SnGeTe samples in a strong magnetic field.[2] In fact, the increase of T_c with increasing field intensity does occur in the case of the excition transition.[13]

In conclusion, let us note that the behavior of a system's responses not associated with the order parameter is not universal for all phase transitions: the responses have to be calculated in each specific case. For example, in Ref. 14 the magnetic-phase-transition-induced electrical-resistance anomalies are studied. In the present paper we have considered another example of the computation of a system's response to an order-parameter-unrelated perturbation; to wit, we have elucidated the magnetic properties of a crystal in the vicinity of a structural phase transition.

The authors are grateful to S. D. Beneslavskiĭ for useful discussions of the paper.

[1]K. I. L. Kobayashi, Y. Kato, I. Katayama, and K. P. Komatsubara, Solid State Commun. **17**, 875 (1975).
[2]H. Kawamura, Proc. Third Conf. on Physics of Narrow-Gap Semiconductors, 1977 (edited by G. Kavalushevich, N. Gorska, and E. Kochmarek), publ. by PWN, Warsaw (1978), p. 7.
[3]V. M. Baginskiĭ, R. O. Kikodze, G. V. Lashkarev, E. I. Slyn'ko, and K. D. Tovstyuk, Fiz. Tverd. Tela (Leningrad) **19**, 588 (1977) [Sov. Phys. Solid State **19**, 338 (1977)].
[4]B. G. Vekhter, V. P. Zenchenko, and I. B. Bersuker, Fiz. Tverd. Tela (Leningrad) **18**, 2325 (1977) [Sov. Phys. Solid State **18**, 1356 (1977)].
[5]Yu. V. Kopaev, Tr. Fiz. Inst. Akad. Nauk SSSR **86**, 3 (1975).
[6]S. D. Beneslavskiĭ and L. A. Fal'kovskiĭ, Zh. Eksp. Teor. Fiz. **69**, 1063 (1975) [Sov. Phys. JETP **42**, 541 (1975)].
[7]V. I. Litvinov and V. L. Volkov, Fiz. Tverd. Tela (Leningrad) **21**, 584 (1979) [Sov. Phys. Solid State **21**, 344 (1979)].
[8]R. A. Ferrel, Contemp. Phys. **1**, Trieste Sympos., 1968, publ. by Intern. Atomic Energy Agency, Vienna (1969), p. 129.
[9]D. J. Amit and M. Zannetti, J. Stat. Phys. **9**, 1 (1973).
[10]M. C. Leung, Phys. Rev. **B11**, 4272 (1976).
[11]B. A. Volkov, A. V. Gurevich, and Yu. V. Kopaev, Fazovye perekhody metall-diélektrik. Doklady 2-ĭ Vsesoyuznoĭ kovferentsii (The Metal-Dielectric Phase Transitions: Papers Presented at the Second All-Union Conf.), Izd. pri L'vovskom universitete izd. ob'edineniya Vishcha shkola, Moscow-Lvov, 1977, p. 191.
[12]T. M. Rice, Phys. Rev. **B2**, 3619 (1970).
[13]B. A. Volkov, A. I. Rusinov, and R. Kh. Timerov, Zh. Eksp. Teor. Fiz. **71**, 1925 (1976) [Sov. Phys. JETP **44**, 1009 (1976)].
[14]S. Alexander, J. S. Helman, and L. Balberg, Phys. Rev. **B13**, 304 (1976).

Translated by A. K. Agyei

Magnetic-ordering temperatures and direct-exchange integral in the rare-earth terbium–yttrium and terbium–gadolinium alloys

S. A. Nikitin

Moscow State University
(Submitted 27 February 1979)
Zh. Eksp. Teor. Fiz. **77**, 343–351 (July 1979)

Measurements were made of the temperatures of the magnetic phase transitions and of the paramagnetic Curie point in single-crystal rare-earth terbium–yttrium and terbium–gadolinium alloys. Concentration intervals with different coefficients of proportionality of the paramagnetic Curie point to the mean square of the spin projection on the total mechanical angular momentum $\bar{G}$ were observed in these alloys. It is established that the difference between the indirect-exchange integrals in the ferromagnetic and antiferromagnetic states in the rare-earth alloys is a universal function of the spin parameter $\bar{G}$. The contributions of the magnetocrystalline interaction and of the indirect exchange interaction to the magnetic ordering temperatures and to the paramagnetic Curie points in terbium–yttrium and terbium–gadolinium alloys are determined.

