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High Pressure Measurements of the Resistivity of β-YbAlB$_4$

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Abstract. The electric resistivity $\rho(T)$ under hydrostatic pressure up to 8 GPa was measured above 2 K using a high-quality single crystal of the Yb-based heavy fermion system β-YbAlB$_4$. We found pressure-induced magnetic ordering above the critical pressure $P_c \approx 2.4$ GPa. This phase transition temperature T_M is enhanced with pressure and reaches 30 K at a pressure of 8 GPa, which is the highest transition temperature for the Yb-based heavy fermion compounds. In contrast, the resistivity is insensitive to pressure below P_c and exhibits the T-linear behavior in the temperature range between 2 and 20 K. Our results indicate that quantum criticality for β-YbAlB$_4$ is also located near P_c in addition to the ambient pressure.

1. Introduction

Quantum-critical phenomena in the Yb-based compounds have not been well explored to date and thus have attracted great interest for possible novel quantum criticality produced by different electronic configurations between the electron-like $4f^1$-Ce^{3+} and hole-like $4f^{13}$-Yb^{3+}. As a prototype of quantum critical phenomena in the Yb-based materials, non-Fermi-liquid of YbRh$_2$Si$_2$ has been well studied [1]. This material exhibits field-tuned quantum criticality by suppressing the low Néel temperature T_N (= 70 mK) by magnetic field. However, except the recently discovered β-YbAlB$_4$, the Yb-based HF superconductivity has never been observed, neither at ambient conditions nor under hydrostatic pressure.

The intermetallic compound β-YbAlB$_4$ is the first Yb-based HF superconductor with the transition temperature T_c (= 80 mK) and exhibits quantum criticality at zero field [2, 3]. Hence, β-YbAlB$_4$ is one of the best systems to study quantum critical phenomena at ambient pressure[4]. For example, the temperature dependence of the zero-field resistivity exhibits non-Fermi-liquid behavior, i.e., T-linear dependence from 4 K to 0.8 K; $T^{3/2}$ dependence from 0.8 K down to T_c [2, 3]. Moreover, in the temperature range $T_c < T < 2$ K, the observation of divergent susceptibility $\chi_c \propto T^{-1/2}$ under a low field of 50 mT applied along the c-axis and $-\ln T$ dependence of the magnetic part of the specific heat C_M/T also strongly suggests that this material has unconventional QCP, where standard theory based on spin density wave type instability is inapplicable. In addition, strong valence fluctuation was observed in β-$YbAlB_4$ ($Yb^{\sim 2.75+}$), in comparison with other Yb-based QC materials such as $YbCu_{5-x}Al_x$ ($Yb^{\sim 2.95+}$) and $YbRh_2Si_2$ ($Yb^{\sim 2.9+}$) [5, 6]. Hence, the valence fluctuations possibly play an important role in understanding this unconventional quantum criticality in β-$YbAlB_4$ and thus exotic behavior may appear through controlling parameters such as pressure and chemical doping.

A study of pressure as one of the control parameters may reveal the phase diagram near QCP in both Ce-based and Yb-based HF systems. In the Yb-based compounds, generally, $4f$ moments are known to become more localized with application of pressure. Hence, with increasing pressure, a long-range magnetic order is expected to be stabilized as observed in $YbRh_2Si_2$ and $YbCo_2Zn_{20}$ [7, 8], in sharp contrast with their Ce-based counterparts. In the case of β-$YbAlB_4$, it is highly interesting to see how the unconventional zero-field quantum criticality observed at ambient pressure is associated with a magnetic order expected to emerge under high pressure. We report here the observation of pressure-induced magnetic order using high-quality single crystals β-$YbAlB_4$ and discuss pressure-tuned quantum phase transition.

