

# Unconventional quantum criticality in $\beta$ -YbAlB<sub>4</sub> detached from its magnetically ordered phase

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## Abstract

We studied the effect of pressure on the Yb-based heavy-fermion superconductor  $\beta$ -YbAlB<sub>4</sub> ( $T_c=80$  mK) near its quantum critical point (QCP) at ambient pressure. Here, the electrical resistivity  $\rho(T)$  of the high-quality single crystal (RRR = 300) is measured under hydrostatic pressure  $P \simeq 2.7$  GPa at low temperatures down to 70 mK. The superconducting transition  $T_c$  gradually decreases with the application of pressure and disappears near 0.9 GPa. However, the non-Fermi liquid (NFL) behavior is found to be robust over a broad range of pressure  $0 \leq P \leq 0.5$  GPa. The NFL state above  $T_c$  gradually changes to the Fermi liquid state with the application of pressure above  $P \simeq 0.5$  GPa. The magnetic order transition is first observed at 50 mK and  $P_c = 2.7$  GPa. The  $P$ - $T$  phase diagram indicates that the QCP lying beneath the superconductivity dome is detached from the magnetically ordered phase.

*Keywords:* quantum criticality, unconventional superconductivity, Yb-based heavy fermion, valence fluctuations

## 1 Introduction

Heavy-fermion (HF) phenomena within inter-metallic compounds have attracted much interest from both the theoretical and experimental perspective because various types of phenomena such as non-Fermi-liquid (NFL) behavior and unconventional superconductivity (SC) emerge near the quantum criticality regime. Quantum criticality arises from competition between the Kondo spin fluctuations and the indirect magnetic inter-site interaction (RKKY interaction). The conventional spin fluctuation theory of the quantum critical point (QCP) has succeeded in explaining a number of NFL properties. The delicate balance associated with the QCP can

be tuned by varying control parameters such as magnetic field, chemical doping, and external pressure. Currently, one topic of intense interest within condensed matter physics is the dependence of the zero-temperature quantum phase transition from a magnetically ordered state to a nonmagnetic ground state on a control parameter other than temperature. Well known examples of the Ce-based quantum critical materials achieved by these control parameters, e.g.,  $\text{CeCu}_2(\text{Si}_{1-x}\text{Ge}_x)_2$  [1, 2],  $\text{CeIn}_3$  [3],  $\text{CePd}_2\text{Si}_2$  [3],  $\text{CeNi}_2\text{Ge}_2$  [1], and the quasi-two-dimensional HF system  $\text{CeMIn}_5$  ( $M = \text{Co}, \text{Rh}, \text{Ir}$ ) [4] are found to reveal unconventional HF superconductivity close to QCP. The superconducting dome observed near the QCP is normally connected with an antiferromagnetically ordered phase in the pressure–temperature phase diagram. Hence, superconductivity could be related to a mechanism with magnetic origins. Nevertheless the unconventional electronic and magnetic properties is still unclear because the SC dome reveals a variety of behaviors, in particular, the coexistence of superconducting and antiferromagnetic phases and the absence of coexisting antiferromagnetism in the first-order phase transition from the conduction phase into a different superconducting phase. Therefore, we need to explore various types of quantum criticality in different HF compounds.

In contrast to these Ce-based materials, quantum-critical phenomena in Yb-based compounds attracts great interest for possible novel quantum criticality produced by different electronic configurations between the electron-like  $4f^1\text{-Ce}^{3+}$  and hole-like  $4f^{13}\text{-Yb}^{3+}$ . Hence, various new types of novel phenomena close to QCP, not seen in Ce-based QCP, are expected in Yb-based HF compounds. As earlier prototypical Yb-based quantum critical phenomena,  $\text{YbRh}_2\text{Si}_2$  has been one system that has been well studied.[5] The material exhibits anti-ferromagnetic ordering with Néel temperature  $T_N$  ( $= 70$  mK) and shows NFL behavior at the field-induced QCP. However, no Yb-based HF superconductivity has been currently observed not only at ambient and but also under hydrostatic pressure except in the recently discovered  $\beta\text{-YbAlB}_4$ .