PACS numbers: 75.30.Kz, 75.30.Et, 75.50.Cc

INTRODUCTION

An investigation of the dependences of the magnetic-ordering temperatures of rare-earth metal (REM) alloys on the atomic number and on the concentration of the alloyed components is needed to elaborate on the theory of the nature of exchange interactions in REM. According to the indirect-exchange theory,[1,2,3] the magnetic ordering temperature and the paramagnetic Curie point are relatively simply connected with the indirect-exchange integral. This permits a comparison of the conclusions of the theory with experiment, which was indeed made in a number of studies.[4-7] The comparison, however, was made by analyzing the experimental data for polycrystalline samples, and the accuracy of the determination of the magnetic phase-transition temperatures was not high enough in a number of cases.

The aim of the present study was to obtain more exact values for the magnetic phase transition temperatures and the paramagnetic Curie point from measurements on single crystals of REM alloys, to determine the

 0038-5646/79/070176-06$02.40

limits of applicability of the formulas that follow from the indirect-exchange theory, to separate the contribution of the magnetic anisotropy to the magnetic-ordering temperature, and to determine the energy gap between the ferro- and antiferromagnetic states in a wide range of concentrations of REM alloys.

The objects of investigation were two REM alloy systems, terbium–yttrium Tb_xY_{1-x} and terbium-gadolinium Tb_xGd_{1-x}, whose magnetic characteristics differ in a certain sense. When the terbium in the first system is magnetically diluted with yttrium both the energy of the exchange interaction and the energy of the magnetic anisotropy decrease.[8] In the second system, the exchange energy increases when the gadolinium content is increased, whereas the magnetic-anisotropy energy decreases.[9]

EXPERIMENTAL RESULTS AND DISCUSSION

The technology of growing terbium-yttrium and teribium-gadolinium alloy crystals, the control of their quality, and the data on the magnetic, magnetostriction, and electric properties were reported earlier.[8-10] In the present study the magnetic-transition temperature a and the paramagnetic Curie point were determined with an accuracy higher than previously,[8,9] so that more exact and new results could be obtained.

The temperatures Θ_2 of the magnetic transition from the paramagnetic into the magnetically ordered state (ferromagnetic or antiferromagnetic), were determined from the kink of the plot of the temperature dependence of the resistivity $\rho_\perp(T)$ measured with the current flowing in the basal plane. The plot of $\rho_\perp(T)$ near Θ_2 consists of two straight-line sections that intersect at the point Θ_2,[10] and this makes it possible to determine the temperature Θ_2 with sufficient accuracy ($\pm 1.5°$)° The temperature Θ_1, of the transition from the antiferromagnetic state into the ferromagnetic one was obtained from the discontinuity on the $\rho_\perp(T)$ curves.

The paramagnetic Curie points $\Theta_p^\parallel$ and $\Theta_p^\perp$ along the hexagonal axis and in the basal plane, respectively, were determined by measuring the magnetic susceptibility along these crystallographic directions, with accuracy $\pm 2°$. The paramagnetic susceptibility was measured from the point Θ_2 to 550 K, which is much higher than the magnetic-ordering temperature (250 K for gadolinium and even higher for alloys). The paramagnetic susceptibility along the hexagonal axis and in the basal plane obey well the Curie-Weiss law:

$$\chi_\parallel = \frac{C}{T-\Theta_p^\parallel}, \quad \chi_\perp = \frac{C}{T-\Theta_p^\perp}. \tag{1}$$

The values of the Curie-Weiss constant C agree for both directions within the limits of error, but the paramagnetic Curie points are noticeably different along the hexagonal axis and in the basal plane.

The experimental values of the points $\Theta_p^\parallel$ and $\Theta_p^\perp$ in single crystals of Tb_xY_{1-x} and Tb_xGd_{1-x} alloys were used to find the paramagnetic Curie point Θ_p of an isotropic polycrystalline sample. It was calculated from formulas that follow from the isotropic averaging

$$\Theta_p = {}^2/_3\Theta_p^\perp + {}^1/_3\Theta_p^\parallel. \tag{2}$$

Calculations of the paramagnetic Curie point Θ_p of an isotropic REM, based on the effective Hamiltonian in the usual Heisenberg form, lead in the molecular-field approximation to the relatively simple expression[1-3]

$$\Theta_p = {}^1/_3 x(g_J-1)^2 J(J+1) A_{\text{ind}}/k_B, \tag{3}$$

where x is the concentration of the REM ions with total quantum angular momentum J, k_B is the Boltzmann constant, and A_{ind} is the indirect exchange integral. The spin parameter $G=(g_J-1)^2J(J+1)$, called the de Gennes factor in the literature,[3] is equal to the square of the spin projection on the total mechanical angular momentum. No account was taken in (3) of the contribution of the magnetic-anisotropy energy, so that this formula is valid only for a polycrystalline sample or for a single crystal with negligibly small anisotropy.