2. Experimental details

Single crystals of β-$YbAlB_4$ were grown by the aluminum self-flux method [9]. To obtain high-quality single crystals, several crystals were selected using the residual resistivity ratio RRR=ρ_{ab}(300K)/ρ_{ab}(0K). We spot-welded electrical contacts to the surface of crystals using 20 μmϕ Au wires. The temperature dependence of the electrical resistivity under various pressures up to 8 GPa was measured for the selected single crystals β-$YbAlB_4$ over RRR = 200 (residual resistivity $\sim$ 1 $\mu\Omega$ cm) in the temperature region between 2 and 300 K using a cubic-anvil-type pressure cell. Hydrostatic pressure up to 8 GPa was applied using a pressure transmitting media, Daphne oil 7373 [10].

3. Results and discussion

Figure 1 displays the in-plane electrical resistivity $\rho_{ab}(T, p)$ of β-$YbAlB_4$ (RRR=200) in a pressure range of $0 \leq p \leq 8$ GPa measured using the cubic anvil pressure cell with the pressure medium of Daphne 7373. While the temperature dependence of the resistivity $\rho_{ab}(T)$ is almost independent of pressure up to 2.1 GPa, $\rho_{ab}(T)$ starts showing a kink above $P=$ 2.4 GPa. The kink may well arise from a magnetic phase transition as the gradual drop in the resistivity is normally associated with the loss of spin-disordered scattering due to magnetic ordering. The kink temperature T_M gradually increases with the application of pressure and reaches 30 K under 8 GPa. The enhancement of T_M with pressure is expected in a magnetically ordered Yb Kondo lattice compound, as we discussed above, and is in sharp contrast with the decrease in T_M with pressure in Ce-based compounds. The electrical resistivity at 300 K gradually increases with pressure, forming a maximum value at 6 GPa and then decreases at $P < 8$ GPa. The temperature

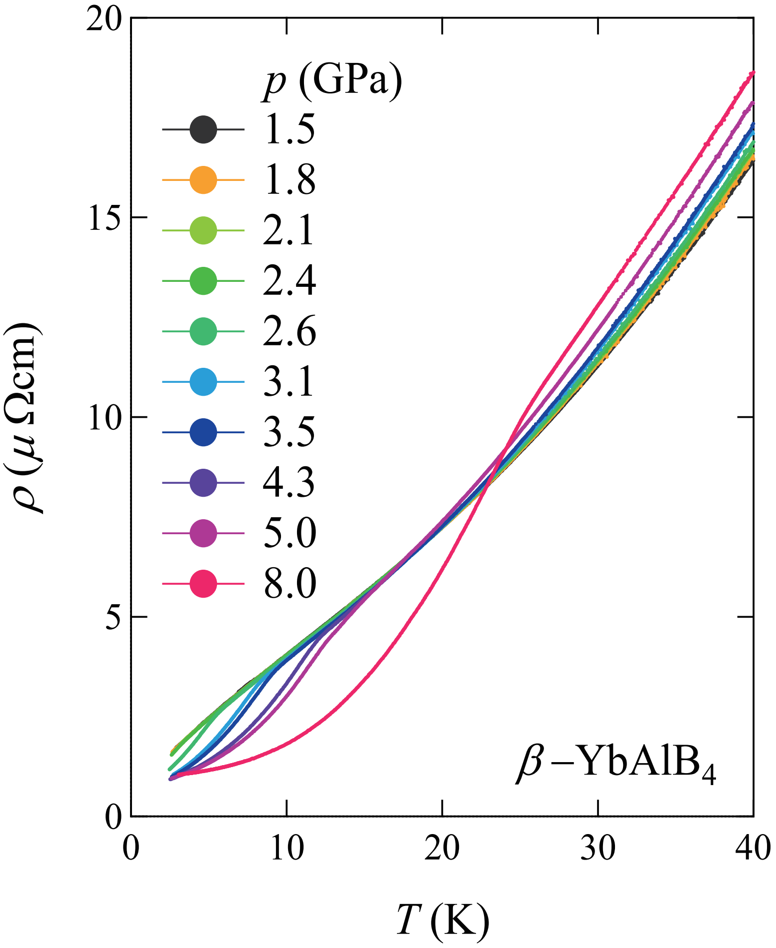

Figure 1. Pressure dependence of the in-plane resistivity ρ_{ab} of β-$YbAlB_4$ (RRR=200) up to pressure of 8 GPa. The inset shows the resistivity over a wide temperature range from 2 to 300 K under various pressures between 0 and 8 GPa. See text for details.

