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Magnetoresistance of the $CeCo_{1-x}Fe_xGe_3$ Alloys

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A transition from $CeCoGe_3$ to the $CeFeGe_3$ compound, i.e. the $CeCo_{1-x}Fe_xGe_3$ series has been studied by magnetoresistance measurements. Previously, it was reported that at the concentration $x \approx 0.6$ the system is in the vicinity of the quantum critical point. In the present research we have performed the isothermal magnetoresistivity investigations (down to 2 K) on polycrystalline samples with $x = 0.3$, 0.4, and 0.6 to gain further insight into the possible existence of quantum critical point in the $CeCo_{1-x}Fe_xGe_3$ series. Additionally, electrical resistivity as a function of temperature has been measured and analyzed showing features of non-Fermi liquid behavior at low temperatures.

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1. Introduction

Strongly correlated systems with d- and f-electrons cannot be described by standard models for metals and insulators. To predict basic magnetic properties of such materials, a Doniach diagram can be used. It shows a competition between the Ruderman–Kittel–Kasuya–Yosida (RKKY) and Kondo-type interactions by plotting the characteristic temperatures as a function of $|JN(E_F)|$ [1], i.e. the product of the interaction integral and the density of states at the Fermi level. With a domination of one of the interaction types, there is a possibility of an occurrence of magnetic order or nonmagnetic phases. A magnetic phase transition at absolute zero temperature is named a quantum critical point (QCP). The appearance of QCP determines interesting physical properties, such as the unconventional superconductivity or novel magnetic phases. Approaching of the material to the QCP can induce a non-Fermi liquid (NFL) behavior of the physical properties. Therefore, observation of the NFL state can provide information about the QCP if it is expected in the investigated material [2]. We have decided to reach QCP by chemical substitution of the *3d* metal element of the magnetically ordered $CeCoGe_3$ compound, i.e. by a transition to the nonmagnetic $CeFeGe_3$.

$CeCoGe_3$ is a well-known antiferromagnetic compound. It shows a complicated magnetic structure with three antiferromagnetic phase transitions at $T_{N1} = 21$ K, $T_{N2} = 12$ K, and $T_{N3} = 8$ K [3–7]. $CeFeGe_3$ is a nonmagnetic heavy fermion with high Kondo temperature (over 100 K) [7–9]. The *3d* elements are nonmagnetic in these alloys and the magnetic moment is mainly due to the Ce ions. Both compounds have the same tetragonal and noncentrosymmetric $BaNiSn_3$-type structure. Substitution of Co with Fe provides the $CeCo_{1-x}Fe_xGe_3$ system. It is expected to reach a QCP at the transition from the antiferromagnetic order to the nonmagnetic phase. It was previously reported [10] based on the resistivity and AC magnetization measurements that for $x \approx 0.6$ the investigated system is in the neighborhood of the QCP.

We have performed a magnetoresistance (MR) experiments. It is expected to determine the dominating type of interactions on the basis of these results. Moreover, an observation of a strong change in these interactions can reveal a proximity of the QCP. As a complementary result we present the resistivity data, which show phase transitions in low temperatures.

2. Experimental details

Polycrystalline samples were synthesized in the induction furnace. To ensure homogeneity they were turned upside-down and remelted several times. In addition, the samples were wrapped in the Ta foil in quartz tubes and annealed at 750 °C for 120 h. The weight losses of all samples after annealing were less than 0.5% of the total mass. X-ray diffraction has shown that all the studied compounds are isostructural, single-phase, and crystallize in the tetragonal $BaNiSn_3$-type structure devoid of the inversion symmetry ($I4mm$ space group).

The magnetoresistance measurements were performed in the temperature range 2–30 K using the Quantum Design PPMS. Applied magnetic field values were up to 9 T. The PPMS device was also used to measure the temperature dependence of resistivity in the temperature range 1.9–300 K with no applied magnetic field. For these experiments a four probe method has been used. In this paper, we present results for $x = 0.3$, 0.4, and 0.6 of the $CeCo_{1-x}Fe_xGe_3$ system.