The outer electron shell is practically the same for trivalent ions of heavy REM, and the ions are the sites of a hexagonal crystal lattice that changes relatively little on going from one metal to another. The indirect-exchange integral A_{ind} in (3), as follows from the theory,[1-3,11] depends on the number of conduction electrons per atom, on the Fermi wave vector, on the s–f exchange interaction integral, on the atomic number, and on the lattice sums. All these quantities can be regarded in first-order approximation as constant, so that the paramagnetic Curie point of the heavy REM and their alloys should be proportional in this approximation to the effective spin parameter

$$\bar{G} = \sum_i x_i G_i, \tag{4}$$

where x_i is the concentration of the rare-earth ions with a de Gennes factor G_i.

Figure 1 shows the data obtained by us on the dependence of Θ_p on the effective spin parameter $\bar{G}$ for the single-crystal Tb_xY_{1-x} and Tb_xGd_{1-x} samples investigated by us, as well as of the previously investigated[12,13] Dy_xY_{1-x} and Dy_xGd_{1-x} single crystals. It is seen that in first-order approximation Θ_p is indeed proportional to the parameter $\bar{G}$. This was established earlier for REM alloys by measurements on polycrystalline samples.[4-7]

In the derivation of relation (3) the theory[2,3] makes use of the assumption that the Fermi surface is spherical. This assumption is not realistic in light of the

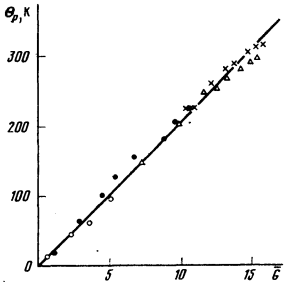

FIG. 1. Dependence of the paramagnetic Curie point Θ_p, (of an isotropic sample) on the spin parameter

$$\bar{G} = \sum_i x_i (g_{J_i}-1)^2 J_i (J_i+1)$$

for the alloys Tb_xY_{1-x}(●), Dy_xY_{1-x}(○), Tb_xGd_{1-x}(×), Dy_xGd_{1-x}(△)

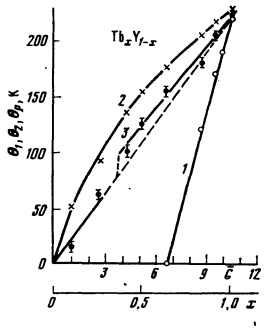

FIG. 2. Temperature Θ_1 of the ferromagnetism–antiferromagnetism transition (curve 1), temperature Θ_2 of the antiferromagnetism–paramagnetism transition (curve 2), and paramagnetic Curie point of the isotropic sample Θ_P (curve 3) for Tb_xY_{1-x} alloys, as functions of the terbium concentrations and of the spin parameter $\bar{G}=xG_{Tb}$ (G_{Tb} is the de Gennes factor for terbium).

latest data on the complex topology of the Fermi surface of REM[11] and the theoretically established[14] connection between the character of the magnetic ordering and the topology of the Fermi surface in REM. However, the fact that the dependence of Θ_p on the atomic constants of the REM can be described in first order by relation (3) indicates that the $s-f$ exchange interaction theory accounts correctly for some of the most general properties of the $s-f$ exchange interaction. The quantity A_{ind} in (3) should be regarded as an effective indirect-exchange integral that depends in a complicated manner on the topology of the Fermi surface. From Fig. 1 and Eq. (3) we can find that the quantity A_{ind}/k_B has a relatively small scatter, of the order of ± 15%, about the mean value 63 K.

The dependence of Θ_p on the spin parameter $\bar{G}$ is shown in Fig. 1 in a very wide range of this parameter, from zero to the maximum value 15.75 possible in an REM (in gadolinium). A more accurate analysis of the determined value of Θ_p with allowance for the experimental error (see Figs. 2 and 3) shows that the $\Theta_p=f(\bar{G})$ curve breaks up into two linear sections: In Tb_xGd_{1-x} alloys the first section is in the interval $\bar{G}=10.5-12$ and the second in the interval 12–15.75; in

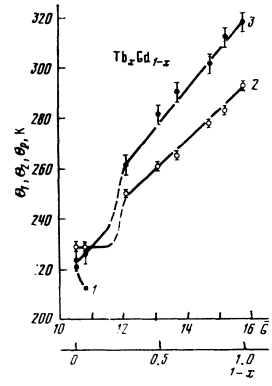

FIG. 3. Temperature Θ_1 of the ferromagnetism–antiferromagnetism transition (curve 1), temperature of the transition from the magnetically ordered state into the paramagnetic state (curve 2), and paramagnetic Curie point Θ_P of an isotropic sample (curve 3) for Tb_xGd_{1-x} alloys, as functions of the gadolinium concentration and of the spin parameter $\bar{G}$.

