Transport properties of the dense Kondo system $Ce_{0.5}La_{0.5}B_6$ at low temperatures

2003 J. Phys.: Condens. Matter 15 S2167

(http://iopscience.iop.org/0953-8984/15/28/344)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **15** (2003) S2167–S2170 PII: S0953-8984(03)62624-X

Transport properties of the dense Kondo system $Ce_{0.5}La_{0.5}B_6$ at low temperatures

S Nakamura[1], **M Endo**[1], **N Kimura**[1], **H Aoki**[1], **T Nojima**[1] **and S Kunii**[2]

[1] Centre for Low Temperature Science, Tohoku University, Aoba-ku, Sendai 980-8577, Japan
[2] Department of Physics, Tohoku University, Aoba-ku, Sendai 980-8578, Japan

E-mail: nakamura@imr.tohoku.ac.jp

Received 12 November 2002
Published 4 July 2003

Abstract

We have investigated transport properties of a cubic Kondo system, $Ce_{0.5}La_{0.5}B_6$, with a Γ_8 ground state. The resistivity shows a non-Fermi liquid behaviour in phase I. In antiferromagnetic phase III, the resistivity follows well the formula $\rho(T) = \rho(0) + AT^2$. The coefficient A for phase III is much larger than that of CeB_6 in phase III. The magnetic phase diagram for $H \parallel [110]$ has been obtained.

$Ce_xLa_{1-x}B_6$ is well known as a cubic Kondo system. The electrical resistivity of this system shows $-\log T$-like temperature dependence in paramagnetic phase I [1]. The ground state Γ_8 carries both magnetic dipolar moments and the electric quadrupolar moments. The coexistence of multipole moments under the influence of the dense Kondo effect results in the complicated magnetic phase diagram of $Ce_xLa_{1-x}B_6$. In this system, four main magnetic phases appear: phase I; an electric antiferroquadrupolar (AFQ) ordered phase, phase II; phase III where antiferromagnetic (AFM) ordering and AFQ ordering coexist; and phase IV whose order parameter has not been established [2–6]. In our previous paper [7], it was reported that two characteristic temperatures are identified in $Ce_xLa_{1-x}B_6$ when the Ce concentration shows a high value. The characteristic temperature for magnetic dipole quenching and that for quadrupole quenching were found to be 5–10 K from the magnetic susceptibility χ_m $(T = 0\,K)$ and to be $\sim$1 K from the strain (quadrupole) susceptibility, respectively. This pronounced difference between the two characteristic temperatures has been proposed as the origin of phases IV and II.

Various anomalous magnetic phases appear in the Kondo alloys $Ce_xLa_{1-x}B_6$ based on the competition and/or delicate balance among the intersite multipole interactions and the screening effect originating from the Kondo effect. $Ce_{0.5}La_{0.5}B_6$ has no ordering (phase I) under low fields, while long-range orderings (phases III, II) are induced by magnetic fields [3, 7]. The magnetic phase diagram of this system is anisotropic [3], suggesting anisotropic RKKY interactions. However, the magnetic phase diagram under fields parallel to

0953-8984/03/282167+04$30.00

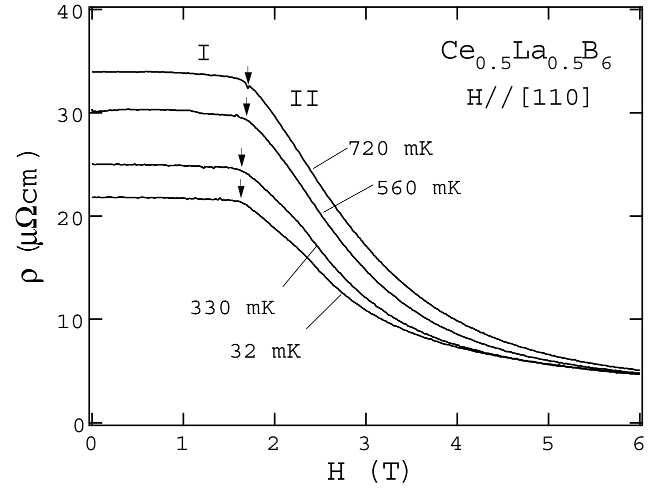

Figure 1. The magnetoresistivity of $Ce_{0.5}La_{0.5}B_6$ under fields $H \parallel [110]$. The current is directed along $[1\bar{1}0]$.

the [110] axis has not been established at very low temperatures. The transport properties of $Ce_{0.5}La_{0.5}B_6$ at very low temperatures have not been clarified. In the present paper we show the electrical resistivity and magnetoresistivity of $Ce_{0.5}La_{0.5}B_6$. The magnetic phase diagram of this system for $H \parallel [110]$ has been obtained. We have found that a strongly correlated Fermi liquid (FL) state and a non-Fermi liquid (NFL) one appear in this system.

