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1998 J. Phys.: Condens. Matter 10 11531

(http://iopscience.iop.org/0953-8984/10/49/039)

J. Phys.: Condens. Matter **10** (1998) 11531–11536. Printed in the UK PII: S0953-8984(98)96527-4

Highly correlated electron systems under multi-extreme conditions

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Received 4 June 1998

Abstract. Electrical and magnetic properties of highly correlated electron systems are investigated under multi-extreme conditions: high pressure, low temperature and high magnetic fields. The instability of the electronic state under multi-extreme conditions is systematically discussed on the basis of the data obtained. It is suggested that one kind of interaction is enhanced but another is suppressed under multi-extreme conditions, which gives rise to a lot of interesting electronic transitions.

1. Introduction

There have been a lot of investigations of the intermetallic compounds including f-electron or rare-earth and actinide elements, because these compounds show a wide variety of electronic and magnetic properties such as heavy-fermion behaviour, superconductivity and metamagnetism [1]. Such studies provide a lot of important information about the role of strong electron correlation in the metallic systems, which is one of the origins of the many anomalous physical properties. The electronic states of these compounds are well known to be strongly dependent on external control parameters such as temperature (this must be low), magnetic field and pressure (these must be high). By making these parameters extreme, a new magnetic and electronic state is readily induced because of the instability of the f-electronic state [2]. With this viewpoint, we have constructed a new high-pressure apparatus which we can use under high magnetic field and at low temperature [3].

In this article we will describe some results concerning highly correlated electron systems under multi-extreme conditions: high pressure, low temperature and high magnetic fields. We selected three specimens: (1) heavy-fermion $CeAl_3$, (2) the borocarbide magnetic superconductor $HoNi_2B_2C$ and (3) the layered compound UNiGa. The results which we obtained recently by using our apparatus will be reported briefly and we will discuss the general trends exhibited by the electronic states of these materials under multi-extreme conditions.

0953-8984/98/4911531+06$19.50

2. Pressure-induced crossover in heavy-fermion systems

The intermetallic compound $CeAl_3$ is a typical HF compound having a large specific heat coefficient γ: as much as 1.5 J mol^{-1} K^{-2} [4, 5]. We mention, in this section, the results of high-pressure measurement of the temperature dependence of electrical resistance for $CeAl_3$ as an example, in order to clarify the effect of volume contraction on the characteristics of HF systems.

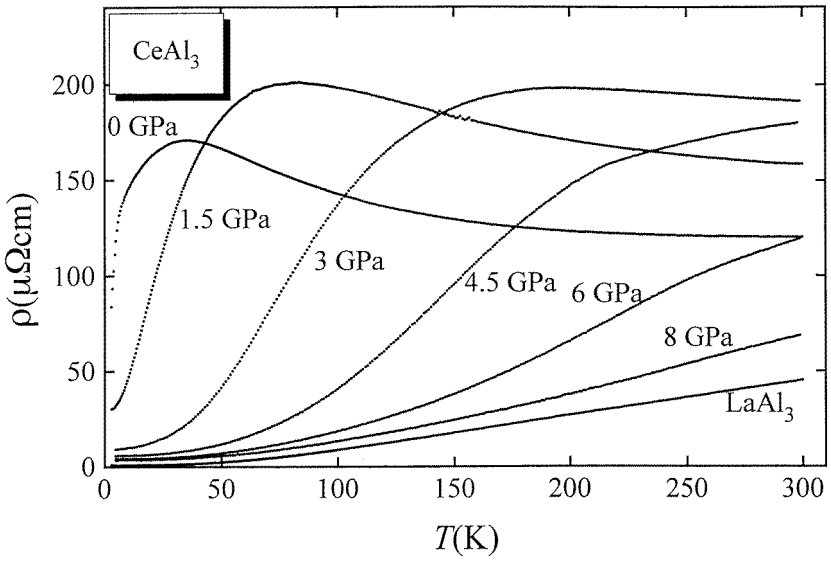

Figure 1. The temperature dependence of the electrical resistivity $\rho(T)$ of $CeAl_3$ at various pressures. $\rho(T)$ for $LaAl_3$ at ambient pressure is also shown for comparison.

