
The behavior of the electrical resistivity and magnetoresistance of lanthanum hexaboride with isolated (~1%) Ce or Ho magnetic impurities has been studied. It has been shown that the low-temperature growth of the resistivity is characteristic of the weak localization regime for charge carriers rather than of the Kondo effect. The negative magnetoresistance observed in Ce,La,B6 and Ho,La,B6 at liquid helium temperatures also cannot be interpreted in terms of the Kondo model and corresponds to the formation of many-body states of a spin-polaron type near magnetic rare-earth ions in LaB6.

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1. Rare-earth (RE) Ce,La,B6 hexaborides represent the most prominent example of the heavy-fermion (HF) systems [1–3]. On cooling, since the densities of charge carriers and 4f centers in CeB6 are nearly the same (n ≈ n4f) [4, 5], an increase in the resistivity of this compound is exceptionally large for HF metals (by a factor of about 3) [5, 6]. The HF state was found, in particular, by measurements of the electronic specific heat in cerium hexaboride. For this compound, the value obtained for the Sommerfeld coefficient, γ ≈ 250 mJ/(mol−1 K−2) [7], significantly (by about a factor of 100) exceeds the corresponding value for the nonmagnetic reference compound LaB6, for which γ ≈ 2.6 mJ/(mol−1 K−2).

It is a common practice to assume that Ce,La,B6 hexaborides are classical examples of the systems exhibiting both (a) the Kondo impurity regime (at x < 0.10) and (b) the Kondo lattice regime (at x = 1) [1–4]. Thus, the formation of heavy fermions in these compounds is assumed to be directly related to the Kondo-type low-temperature compensation of the localized magnetic moments of Ce4+ ions. Such compensation gives rise to the Kondo singlet state (Kondo “cloud”) in a broad spatial range around RE ions at distances far exceeding the lattice constant, a ≈ 4.1 Å. At the same time, it is commonly supposed to be trustworthy that the characteristic temperature of spin fluctuations $T_K$ in these compounds is about 1–2 K and depends only slightly on the density of magnetic centers [6, 8].

It was quite recently found that the low-temperature growth of the resistivity in Ce,La,B6 substitutional solid solutions is described by a power law $\Delta \rho \sim T^{\alpha}$ ($\alpha = 0.36–0.49$ depending on x) within a wide temperature range ($T \leq 20$ K). Such behavior is observed both in the regime of low impurity density ($x = 0.03$ and 0.10) and for the lattice formed by magnetic Ce centers ($x = 1$) [5, 9, 10]. It corresponds to the weak localization of charge carriers [11]. In [9, 10], it is shown that the magnetic contribution to the resistivity for the compound with x ≤ 0.10 cannot be described by the Kondo-type logarithmic law $\Delta \rho \sim –\ln T$ suggested earlier in [6, 12] for fitting the $\rho(T)$ curves only within the temperature range of 0.5–2 K. In addition, it was reported in [10] that the effect of negative magnetoresistance observed at low temperatures in Ce,La,B6 with $x = 0.03$ and 0.10 can be quantitatively described by the relation $-\Delta \rho/\rho \sim M^2 - x_{\text{loc}}^2 H^2$ ($M$ and $x_{\text{loc}}$ are the local magnetization and susceptibility, respectively). This relation was derived by Yosida [13] in the framework of the $s–d$ exchange model. The result by Yosida is based on the spin-polaron effect providing a description of the many-body resonance in the electron density of states near the Fermi energy, which is a possible alternative to the Kondo-type description. Along with the weak-localization asymptotic behavior
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for the resistivity obtained in [9, 10], the result by Yosida allows an interpretation of the nature of heavy fermions in CeₓLa₁₋ₓB₆ different from the generally accepted one. To make the choice between these two possibilities, it could be of interest to comparatively analyze low-temperature contributions to the resistivity arising when Kramers (Ce³⁺) or non-Kramers (non-Kondo) RE ions are introduced into the non-magnetic LaB₆ matrix.

2. To get an insight into the nature of many-body states arising near magnetic RE ions in the LaB₆ matrix, we studied the resistivity and magnetoresistance of lanthanum hexaboride with substitutional impurities of cerium (4f¹ configuration) and holmium (4f¹⁰ configuration) ions. According to the results reported in [6], the effects of interaction between the heavy-fermion states of neighboring Ce³⁺ ions become significant even for the compounds with x > 0.03. For this reason, we studied RₓLa₁₋ₓB₆ (R = Ce, Ho) hexaborides with the doping levels x(Ho) = 0.005 and x(Ce) = 0.011. The high-quality single-crystalline samples under study were grown by vertical crucible-free zone melting in an argon atmosphere at the Frantsevich Institute for Problems of Materials Science, National Academy of Sciences of Ukraine (Kyiv). The Ce and Ho concentrations in LaB₆ single crystals were determined by microprobe analysis using a JXA 8200 facility (JEOL, Japan). The measurements of resistance were performed within the temperature range of 1.8–300 K in an applied magnetic field up to 8 T by the dc four-probe technique at the homemade setup described in [5].

3. In Fig. 1, we show the temperature dependence of the resistivity at zero magnetic field and at 8 T for (a) Ce₀.₀₁₁La₀.₉₈₉B₆ and (b) Ho₀.₀₀₅La₀.₉₉₅B₆ samples. In panel (c), we show for comparison the corresponding ρ(T) curves at μ₀H = 0 and 8 T for the nonmagnetic reference compound LaB₆. In Fig. 1c, we can see that the resistivity of lanthanum hexaboride is characterized by the metallic type behavior and the values of ρ at room and liquid helium temperatures differ by a factor as large as 370. With the growth of the applied magnetic field, LaB₆ exhibits a large positive magnetoresistance; its value in the temperature range T < 30 K at the field of 8 T is 750%. The doping of LaB₆ with Ce and Ho magnetic impurities gives rise to a range in ρ(T) curves below 20 K, where the resistivity grows on cooling (see Figs. 1a and 1b). At temperatures near the minimum in ρ(T) curves at a nonzero applied magnetic field, we observe a positive magnetoresistance, whereas at liquid helium temperatures in a field of 8 T, there appears a pronounced negative magnetoresistance (see Figs. 1a and 1b). The measurements of the magnetic field dependence of the magnetoresistance allow us to study in more detail the crossover from the positive magnetoresistance regime in Δρ/ρ = f(H, T₀) curves (Fig. 2). In Fig. 2, we see that the positive magnetoresistance is the dominant one at temperatures exceeding 8 and 3 K in the samples with Ce and Ho impurities, respectively. With the growth of the magnetic field, the linear portion in the temperature dependence of the positive magnetoresistance passes to saturation (see curves corresponding to T₀ = 9 and 5 K in Figs. 2a and 2b, respectively). Moreover, in the case of the Ho₀.₀₀₅La₀.₉₉₅B₆ crystal at T > 3 K, we also observe the quantum oscillations of the resistivity (the Shubnikov–de Haas effect). In contrast to that, the characteristic features in the magnetic field dependence of the magnetoresistance at T₀ ~ 2 K are determined by the effect of negative magnetoresistance (see the curves corresponding to T₀ = 2.1 K in Fig. 2).