In conclusion, the authors thank A. F. Uvarov for constructing the piezometer, and V. I. Fedosimov and A. M. Nikolaenko for hlep with the data reduction.

[1)] To be published.

[2)] In this connection the significance of the data of [8] seems uncertain, in view of the lack of data on the measures taken to prevent interaction between the cesium and the pressure-transmitting medium.

[3)] Since it is impossible to include in this brief communication a complete summary of the experimental data, the table lists only the smoothed values of the thermodynamic quantities.

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ELECTRON RESONANCE WITH LOCALIZED MAGNETIC MOMENTS OF Er in SUPERCONDUCTING La

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Electron resonance absorption by localized moments of Er in superconducting La was observed. The temperature and concentration dependences of the g-factor and of the line width were investigated. A possible qualitative interpretation of the results is presented.

The feasibility in principle of investigating electron paramagnetic resonance (EPR) in type-II superconductors was demonstrated experimentally in [1], where we were the first to observe a spin resonance signal from Gd^{3+} ions in the in-ermetallic compound $La_{3-x}Gd_xIn$ in a superconducting (SC) state below H_{c2}. More detailes investigations of EPR with Gd impurities in the SC compound $La_{1-x}Gd_xRu_2$ were subsequently carried out in [2].

We present here preliminary results of the study of EPR with localized magnetic moments of Er in La. The choice of Er as the paramagnetic impurity has made it possible to conduct the research in a much larger range of concentrations and in weaker resonant fields. The measurements were made at ∿ 9400 MHz in the temperature interval 2 - 4.5°K, on bulky samples of polycrystalline La with Er concentrations from 0.5 to 3 at.%.

Figure 1 shows a typical plot of the EPR signal superimposed on the surface-impedance curve of the SC sample. The resonance line has a near-Lorentz shape, with an asymmetry parameter A/B = 2.5. The measured g-factor was $g_{exp} = 6.83 \pm 0.05$. It is known that metallic La crystallizes in the form of a mixture of two modifications with a hexagonal lattice (α-La) and a cubic lattice (β-La). Measurement of the temperature dependence of H_{c2} in our samples has revealed the presence of an appreciable fraction of β-La. It is impossible to observe the EPR signal from Er^{3+} in polycrystalline α-La, owing to the large anisotropy of the

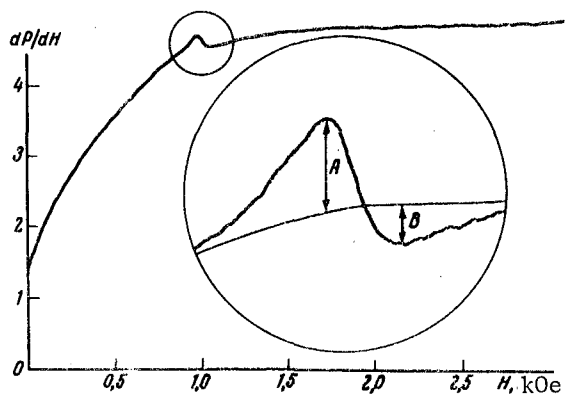

Fig. 1. Plot of EPR signal (dP/dH in relative units) for a sample of La + 1.5 at.% Er at T = 2.5°K and ν = 9369.4 MHz.

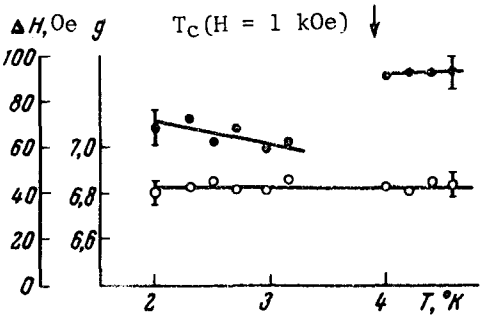

Fig. 2. Temperature dependence of ΔH and of the g-factor for a sample of La + 2 at.% Er: o — ΔH; o — g-factor.