3. Results and discussion

The temperature dependence of the normalized electrical resistivity $\rho(T)/\rho(300)$ for the investigated alloys is presented in Fig. 1. A broad peak around the temperature of 100 K is visible for all samples. It is mainly due to the crystalline electric field (CEF) and the Kondo

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effect with a possibility of the Kondo lattice appearance. With the increase of the Fe content the relative resistivity values around the peak increase, which suggests stronger Kondo interactions. A residual resistivity, ρ_0, is of about 95 $\mu\Omega$cm for all samples, indicating low values of the residual resistivity ratios RRR $= \rho(300)/\rho_0 = 2.34$, 1.58, and 1.92 for $x = 0.3$, 0.4, and 0.6, respectively. This behavior is connected with a nature of our polycrystalline samples and the possible crystallographic defects. In the low temperature regime for samples with $x = 0.3$ and 0.4 there is a peak related to the antiferromagnetic ordering. For sample with $x = 0.6$ we do not observe any clear sign of long range magnetic order. This indicates no occurrence of the antiferromagnetic phase within the measured temperature range. Moreover, the electrical resistivity shows a power law dependence $\rho \sim T^{\alpha}$ with $\alpha = 1.14$ (inset of Fig. 1) instead of $\rho \sim T^2$ typical of metals. This is known as one of signs of NFL behavior, thus we observe a neighborhood of the QCP, which was reported by Medeiros et al. [10].

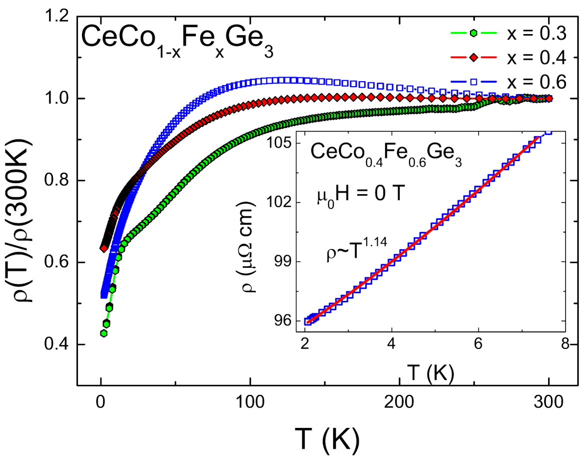

Fig. 1. Dependences of the normalized $\rho(T)/\rho(300)$ electrical resistivity as a function of temperature for compounds with $x = 0.3$, 0.4, and 0.6 of the system $CeCo_{1-x}Fe_xGe_3$. Inset shows the low temperature regime of the electrical resistivity for $x = 0.6$ fitted with the power law $\rho \sim T^{\alpha}$. The determined value $\alpha = 1.14$ is characteristic of NFL behavior.

The isothermal magnetoresistance measurements are presented in Fig. 2. Values of magnetoresistance are defined as MR $= (\rho(\mathrm{H,T}) - \rho(0,\mathrm{T}))/\rho(0,\mathrm{T})$. Similarly to the results of the temperature dependence of resistivity, samples with $x = 0.3$ and 0.4 (Fig. 2a and b, respectively) show antiferromagnetic ordering in low temperatures. Below 10 K there is a broad peak with positive values of MR of about 2 %. After that, the MR decreases to negative values reaching approximately MR $\sim -10\%$ for $\mu_0 H = 9$ T. This is a typical shape of the isothermal curves for antiferromagnets. For temperatures of 20 K and 30 K the isotherms show a smoother shaped curves with negative values in the whole magnetic field range. This a typical behavior of MR for a single-ion Kondo system, which is known for the Ce-based compounds [11, 12]. Moreover, it suggests a magnetic phase transition around 10 K, which is in a good agreement with the presented resistivity results.