A single crystal of $Ce_{0.5}La_{0.5}B_6$ was grown by the floating zone method. The sample was polished to a thin rectangle with dimensions $0.265 \times 0.65 \times 8$ mm^3. We measured the resistivity by the dc four-terminal method down to 32 mK. The current was 70–600 μA and directed along the $[1\bar{1}0]$ axis. We used a top-loading-type dilution refrigerator with a 17 T superconducting magnet.

In figure 1 we show the magnetoresistivity of $Ce_{0.5}La_{0.5}B_6$ at various temperatures. Magnetic fields are applied along the [110] axis. The magnetoresistivity is almost field independent in phase I, but it starts to decrease in phase II with increasing field. The arrows indicate the phase I–II transition points. The large residual resistivity at 32 mK in zero field implies a large scattering by randomly placed Ce ions. This large scattering may arise from the Kondo effect, because it decreases with increasing field. At 32 mK, the resistivity at $H = 16$ T is only 10% of that at 0 T. Because the strengths of the RKKY interactions are sensitive to the mean free path of the conduction electrons, the magnetic phase diagram of $Ce_{0.5}La_{0.5}B_6$ may be affected by the Kondo effect. Theoretical investigation on this point is needed.

We illustrate the magnetic phase diagram of $Ce_{0.5}La_{0.5}B_6$ in figure 2 under fields along the [110] axis. For comparison, this figure includes the magnetic phase diagram for $H \parallel [001]$ taken from [3]. In an H–T plane, phase I appears in low fields, and phase II extends to the higher-field side. No clear indication of phase III is shown for $H \parallel [110]$. The magnetic phase diagram is sensitively dependent on the direction of the field. When the field is rotated a few degrees from the [110] axis, phase III appears between phases I and II. In the AFQ phase under finite fields, through the LS-coupling, the strength of the dipolar interaction of the RKKY mechanism would be dependent on the direction of the fields. The competition between the dipolar interaction and the dense Kondo effect may be the reason for the absence of phase III for $H \parallel [110]$. The former is predominant for $H \parallel [001]$, while the latter is predominant for

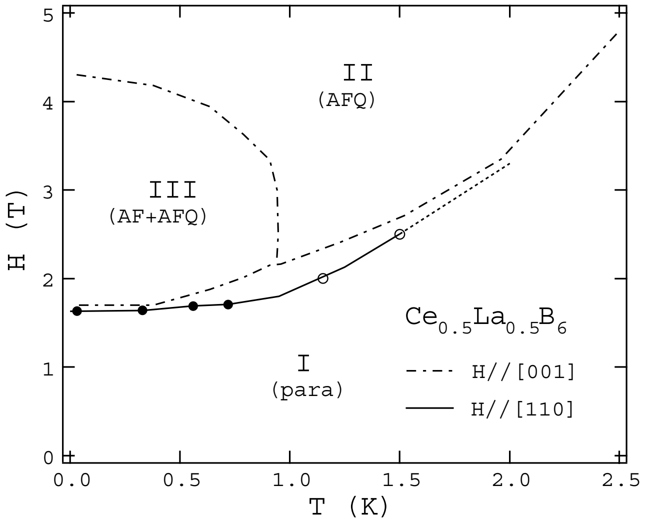

Figure 2. The magnetic phase diagram of $Ce_{0.5}La_{0.5}B_6$ under fields $H \parallel [110]$. For comparison, this figure includes the magnetic diagram for $H \parallel [001]$ taken from [3]. Closed circles are present results and open circles are taken from [8].