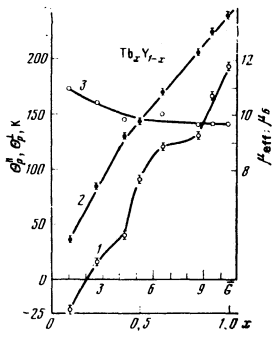

FIG. 4. Paramagnetic Curie points $\Theta_P^{\parallel}$ (curve 1) and $\Theta_P^{\perp}$ (curve 2) and effective magnetic moment μ_{eff} per terbium ion (curve 3) as functions of the terbium concentration x and of the spin parameter $\bar{G}=xG_{Tb}$ for the alloys Tb_xY_{1-x}.

Tb_xY_{1-x} alloys the first and section sections are in the $\bar{G}$ intervals 0–4.5 and 4.5–10.5, respectively.

The singularities observed by us in the function $\Theta_p=f(\bar{G})$ cannot be attributed to structural phase transitions, since x-ray structure investigations[15] show that such transitions do not occur in these alloys, which are solid solutions with hexagonal close-packed lattice that is changed little by the alloying. Even sharper kinks are observed on the $\Theta_p^{\parallel}=f(\bar{G})$ and $\Theta_p^{\perp}=f(\bar{G})$ curves, which can also be represented as consisting of two sections (see Figs. 4 and 5). In the Tb_xY_{1-x} alloys the $\Theta_p=f(\bar{G})$ reveals furthermore a nonlinear section in the interval $\bar{G}=4.5-8.5$ (see Fig. 4). It should be noted that the kinks on the $\Theta_p^{\parallel}=f(\bar{G})$ and $\Theta_p^{\perp}=f(\bar{G})$ curves are more strongly pronounced, the reason being that the accuracy with which $\Theta_p^{\parallel}$ and $\Theta_P^{\perp}$ are determined is double the accuracy of Θ_P.

In accord with the conclusions of the theory,[14] the change of the coefficient of proportionality of the paramagnetic Curie point to the mean value of the square of the spin projection on the total mechanical angular momentum must be interpreted as the result of a change in the indirect exchange integral and of the topology of the Fermi surface when terbium is alloyed with yttrium, and also when terbium is alloyed with gadolinium. It is known[11] that the Fermi surfaces of terbium, yttrium, and gadolinium are in the main similar. Individual

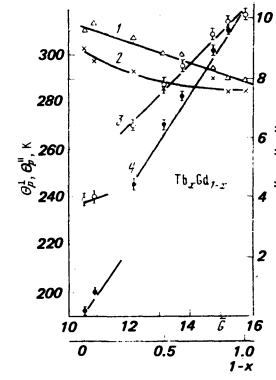

FIG. 5. Effective magnetic moment μ_{eff} (curve 1) and mean value of the magnetic moment μ_0 at 4.2 K (curve 2) per rare earth ion, and the paramagnetic Curie points $\Theta_P^{\perp}$ (curve 3) and $\Theta_P^{\parallel}$ (curve 4) of the alloys Tb_xGd_{1-x} as functions of the gadolinium concentration and of the spin parameter $\bar{G}$.

singularities of the Fermi-surface structure (ribbon singularities), which determine the periods of the magnetic structures, are different in these REM. According to measurements[9-10], in the regions of the kinks on the $\Theta_P = f(\bar{G})$, $\Theta_P^{\parallel} = f(\bar{G})$ and $\Theta_P^{\perp} = f(\bar{G})$ curves one observes also anomalies of the magnetostriction and of the electric properties; these can be attributed to a change in the area of the Fermi surface after the alloying of the REM.

As seen from Figs. 4 and 5, the paramagnetic Curie points $\Theta_P^{\parallel}$ and $\Theta_P^{\perp}$ differ noticeably from each other, except for compositions close to gadolinium, where $\Delta\Theta_P$ is quite small. The differences in the values of $\Theta_P^{\parallel}$ and $\Theta_P^{\perp}$ are due to the fact that they depend, besides on the indirect-exchange integral A_{ind}, also on the magnetocrystalline interaction that leads to magnetic anisotropy[2]:

$$k_B\Theta_P^{\parallel}(\mathbf{Q}) = {}^1/_3\bar{G}A_{\text{ind}}(\mathbf{Q}) - {}^1/_{10}(4J(J+1)-3)v_2^0, \quad (5)$$

$$k_B\Theta_P^{\perp}(\mathbf{Q}) = {}^1/_3\bar{G}A_{\text{ind}}(\mathbf{Q}) + {}^1/_{20}(4J(J+1)-3)v_2^0. \quad (6)$$

