Anisotropic transverse magnetoresistivity in α-YbAlB$_4$

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Abstract. We measured the transverse magnetoresistivity of the mixed valence compound α-YbAlB$_4$. Two configurations were used where current was applied along [110] direction for both and magnetic field was applied along [-110] and c-axis. We found the transverse magnetoresistivity is highly anisotropic. In the weak field below 1 T, it is consistent with stronger c-f hybridization in the ab plane which was suggested from the previous zero field resistivity measurements. At the higher field above 3 T, we observed a negative transverse magnetoresistivity for the field applied along the c-axis. The temperature dependences of the resistivity measured at several different fields suggest the suppression of the heavy fermion behavior at the characteristic field of $\sim$ 5.5 T.

1. Introduction
Quantum criticality (QC) in heavy fermion systems has been studied extensively for the past few decades. To date, the most of the studies have been restricted to the Kondo lattice systems with integer valence where a quantum critical point (QCP) is usually found on the border of magnetism. On the other hand, there is a growing attention to the possibility of a novel QC beyond the conventional understanding based on the spin-density-wave type instability[1, 2]. Among them, the first Yb-based heavy fermion superconductor β-YbAlB$_4$ provides a unique example of a QC in the strongly mixed valence state [3, 4, 5, 6]. Indeed, the QC cannot be described by the standard theory for the spin-density-wave instability[7, 8, 9]. The diverging magnetic susceptibility along the c-axis exhibits the $T/B$ scaling in the wide temperature ($T$) and magnetic field ($B$) region spanning 3 ~ 4 orders of magnitude[5]. This indicates that the QC emerges without tuning any control parameter, suggesting a formation of an anomalous metallic phase.

β-YbAlB$_4$ has the locally isostructural polymorph α-YbAlB$_4$, which is also strongly mixed valent. The Yb valence estimated by a hard x-ray photoemission spectroscopy is +2.73 for α-YbAlB$_4$ and +2.75 for β-YbAlB$_4$ at 20 K [6]. The valence fluctuation temperature scale was estimated to be $\sim$ 200 - 300 K for both compounds[5, 10, 11]. Surprisingly, these two systems exhibit a heavy fermion (HF) behavior with a characteristic temperature scale of $\sim$ 8 K, which is far lower than the valence fluctuation scale [5]. This is quite unusual because Pauli paramagnetism is usually expected in the mixed valence compounds below the valence fluctuation temperature scale. The small temperature scale of $\sim$ 8 K for the anomalous HF state may indicate that α-YbAlB$_4$ is also close to a QCP although it has a Fermi liquid (FL)
ground state at zero field in contrast to $\beta$-YbAlB$_4$[10]. Recently, it is suggested that the HF behavior is suppressed under the field above $\sim$5 T in both compounds[12, 13].

Another remarkable feature for both systems is the anisotropic hybridization between conduction and $f$ electrons ($c$-$f$ hybridization). From the argument based on the local symmetry of the Yb site, the crystal field ground doublet of both $\alpha$- and $\beta$-YbAlB$_4$ is suggested to be made solely of $|J_z = \pm 5/2\rangle$ which is is anisotropic and have a node along the $c$-axis[15]. Indeed, it was already suggested experimentally from the resistivity measurements of $\alpha$-YbAlB$_4$[10]. The resistivity is highly anisotropic and the one in the $ab$-plane is 10 times larger than the one along the $c$-axis, which is consistent with the hybridization node along the $c$-axis. Interestingly, it has also been pointed out that the anisotropic $c$-$f$ hybridization plays an important role in the formation of HF state under the strong valence fluctuation and the novel QC found in $\beta$-YbAlB$_4$[16, 13, 15].

In order to further examine the possibility of the anisotropic $c$-$f$ hybridization, here, we measured the transverse magnetoresistivity (TMR) of $\alpha$-YbAlB$_4$ for the current ($I$) along [110] direction at low temperatures below 1 K. We found the TMR is highly anisotropic. The one in the field applied along the $c$-axis is quite different from the one in the field applied along the $ab$-plane. Furthermore, the anisotropy in the weak field below 1 T is consistent with the stronger $c$-$f$ hybridization in the $ab$-plane. On the other hand, we observed a negative TMR for the field applied along the $c$-axis above $\sim 3$ T, which corresponds to the suppression of the HF behavior mentioned above. The suppression of the HF behavior was also observed in the temperature dependence of the resistivity measured at several different fields.

We used a high purity single crystal of $\alpha$-YbAlB$_4$ with RRR (Residual Resistivity Ratio) $\sim$ 20 grown by a flux method [17]. It was reshaped to a size of $0.5$ mm in [110] direction and $\sim 20 \mu$m $\times \sim 20 \mu$m in its perpendicular direction. The resistivity and TMR measurements were made by the conventional AC four-terminal method.