The temperature dependence of the electrical resistivity $\rho(T)$ of $CeAl_3$ at various pressures up to 8 GPa is indicated in figure 1. $\rho(T)$ for $LaAl_3$, shown for comparison, is similar to that for ordinary non-magnetic metal—it behaves linearly against temperature above 100 K, with no anomaly—whereas, at ambient pressure, ρ for $CeAl_3$ increases logarithmically with decreasing temperature but decreases rather rapidly upon cooling below 35 K and has a shoulder near 6 K. This behaviour is due to Kondo scattering on a thermally populated level split by the crystalline electric field. With increasing pressure, the peak and the shoulder merge into one broad peak, which is shifted towards higher temperatures. $\rho(T)$ at 8 GPa is similar to that for $LaAl_3$. This is interpreted as follows: the characteristic energy of the system, for example the Kondo temperature T_K, is enhanced by volume contraction, which enhances the strength of hybridization between f- and conduction-band electrons in these concentrated Kondo (CK) compounds. Application of pressure, in other words, induces a crossover in the electronic configuration from a low-T_K HF state to a high-T_K mixed-valence (MV) state, associated with the enhancement of T_K, which has also been observed in other CK compounds [6–8].

Next we focus on low-temperature properties. It was reported that ρ for $CeAl_3$ has a quadratic temperature dependence below $\simeq$1 K with a coefficient of 35 $\mu\Omega$ cm K^{-2}, which is larger than that for normal metal by two orders of magnitude [4]; this is considered as evidence of a strongly correlated Fermi liquid state. In order to probe the Fermi liquid state

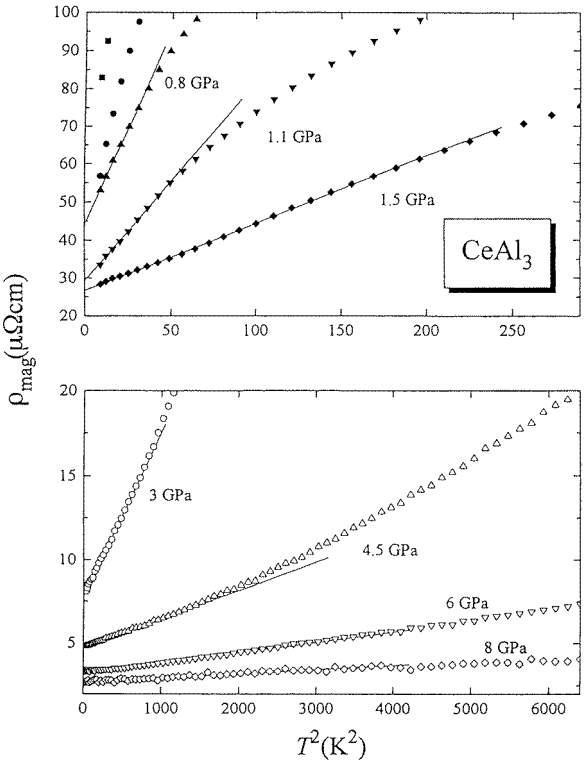

Figure 2. The magnetic part of the electrical resistivity, ρ_{mag}, as a function of T^2 for $CeAl_3$.

under pressure, the magnetic contribution $\rho_{mag}(T)$ is estimated as $\rho(T)$ at high pressures with $\rho(T)$ for $LaAl_3$ subtracted from it, and then plotted as a function of T^2 in figure 2. The solid lines show a quadratic dependence on temperature. The T^2-term was not observed down to the lowest temperature in this experiment at ambient pressure, but appears at high pressure above 0.8 GPa. With increasing pressure, the slope becomes small and the region of T^2-dependence extends to higher temperatures. This also implies the enhancement of T_K. This also implies the enhancement of T_K because of the relation $A \propto 1/T_K^2$ [9]. To get at the essence of the change in the electronic state, we have to consider the quantity as a function of the volume, not the pressure.