The layered inter-metallic compound  $\beta\text{-YbAlB}_4$  is the first Yb-based unconventional HF superconductor  $T_c$  ( $= 80$  mK) and is found to be very near the QCP at zero field and zero temperature. [6, 7] Hence,  $\beta\text{-YbAlB}_4$  is an ideal Yb-based HF system to study NFL behavior near the QCP at ambient pressure. At 20 K,  $\beta\text{-YbAlB}_4$  exhibits the intermediate valence state ( $\text{Yb}^{\sim+2.73}$ ).[8] The Yb valence value slightly decreases with decreasing temperature. Hence the quantum criticality is expected to be affected by strong valence fluctuations. This material crystallizes in a distorted honeycomb lattice of Boron on the  $ab$ -plane sandwiched by Yb and Al ions. In particular, the closest Yb-Yb pairs form along the  $c$ -axis with bond length equal to its lattice parameter. The temperature dependence of the  $ab$ -plane resistivity  $\rho_{ab}$ , moreover, follows a NFL behavior (almost  $T$ -linear dependence) from 10 K to 1 K and  $T^{3/2}$  dependence is found from 1 K to  $T_c$ . [7, 9] In Yb-based Kondo lattice systems, nonmagnetic  $\text{Yb}^{2+}$  ( $4f^{14}$ ) tends to become magnetic  $\text{Yb}^{3+}$  ( $4f^{13}$ ) under sufficient pressure. Hence, long-range magnetic ordering is expected to stabilize the system at elevated pressures. In several Yb-based systems, e.g.,  $\text{YbRh}_2\text{Si}_2$  and  $\text{YbCo}_2\text{Zn}_{20}$ , the pressure-induced magnetic ordering is actually observed near QCP [10, 11]. Hence, pressure-related studies of  $\beta\text{-YbAlB}_4$  showing unconventional SC are very important in investigating pressure-induced magnetic order. In this paper, we report pressure-dependent results near the QCP of high-quality single crystals  $\beta\text{-YbAlB}_4$  obtained using electrical resistivity measurements obtained at low temperatures.

## 2 Experimental

High-quality single crystals of  $\beta\text{-YbAlB}_4$  were grown using the aluminum self-flux method [12]. Tests for crystal quality were performed; a residual resistivity ratio (RRR) for each sample was obtained from resistivity measurements (with noise levels of  $\leq 40$  pVHz $^{-1/2}$ ). We used high-

quality samples with  $\rho_{ab}(300\text{ K})/\rho_{ab}(0)=300$  (residual resistivity  $\rho_0 = \rho_{ab}(0) \sim 1\ \mu\Omega\text{ cm}$ ) to measure the  $ab$ -plane resistivity at low temperatures down to 40 mK. Here, spot welding using 20  $\mu\text{m}\phi$  Au wires was used to form the electrical contacts on the surfaces of the samples. The four-point probe resistivity measurements were performed using a lock-in amplifier (SR830, Stanford Research Systems, Sunnyvale, CA) and low temperature transformer attached to  $^3\text{He}/^4\text{He}$  dilution refrigerators. A hybrid CuBe/NiCrAl piston-cylinder-type pressure cell was filled with high-pressure medium Daphne 7373 and attains a hydrostatic pressure of up to 3 GPa [13]. The pressure was calibrated by both superconducting transitions of Al or Sn. These superconducting signals were detected using  $ac$ -susceptibility techniques. [14, 15]