2. Results and discussion

First we present in Fig. 1 (a) the field dependence of the TMR of $\alpha$-YbAlB$_4$ measured at 24 mK for the two configurations described above. Here, TMR, which is expressed as $\Delta \rho(B)$, is normalized by the zero-field resistivity $\rho(0)$. As clearly seen from the figure, TMR is highly anisotropic. While TMR for the field along the [-110] direction shows a monotonic increase, the one for the $c$-axis exhibits negative magnetoresistivity at field above $\sim 3$ T. In order to see the low field region in detail, we plot the full logarithmic version of TMR versus $B$ in Fig. 1 (b), where we find a clear power law behavior of $\Delta \rho(B)/\rho(0) \propto B^{1.8}$ for $B$ $\parallel$ [-110] up to $\sim 1.5$ T. On the other hand, TMR for $B$ $\parallel$ $c$ is smaller and it is rather hard to see if there is a power law behavior in the low field limit.

In the low field, TMR is expected to be proportional to ($m^*$)$^{-2}$ where $m^*$ is a (cyclotron) effective mass[18]. TMR arises from a cyclotron motion of electrons which is perpendicular to the applied magnetic field. Therefore, while TMR for $B$ $\parallel$ $c$ reflects the motion within the $ab$-plane, TMR for $B$ $\parallel$ $ab$ reflects the motion both within the $ab$-plane and along the $c$-axis. If we assume that $m^*$ for the motion within the $ab$-plane ($m^*_{ab}$) and $m^*$ along the $c$-axis ($m^*_c$) are different, then, TMR will be also anisotropic depending on the field direction. Assuming ($\Delta \rho(B))_{B \parallel c} \propto (m^*_c)^{-2}$ and ($\Delta \rho(B))_{B \parallel ab} \propto (m^*_abm^*_c)^{-1}$, the ratio between the two will be given by

$$\left(\frac{\Delta \rho(B))_{B \parallel ab}}{(\Delta \rho(B))_{B \parallel c}} \right) \sim \frac{m^*_c}{m^*_ab}. \tag{1}$$

In our results, TMR is larger for $B$ $\parallel$ $ab$ in the weak field. This indicates that $m^*_ab$ is larger than $m^*_c$ according to the above equation, consistent with the stronger $c$-$f$ hybridization within the $ab$-plane.
Figure 1. (a) Normalized transverse magnetoresistivity $\Delta \rho(B)/\rho(0)$ of $\alpha$-YbAlB$_4$ measured at $T = 24$ mK for $B || [-110]$ and $B || c$. Current is applied along [110] for both. Here, $\rho(0)$ is a zero-field resistivity at $T = 24$ mK and $\Delta \rho(B) = \rho(B) - \rho(0)$. (b) $\Delta \rho(B)/\rho(0)$ in full logarithmic scale. The long dashed short dashed line represents a power law fit for $B || [-110]$ below 1.5 T, which indicates $\Delta \rho(B)/\rho(0) \propto B^{1.8}$ behavior. The dashed line represents a power law fit with a power fixed to 1.8 for $B || c$ below 0.9 T. See text for detail.

To estimate the ratio between $m_{ab}^*$ and $m_c^*$, we also made a power law fit to TMR for $B || c$ below 0.9 T as shown in Fig. 1 (b). Here we assumed $\Delta \rho(B)/\rho(0) \propto B^{1.8}$. By comparing the coefficients of the $B^{1.8}$ behavior for both $B || ab$ and $B || c$, the ratio in the low field below 0.9 T was roughly estimated to be $m_{ab}^*/m_c^* \sim 2.9$. On the other hand, another estimation is available from $A$ coefficient of the $T^2$ temperature dependence of the resistivity defined as $\rho = \rho_0 + AT^2$. Here, $\rho_0$ is the resistivity at zero temperature limit (residual resistivity). As already discussed in the previous work[10], $A$ coefficient is highly anisotropic, i.e., the one for the current applied along the $ab$-plane ($A_{ab}$) is 13 times larger than the one along the $c$-axis ($A_c$). Using $A \propto (m^*)^2$, the anisotropy in the effective mass is roughly estimated to be $m_{ab}^*/m_c^* = \sqrt{A_{ab}/A_c} \sim 3.7$, which is of the same order as the above estimate from TMR. Note that, as we will discuss later, the temperature dependence of the resistivity along the $ab$-plane is slightly different from $T^2$ behavior expected for the FL. Instead, it exhibits $T^{1.8}$ dependence as it was already pointed out in the previous work[10]. Strictly speaking, this indicates that the $A$ coefficient can not be defined for the resistivity along the $ab$-plane. Nevertheless, in order to estimate $m_{ab}^*/m_c^*$, here we tentatively fixed the exponent to 2.0, the same value as in the determination of $A_c$.