According to previous work [10] in an x-ray diffraction study of $CeAl_3$ at high pressure, a pressure of 8 GPa corresponds to a 12% decrease in volume. The quite large change in the electronic state that is reflected in the multiplicative enhancement in T_K is caused by only a small change in volume. We estimated the Grüneisen parameter of T_K to be 97 [6], which is quite large, implying an instability in the electronic state of HF systems against volume contraction.

3. Superconductivity of $HoNi_2B_2C$

The borocarbide $HoNi_2B_2C$ shows superconductivity near 8 K ($=T_c$); this region is followed by an antiferromagnetic transition (at $T = T_N$) between 6 and 5 K [11]. Below T_N, the superconductivity coexists with the antiferromagnetic order. It is well known that there

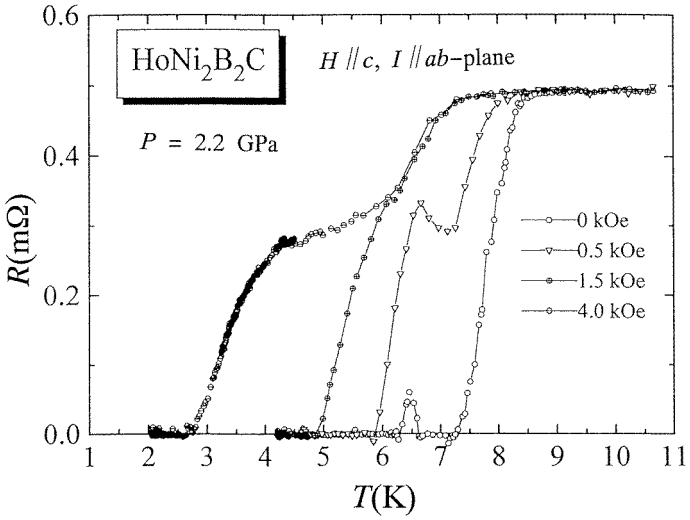

Figure 3. The electrical resistance of $HoNi_2B_2C$ in the current direction $\boldsymbol{I} \parallel ab$-plane and $\boldsymbol{H} \parallel \boldsymbol{c}$ at 2.2 GPa.

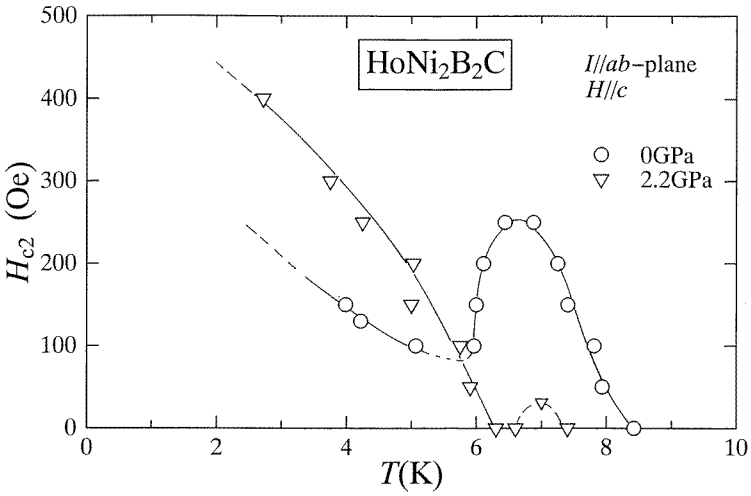

Figure 4. H_{c2} for $HoNi_2B_2C$ as a function of temperature at 0 GPa and 2.2 GPa.

is a drastic dip in $H_{c2}(T)$ near T_N showing a suppression of the superconductivity. In order to examine the interplay between antiferromagnetism and the superconductivity in this compound, the electrical resistance was measured under multi-extreme conditions.

Figure 3 shows an example of the R versus T curves under 2.2 GPa and at the magnetic fields of $H = 0$, 0.5, 1.5 and 4.0 kOe. At $H = 0$, T_c and T_N are 7.4 and 6.4 K, respectively. The $R(T)$ data indicate a re-entrant behaviour of the superconductivity below 6 K. On applying a magnetic field of 0.5 kOe, the superconductivity above T_N is found to disappear and T_c for the re-entrant phase decreases with increasing H. But there is a small dip in the $R(T)$ curve near 7 K at $H = 0.5$ kOe.