slope change of the resistivity $\rho_{ab}(T)$ appears around 40 K corresponding to the peak found in the Hall coefficient R_{H}, and may well come from the formation of the coherent state [11]. In particular, near this T range close to 40 K, a systematic change in $\rho(T)$ as a function of pressure was observed.

The sharper increase of the kink temperature observed near $P_{\mathrm{c}} \approx 2.5$ GPa indicates that the magnetically ordered phase is not connected to the SC phase and is separated from the quantum criticality observed for B=T=0 at ambient pressure [4, 12]. Almost no change in resistivity is observed in the pressure rage between 0 and 2 GPa. However, the magnetic transition of β-$YbAlB_4$ was suddenly found at $P >$2 GPa. Significantly, the phase transition of β-$YbAlB_4$ reaches 30 K under 8 GPa. Such high magnetic transition temperatures over 10 K has never been achieved in Yb-based HF materials, e.g., $YbInCu_4$ (T_{M}=2.4 K at p=4 GPa [13]) , $YbCu_2Si_2$ (T_{M}=10 K at p=10 GPa [14]), $YbRh_2Si_2$ (T_{M}=7 K at p=8 GPa [15]), and $YbNi_2Ge_2$ (T_{M}=2 K at p=100 GPa [16]) . Hence, the transition temperature of 30 K is the highest transition in the Yb-based HF compounds. In addition, the transition temperature is as high as that for $CeRu_2Al_{10}$

showing significantly enhanced T_N in Ce-based HF compounds [17].

4. Conclusion

A pressure-induced magnetic phase transition of β-$YbAlB_4$ above $P_c \approx 2$ GPa has been observed by the electrical resistivity measurements. In the intermediate pressure region $0< P <2$ GPa, the resistivity is almost pressure independent and no magnetic order is found down to 2 K. Our resistivity measurements under pressure has revealed that non-Fermi-liquid state arises nearby the critical pressure of the magnetism, suggesting a magnetic quantum criticality near $P_c = 2.4$ GPa. Furthermore, the dramatic difference in the phase diagram between those obtained by different pressure medium indicates that the magnetic quantum phase transition may be the first order. Given the fact that β-$YbAlB_4$ exhibits the zero-field quantum criticality under ambient pressure [2, 3], several scenarios are possible. (1) β-$YbAlB_4$ may have the 1st-ordered phase transition at $P_c = 2.5$ GPa such as a magnetic transition from a low moment magnetic state to a high moment magnetic state, as seen in the low pressure side of $YbRh_2Si_2$ near 2 GPa [18, 19] or a valence transition with changes in Yb valence as seen at the high-pressure side of $YbRh_2Si_2$ near 9 GPa [7]. (2) In the Ce-based HF superconductors, the superconducting phase and quantum criticality are connected to the AF magnetically ordered phase [20]. In β-$YbAlB_4$, however, the SC phase and the ambient pressure quantum criticality may be separated from the magnetically ordered state. It is highly interesting to see if the non-Fermi liquid state at the ambient pressure forms a phase reaching to the critical pressure of the magnetism as has been observed in MnSi [21]. (3) β-$YbAlB_4$ may have two quantum critical regions at around ambient pressure and at around P_c, which are separated by the Fermi liquid state.

In any case, a new type of phenomena in the Yb-based HF compounds is expected, and thus we need to further investigate the pressure dependence for β-$YbAlB_4$ at low temperatures to uncover the ground state evolution from the non-Fermi-liquid state and unconventional superconductivity to the magnetically ordered state under pressure.

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