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Magnetoresistance and magnetization anomalies in CeB_6 ☆

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Abstract

High precision magnetoresistance (MR) $\Delta\rho/\rho(H,T)$ and magnetization $M(H,T)$ measurements have been carried out for well known and typical strongly correlated electron system—cerium hexaboride. The detailed measurements have been fulfilled on single crystalline samples of CeB_6 over a wide temperature range $T \geqslant 1.8$ K in magnetic fields up to 70 kOe. It was shown that the MR anomalies in the magnetic heavy fermion compound under investigation can be consistently interpreted in the frameworks of a simple relation between resistivity and magnetization—$\Delta\rho/\rho \sim M^2$ obtained by Yosida [Phys. Rev. 107(1957)396]. A local magnetic susceptibility $\chi_{loc}(T,H) = (1/H^*(d(\Delta\rho/\rho)/dH))^{1/2}$ was deduced directly from the MR $\Delta\rho(H,T)$ measurements and compared with the experimental data of magnetization $M(H,T)$. The magnetic susceptibility dependences $\chi_{loc}(T,H)$ and $\chi(T,H)$ obtained in this study for CeB_6 allow us to analyze the complicated H–T magnetic phase diagram of this so-called dense Kondo-system.

Keywords: Heavy fermions; Magnetoresistance; Magnetization

The large negative magnetoresistance (MR) is well-established and widely discussed feature of anomalous transport in canonical strongly correlated electron systems (SCES)—dense Kondo-systems ($CeAl_3$, $CeCu_6$ [1,2]), magnetic Kondo-lattices ($CeAl_2$, CeB_6, $CePb_3$ [3–5]), Kondo-insulators ($Ce_3Bi_4Pt_3$, CeNiSn [6,7]), etc. A commonly used interpretation of negative MR in the SCES is based on the depression of the mechanism of Kondo-compensation [8–10], resulting in an essential decrease of resistivity in magnetic fields $H \sim k_B T_{sf}/\mu_B$ (T_{sf}-spin fluctuation temperature). Besides, an abrupt change of negative MR amplitude observed in the vicinity of metamagnetic transition is widely used in plotting magnetic phase diagrams [2,11,12]. Thus the "correlated" behavior of magnetization and MR in the systems with strong electron correlations is commonly accepted. At the same time, as far as we know, there is a lack of detailed quantitative analysis of negative MR effect in conductors in concentrated limit corresponding to the existence of localized magnetic moments (LMM) in every unit cell of crystal lattice.

To shed more light on this problem, the comprehensive study of MR $\Delta\rho/\rho(H,T)$ and magnetization $M(H,T)$ has been carried out for well known and archetypal magnetic SCES-CeB_6. The detailed measurements have been fulfilled on single crystals of CeB_6 over a wide temperature range $T \geqslant 1.8$ K in magnetic fields up to 70 kOe. The measurements of $\Delta\rho(T,H)$ were performed in transverse geometry ($I \perp H$) using the dc four-probe technique. Two-channel nanovoltmeters Keithley 2182 included to the experimental setup similar to that one described in [13] were used for precision measurements of nanovolt level voltage from potential contacts to the sample. The required temperature

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stabilization accuracy (about 0.01 K) of the measuring cell with the sample was achieved with the help of the original domestic temperature controller based on digital signal processors and standard resistance thermometer CERNOX 1050. The magnetic measurements $M(H,T)$ were made on the improved vibration sample magnetometer LDJ-1500 (USA).

Temperature dependence of resistivity $\rho(T)$ is presented in Fig. 1a. The data of Fig. 1a show that resistivity significantly increases (approximately by factor of 3) with temperature lowering in the interval $T \leqslant 150\,\mathrm{K}$ and shows maximum in the vicinity of magnetic antiferro-quadrupole (AFQ) phase transition ($T_Q \approx 3.2\,\mathrm{K}$) followed by falling of $\rho(T)$. Then, a pronounced kink on the resistivity curve (Fig. 1a) indicates the antiferromagnetic (AF) phase transition at $T_N \approx 2.3\,\mathrm{K}$, which is accompanied by a further decrease in resistivity. The application of magnetic field (up to 70 kOe) dramatically decreases the amplitude of resistivity maximum and shifts its position to higher temperatures. The typical MR dependencies $\Delta\rho(H,T_0)/\rho_0$ recorded at fixed temperatures ($2\mathrm{K} \geqslant T \geqslant 24\mathrm{K}$) in magnetic field range up to 70 kOe are presented in Fig. 1b. The negative MR effect at low temperatures $T \approx 2\,\mathrm{K}$ reaches ~95% in magnetic fields up to 70 kOe. In the paramagnetic phase MR shows the "Brillouin"-type behavior ($-\Delta\rho/\rho \sim H^2$) that is proved by linear approximation of derivative dependencies $\mathrm{d}(\Delta\rho/\rho)/\mathrm{d}H = f(H,T_0)$ in low magnetic field (see, e.g. Fig. 1c). The abrupt kinks on $\Delta\rho(H,T_0)/\rho_0$ curves observed with increase of magnetic field (Fig. 1b) correspond to magnetic transitions to AFQ ($T \approx T_Q$) and AF ($T \approx T_N$) phases.

