noncollinear structure transforms to the collinear. But as has already been mentioned, a situation is possible in which the low-field noncollinear structure transforms directly to the high-field. Then on the field-dependence curves of the magnetization and magnetostriction there can occur approximately horizontal sections, imitating the phenomenon of saturation. If this is so, then our value of the anisotropy constant is much too low (by more than an order of magnitude), and the observed hysteretic phenomena are actually connected with phase transitions within the noncollinear phase. This assumption would also explain the appreciable hysteresis in a field directed along the axis *a*. A final explanation of this question requires additional experimental data (we remark that in this situation, difficulties arise in the determination of the anisotropy constant by traditional methods, that is from magnetization and torque curves).

The presence in $DyCo_{5.3}$ of a hexagonal anisotropy considerably exceeding that measured by us would lead to a substantial broadening of the range of metastability near the compensation temperature. In this case, a collinear structure may not be observed in a field directed along the axis *a*, for the following reason. In the absence of an external field, as has already been mentioned, there exist in a hexagonal crystal several types of domains. If it turns out that the fields for displacement of domain boundaries exceed the critical field for loss of stability of the collinear phase, then the transition to the high-field noncollinear phase occurs from a multidomain (nonuniform) state, avoiding the uniform collinear phase. Such a situation is especially

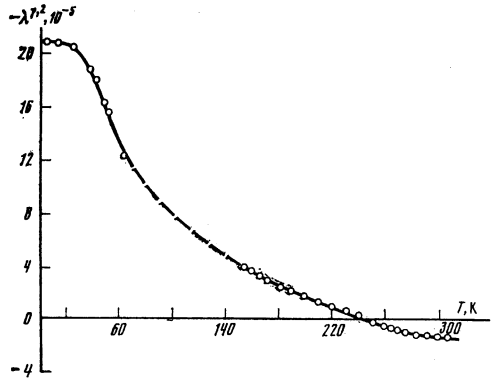

FIG. 5. Experimental temperature dependence of the constant $\lambda^{\gamma,2}$ of hexagonal magnetostriction.

probable near the compensation temperature, where, because of the weak interaction of the magnetic moments of the domains with the external field, the field for displacement of domain boundaries may be large.

There is also another reason explaining the absence of a collinear phase along axis *a*. In a real crystal there may be homogeneous regions (grains) with somewhat different values of the magnetic moment per elementary cell; that is, with different compensation points. Such a possibility exists because of the replacement, which may not be completely statistical, of dysprosium atoms by cobalt. Then what is observed experimentally will be a mean value of the magnetostriction produced by asynchronous rotation of the sublattices in each such grain. The phase transition may then turn out to be so "smeared out" that determination of the critical field becomes impossible. Along axis *a* this will lead to apparent absence of a collinear phase near the compensation temperature; along axis *b*, to an increase of the range of existence of the noncollinear phase.

The presence in the crystal of grains with different magnetic moments may also explain other anomalies, for example the fact that the spontaneous magnetization does not vanish exactly at the compensation point (the "residual" magnetization is approximately 10 G)—a result already noted in Refs. 5 and 9; and also the unusual behavior of the field dependence of the magnetostriction at the compensation temperature in a field applied along axis *b* (Curve 2 in Fig. 2b). The increase of magnetostriction observed here experimentally indicates that at least some of the magnetic moments rotate toward the field direction, whereas theoretically there should occur a change-over of domains forming angle 60° with the field direction to domains oriented perpendicular to the field (Curve 5 in Fig. 4b).

Figure 5 shows the temperature variation of the magnetostriction constant $\lambda^{\gamma,2}$ (with sign reversed), determined as the difference $\lambda^s_{aa}-\lambda^s_{ab}$ between the saturation magnetostrictions obtained from measurements in the longitudinal-transverse solenoid [see formula (5)]. For the reasons indicated above (the specimen is not put into a single-domain state), $\lambda^{\gamma,2}$ cannot be determined in the temperature range 85–135 K. It is seen that the constant of hexagonal magnetostriction decreases rapidly (in absolute value) with rise of temperature and changes sign at 240 K. The latter phenomenon is apparently due to the fact that at low temperatures the dominant role is played by the magnetostriction of the Dy sublattice whereas at high temperatures the resultant magnetostriction is determined primarily by the Co sublattice, for which it is of the other sign and varies only slightly with temperature. Torque measurements in the basal plane showed that the change of sign of the magnetostriction is not accompanied by a phase transition and that the axis *a* remains easy up to 320 K. On the basis of the single-ion model[13] and of the temperature dependences of the spontaneous magnetizations of the sublattices, the contributions of the individual sublattices to $\lambda^{\gamma,2}$ were estimated: $|\lambda^{\gamma,2}_{Dy}/\lambda^{\gamma,2}_{Co}| \gtrsim 15$ at 4.2 K.

