Low-temperature thermal transport coefficients of heavy fermion $\beta$-YbAlB$_4$

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Abstract. The first Yb-based heavy fermion superconductor $\beta$-YbAlB$_4$ with $T_c = 80$ mK is stoichiometrically quantum critical under ambient pressure and under zero magnetic field. We report the low-temperature thermoelectric power $S(T)$ on a high-quality single crystal of $\beta$-YbAlB$_4$ down to 40 mK. In zero field, $S(T)/T$ exhibits a dramatic enhancement and takes large negative values at low temperatures, followed by a fast drop below 80 mK as an indication of the superconducting transition. Under the field of $B = 25$ mT ($\geq B_{c2}$), $-S(T)/T$ is found to continuously increase down to the lowest temperature, which is highly in contrast to what is expected for the Fermi liquids ($S/T = \text{const.}$).

1. Introduction
Heavy fermion compounds have been intensively studied for their ability to use the pressures or the magnetic fields to tune continuously from a magnetic phase into a Fermi liquid through a quantum critical point (QCP). One consequence of the QCP is the vanishing characteristic energy scale of the Fermi liquid. So far, this behavior has been indicated mainly by the divergence of the electronic specific heat [1]. In some cases, however, the dominant nuclear contributions at low temperatures prevent the detailed studies on the QCP by means of the specific heat. Recently, new insight on the QCP via the thermoelectric coefficients, e.g., the thermoelectric power and the Nernst coefficient, has been examined as a promising probe to unravel the nature of the QCP because of their sensitivity to the low-energy excitations [2,3].

Here, we present the results of the low-temperature thermoelectric power of $\beta$-YbAlB$_4$ using a high-quality single crystal. $\beta$-YbAlB$_4$ is the first Yb-based heavy fermion superconductor with $T_c = 80$ mK [4]. Moreover, the system is stoichiometrically quantum critical under ambient pressure and under zero magnetic field. This enable us to make detailed investigations to elucidate the nature of quantum criticality.

2. Experiments
Single crystals were grown by using the Al-flux method as described in the literature [4]. Thermal transport coefficient was measured by employing a steady-state method in a dilution refrigerator. The heat current $q$ was injected parallel to the $ab$ plane, and the magnetic field was applied parallel to the $c$ axis on the sample with a rectangular shape (500 $\times$ 100 $\times$ 7$\mu$m). The thermal
contacts with resistance of $\sim 10 \, \text{m\Omega}$ at room temperature were made to the sample by using a spot welding technique. The same contacts were used to measure the resistivity by a standard four-contact method.

3. Results and Discussions

First, we demonstrate the high-quality of our sample from the resistivity measurements. Figure 1 displays the temperature dependence of the electrical resistivity $\rho(T)$ under zero field and 25 mT. The inset of Fig. 1 shows the high-temperature part of zero-field resistivity. Under zero field, $\rho(T)$ steeply decreases on cooling and shows a sharp drop at 80 mK associated with the superconducting transition. As denoted by a dotted line in Fig. 1, the normal state $\rho(T)$ is well described by the power-law form $\rho(T) = \rho_0 + AT^{1.5}$, consistent with the previous report [4]. The low residual resistivity $\rho_0 = 0.48 \, \mu\Omega\text{cm}$ with a high residual resistivity ratio $RRR \approx 270$ indicates high-quality of the sample. By applying the field of 25 mT, which is just above the upper critical field $B_{c2}$ along the $c$ axis [5], the superconducting transition is entirely suppressed.

Next, we concentrate on the thermal transport properties of $\beta$-YbAlB$_4$. Figure 2 shows the temperature dependence of the thermoelectric power divided by temperature $-S(T)/T$ under zero field and 25 mT. Above 0.2 K, $-S(T)/T$ exhibits a dramatic enhancement with a nearly logarithmic form and reaches a large negative value $-S/T \approx 6 \, \mu\text{V/K}^2$, which is two orders of magnitude larger than the values for simple metals such as Cu ($S/T \approx 10 \, \text{nV/K}^2$ at 1 K) [6]. The large $S/T$ is also found in other heavy-fermion compounds [2,3,7] and are considered to be related to the strongly enhanced specific heat. Indeed, the dimensionless ratio $(q = S_N \epsilon c / T)$, $N_A$ and $c$ represent the Avogadro number and the charge of electron, respectively) linking the thermoelectric power and the specific heat $C$ is found to be of the order of unity in a wide range of systems [8]. On further decreasing the temperature, $-S(T)/T$ under zero field shows steep increase even below 0.2 K but with a smaller slope followed by a sudden drop at 80 mK due to the superconducting transition. By contrast, under 25 mT ($> B_{c2}$), the drop disappears and $-S(T)/T$ is found to continuously increase down to the lowest temperature, incompatible
with the Fermi liquid behavior in which \( S(T)/T \) is expected to be constant [8]. Moreover, the pronounce increase near the QCP is in contrast to the other quantum critical heavy-fermion compounds, e.g., CeCoIn\(_5\) [2] and YbRh\(_2\)Si\(_2\) [3,9], in which the downturn of \( |S/T| \) was observed around the field-induced QCP.