Here $\mathbf{Q}$ is the wave vector of the helix of the helicoidal antiferromagnetic REM structure ($\mathbf{Q}=0$ for a ferromagnetic REM), and v_2^0 is a parameter of the crystal field. It follows from (5) and (6) that the anisotropy of the paramagnetic Curie points is determined by the magnetocrystalline interaction:

$$\Delta\Theta_P = \Theta_P^{\parallel}(0) - \Theta_P^{\perp}(0) = \Theta_P^{\parallel}(\mathbf{Q}) - \Theta_P^{\perp}(\mathbf{Q}) = -\frac{3}{20k_B}[4J(J+1)-3]v_2^0. \quad (7)$$

Thus, the decrease of Θ_P with increasing gadolinium concentration in the Tb_xGd_{1-x} alloys (see Fig. 5) can be attributed, in accord with Eq. (7), to a decrease of the magnetic-anisotropy energy as $x \to 0$, in agreement with the data that indicate that gadolinium and alloys with a high gadolinium concentration have a relatively weak magnetic anisotropy.[9]

It is seen from Fig. 2 that the point Θ_2 (curve 2) in Tb_xY_{1-x} alloys exceeds noticeably (by tens of degrees for some compositions) the paramagnetic Curie point Θ_P (curve 3). In these alloys, Θ_2 is the temperature of the transition from paramagnetism to helicoidal antiferromagnetism.[5,8] In Tb_xGd_{1-x} alloys Θ_2 is the temperature of the paramagnetism–antiferromagnetism transition only at $x > 0.94$,[9] with $\Theta_2 > \Theta_P$. In these alloys at $x < 0.94$, however, the point Θ_2 is already the paramagnetism–ferromagnetism transition temperature, and in this case Θ_2 (curve 2 on Fig. 3) is smaller than Θ_P (curve 3).

We consider now the physical mechanisms responsible for the difference between Θ_2 and Θ_P. In experiment one observes in place of $\Theta_P^{\perp}(Q)$ the point Θ_2 (the Néel point), since spin-spin correlations of the helicoidal type vanish when the temperature is slightly higher than Θ_2. Using this circumstance, we find from (5) and (6) that the difference between the magnetic-ordering temperature and the paramagnetic Curie point of an isotropic sample is

$$\Theta_2 - \Theta_P \approx \Theta_P^{\perp}(\mathbf{Q}) - \Theta_P = \frac{1}{3}\bar{G}\frac{A_{\text{ind}}(\mathbf{Q}) - A_{\text{ind}}(0)}{k_B} + \frac{4J(J+1)-3}{20k_B}v_2^0. \quad (8)$$

It is seen from (8) that the difference between Θ_2 and Θ_P can be attributed to two causes: first, to the fact that the indirect exchange integrals in the ferromagnetic state and in the state with helicoidal magnetic structure are not equal; second, to the contribution of the magnetocrystalline interaction (anisotropy) $\Delta\Theta_A$.

TABLE I. Contributions made to $\Theta_2 - \Theta_P$ by the magnetic-crystal interaction, $\Delta\Theta_A$, and by the energy gap between the ferro- and antiferromagnetic states, $\Delta\Theta_e$, for Tb_xY_{1-x}.

x	$\Theta_2-\Theta_P$, K	$2\Delta\Theta_e$, K	$\Delta\Theta_A$, K	$\frac{2\Delta\Theta_e}{\Theta_P}$	$\frac{\Delta\Theta_A}{\Theta_P}$	x	$\Theta_2-\Theta_P$, K	$2\Delta\Theta_e$, K	$\Delta\Theta_A$, K	$\frac{2\Delta\Theta_e}{\Theta_P}$	$\frac{\Delta\Theta_A}{\Theta_P}$
1	6	1	16	0.004	0.072	0.50	29	26	18	0.21	0.14
0.91	13	3	19	0.015	0.093	0.415	36	34	30	0.34	0.30
0.835	25	9	25	0.05	0.14	0.26	31	34	23	0.56	0.38
0.63	23	11	17	0.074	0.11	0.10	37	19	21	1.28	1.43

The table lists the values of $\Delta\Theta_A$ calculated for the alloys investigated by us from the formula

$$\Delta\Theta_A = \frac{4J(J+1)-3}{20k_B}v_2^0 = -\frac{1}{3}\Delta\Theta_P. \quad (9)$$

In the Tb_xY_{1-x} alloys the value of $\Delta\Theta_A$ is of the order of 16–30 K and does not fall to zero even when the terbium is strongly diluted with yttrium. In the Tb_xGd_{1-x} alloys the value of $\Delta\Theta_A$ reaches approximately ~16 K in terbium-rich compositions, but decreases with increasing gadolinium content.

