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THE PROBLEMS OF MAGNETIC INSTABILITY OF THE SUBSYSTEM OF ZONAL *d*-ELECTRONS

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Abstract. *When studying the specific features of magnetism of metals and intermetallic compounds, the phenomena associated with magnetic instability of the subsystem of zonal d-electrons are of great interest. These phenomena are caused by the threshold nature of ferromagnetism of the system of collectivized electrons, according to which, with certain characteristics of the zonal structure, a situation when the density of states at the Fermi level ε_F increases with the increasing magnetic field is possible. If in the zero field the system of collectivized electrons was in a paramagnetic state, in a certain field H_M, a jump-like (metamagnetic) transition of the system of collectivized electrons from the paramagnetic state to the ferromagnetic one takes place. The investigation of the effect of the $f-d$ exchange field on metamagnets is an efficient method of studying their properties. The objective of this work was to study the effect of the exchange field on the behavior of zonal metamagnets and to determine their basic magnetic state.*
Keywords:*magnetization, metamagnetizm, susceptibility.*

Introduction

The magnetic properties of solids are mainly determined by magnetic moments of the electrons they contain. In metals, alloys, intermetallic compounds, etc., along with magnetized electrons, there are other electrons that break from atoms (ions) and collectivize. However, the electrons are charged particles, and there is electrostatic interaction between them. Along with classical Coulomb energy, this interaction generates the so-called exchange energy, depending on the mutual orientation of electron spins

$$\varepsilon_{ex} = -\frac{1}{2} I\vec{S}_i\vec{S}_j \qquad (1)$$

As follows from eq. (1), when the exchange interaction coefficient I is positive, the exchange interaction strives to orient spins and hence the magnetic moments in parallel to each other. As a result, the exchange interaction enhances paramagnetism, the magnetic susceptibility χ_{ex} of which increases as compared to that of free electron gas χ_p

$$\chi_{ex} = \frac{\chi_p}{1-\lambda\chi_p} \qquad (2)$$

Hence it follows that, when the relationship

$$\lambda\chi_{\exp} \geq 1 \qquad (3)$$

is fulfilled, ferromagnetim emerges in the system of collectivized electrons [1]. Sometimes it is written in terms of $N(\varepsilon_F)$ $N(\mathcal{E}_F)$ as follows

$$IN(\varepsilon_F) \geq 1 \qquad (4)$$

Where $N(\varepsilon_F)$ $N(\mathcal{E}_F)$is the density of states at the Fermi level ε_F $\mathcal{E}_F$[1].

With certain characteristics of the zonal structure, the situation is possible when the density of states at the Fermi level $\mathcal{E}_F$ increases with the increasing external magnetic field [2,3]. Then, if in

ISSN 1512-1461

the zero field the system of collectivized electrons was in the paramagnetic state, in the definite field H_M, a metamagnetic transition of the system of collectivized electrons from the paramagnetic state into the ferromagnetic one occurs [4]. An efficient method of studying the properties of zonal metamagnets is to affect them by the $f-d$ exchange field, which under certain conditions allows reducing the critical field of the magnetic transition. Intermetallic compounds YCo_2 are zonal metamagnets [5]. For optimization of the conditions of the experiment, $A\ell$-substituted compounds YCo_2: $Y(Co_{1-x}A\ell_x)_2$ were used. To exclude the effect of the crystal field, gadolinium was used as a magnetizing rare-earth element. Thus, polycrystalline systems $Y_{1-t}Gd_t(Co_{1-x}A\ell_x)_2$ were synthesized.

Experimental method

Polycrystalline samples of intermetallic compounds $Y_{1-t}Gd_t(Co_{1-x}A\ell_x)_2$, where $0 \le t \le 0.20$ and $x = 0, 0.05, 0.07, 0.085, 0.105$, were smelted in the induction furnace in the atmosphere of spectrally pure argon in a water-cooled copper crucible under quasi-levitation.

The magnetization was measured in static magnetic fields up to $60kOe$ and pulse magnetic fields up to $300kOe$ over the range from $4.2K$ to $300K$. The magnetic susceptibility was measured in weak alternating fields over the same temperature range.