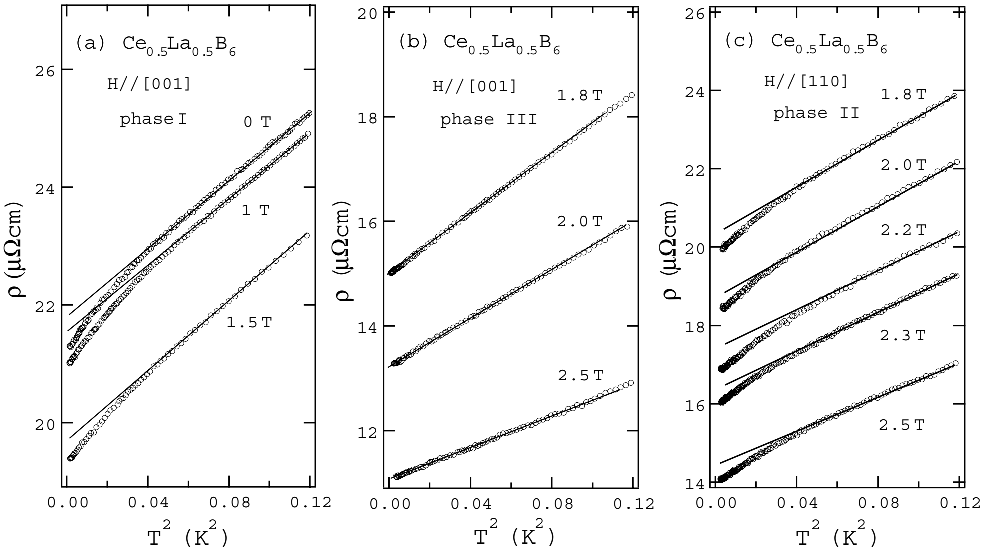

Figure 3. The electrical resistivity of $Ce_{0.5}La_{0.5}B_6$ (a) in phase I, (b) in phase III, and (c) in phase II as a function of T^2. The fields are parallel to the ((a), (b)) [001] and (c) [110] axes. The current is in the direction parallel to the $[1\bar{1}0]$ axis. The solid lines are guides to the eye.

$H \parallel [110]$. Therefore, in the magnetic field range $1.7 < H < 4.3$ T, $Ce_{0.5}La_{0.5}B_6$ undergoes a quantum phase transition with rotation of the direction of the field.

In figure 3, the resistivity of $Ce_{0.5}La_{0.5}B_6$ is shown as functions of T^2. Magnetic fields are applied along the ((a), (b)) [001] and (c) [110] axes. As shown in figure 3(a), the resistivity deviates from the formula $\rho(T) = \rho(0) + AT^2$ below ~150 mK when $Ce_{0.5}La_{0.5}B_6$ is in phase I. This strongly suggests that a NFL state is realized in phase I. When $Ce_{0.5}La_{0.5}B_6$ is in phase III, the resistivity follows well the formula $\rho(T) = \rho(0) + AT^2$. The AT^2-term is not explained in terms of the scattering by AFM magnons, because this scattering leads to resistivity proportional to T^4. The coefficient A for $Ce_{0.5}La_{0.5}B_6$ for $H = 1.8$ T is 28.8 $\mu\Omega$ cm K^{-2}. This is about 35 times larger than that for CeB_6 for $H = 0$ (0.832 $\mu\Omega$ cm K^{-2}) [1]. Probably, in $Ce_{0.5}La_{0.5}B_6$, massive quasiparticles are generated in phase III. Large AT^2-terms in the resistivity are also shown by $Ce_{0.65}La_{0.35}B_6$ in phase IV (not shown). The resistivity in phase II under fields $H \parallel [110]$ is shown in figure 3(c). Similarly to the case for phase I, a deviation from T^2-behaviour is shown in this phase. As mentioned before, $Ce_{0.5}La_{0.5}B_6$ is in the neighbourhood of the quantum phase transition point. This suggests that some quantum critical phenomenon may be the origin of the NFL behaviour in phase II. When the field ($H \parallel [110]$) becomes stronger, FL behaviour appears in the resistivity (not shown). We have detected dHvA signals from α_3- and α_1-branches [9] in $Ce_{0.5}La_{0.5}B_6$ in phase II in the range $13.5 < H < 16$ T ($H \parallel [110]$). The effective mass for the α_3-branch was found to be $\sim 7\ m_0$.

In summary, we have reported results on the electrical resistivity and magnetoresistivity of the cubic dense Kondo system $Ce_{0.5}La_{0.5}B_6$. Phase III is probably absent under fields parallel to the [110] axis. In $Ce_{0.5}La_{0.5}B_6$, heavy quasiparticles and long-range orderings coexist in phase III, regardless of the random distribution of Ce ions. In this phase, the correlation among the conduction electrons is much stronger than that in CeB_6. We have found that the NFL state is realized in $Ce_{0.5}La_{0.5}B_6$.

Acknowledgments

The authors thank H Miura, S Tanno and K Hosokura for operation of low-temperature apparatus. This study was partly supported by a Grant-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

[1] Sato N *et al* 1985 *J. Phys. Soc. Japan* **54** 1923
[2] Effantin J M *et al* 1985 *J. Magn. Magn. Mater.* **47** 145
[3] Nakamura S *et al* 1995 *J. Phys. Soc. Japan* **64** 3941
[4] Tayama T *et al* 1997 *J. Phys. Soc. Japan* **66** 2268
[5] Hiroi M *et al* 1997 *J. Phys. Soc. Japan* **66** 1762
[6] Suzuki O *et al* 1998 *J. Phys. Soc. Japan* **67** 4243
[7] Nakamura S *et al* 2000 *Phys. Rev.* B **61** 15203
[8] Nakamura S *et al* 1997 *Physica* B **230–232** 233
[9] Ishizawa Y *et al* 1977 *J. Phys. Soc. Japan* **42** 112