The negative TMR found for $B || c$ above $\sim 3$ T may correspond to the suppression of the HF behavior. We observed the suppression behavior also in the temperature dependences of the resistivity measured at several different fields in the same current and field configurations as TMR measurements. The measurements were done at the temperature range $0.02 \leq T \leq 0.7$ K.

Figure 2 (a) shows the temperature dependence of the resistivity with $I || [110]$ and $B || c$. Corresponding to TMR discussed above, by applying magnetic field, it increases slightly up to 2 T and decreases above 3 T. If we subtract $\rho_0$ from the data, Figure 2 (b) is obtained, where we note that the temperature dependence is significantly suppressed above 3 T while it does not indicate almost any change up to this field. As we will discuss later, this corresponds to the
Figure 2. (a) Temperature dependence of the resistivity with the current along [110] at various fields along the c-axis. Inset shows the enlargement of the low temperature part of the data at $B = 3.0$ T or lower fields. (b) Temperature dependence of $\Delta \rho$ for the same data as in (a). Here $\Delta \rho = \rho - \rho_0$ and $\rho_0$ is the residual resistivity. Inset shows the full logarithmic plot of the main figure. The dashed line indicates $\Delta \rho \propto T^{1.8}$ behavior.

Figure 3. (a) Temperature dependence of the resistivity with the current along [110] at various fields along [-110] direction. (b) Temperature dependence of $\Delta \rho$ for the same data as (a). Here $\Delta \rho = \rho - \rho_0$ and $\rho_0$ is the residual resistivity. Inset shows the full logarithmic plot of the main figure.

The temperature dependence indicates the power law behavior $\Delta \rho \propto T^{1.8}$ at low field as shown in the inset of Fig. 2 (b).

The temperature dependences of the resistivity measured with $I \parallel [110]$ and $B \parallel [-110]$ are shown in Fig. 3 (a) and (b). By applying magnetic field, the isothermal resistivity increases due to TMR. If we compare $\Delta \rho$ obtained after subtracting $\rho_0$, they overlap quite well to each
other up to \( B = 8 \) T. Therefore, there is no suppression of the HF behavior for \( B \parallel [-110] \), which is consistent with the Ising anisotropy of the system. They exhibit the power law behavior \( \Delta \rho \propto T^{1.8} \) up to \( B = 8 \) T as shown in the inset of Fig. 3 (b).

In order to discuss the temperature dependence in detail, we estimated the exponent \( \alpha \) defined by \( \Delta \rho = A_\alpha T^\alpha \) at each field. The definition of \( \alpha \) gives \( \alpha = \partial \log \Delta \rho / \partial \log T \) as a temperature dependent quantity. We found that \( \alpha \) is almost temperature independent up to \( \sim 0.7 \) K for all the field up to \( 8 \) T in both \( B \parallel c \) and \( B \parallel [-110] \). The field dependences of \( \alpha \) obtained at \( 0.1 \) K for each field direction are shown in Fig. 4(a). The error bars are mostly coming from the errors in \( \rho_0 \) for each data. For \( B \parallel [-110] \), \( \alpha \) is almost field independent with a value \( \sim 1.8 \). On the other hand, it increases a little bit towards the normal value of \( 2.0 \) above \( 5 \) T for \( B \parallel c \). This may indicate that the ground state of \( \alpha \)-YbAlB\(_4\) is slightly deviating from the FL at zero-field and recovers the FL state after the suppression of the HF behavior above \( 5 \) T along the \( c \)-axis.

The suppression of the HF behavior is clearly seen in Fig. 4 (b). Here, we estimated a coefficient \( A' \) defined by \( \Delta \rho = A'T^{1.8} \) because \( \Delta \rho \propto T^{1.8} \) behavior is always observed except for the slight increase of the exponent \( \alpha \) above \( 5 \) T for \( B \parallel c \). Although the definition is different from the one for FL, \( A' \) is still expected to give an estimate of \( m^* \). Note that the same field evolution is obtained even if we plot \( A \) defined by \( \Delta \rho = AT^2 \). The field evolution of \( A' \) indicates the suppression of the HF behavior above a field scale of \( \sim 5.5 \) T, characterized by the inflection point.

3. Conclusion

We measured the transverse magnetoresistivity (TMR) in \( \alpha \)-YbAlB\(_4\) for the current \( (I) \) along [110] direction at low temperatures below 1 K. We found the TMR is highly anisotropic and those in the field applied along \( c \)-axis and in the \( ab \)-plane are quite different to each other. The anisotropy in the weak field below 1 T is consistent with the stronger \( c-f \) hybridization in the \( ab \)-plane. Furthermore, we observed a negative TMR for the field applied along the \( c \)-axis above \( \sim 3 \) T, which should arise from the suppression of the HF behavior by magnetic field. The temperature dependence of the resistivity also indicates the suppression of the HF behavior with a characteristic field scale of \( \sim 5.5 \) T.
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