It is commonly considered, that the low-temperature maximum in $\rho(T)$ dependencies of Ce-based heavy fermion compounds (Fig. 1a) results from the crossover

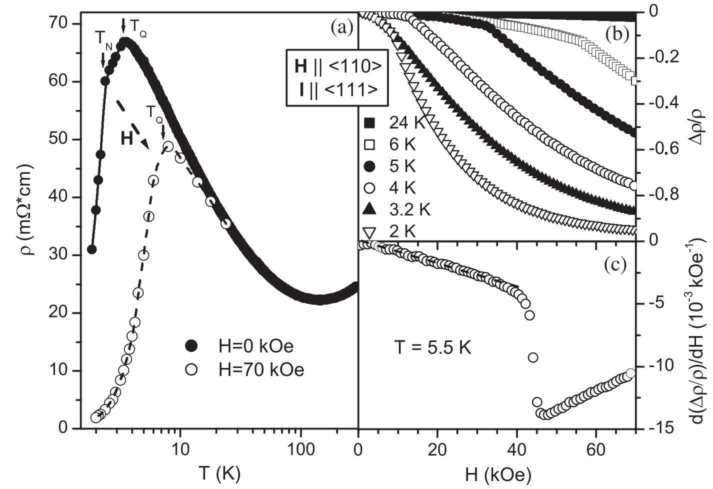

Fig. 1. (a) Temperature dependencies of resistivity $\Delta\rho(H_0,T)$ in magnetic fields $H = 0$ and 70 kOe. (b) Field dependencies of magnetoresistance $\Delta\rho/\rho(H,T_0)$ for different temperatures $2\,\mathrm{K} \leqslant T \leqslant 24\,\mathrm{K}$. (c) Field dependence of derivative $\mathrm{d}(\Delta\rho/\rho)/\mathrm{d}H = f(H)$ at $T_0 = 5.5\,\mathrm{K}$.

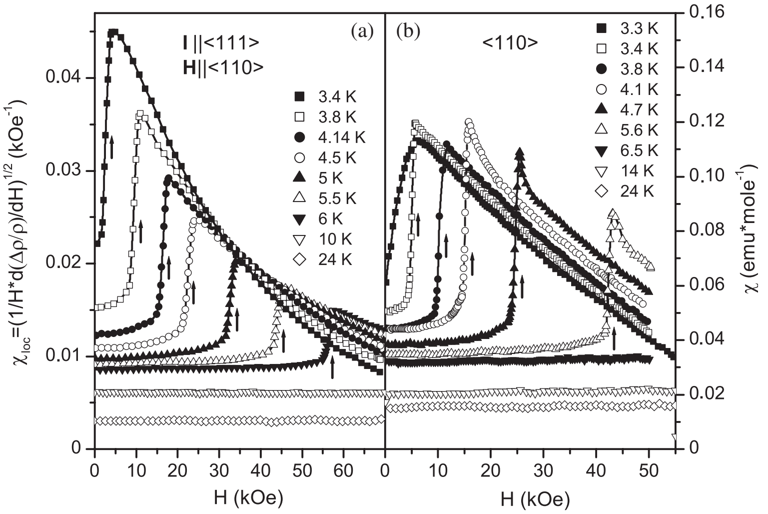

Fig. 2. Magnetic field dependencies of: (a) local (χ_{loc}) and (b) bulk (χ) susceptibility of $\mathrm{CeB_6}$ for temperatures $T \geqslant 3.3\,\mathrm{K}$. Arrows mark the features on susceptibility curves.

