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# Evolution of the Fermi surface of the strongly correlated f electron system under hydrostatic and uniaxial pressures

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**Abstract**

We report our recent developments of experimental systems for measuring the de Haas–van Alphen (dHvA) effect under hydrostatic and uniaxial pressures. The dHvA effect of $CeB_6$ has been studied under both hydrostatic and uniaxial pressures and the effects of the pressures on the electronic structure are discussed.

## 1. Developments of detection systems for the dHvA effect under pressures

The properties of the strongly correlated f electron systems are very sensitive to external pressure. In some compounds, the magnetic transition temperatures are significantly suppressed and reach zero at a critical pressure (quantum critical point (QCP)) with application of pressure that can be produced by conventional methods in a laboratory. Often superconductivity emerges near the QCP. The heavy-fermion states are thought to reside near the QCP and their physical properties are particularly sensitive to external pressure. Such phenomena are closely related with the peculiar electronic structure at the Fermi level of the strongly correlated f electron system. It is therefore very interesting to study the changes of the properties under pressure together with those of the electronic structures, particular the Fermi surface properties.

The de Haas–van Alphen (dHvA) effect is a very powerful tool for investigating the Fermi surface properties of metals. We have developed a system to measure the dHvA effect under hydrostatic pressures up to 10 kbar, temperatures down to 50 mK and magnetic fields up to 20 T. It was used to study the electronic structure of various strongly correlated f electron systems such as $CeRu_2Si_2$ under pressure [1, 2]. We are extending the pressures up to 30 kbar. The new system has been successfully applied to study the electronic change across the QCP of a ferromagnet $UGe_2$ which exhibits superconductivity under high pressures. It is found that the Fermi surface changes drastically across the QCP and effective masses are enhanced

  

near the QCP. The details of the results and the correlation of the electronic structure with superconductivity will be reported elsewhere.

We have recently developed a system to measure the dHvA effect under uniaxial pressure [3]. Application of uniaxial pressure is particularly interesting for the compounds where the quadrupolar ordering takes place. The order originates from the degenerate ground state or the high crystal symmetry of the compound, such as cubic symmetry. The uniaxial compression lowers the symmetry of the crystal and thereby is expected to change effectively the properties associated with the quadrupolar order or the degenerate ground state. The comparison with the hydrostatic pressure effect will give useful information for studying the mechanism of the quadrupolar ordering.

In this paper, we report results on $CeB_6$, where Fermi surface studies as well as physical properties have been performed for the first time both under hydrostatic and uniaxial pressures.

## 2. Application to $CeB_6$

### *2.1. Magnetic phase diagram*

$CeB_6$ crystallizes into the $CaB_6$ structure and exhibits an antiferroquadrupolar transition at 3.3 K and then an antiferromagnetic transition at 2.4 K. It also shows dense Kondo behaviour. These competing interactions give rise to very interesting properties of this compound.

Figure 1 shows the magnetic phase diagram of $CeB_6$ under uniaxial pressures. The uniaxial pressure and magnetic field are applied parallel to the [001] axis. The phase boundaries are determined by measuring the AC susceptibility with a sweeping field at constant temperature or a sweeping temperature at constant field. At ambient pressure three phases, i.e., paramagnetic (I), antiferroquadrupolar (II) and antiferromagnetic (III) phases, appear. There are also two different phases $II_A$ and $II_B$ in phase II and three different phases III, III$'$ and III$''$ in phase III. The lowest phase boundaries in phases II and III seem to be connected with each other, indicating that the structures of the quadrupolar order and antiferromagnetic order of the phases are closely related to each other. With increasing pressure, the phase boundary between phases II and III moves to higher fields. The phase boundary become obscure, or the humps and the peaks of the AC susceptibility for determining the phase boundary become broader. In particular, the AC susceptibility changes smoothly in phase III at low fields and no obvious phase boundary can be found between phase III$''$ and III at 3 kbar. On the other hand, the quadrupolar transition temperature ($T_Q$), the phase boundary between phases I and II, and the antiferromagnetic transition temperature ($T_N$) do not change within experimental error.

For hydrostatic pressures, the phase boundary between phases II and III moves to lower fields and $T_N$ decreases slightly. That is, the effect of hydrostatic pressure on the phase boundary between phases II and III is contrary to that for uniaxial pressure. The boundary between phases I and II moves very slightly to the higher-temperature side at high pressures [4, 5].

### *2.2. dHvA effect of $CeB_6$ under pressure*

The Fermi surface of $CeB_6$ consists of a main Fermi surface and smaller Fermi surfaces. The $\alpha$-oscillation arises from the main Fermi surface. Figures 2(a) and (b) show the dHvA oscillation and under uniaxial pressure of 3 kbar and its Fourier spectrum. The magnetic field and uniaxial pressure are applied parallel to the [001] axis. Although the uniaxial pressure could produce microscopic strain, a clear signal can be observed.