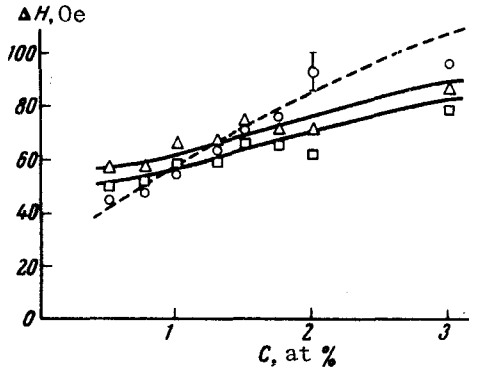

Fig. 3. Concentration dependence of ΔH at different temperatures: circles — normal phase, 4.2°K; triangles and squares — SC phase, 3°K and 2°K, respectively. Expressions (1) correspond to the dashed line in the normal phase and to the solid line in the SC phase.

g-factor. In a cubic field, the lower energy level is the Kramers doublet Γ_7 with g = 6.77 when the intermediate coupling is taken into account. The proximity of the observed g-factor to the theoretical value is an unequivocal confirmation that the resonance signal is due to the cubic phase. We note that when the sample goes over into the SC state the g-factor does not undergo noticeable changes within the limits of the measurement accuracy (see Fig. 2).

Figures 2 and 3 show typical temperature and concentration dependences of the line width ΔH (half width at half maximum). It follows from the presented results that: 1) ΔH depends little on the temperature in the normal region, 2) the line width decreases sharply on going to the SC state, 3) ΔH increases with decreasing temperature in the SC, 4) ΔH decreases with decreasing concentration, and the slopes of the concentration-dependence curves differ noticeably for the normal and SC phases. The results can be qualitatively interpreted in the following manner:

1. Normal state. The main contributions to the line width of the EPR with the localized magnetic moments are due to the interactions between these moments (dipole-dipole and exchange interactions), with the conduction electrons (the Korringa mechanism), and with the inhomogeneities of the crystal lattice. An estimate of the line broadening due only to the dipole-dipole interactions leads to $\Delta H = 4.9\times10^3 c$, which greatly exceeds the concentration-dependent part of the observed width. It can be assumed that the narrowing of the line in the investigated samples is the consequence of indirect exchange via -he conduction electrons in accordance with the Ruderman-Kittel-Kasuya-Yoshida (RKKY) theory, since direct exchange between the f-electrons has low probability. In this case we have for the half-width of the Lorentz curve $\Delta H = (\pi/2\sqrt{3})M_2^{3/2}/M_4^{1/2}$, where M_2 and M_4 are the second and fourth moments, respectively. It follows then from [3], after averaging over the magnetic-field directions, that

$$M_2 = 3.8(g^2\beta^2/v)^2 + \sigma^2; \quad M_4 = 5.5(g^2\beta^2/v)^4 c + 12.8(g^2\beta^2/v)^2 I^2 c^2. \qquad (1)$$

Here δ^2 is the contribution made to M_2 by the lattice defects and the Korringa mechanism (not taken into account in M_4), I is the exchange integral between the ions for the nearest lattice sites, c is their concentration in atomic fractions, and v is the volume per atom. We note that in the case S = 1/2 the exchange part of M_4 does not contain a term linear in the concentration. As seen from Fig. 3, the experimental results for T = 4.2°K are satisfactorily described by these formulas if we put δ = 23 Oe and I_H = 3.3°K.