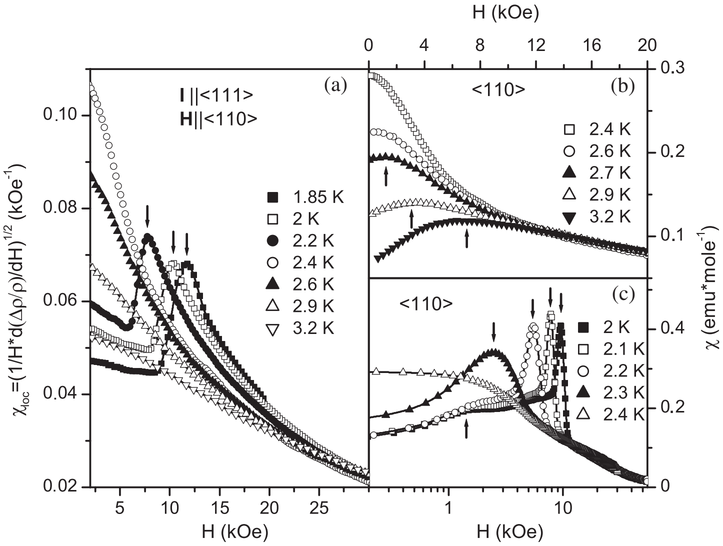

Fig. 3. Field dependencies of: (a) local (χ_{loc}) and (b) bulk (χ) susceptibility of CeB$_6$ for temperatures $1.8\,\mathrm{K} \leqslant T \leqslant 3.2\,\mathrm{K}$. Arrows mark the features on susceptibility curves.

in scattering character of charge carriers from the spin–flip Kondo-scattering (leading to LMM compensation on Ce-centers) to the coherent regime that is realized at low temperatures in dense Kondo-systems. Thus, the decrease of this maximum of $\rho(T)$ with magnetic field seems to be due to depression of the mechanism of Kondo-compensation. However, the analysis of the experimental dependence $\rho(T)$ does not reveal any extended range of the Kondo-like behavior of resisivity in CeB$_6$. Moreover, neither negative sign of Hall coefficient nor unusual Seebeck coefficient temperature behavior could be explained in frameworks of Kondo scattering model [14].

In our point of view, one of the simple, relatively long known and widely applied approaches to the description of negative MR effect in conductors with embedded LMM is the model offered by Yosida [15]. In particular, it was shown on the basis of calculations within *s–d* exchange model [15] that charge carriers scattering at LMM leads to the large contribution in resistivity which is suppressed by external magnetic field. As a result, the negative MR effect is found to be proportional to squared local magnetization [15]

$$-\Delta\rho/\rho = 0.61\langle M\rangle^2/S^2 = \beta M_{\mathrm{loc}}^2. \tag{1}$$

In low magnetic fields, relation (1) can be simplified

$$-\Delta\rho/\rho = \beta\chi_{\mathrm{loc}}^2 H^2. \tag{2}$$

Turning to the analysis of experimental results, it should be mentioned that the interpretation of the MR data (Fig. 1b) in terms of relations (1) and (2) allows to estimate the local magnetization $M_{\mathrm{loc}}(H,T)$ in the immediate vicinity of Ce-centers in this SCES. According to (2), the numerical differentiation of MR data (see, $\mathrm{d}(\Delta\rho/\rho)/\mathrm{d}H = f(H,T_0)$ curves in Fig. 1c) immediately results to the family of $\chi_{\mathrm{loc}}(H,T_0) \equiv (1/H^*(\mathrm{d}(\Delta\rho/\rho)/\mathrm{d}H))^{1/2}$ curves for the Ce-based compound under investigation.

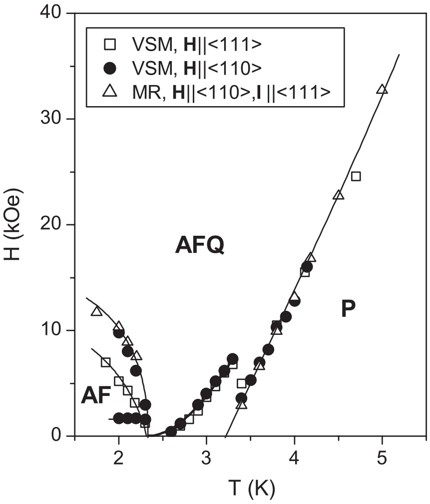

Fig. 4. *H–T* magnetic phase diagram for CeB$_6$, VSM-data of vibrating sample magnetometer $\chi(H,T)$, MR-data of magnetoresistance measurements ($\chi_{\mathrm{loc}}(H,T)$).