Theoretical model

Theoretical discussion of the basic magnetic properties of the $Y_{1-t}Gd_t(Co_{1-x}A\ell_x)_2$ compounds under consideration can be carried out using the mean field model. We should note at the outset that this model is approximate, it does not take into account either spin fluctuations in the itinerant zonal d-subsystem or magnetic clusters which can form small gadolinium concentrations. Let us consider the zonal d-subsystem of these compounds in the scope of the Wohlfahrt model of weak zonal ferromagnetism. Then, taking into account the $f-d$ exchange interaction, we can write the equation of state for the zonal subsystem in the form

$$\alpha\vec{M}_d + \beta\vec{M}_d^3 + \gamma\vec{M}_d^5 = \vec{H}_{eff}^d \qquad (7)$$

Here $\vec{M}_d$ is the magnetization of the d - subsystem; $\vec{H}_{ef}^d$ is the effective field affecting this system

$$\vec{H}_{eff}^d = \vec{H} + \lambda_{fd}t\vec{M}_f \qquad (8)$$

where$\vec{H}_{mol}^d = \lambda_{fd}t\vec{M}_f$ is the molecular field affecting the subsystem; λ_{fd} is the coefficient of the molecular field of the $f-d$ exchange interaction; M_f is the magnetization of the f - subsystem. In this model, the basic state is ferromagnetic, because the exchange interaction between f - and d - subsystems and heavy rare-earth elements is negative ($\lambda_{fd} < 0$).

For metamagnetic compounds, the analysis of the behavior of magnetization in the magnetic field can be carried out based on equations (7) and (8). If the magnetization of the d -subsystem is higher than that of the f -subsystem ($M_d > tM_f$), the magnetic moment of the d -subsystem is oriented in parallel to the external field, while the moment of the f - subsystem is anti-parallel to it, and the $f-d$ exchange interaction leads to the reduction of the metamagnetic transition field

$$H_M(t) = H_M(0) - (-t\lambda_{fd}M_f) \qquad (9)$$

(recall that $\lambda_{fd} < 0$).

When $M_d < tM_f$ $\mathbf{M_d < tM_f}$, the magnetization of the f -subsystem is oriented along the field. Inthis case, with application of the magnetic field, the d -subsystem first gets demagnetized

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and then gets established in parallel with the magnetic field. Thus, in this case, the $f-d$ interaction leads to an increase in the metamagnetic transition field

$$H_M(t) = H_M(0) + (-t\lambda_{fd} M_f) \qquad (10)$$

In the fields smaller than the metamagnetic transition field, the susceptibility of the d-subsystem can be approximately deemed field-independent. The condition under which the introduction of a magnetic rare-earth element facilitates a decrease in the metamagnetic transition field looks like

$$-\chi_d \lambda_{fd} = 1 \qquad (11)$$

We should note the approximate character of condition (11), which was obtained in the approximation that the d-subsystem susceptibility is field-independent in fields $H < H_M$, furthermore, it includes only collinear two sublatticestructurues without considering the possibility that the sublatttices could split into sub-sublattices. It is well-known that, in the strongly ferrimagnetic phase, a noncollinear magnetic structure should appear in an external field [6].

Results and discussion

The measurements showed that the magnetic systems $Y_{1-t}Gd_t(Co_{1-x}Al_x)_2$ depended on the content of aluminum, and they could be divided into two groups with different magnetic behavior: the compositions with a low concentration of aluminum and the compositions with a high concentration of aluminum.