Figure 3 shows the relative effective mass change $(m^*(P) - m^*(0))/m^*(0)$ of the $\alpha$-oscillation as a function of uniaxial pressure. The effective mass has been determined from the

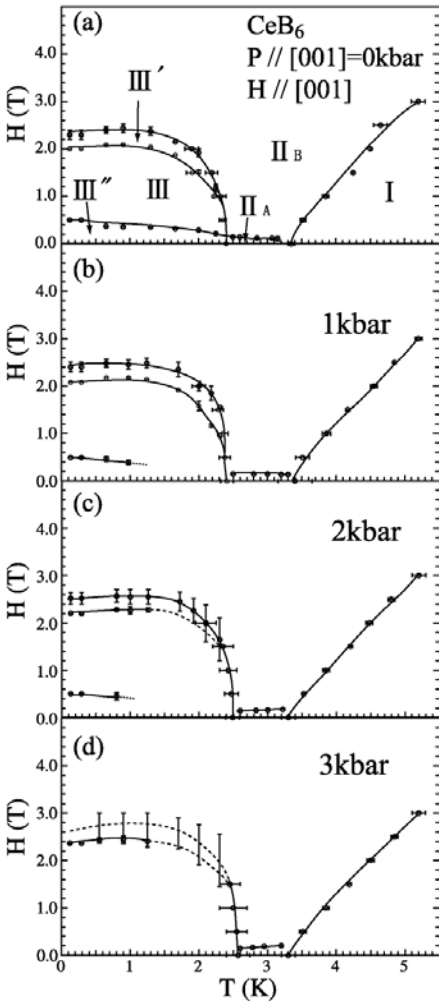


**Figure 1.** The magnetic phase diagram of $CeB_6$ under uniaxial pressures.

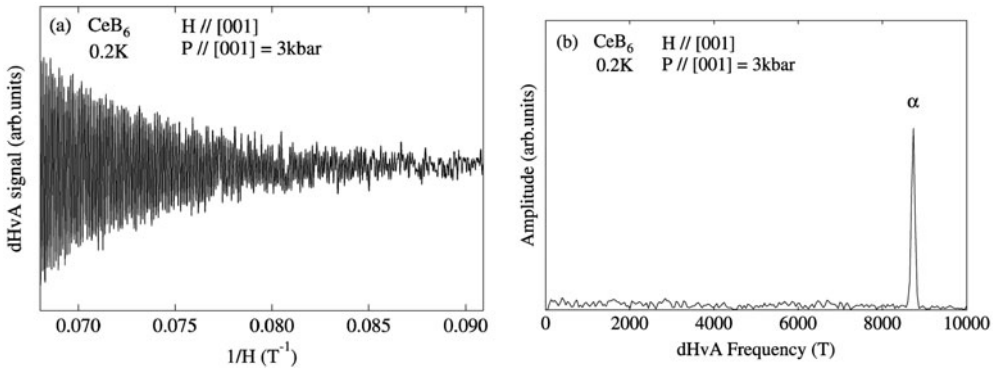


**Figure 2.** (a) dHvA oscillation and (b) its Fourier spectrum.

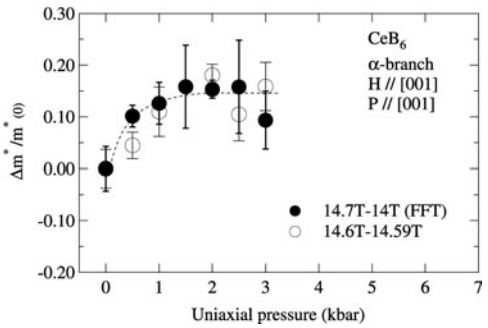


**Figure 3.** Relative effective mass change with uniaxial pressure.

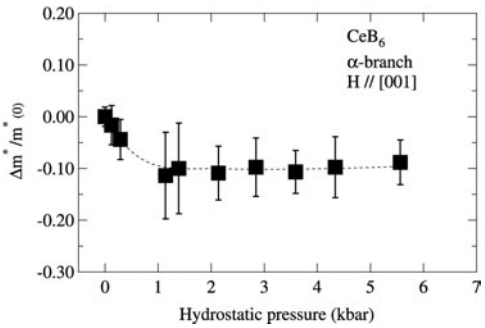


**Figure 4.** Relative effective mass change with hydrostatic pressure.

amplitude of the Fourier analysis of the oscillation between 14 and 14.7 T and also from the oscillation amplitude at 14.59–14.6 T. They are denoted by the closed and open circles in figure 3, respectively. It is noted that the effective mass increases considerably with application of a small pressure and stays nearly constant with further application of higher pressures, indicating that the electronic structure changes considerably with application of a small pressure.

Figure 4 shows the relative effective mass change as a function of hydrostatic pressure. The magnetic field is applied parallel to the [001] axis. The effective mass was determined from the amplitude of the Fourier analysis between 11 and 13.8 T. The effective mass decreases considerably with application of a small pressure and stays nearly constant with further application of higher pressures. The behaviour is qualitatively different from that under uniaxial pressure.

It can be assumed that the hybridization between conduction and f electrons increases with application of hydrostatic pressure and consequently the Kondo temperature increases. The decrease of effective mass may be attributed to the increase of the Kondo temperature. Then, the increase of the effective mass may indicate that the Kondo temperature or the hybridization decreases with uniaxial pressure

The present study shows that uniaxial pressure gives an opposite effect to that of the hydrostatic pressure for both the magnetic phase diagram and electronic structure, but that both the hydrostatic and uniaxial pressures have little effect on the quadrupolar order.

One possible mechanism to mediate the quadrupolar interaction is thought to be the interaction between the conduction electron and the quadrupole—like the Ruderman–Kittel–Kasuja–Yosida (RKKY) interaction of the magnetic order. The present result may indicate that the hybridization or the interaction between the f and conduction electrons is not very significant for the quadrupolar interaction. Further studies are necessary to clarify the mechanism of quadrupolar interaction.

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