By using these data, we constructed a phase diagram for $HoNi_2B_2C$ at high pressure, which is shown as figure 4. It is easily seen that the superconducting phase above T_N is suppressed by pressure, while the one below T_N is stabilized at high pressure: T_c is increased by pressure in the superconducting phase below T_N. This result suggests that the effect of pair breaking is very significant in the temperature range $T > T_N$, which gives rise to a decrease in T_c above T_N as pressure increases.

4. Magnetostriction of UNiGa

UNiGa belongs to the wide variety of UTX (T: transition metal; X: p metal) compounds which crystallize in the hexagonal ZrNiAl-type structure. Below $T_N = 39$ K, UNiGa orders antiferromagnetically. It is known that the magnetic phase diagram of UNiGa contains six magnetically ordered phases at 0 GPa and in a magnetic field [12]. A relatively low magnetic field (1–1.5 T) applied along the *c*-axis induces metamagnetic transitions from the antiferromagnetic (AF) structures to a ferromagnetic (F) one. The metamagnetic transitions are accompanied by giant magnetoresistance, magnetostriction and anomalies in other physical properties [12–14].

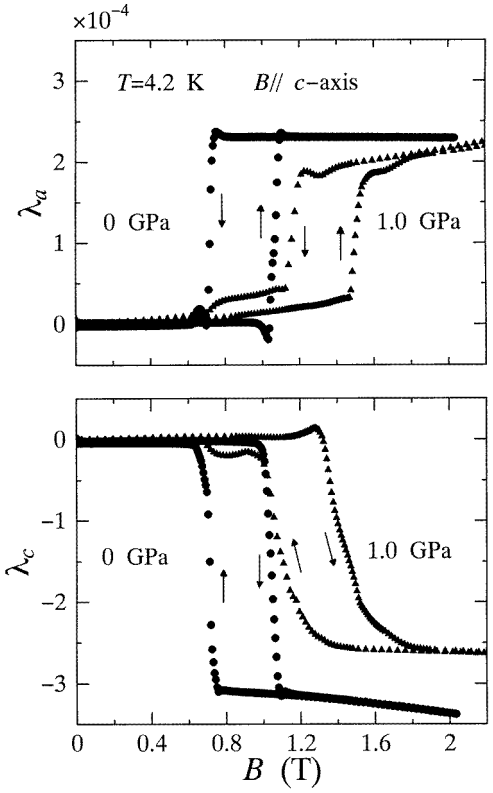

Figure 5. The magnetostriction of UNiGa along the *a*- and *c*-axes at 0 and 1.0 GPa, and at 4.2 K, for a magnetic field along the *c*-axis.

Figure 5 shows the field dependence of the magnetostriction at 0 GPa and 1.0 GPa, and at 4.2 K. The magnetostriction of UNiGa is found to be very anisotropic. The *a*-

axis expands but the c-axis shrinks at 1 T (with increasing magnetic field), these changes accompanying the metamagnetic transition from the AF phase to the F phase. Therefore, the c/a ratio decreases drastically at the metamagnetic transition, and the type of magnetic ordering of UNiGa is connected strongly with the c/a ratio. Since the linear compressibility of UNiGa along the a-axis is larger than that along the c-axis [15], the c/a ratio will increase with increasing pressure which should lead to stabilization of the AF phase and to increase of the field B_c at which the metamagnetic transition occurs. This is indeed seen in figure 5. B_c increases with increasing pressure. The pressure dependence of B_c is almost linear: 0.5 T GPa^{-1}. The results are in good agreement with the data from neutron diffraction measurements under high pressure [12]. We can conclude that the application of pressure apparently promotes AF coupling.

5. Summary

In the present work we have described three examples of experimental results for highly correlated electron systems. A crossover in the electronic state and magnetic and superconducting phase transitions have been discussed briefly. There are several kinds of interaction in these materials which dominate the crossover or phase transition. The variety of the results given in the present work indicates that these interactions respond in different ways to external forces such as pressure and magnetic fields.

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