2. Superconducting state. On going to the superconducting phase, another cause of EPR linebroadening appears, due to the onset of an inhomogeneous magnetic-field distribution in the sample at $H_{c1} < H < H_{c2}$. Nonetheless, as already noted, a noticeable narrowing of the EPR line occurs and decreases with decreasing paramagnetic-impurity concentration. It is not excluded that such a line narrowing can be the consequence of the increase in the indirect RKKY exchange interaction on going to the SC state, which can be attributed to the increased density of states on both sides of the energy gap and to coherence effects. The data shown in Fig. 3 for T = 3°K can be reconciled with (1) at δ = 30 Oe and I_{SC} = 5,6°K. The observed temperature dependence of δ is probably determined by the competing broadening mechanisms due to the inhomogeneous field distribution and the exchange narrowing.

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CONTRIBUTION TO THE THEORY OF INVAR ALLOYS

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One of us, together with Sedov, has shown in [1] that the anomalies of invar alloys can be explained by assuming that an exchange interaction that disrupts in part the parallel spin orientation exists between the electrons of neighboring iron ions in the face-centered lattice of these alloys. That is to say, the exchange integral is negative for neighboring iron ions, $I^{FeFe} < 0$, whereas the corresonding integrals I^{FeNi} and I^{NiNi} are positive. The model proposed in [1] was further devloped in [2, 3]. The features of invar alloys were discussed recently also from the point of view of the model of rigid bands in [4, 5].

The main shorcoming of [1 - 3] was that the localized-spin model used in them was more readily suitable for dielectrics than for metallic alloys. The shortcoming of [4, 5], to the contrary, was that they were based on a model in which no account was taken of the singularities of the state-density curve for a disordered alloy. Nor was allowance made for the exchange interaction between nearest neighbors, which strongly influences the magnetic properties of alloys [6, 7].

In the present article we discuss the properties of invar alloys from the point of view of the model of strongly coupled electron and we use the coherent potential method (CPA) proposed by Soven [8] and by Velicky et al [9] (see also [10]). We introduce in the Hamiltonian additional parameters that characterize the electron exchange interaction between neighboring ions, averaged over the configurations.

We express the Hamiltonian for a binary ferromagnetic alloy in the form

$$H = H_1 + H_2, \tag{1}$$

$$H_1 = \sum_{n,m\sigma} t_{nm} a^+_{n\sigma} a_{m\sigma} + \sum_{n,\sigma} \epsilon_n n_{n\sigma} + (1/2) \sum_{n,\sigma} U_n n_{n\sigma} n_{n,-\sigma}, \tag{2}$$

$$H_2 = -2 \sum_{n,m} I_{nm} (S^x_n S^x_m + S^y_n S^y_m + S^z_n S^z_m), \tag{3}$$

$$\begin{aligned} S^x_n &= (1/2)(a^+_{n\uparrow} a_{n\downarrow} + a^+_{n\downarrow} a_{n\uparrow}), \\ S^y_n &= (1/2i)(a^+_{n\uparrow} a_{n\downarrow} - a^+_{n\downarrow} a_{n\uparrow}), \\ S^z_n &= (1/2)(n_{n\uparrow} - n_{n\downarrow}), \end{aligned} \tag{4}$$

where $t_{nm} = t^{AA}_{nm}$, t^{AB}_{nm}, t^{AB}_{nm} are the transfer integrals and $I_{nm} = I^{AA}$, I^{AB}, and I^{BB} are the exchange integrals between the electrons of the nearest-neighbor ions A and B occupying lattice points n and m, $\epsilon_n = \epsilon^A$, ϵ^B, $U_n = U^A$, U^B are integrals characterizing the Coulomb interaction of the electrons at the ions of kind A and B occupying the site n, and $a^+_{n\sigma}$ and $a_{n\sigma}$ are the creation and annihilation operators for electrons with spin σ at the site n. We associate with each site two states, one with spin up and the other with spin down. In the considered case of invar alloys we assume, as in [1], that $I^{AA} < 0$, $I^{AB} > 0$, $I^{BB} > 0$ and $U^A = U^B = U$.

We seek a solution for the average energy and the average magnetic moments in the Hartree-Fock approximation, replacing in the third sum of the Hamiltonian H_1 the operator $n_{n,-\sigma}$ by its