Finally, let us examine the dimensionless ratio \( q \) of the thermoelectric power \( S \) and the specific heat \( C \) for \( \beta\)-YbAlB\(_4\). Figure 3 displays the temperature dependence of \( q \) for \( \beta\)-YbAlB\(_4\) together with the results in the vicinity of the QCP for CeCoIn\(_5\) [2] and YbRh\(_2\)Si\(_2\) [9]. For \( \beta\)-YbAlB\(_4\), we obtained \( q \) by combining the specific heat data reported in Ref. [4] with our thermopower data. Here, the specific heat data below 0.4 K is estimated by assuming that it increases logarithmically down to the lowest temperature. It can be clearly seen that \( q \) for all the three systems takes the values of the order of unity at high temperatures. Nevertheless, \( q \) for \( \beta\)-YbAlB\(_4\) is almost temperature-independent below 0.2 K, while the one for CeCoIn\(_5\) and YbRh\(_2\)Si\(_2\) decreases upon cooling. The apparently different behavior of \( q(T) \) among the quantum critical materials would be useful to distinguish the nature of the quantum criticality. Theoretically, it is argued that \( q \) decreases considerably toward antiferromagnetic QCP while it remains essentially unchanged for the ferromagnetic QCP or QCP due to a local criticality [10]. To further elucidate the quantum criticality of \( \beta\)-YbAlB\(_4\), detailed investigations are highly required.

4. Summary
Our results of the low-temperature thermoelectric power \( S \) measurements using the high-quality single crystal of \( \beta\)-YbAlB\(_4\) reveal the dramatic enhancement of \( S/T \) toward the QCP, giving rise to the apparently different behavior of the dimensionless ratio \( q \) compared with CeCoIn\(_5\) and YbRh\(_2\)Si\(_2\).

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Figure 3. Temperature dependence of the dimensionless ratio $|q|$ of the thermoelectric power and the specific heat for $\beta$-YbAlB$_4$ (0 T, closed circles and 25 mT, open circles), CeCoIn$_5$ (squares) [2] and YbRh$_2$Si$_2$ (triangles) [9] in the vicinity of the QCP.

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References
[1] Custers J, Gegenwart P, Wilhelm H, Neumaier K, Tokiwa Y, Trovarelli O, Geibel C, Steglich F, Pépin C and Coleman P 2003 Nature 424 524
[2] Izawa K, Behnia K, Matsuda Y, Shishido H, Settai R, Onuki Y and Flouquet J 2007 Phys. Rev. Lett. 99 147005
[3] Hartmann S, Oeschler N, Krellner C, Geibel C, Paschen S and Steglich F 2010 Phys. Rev. Lett. 104 096401
[4] Nakatsuji S, Kuga K, Machida Y, Tayama T, Sakakibara T, Karaki Y, Ishimoto H, Yonezawa S, Maeno Y, Pearson E, Lonzarich G G, Balicas L, Lee H and Fisk Z 2008 Nat. Phys. 4 603
[5] Kuga K, Karaki Y, Matsumoto Y, Machida Y and Nakatsuji S 2008 Phys. Rev. Lett. 101 137004
[6] Rumbo E R 1976 J. Phys. F: Met. Phys. 6 85
[7] Benz J, Pfleiderer C, Stockert O and Löhneysen H v 1999 Physica B 259-261 380
[8] Behnia K, Jaccard D and Flouquet J 2004 J. Phys.: Condens. Matter 16 5187
[9] Machida Y, Tomokuni K, Izawa K, Lapertot G, Knebel G, Brison J-P and Flouquet J unpublished
[10] Miyake K and Kohno H 2005 J. Phys. Soc. Jpn. 74 254