To take into account the contribution of the "helicoidality energy" to the temperature

$$\Delta\Theta_e = \frac{1}{3}\bar{G}\frac{A_{\text{ind}}(\mathbf{Q}) - A_{\text{ind}}(0)}{k_B}, \quad (10)$$

we made use of the measurements of the critical magnetic fields H_{cr} and of the magnetization. In a magnetic field in the basal plane, at $H > H_{cr}$ the helicoidal antiferromagnetic structure is destroyed and ferromagnetic order is established. This process is a result of the fact that the energy in the magnetic field becomes equal to or higher than the energy barrier $[A_{\text{ind}}(\mathbf{Q}) - A_{\text{ind}}(0)](x\bar{S})^2$ between the ferromagnetic and antiferromagnetic structures ($\bar{S}$ is the mean value of the spin and x is the concentration of the REM ions). The magnetic energy calculated per ion is equal to

$$E_m = -H\mu x, \quad (11)$$

where μ is the mean value of the magnetic moment of the rare-earth ion. In the molecular field approximation we therefore have at $H = H_{cr}$

$$H_{cr}x\mu \approx [A_{\text{ind}}(\mathbf{Q}) - A_{\text{ind}}(0)](x\bar{S})^2. \quad (12)$$

The quantity $A_{\text{ind}}(\mathbf{Q}) - A_{\text{ind}}(0)$ was calculated by us from Eq. (12) using the experimental values of the magnetization and critical field published previously for the alloys Tb_xY_{1-x},[16] Tb_xGd_{1-x},[9] Dy_xY_{1-x},[17] Gd_xY_{1-x},[18] Tb_xHo_{1-x}.[19] We substituted in (12) the values of H_{cr}, μ, and $\bar{S}$ determined in the temperature region in which we can neglect the influence of the magnetic anisotropy in the basal plane and of the magnetostriction on the value of H_{cr}; this corresponds to the region where H_{cr} is increased by cooling.[20]

The dependence of the difference $A_{\text{ind}}(\mathbf{Q}) - A(0)$ between the exchange integrals in the ferromagnetic and antiferromagnetic states on the spin parameter $\bar{G}$ can be described by a universal curve (Fig. 6). The energy

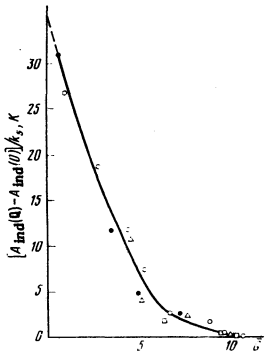

FIG. 6. Energy gap between the ferro- and antiferromagnetic states $[A_{ind}(Q)-A_{ind}(0)]/k_B$ as a function of the spin parameter $\bar{G}$ for the alloys Tb_xY_{1-x}(○), Dy_xY_{1-x}(●), Gd_xY_{1-x}(□), Tb_xHo_{1-x}(△).

gap between the ferromagnetic and the antiferromagnetc states is exceedingly small at $\bar{G}\sim 10.5$, and gadolinium and alloys having $\bar{G}>10.5$ are ferromagnetic. When the mean square of the spin projection on the total angular momentum $\bar{G}$ is increased the quantity $A_{ind}(Q)-A_{ind}(0)$, which is equal to the energy gap between the ferro- and antiferromagnetic states, increases sharply and tends as $\bar{G}\to 0$ to a certain limit, approximately 35 K (see Fig. 6).

The regular variation of $A_{ind}(Q)-A_{ind}(0)$, observed by us for the REM alloys, correlates with the universal plot of the initial helicoid angle ω_i against the factor $\bar{G}$, obtained in neutron-diffraction investigations[5] for heavy REM and their alloys that have in the antiferromagnetic state a helicoidal magnetic structure. The helicoid angle ω_i also tends as $\bar{G}\to 0$ to a certain limit, approximately 50°.