As an example, Fig. 1 shows the dependence of magnetization on the field of some

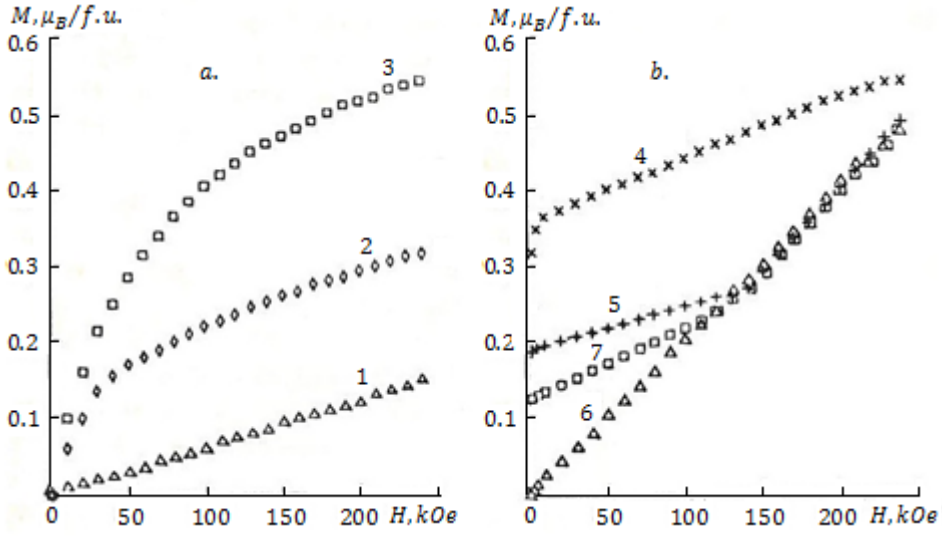


Fig. 1. Magnetization curves of the compounds $Y_{1-t}Gd_t(Co_{0.95}Al_{0.05})_2$ at $4.2K$: a - $t = 0.0\ (1), 0.02(2), 0.04\ (3)$; b - $0.10\ (4), 0.15\ (5), 0.18\ (6), 0.20\ (7)$.

compositions of the systems $Y_{1-t}Gd_t(Co_{0.95}Al_{0.05})_2$ at $4.2K$ with low concentration of aluminum ($x = 0.00$ and $x = 0.05$). It is seen that, with small gadolinium substitutions ($t \le 0.10$), there is no spontaneous magnetization. The increase in the content of gadolinium leads to an increase in the susceptibility in weak fields, the magnetization curves of compositions with gadolinium get nonlinear and tend to saturation in strong fields. The compositions with content of gadolinium $t \ge 0.10$ $t \geq 0.10$ possess a spontaneous moment. The value of this spontaneous moment decreases

with the increasing gadolinium concentration, passes through the minimum at $t_c \approx 0.17 \div 0.18$, and then increases again, i.e. this concentration is the compensation point by content. In the systems in

ISSN 1512-1461

the vicinity of t_c t_c, in the magnetization curves, there are observed flexures characteristic for the transitions from a collinear ferromagnetic phase into a noncolinear one.

Essentially different pattern of magnetization is observed with the system with high content of aluminum ($x = 0.00$, $x = 0.085$ and $x = 0.105$ $x = 0.07, 0.085$ *and* 0.105). Figure 2 shows the magnetization curves of the system $Y_{1-t}Gd_t(Co_{0.915}A\ell_{0.085})_2$ at $4.2K$. It is seen that the initial compound $Y(Co_{0.915}A\ell_{0.085})_2$ is a zonal metamagnet with a critical metamagnetic transition field $H_M = 225kOe$ $H_M = 225kOe$. As the concentration of gadolinium increases, the metamagnetic transition field H_M H_M decreases, and at the concentrations $t \geq 0.04$ these compounds have spontaneous magnetization. In the magnetically ordered area, at relatively low concentrations of gadolinium ($0.04 \leq t \geq 0.06$ $0.04 \leq t \leq 0.06$), spontaneous magnetization is small, and, in the field, a metamagnetic transition from the weakly ferromagnetic to strongly ferromagnetic state occurs. There are not observed metamagnetic transitions at higher concentration of gadolinium ($t \geq 0.06$ $t \geq 0.06$): in the zero field, such compounds are in a strongly ferrimagnetic state. Saturation magnetization decreases as the concentration of gadolinium increases up to $t_c \approx 0.17 \div 0.18$ $t_c \approx 0.17 \div 0.18$, and then increases with the further increase in the concentration of gadolinium. Like in the compositions with low content of aluminum, close to this concentration, transitions from the noncollinear ferromagnetic to noncollinear phase in the external magnetic field are observed.