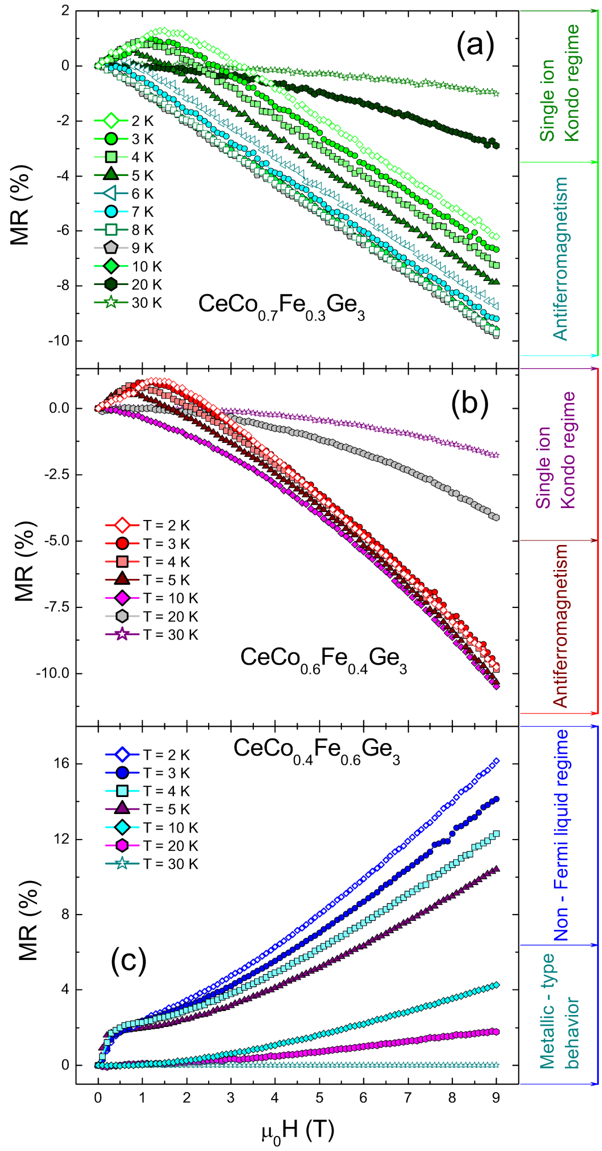

Fig. 2. The magnetic field dependence of magnetoresistivity isotherms for the system $CeCo_{1-x}Fe_xGe_3$. For $x = 0.3$ (a) and $x = 0.4$ (b) antiferromagnetism at low temperatures and single ion Kondo regime for higher temperatures. Sample $x = 0.6$ (c) shows in low temperature regime positive MR connected with the NFL behavior, for higher temperatures it presents metallic type magnetoresistance shape of curves.

For the sample with $x = 0.6$, MR measurements present a completely different behavior in comparison to the other investigated alloys. In Fig. 2c it has been shown that for the whole magnetic field range the MR values are positive, opposite to the case of $x = 0.3$ and 0.4. It is a confirmation of the change of the dominating type of interactions. For temperatures below 5 K and magnetic field changing from 0 to about 0.5 T, there is a visible rapid increase of the MR values, up to about 2.5%. This metamagnetic transition can be connected with a residual magnetism. The shape of the curves above 0.5 T for $T < 10$ K and for the entire magnetic field range for other temperatures is approximately parabolic, which indicates simple metallic-type behavior. This is not finally decided if the shape of the curves is determined by quantum criticality. However, it was reported for $CeCu_2Si_2$ and $CeNi_2Ge_2$ [13, 14] that positive MR occurs for NFL systems close to the QCP as antiferromagnetic fluctuations are suppressed. Considering (i) previous predictions of the possible appearance of QCP in $CeCo_{1-x}Fe_xGe_3$, (ii) the present evidence of the change of the magnetoresistivity character for a transition of the system from antiferromagnetic to nonmagnetic with the doping x, and (iii) the present resistivity results, we can assume that the positive MR for sample with $x = 0.6$ is related to quantum fluctuations near QCP, and, therefore to the NFL behavior.

4. Conclusions

In this paper we have analyzed the possible appearance of the QCP in the system $CeCo_{1-x}Fe_xGe_3$ by using the magnetoresistivity measurements. The presented electrical resistivity results have revealed a diminishing magnetic order with the doping x and the dependence of resistivity on temperature has provided a confirmation of the NFL behavior for the sample with $x = 0.6$.

Magnetoresistance isotherms $MR(\mu_0 H)$ have shown a significant change of behavior, from antiferromagnetic and single ion Kondo type for $x = 0.3$ and 0.4, to a metallic type for $x = 0.6$, indicating a possible appearance of a quantum phase transition around $x = 0.6$. To precisely analyze the nature of the magnetoresistance behavior and its connection with the QCP proximity, MR measurements for x varying between 0.5 and 0.7 are undertaken.

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