Substituting $A_{ind}(Q)-A_{ind}(0)$ in formula (10), we calculated the quantity $\Delta\Theta_e$ that determines the contribution of the helicoidality energy to the temperature Θ_2 (first term of Eq. (8)). The value of $\Delta\Theta_e$ increases strongly when the terbium is enriched with yttrium, reaching 17 K in Tb_xY_{1-x} alloys at $x=0.415$, comparable with the contribution $\Delta\Theta_A$ made to the transition temperature Θ_2 by the magnetocrystalline interaction (see the table). At small yttrium concentrations we have $\Delta\Theta_e \ll \Delta\Theta_A$. For example, in terbium $\Delta\Theta_e<1$ K and $\Delta\Theta_A\sim 16$ K. It follows also from the table that in the case of strong dilution of the terbium by yttrium the ratio of the magnetic anisotropy energy to the exchange energy is $\Delta\Theta_A/\Theta_P$, just as the ratio $\Delta\Theta_e/\Theta_P$ of the energy gap between the ferromagnetic and antiferromagnetic states to the exchange energy, increases strongly (by one order of magnitude). In $Tb_{0,1}Y_{0,9}$ we have $\Delta\Theta_A>\Theta_P$ and $\Delta\Theta_e\sim\Theta_P$, whereas in terbium $\Delta\Theta_A\ll\Theta_P$ and $\Delta\Theta_e\ll\Theta_P$. Calculations[21] have shown that at large ratios $\Delta\Theta_A/\Theta_P$ the dependence of the temperature of the magnetic ordering on the energy of the magnetocrystalline interaction becomes essentially nonlinear. This can explain the nonlinear dependence of the temperature Θ_2 on the spin parameter $\bar{G}$ and the terbium concentration (see Fig. 2), and also the discrepancy between the values of $\Theta_2-\Theta_P$ and $\Delta\Theta_e+\Delta\Theta_A$ (see the table). Our experimental values of the temperature Θ_2 in the Tb_xV_{1-x} alloys can be described the by empirical relation (accurate to 8%)

$$\Theta_2=\vartheta x^{5/2}, \tag{13}$$

where ϑ is a certain coefficient and changes relatively little with changing terbium concentration:

x:	1	0.95	0.91	0.835	0.63	0.50	0.415	0.26	0.1
ϑ, K:	231	226	231	227	238	244	242	235	245

The temperature Θ_2 is also definitely influenced by effects of short-range magnetic order.[1] In terbium, in view of the small value of the helicoidality energy ($\Delta\Theta_e\sim 1$ K), the differences between Θ_2 and Θ_p are due, in accord with (8), only to the contribution of the magnetocrystalline interaction $\Delta\Theta_A$, which is equal to 16 K in terbium. It follows, however, from the experimental data that in terbium $\Theta_2-\Theta_p\approx 6$ K. This discrepancy can be attributed to effects of short-range magnetic order, the relative role of which in Tb_xGd_{1-x} alloys increases with increasing gadolinium concentration. In fact, in these alloys at $x<0.94$ we have $\Theta-\Theta_p<0$, i.e., the ferromagnetic Curie point Θ is lower than the paramagnetic one, a fact that cannot be satisfactorily explained by Eq. (8), inasmuch in these alloys we always have $\Delta\Theta_e>0$ and $\Delta\Theta_A>0$.

CONCLUSIONS

Thus, the results of an experimental investigation of the magnetic ordering temperatures and of the paramagnetic Curier points of the alloys Tb_xY_{1-x} and Tb_xGd_{1-x} as well as a theoretical discussion of the present results and the published data, lead to the following conclusions.

1. The mean value of the square of the spin projection on the total mechanical angular momentum

$$\bar{G}=\sum_i x_i G_i$$

is a fundamental quantity in heavy REM and their alloys, and the exchange energy, paramagnetic Curie point, as well as the difference of the exchange integrals in the ferro- and antiferromagnetic states depend on this quantity.

2. The change observed by us in the coefficient of the proportionality of the paramagnetic Curie points to the mean values of the square of the spin projection on the total mechanical angular momentum attests to a change in the electronic structure and of the exchange integrals when terbium is alloyed with yttrium and terbium with gadolinium.

3. The experimentally observed difference in the temperature of the transition from the paramagnetic state to the magnetically ordered and in the paramagnetic Curie point in the investigated REM alloys is due to three causes:

a) the magnetocrystalline interaction, which leads to magnetic anisotropy of REM and their alloys;

b) the contribution due to the difference between the indirect exchange energy in the ferromagnetic and antiferromagnetic states;

c) the short-range magnetic order.

[1]S. V. Vonsovskiĭ, Magnetizm (Magnetism), Nauka, 1971 [Halsted, 1975].