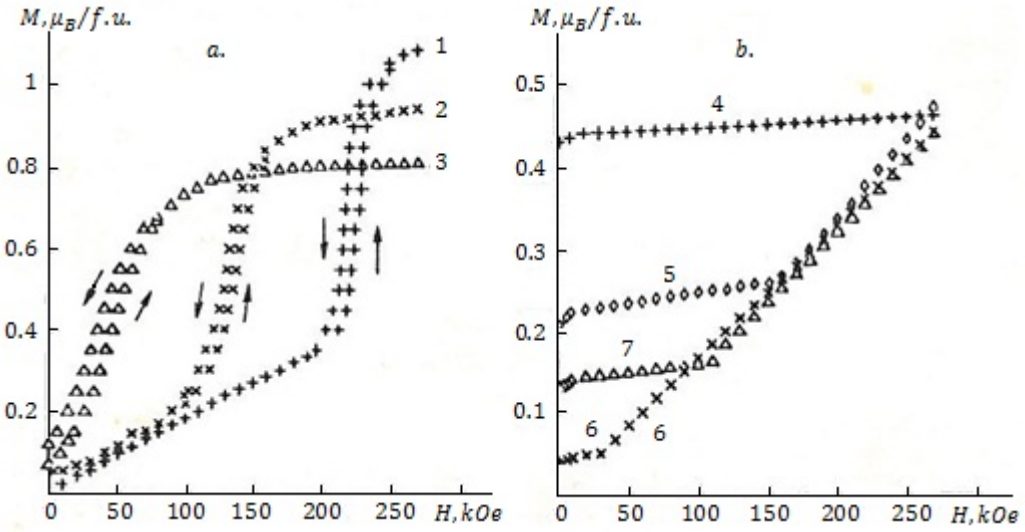
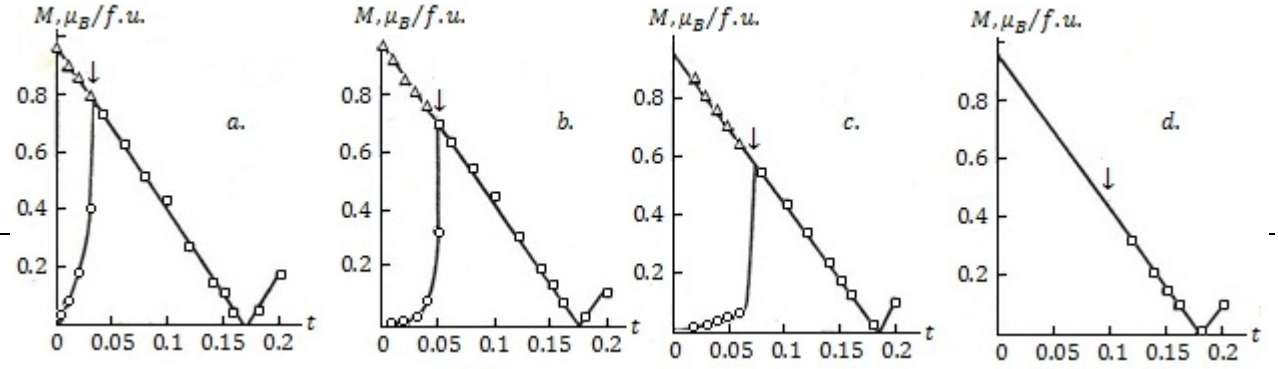


Fig. 2. Magnetization curves of the compounds $Y_{1-t}Gd_t(Co_{0.915}A\ell_{0.085})_2$ at $4.2K$: a - $t = 0.0$ (1), 0.02(2), 0.04 (3); b - $t = 0.10$ (4), 0.15 (5), 0.18 (6), 0.20 (7).

All these specific features are clearly seen in Fig. 3, where the data on the magnetization depending on the concentration of gadolinium for systems with different t. In the most systems, at



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concentrations $(10 \div 14)\%Gd$ these compounds become magnetically ordered. A specific feature of all studied samples, with the concentration of gadolinium about $18\%Gd$ $18\%\ Gd$,the values of magnetization of the f- and d-subsystems become equal. Figure 3 shows the spontaneous magnetization of weakly and strongly ferromagnetic samples and the magnetization in the field $H_M = 270kOe$ for the samples with metamagnetic transitions, illustrating the emergence of magnetic compensation at $4.2K$.

Conclusion

The comparison of the experimental data with calculations for $f-d$ magnetic systems showed a good agreement of the data in most cases, at least qualitatively:

Firstly, in most cases, when the concentration of gadolinium increases, there occurs theoretically predicted transitions from the paramagnetic phase with metamagnetism to a weakly ferromagnetic metamagnetic phase and then to a strongly ferromagnetic phase.

Secondly, as predicted theoretically, the metamagnetic transition fields of the systems with high concentrations of aluminum ($x = 0.07, 0.085$ and 0.105), in which the susceptibility of the subsystems is high, decrease practically linearly with the increasing concentration of gadolinium.

Thirdly, metamagnetic transitions were not found in the systems with low concentrations of aluminum ($x = 0.00$ and 0.05). This fact can be related to low susceptibility of the d-subsystem due to which, in these compounds, the magnetic moment of the f-subsystem is oriented along the field.

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