Relation between Metamagnetic Transition and Quantum Critical Point in Heavy Fermion Compound YbIr$_2$Zn$_{20}$

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Abstract. We measured the electrical resistivity in magnetic field $H$ under pressure $P$ for a heavy fermion compound YbIr$_2$Zn$_{20}$. The quantum critical point is found to be defined as an electronic state where the metamagnetic transition field $H_m$ becomes zero. This is realized at $P_c \cong 5.2$ GPa. The most characteristic feature in the quantum critical pressure region is an anomalously large $A$ value of the electrical resistivity $\rho = \rho_0 + AT^2$, reaching $A = 380 \mu \Omega \cdot \text{cm/K}^2$ at 5.0 GPa, which is, however, strongly reduced with increasing the magnetic field: $A = 1.45 \mu \Omega \cdot \text{cm/K}^2$ at 80 kOe. From the result of the de Haas-van Alphen experiment at ambient pressure, the corresponding cyclotron effective mass of conduction electrons at 5.0 GPa is $400 - 500 \ m_0$ ($m_0$: rest mass of an electron).

1. Introduction
The electronic states in Ce and U compounds can be tuned by applying pressure $P$ and/or magnetic field $H$. For example, the Néel temperature $T_N = 5$ K in CeIrSi$_3$ becomes a guiding parameter to tune the electronic state under pressure. The quantum critical point is therefore defined as the electronic state at which the Néel temperature becomes zero at the critical pressure $P_c$: $T_N \to 0$ at $P \to P_c$ ($= 2.25$ GPa).[1] In a wide pressure region around $P_c$, unconventional superconductivity is found in CeIrSi$_3$.

On the other hand, a non-magnetic Yb compound of YbCu$_2$Si$_2$ is known to become a magnetically ordered compound above 8 GPa, for example.[2] What is a guiding parameter in the non-magnetic Yb compound? In this paper, we introduce a new guiding parameter of the metamagnetic transition field $H_m$ in a heavy fermion compound YbIr$_2$Zn$_{20}$ with the cubic cage structure. The quantum critical point is realized at $P_c \cong 5.2$ GPa, where $H_m = 97$ kOe at ambient pressure for $H \parallel <100>$ becomes zero.

2. Experimental Results
One of the characteristic properties in the heavy fermion compound is the metamagnetic behavior or an abrupt nonlinear increase of magnetization at the magnetic field $H_m$. YbIr$_2$Zn$_{20}$ belongs to
the heavy fermion compound with the electronic specific heat coefficient $\gamma = 540$ mJ/(K$^2$·mol).[3] In fact, we detected the large cyclotron effective mass of $10 - 30 m_0$ ($m_0$: rest mass of an electron) from the de Haas-van Alphen (dHvA) effect.[4, 5]

Figure 1(a) shows the magnetization curve at 1.3 K for $H \parallel <100>$. The metamagnetic transition is observed at $H_m = 97$ kOe. The present metamagnetic transition is also found in the longitudinal magnetoresistance, as shown in Fig. 1(b). A small change of the magnetoresistance is also observed at $H_m' = 60$ kOe and $H_m'' = 120$ kOe. Almost the same results are observed in the de Haas-van Alphen (dHvA) oscillations, as shown in Fig. 1(c). Later we neglect the change at $H_m'$ and $H_m''$ because it is not observed under pressure.

We measured the transverse magnetoresistance at 0.1 K under several pressures, as shown in Fig. 2(a). With increasing pressure, the transition field $H_m$, shown by arrows, shifts to lower
magnetic fields, and the resistivity anomaly at $H_m$ becomes sharp and distinct, revealing a peak structure at 2.2 and 3.4 GPa. Moreover, the resistivity $\rho_0$ is steeply enhanced at 5.0 and 5.5 GPa, but is reduced strongly in magnetic fields. It is noticed that the metamagnetic transition is observed at $H_m = 1.4$ kOe at 5.0 GPa, but is not observed at 5.5 GPa. It is thus concluded that the critical pressure is $P_c \simeq 5.2$ GPa. The metamagnetic transition field is thus a good tuning parameter to reach the quantum critical point.

We measured the temperature dependence of the electrical resistivity below 0.8 K under magnetic field and pressure. The Fermi liquid relation of $\rho = \rho_0 + AT^2$ is satisfied and the obtained $A$ value is shown in Fig. 2(b) as a function of magnetic field. A broad peak at $H_m = 97$ kOe at ambient pressure in the $A$ value is changed into a distinct peak at 2.2 and 3.4 GPa, together with an anomalous enhancement of $A$ value at high pressures, $A = 380 \mu\Omega \cdot \text{cm/K}^2$ at 0 kOe under 5.0 GPa, for example.

We studied the relation between $\sqrt{A}$ and the cyclotron effective mass $m^*_c$ obtained from the dHvA experiment. Figure 3 shows the field dependence of the cyclotron mass for the dHvA frequency $F = 1.1 \times 10^7$ Oe in the magnetic field $H \parallel <100>$ at ambient pressure, shown by open squares. [4, 5] The cyclotron mass increases slightly with increasing magnetic field up to $H_m = 97$ kOe, but decreases gradually in much higher fields. The cyclotron mass well correlates with the $\sqrt{A}$ value at 0 GPa. From the experimental results of $\sqrt{A}$ at 0 and 5.0 GPa in Fig. 3, we can estimate the cyclotron mass at 0 kOe to be about 450 $m_0$ at 5.0 GPa, revealing an extremely large cyclotron mass. The detected cyclotron mass at ambient pressure is in the range from 10 to 30 $m_0$, depending on the field direction and the corresponding dHvA branch. Much larger cyclotron masses are expected to exist at 5.0 GPa. These heavy cyclotron masses of 400 - 500
Figure 3. Field dependence of the cyclotron effective mass $m^*_c$ at 0 GPa, shown by open squares and the $\sqrt{A}$ value under 0 and 5.0 GPa, shown by circles in YbIr$_2$Zn$_{20}$.

$m_0$ are strongly reduced in magnetic fields.

3. Conclusion
We found the metamagnetic transition at $H_m = 97$ kOe for $H \parallel <100>$ in a heavy fermion compound YbIr$_2$Zn$_{20}$. The transition field shifts to lower magnetic fields with increasing pressure and becomes zero at $P_c \simeq 5.2$ GPa, reaching the quantum critical point. The metamagnetic transition field is found to be a new guiding parameter. Correspondingly, the $A$ value of the electrical resistivity $\rho = \rho_0 + AT^2$ increases extremely in magnitude from $A = 0.29 \mu\Omega \cdot cm/K^2$ at ambient pressure to 380 $\mu\Omega \cdot cm/K^2$ at 5.0 GPa under 0 kOe, which is strongly reduced to 1.45 $\mu\Omega \cdot cm/K^2$ in magnetic field of 80 kOe.

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