[2]T. Kasuya, Magnetism, Vol. 2B. G. T. Rado and H. Suhl, eds., Academic, 1966, p. 215.
[3]P. de Gennes, Compt. Rend. **247**, 1836 (1958).
[4]S. Weinstein, R. Craig, and W. Wallace, J. Appl. Phys. 34, 1354 (1963).
[5]H. Child, W. Koehler, E. Wollan, and J. Cable, Phys. Rev. A. **138**, 1655 (1965).
[6]R. Bozorth and R. Gambino, Phys. Rev. 147, 487 (1966).
[7]K. P. Belov and S. A. Nikitin, in: Ferrimagnetizm (Ferrimagnetism), MGU, 1975, p. 92.
[8]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)].
[9]S. A. Nikitin, N. A. Sheludko, V. P. Posyado, and G. E. Chuprikov, *ibid.* **73**, 1001 (1977) [**46**, 530 (1977)].
[10]K. P. Belov, S. A. Nikitin, V. P. Posyado, and G. E. Chuprikov, *ibid.* **71**, 2204 (1976) [**44**, 1162 (1976)].
[11]A. Freeman, Magnetic Properties of Rare Earth Metals, Plenum Press, London, 1972, p. 258.
[12]R. Z. Levitin, T. M. Perekalina, L. P. Shlyakhina, O. D. Chistyakov, and V. L. Yakovenko, Zh. Tksp. Teor. Fiz. **63**, 1401 (1972). [Sov. Phys. JETP **36**, 742 (1972)].
[13]V. G. Demidov, R. Z. Levitin, and O. D. Chistyakov, *ibid.* **71**, 2381 (1976) [**44**, 1256 (1976)].
[14]I. E. Dzyaloshinskiĭ, *ibid.* **47**, 336 (1964) [**20**, 223 (1964)].
[15]V. S. Belovol, V. A. Finkel', and V. E. Sivokon', *ibid.* **69**, 1734 (1975) [**42**, 880 (1975)].
[16]S. A. Nikitin, A. S. Andreenko, V. P. Posyado, and G. E. Chuprikov, Fiz. Tverd. Tela (Leningrad) **19**, 1792 (1977) [Sov. Phys. Solid State **19**, 1045 (1977)].
[17]S. A. Nikitin, S. M. Nakvi, I. K. Solomkin, and O. D. Chistyakov, *ibid.* **19**, 2301 (1977) [**19**, 1347 (1977)].
[18]T. Ito, J. Sci. Hiroshima Univ., ser. A. 37, 107 (1973).
[19]F. Spedding, R. Jordan, and R. Williams, J. Chem. Phys. 51, 509 (1969).
[20]S. A. Nikitin, Izv. AN SSSR ser. fiz. 42, 1707 (1978).
[21]V. V. Druzhinin, S. P. Zapasskii, and V. M. Povyshev, Fiz. Tverd. Tela (Leningrad) **17**, 23 (1975) [Sov. Phys. Solid State **17**, 12 (1975)].

Translated by J. G. Adashko

Kinetic properties of a superconductor with a structural transformation

Yu. V. Kopaev, V. V. Manyaĭlenko, and S. N. Molotkov

P. N. Lebedev Physics Institute, USSR Academy of Sciences
(Submitted 1 March 1979)
Zh. Eksp. Teor. Fiz. **77**, 352–364 (July 1979)

The kinetic properties (absorption of high frequency ultrasound, relaxation of nuclear spin) of superconductors with partial dielectrization of the conduction electrons with a charge density wave are considered. It is shown that in the case of simultaneous Cooper and electron-hole pairing the ultrasound absorption coefficient has a maximum at the superconducting-transition temperature T_c. The rate of relaxation of the nuclear spin can have a maximum both at T_c and at a lower temperature. It is shown that if T_c is much lower than the structural-transition temperature, the kinetic properties differ insignificantly from the properties obtained in the BCS theory. Intraband Cooper pairing in a semimetal is investigated. It is shown that when account is taken of Hamiltonian terms with transition of a pair of particles from one band to another, the relative phase difference of the order parameters is fixed at either 0 or π. The order-parameter phase shifts due to the phase transitions can lead to observable physical phenomena. The results (in the case $T_p \gtrsim T_c$) agree qualitatively with the experimentally observed singularities of the kinetic properties of semiconductors with β-W structure.

PACS numbers: 74.30.Gn

1. INTRODUCTION

It is well known that the compounds having the highest superconducting transition temperature undergo a structural transformation near this temperature.[1] The influence of the structural distortions on the critical superconducting transition temperature was investigated in a number of studies, using the model of a semimetal with almost identical electron and hole Fermi surfaces,[2] the model of a single-band metal with flat sections of the Fermi surface,[3,4] as well as the model of a quasi-one-dimensional metal.[5] In all the foregoing cases the system turned out to be unstable to electron–hole pairing. In addition, the singularities of the single-particle electron spectrum lead also to instability of the photon subystem,[6] i.e., to structural distortions. As a result of the electron–hole pairing, the state density at the edges of the dielectric gap can increase significantly. If, following the dielectric pairing, the Fermi level of the system is at least partially outside the dielectric gap (this occurs if the Fermi surfaces of the electrons and holes are not completely congruent), superconducting pairing becomes possible. The latter takes place against a background of increased state density, on account of which a substantial rise of T_c is possible. It has also been shown,[2,3] that there exist optimal conditions at which T_c can substantially exceed the superconducting-transition temperature in the absence of dielectric pairing (and hence in the absence of the structural transformation).

We consider in this paper the kinetic properties (the absorption of high-frequency ultrasound, the rate of

 0038-5646/79/070181-07$02.40