### 3 Results and Discussion

Figure 1(a) shows the pressure dependence of the electrical resistivity  $\rho_{ab}(T)$  for  $\beta\text{-YbAlB}_4$  (RRR=300) obtained using the pressure cell at temperatures down to 40 mK. Over a wide temperature range from 10 to 1 K,  $\rho_{ab}(T)$  displays a quasilinear  $T$  dependence. From 0.8 K to the superconducting transition  $T_c$ ,  $\rho_{ab}(T)$  exhibits a  $T^{1.5}$  dependence indicating a NFL. A sharp drop below  $T_c = 85$  mK indicating onset  $T_c$  was observed under ambient pressure. The zero resistance was also observed at a temperature 5 mK below the onset  $T_c$ . With application of pressure, onset  $T_c$  gradually decreases falling below 40 mK at a pressure of 0.9 GPa; The change in onset  $T_c$  with pressure gives estimate  $dT_c/dP = -33$  mK/GPa. The current  $I$  used for the resistivity measurements near  $T_c$  is set to one-third of the critical current for the superconductor  $I_c$  at the lowest temperature of 40 mK. From Fig. 1(a), there is a peak around the onset  $T_c$  which abruptly decreases to zero. The appearance of a peak at the superconducting transition is not novel; peaks are also observed for other high  $T_c$  superconductors.[16] However, no finite interpretation has been presented so far.

Figure 1(b) and (c) plots  $\rho_{ab}(T)$  as a function of  $T^{1.5}$  and of  $T^2$  to describe the respective NFL and Fermi-liquid (FL) behaviors. Although  $T_c$  is gradually suppressed with pressure, the quantum critical behavior with NFL  $\rho_{ab} - \rho_0 \sim T^{3/2}$  is robust against pressures up to 0.4 GPa, suggesting the formation of a strange metal phase. Here, a crossover from NFL  $\rho_{ab} - \rho_0 \sim T^{3/2}$  to FL  $\rho_{ab} - \rho_0 \sim T^2$  was observed near 0.4 GPa. The arrows drawn in Fig. 1(b) mark the FL temperatures  $T_{\text{FL}}$  determined by the temperature dependence of power law exponent  $\alpha = \partial \ln(\rho_{ab}(T) - \rho_0) / \partial T = 2 \pm 0.05$ . [17] The  $T_{\text{FL}}$ , below which the resistivity obeys the FL expression  $\rho_{ab} - \rho_0 \sim T^2$ , is gradually enhanced with application of pressure.

Under pressure of 2.7 GPa, a kink appears around 80 mK. Using a cubic anvil pressure cell and piston-cylinder.[17] the same type of kink is also seen in  $\rho_{ab}(T)$  at higher temperatures ( $T \geq 2$  K) under  $P \geq 2.4$  GPa. It assumes that with the application of pressure  $T_N$  (=80 mK) is significantly enhanced and connected to the high temperature side of  $T_N$ , reaching 30 K under 8 GPa. [17] Hence, this suggests that this pressure-induced phase transition is caused by long-range ordering of the Yb  $4f$  moments. Under elevated pressure, the large enhanced transition is probably affected by valence fluctuations in  $\beta\text{-YbAlB}_4$ . We found clear evidence that an unconventional type of quantum criticality/superconductivity under ambient pressure has been separated from the magnetic instability by a FL phase and most likely has formed a strange metal phase. The same type of  $P$ - $T$  phase was also confirmed in the functional dependence of chemical pressure with Fe-doping. Fe-doped samples  $\beta\text{-YbAl}_{1-x}\text{Fe}_x\text{B}_4$  were confirmed to exhibit chemical pressure effects dependent on the lattice parameter. [17, 18]