The data of Figs. 2 and 3 present the calculated values of $\chi_{\mathrm{loc}}(H,T)$ in comparison to the data of bulk susceptibility $\chi(H,T)$. Very similar behavior of $\chi_{\mathrm{loc}}(T,H)$ and $\chi(T,H)$ dependencies can be considered as an evidence in favor of Yosida's approach [15] to describe the charge transport in the SCES under investigation. Both local $\chi_{\mathrm{loc}}(H,T)$ and bulk $\chi(H,T)$ magnetic susceptibilities remain constant in paramagnetic phase with magnetic field and monotonously go up with temperature decrease (see Fig. 2a and b). Then, at temperatures $T < T_{\mathrm{Q}}(H)$ $\chi_{\mathrm{loc}}(H,T)$ and $\chi(H,T)$ curves demonstrate strong magnetic field dependences which are characterized by the abrupt kinks corresponding to magnetic transition to AFQ phase. In the vicinity of transition to AF phase ($T \approx T_N(H)$) susceptibility shows narrow positive maxima in small enough magnetic fields <12 kOe (see Fig. 3). Furthermore, in AF phase bulk $\chi(H,T)$ magnetic susceptibility demonstrates additional feature (kink) in magnetic field ≈ 2 kOe that seems to be connected with reorientation of AF domains.

The above mentioned features of $\chi_{loc}(T,H)$ and $\chi(T,H)$ dependencies (Figs. 2 and 3, marked by arrows) obtained in this study for CeB_6 were used to reconstruct complicated low-temperature H–T magnetic phase diagram. Note that the phase diagram presented in Fig. 4 is in good consistence with the literature data (see, e.g., studies [16,17]). However, an addition feature in AFQ phase which was observed for the first time in this study at temperature interval $T_N < T < T_Q$ (see Fig. 4) makes it necessary to perform additional investigations of unusual magnetic and transport properties of this SCES.

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References

[1] N.B. Brandt, V.V. Moshalkov, N.E. Sluchanko, E.M. Savitskii, T.M. Shakatova, Solid State Commun. 53 (1985) 645.

[2] T. Penney, F. Milliken, S. von Molnar, F. Holtzberg, Z. Fisk, Phys. Rev. B 34 (1986) 5959.

[3] F. Lapierre, P. Haen, A. Briggs, M. Sera, J. Magn. Magn. Mater. 63–64 (1987) 76.

[4] A. Takase, K. Kojima, T. Komatsubara, T. Kasuya, Solid State Commun. 36 (1980) 461.

[5] U. Welp, G. Remenyi, J. Flouquet, P. Morin, A. Briggs, G. Cors, J. Magn. Magn. Mater. 63–64 (1987) 28.

[6] G.S. Boebinger, A. Passner, P. Canfield, Z. Fisk, Physica B 211 (1995) 227.

[7] T. Takabatake, M. Nagasawa, H. Fujii, M. Nohara, T. Suzuki, T. Fujita, G. Kido, T. Hiraoka, J. Magn. Magn. Mater. 108 (1992) 155.

[8] N.B. Brandt, V. Moshchalkov, Adv. Phys. 33 (1984) 373.

[9] V. Zlatic, J. Phys. F 11 (1981) 2147.

[10] Y. Lassailly, A. Bhattacharjee, B. Coqblin, Phys. Rev. B 31 (1985) 7424.

[11] A.K. Nigam, S. Radha, S.B. Roy, G. Chandra, Physica B 205 (1995) 421.

[12] H.P. Kunkel, X.Z. Zhou, P.A. Stampe, J.A. Cowen, G. Williams, Phys. Rev. B 53 (1996) 15099.

[13] N.E. Sluchanko, A.V. Bogach, V.V. Glushkov, S.V. Demishev, M.I. Ignatov, N.A. Samarin, G.S. Burkhanov, O.D. Chistyakov, JETP 98 (2004) 793.

[14] N.E. Sluchanko, A.V. Bogach, V.V. Glushkov, S.V. Demishev, M.I. Ignatov, Yu.B. Paderno, N.A. Samarin, N.Yu. Shitsevalova, cond-mat/0505475.

[15] K. Yosida, Phys. Rev. 107 (1957) 396.

[16] S. Horn, F. Steglich, M. Loewenhaupt, H. Scheuer, W. Felsch, K. Winzer, Z. Phys. B 42 (1981) 125.

[17] S.V. Demishev, A.V. Semeno, Yu.B. Paderno, N.Yu. Shitsevalova, N.E. Sluchanko, Phys. Stat. Sol. B 242 (2005) R27.