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[1)] In the magnetization measurements there is also observed a slight temperature-dependent difference (of the order of 10–15%) between the curves for increase and decrease of the field. This difference is not shown in Fig. 1, because in measurement of the magnetization in a pulsed field a characteristic noise is induced by "bifurcation" of the signal because of phase distortion. From our experimental data on the magnetization, it is possible to conclude only that there are hysteretic phenomena not due to experimental error. It is not possible to determine the exact form of the curves for increase and decrease of the field; Fig. 1 shows the mean variations obtained with an increasing field.

[2)] From the experimental $K_6(T)$ relation it is possible to conclude only that both the constants K_{6Dy} and K_{6Co} are positive.

[3)] For more details, see Ref. 2.

[4)] Allowance for the fact that the magnetizing of the specimen in the pulsed solenoid is nearly adiabatic does not change the essence of the matter. As is shown by estimates, during the process of magnetizing the specimen at 4.2 K its temperature rises no more than 1–5 K; in the noncollinear phase (with allowance for the smallness of the hexagonal anisotropy as compared with the Dy–Co exchange interaction), the temperature of the specimen is constant.[14]

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Inhomogeneous collective oscillations of magnons

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An experimental investigation was made of oscillations excited by a radiofrequency (rf) field in a system of interacting microwave magnons. The range of existence of oscillations was determined from the magnitizing field and the rate of microwave pumping of magnons. A study was made of the behavior of the oscillation amplitude when the microwave field power and the rf signal were varied. Parametric excitation of two oscillation modes with different frequencies by a monochromatic rf signal was detected. The results obtained were in agreement with theoretical ideas on collective oscillations of magnons and on their dispersion law.

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1. INTRODUCTION

A system of magnons in a parametrically excited ferromagnet exhibits, under certain conditions, a secondary instability in the form of transient collective low-frequency oscillations of the magnon gas density. Under stable conditions these oscillations can be excited by an alternating field of appropriate frequency. Natural frequencies $\Omega_\varkappa$ of collective magnon oscillations depend on the rate of excitation of a system (i.e., on the number of magnons N) as well as on the effectiveness of the interaction of magnons and the nature of their spectrum governing the derivatives of the magnon frequency ω_k with respect to the wave number k, and particularly the magnon group velocity v. According to the calculations reported in Refs. 1 and 2, the spectrum of collective oscillations without allowance for for the damping is

$$\left.\begin{aligned}\Omega_\varkappa^2&=\left[2(T+S)N+\frac{\partial^2\omega_k}{\partial k_z^2}\frac{\varkappa^2}{2}\right]^2-(2TN)^2, \quad \varkappa\|\mathbf{M},\\ \Omega_\varkappa^2&=4S(2T+S)N^2+v^2\varkappa^2, \quad \varkappa\perp\mathbf{M}.\end{aligned}\right\} \tag{1}$$

Here, T and S are the coefficients of the Hamiltonian describing the interactions of magnons and $\varkappa$ is the wave vector of their collective oscillations.

There have been several experimental investigations of the simplest type of collective oscillations, which is a homogeneous mode Ω_0 corresponding to the gap in the spectrum (1). Earlier studies[3,4] were concerned with a system of microwave magnons in which homogeneous oscillations were induced by a resonant ($\Omega=\Omega_0$) action of a radiofrequency (rf) field. Parametric excitation of such oscillations by a field of double the frequency $\Omega=2\Omega_0$ was reported in Ref. 5. This method, known as the double paramagnetic resonance of magnons, makes it possible to generate both homogeneous and inhomogeneous collective modes with $\varkappa\neq 0$ but their identification is difficult because the signals due to the two types of oscillation are indistinguishable in a detector which records simply changes in the integrated magnetization.

Since the question of the existence of inhomogeneous collective magnon oscillations is of fundamental importance and direct observations of a signal of two such oscillations have not yet been made, we decided to detect inhomogeneous oscillations by investigating typical dependences characteristic only of these oscillations. This gave us certain positive data not only confirming the hypothesis of the existence of inhomogeneous collective magnon oscillations but also providing information on the form of their spectrum.

2. EXPERIMENTS

Collective magnon oscillations were investigated in a single crystal of yttrium iron garnet in a configuration providing the most stable conditions for spontaneous oscillations of the magnetization $\mathbf{M}\|\langle 001\rangle$. A magnon system was created parametrically by a microwave field $h\exp\{i\omega_r t\}$ of frequency 9.4 GHz by the parallel pumping method. Collective oscillations were produced by pumping additionally with an rf field $H_m\exp\{i\Omega_r t\}$ ($\Omega_r\approx 1$ MHz) polarized parallel to the static magnetic field. At a low amplitude of the rf pumping under the usual linear resonance conditions corresponding to $\Omega_r\approx\Omega_0$ the excitation produced homogeneous collective oscillations and, when a certain threshold amplitude was reached, also inhomogeneous parametric oscillations in accordance with the condition

$$\Omega_r\approx\Omega_{\varkappa_1}+\Omega_{\varkappa_2}\approx 2\Omega_\varkappa, \quad \varkappa_1\approx-\varkappa_2. \tag{2}$$

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