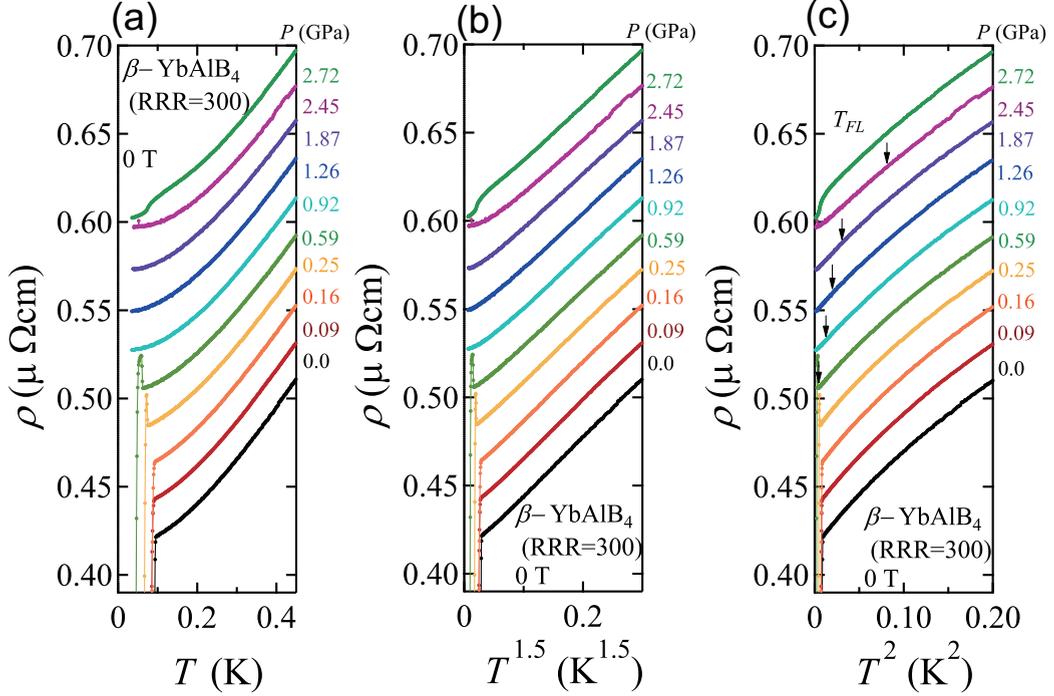


Figure 1: Temperature dependence of in-plane resistivity  $\rho_{ab}$  of  $\beta\text{-YbAlB}_4$  (RRR=300) at selected pressures. (a)  $T$ -linear dependence, (b)  $T^{1.5}$  dependence and (c)  $T^2$  dependence of the resistivity are shown at low temperatures down to 40 mK under zero field. Resistivity data are shifted to highlight the difference between the pressures. The arrows mark  $T_{FL}$ s; see text for details.

## 4 Summary

We investigated the pressure dependence of resistivity for the clean heavy-fermion metal  $\beta\text{-YbAlB}_4$ . A pressure-induced magnetic phase transition is observed at a temperature of around 80 mK in the electrical resistivity of  $\beta\text{-YbAlB}_4$  under  $P_c=2.7$  GPa. In contrast, a FL phase exists in the intermediate pressure range of  $1 < P < 2$  GPa between the ambient QCP lying beneath the SC dome and the pressure-induced magnetically ordered phase. In a past study, we suggested that a first QCP in  $\beta\text{-YbAlB}_4$  appears near zero-field and zero-temperature under ambient pressure.[6, 7] Hence, a magnetic phase transition observed around  $P_c=2.7$  GPa far from ambient pressure indicates that a second QCP may exist around  $P_c$ ;  $\beta\text{-YbAlB}_4$  may have two distinct QCPs. Hence, our study indicates that a new type of ambient QCP (the first QCP), detached from the magnetically ordered phase, is realized. An NFL behavior with  $\rho(T)_{ab} - \rho_0 \sim T^{1.5}$  above  $T_N$  is indeed observed near the pressure of 2.7 GPa, as the same as that above  $T_c$  near the first QCP. A phase diagram with two QCPs was also reported for  $\text{Yb}_2\text{Pd}_2\text{Sn}$  [19]. In many Ce-based HF, a QCP appears in the magnetically ordered phase and FL ground state. The anomalous phase behavior of  $\beta\text{-YbAlB}_4$  may be a phenomenon appearing only in Yb-based HF compounds influenced by its strong intermediate valence. We need to investigate  $\beta\text{-YbAlB}_4$  under higher pressures and at low temperatures to understand the ground state properties and transitions from the FL state to the magnetically ordered state and explain why

the magnetically ordered phase is far from the ambient QCP.

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