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# Scaling relation found in anomalous electrical transport and superconductivity of heavy fermion superconductor $URu_2Si_2$

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**Abstract.** The pressure dependent electrical resistivity of $URu_2Si_2$ has been studied at high pressure across the first order phase boundary of $P_x$ where the ground state switches under pressure from "hidden order" (HO) to large moment antiferromagnetic (LAFM) states. We have measured an ultra-clean single crystal whose quality is the highest among those used in previous studies. We have previously analyzed the resistivity data with the generalized power law $\rho = \rho_0 + A_n T^n$. It was found that the electric transport property deviates from Fermi liquid theory in the HO phase but obeys the theory well above $P_x$. In this paper, we re-analyze the data using the polynomial in $T$ expression $\rho = \rho_0 + \alpha_1 T + \alpha_2 T^2$. The analysis finds the relation $\alpha_1/\alpha_2 \propto T_{sc}$ in the HO phase. While the pressure dependence of $\alpha_2$ is very weak, $\alpha_1$ is roughly proportional to $T_{sc}$. This suggests a strong correlation between the anomalous quasiparticle scattering and the superconductivity and that both have a common origin. The present study clarifies a universality of the HO phase inherent in strongly correlated electron superconductors near quantum criticality.

## 1. Introduction

$URu_2Si_2$ is a heavy-fermion superconductor that shows a superconducting (SC) transition temperature $T_{sc} = 1.5$ K at ambient pressure [1]. A second order phase transition takes place at $T_0 = 17.5$ K, and the ordered state coexists with the unconventional superconductivity. Although many studies have been done for the ordered state [2, 3, 4, 5], the nature of the state is still not understood and is known as "hidden order" (HO). The application of the pressure changes the ground state of $URu_2Si_2$ from the HO to a large moment antiferromagnetic (LAFM) state at $P_x = 0.5 \sim 0.9$ GPa [6, 7, 8]. The bulk-SC state exists only below $P_x$[7, 8].

The electrical transport in $URu_2Si_2$ shows a strong sample dependence that has been carefully studied using high quality single crystals by us [9, 10]. The electrical resistivity of samples with different quality have been analyzed with a general power law $\rho_0 + AT^n$ just above $T_{sc}$ at ambient pressure. It was revealed that the values of the power law exponent $n$ are $1.5 \pm 0.1$ and $1.6 \pm 0.1$ for the electrical resistivity for the current along the $a$ and $c$-axes, respectively in samples with higher quality at ambient pressure [10]. We have previously studied the electrical transport of $URu_2Si_2$ under high pressure[11]. The resistivity data were analyzed with the power law.

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The values of the exponent $n$ are generally about $1.5 \pm 0.1$ in the HO phase below $P_x$. Above the critical pressure, $n$ increases with increasing pressure and the value is about 2.0 at 1.51 GPa, expected from the Fermi liquid theory. The derivation of the electrical transport from the theory seems to be intrinsic to the HO state. In this study, we re-analyze the data with a new expression and find an interesting scaling relation between the anomalous electrical transport and the unconventional superconductivity in $URu_2Si_2$.

## 2. Experimental

The details of the experimental methods are given in the ref. 11. In this study, we have used the high quality single crystal of $URu_2Si_2$. It is difficult to estimate the residual resistivity ratio RRR ( $= \rho_{RT}/\rho_0$), where $\rho_0$ and $\rho_{RT}$ are a residual resistivity and the value of the resistivity at room temperature, respectively, because $\rho_0$ is negative if the resistivity just above $T_{sc}$ is simply extrapolated to 0 K. Therefore, the value of RRR was estimated as 300 using the resistivity value ($\rho_{T_{sc}}$) just above $T_{sc}$ (RRR $= \rho_{RT}/\rho_{T_{sc}}$). The residual resistivity is very small and the real RRR value exceeds 1000, indicating ultra-cleaness of the single crystal [9]. The resistivity data under high pressure are analyzed with a polynomial in $T$ expression $\rho = \rho_0 + \alpha_1 T + \alpha_2 T^2$ that has been used in the analysis of the anomalous electrical transport in the organic superconductors, the iron pnictide superconductors, and the high-$T_c$ cuprate superconductors [12, 13, 14] .

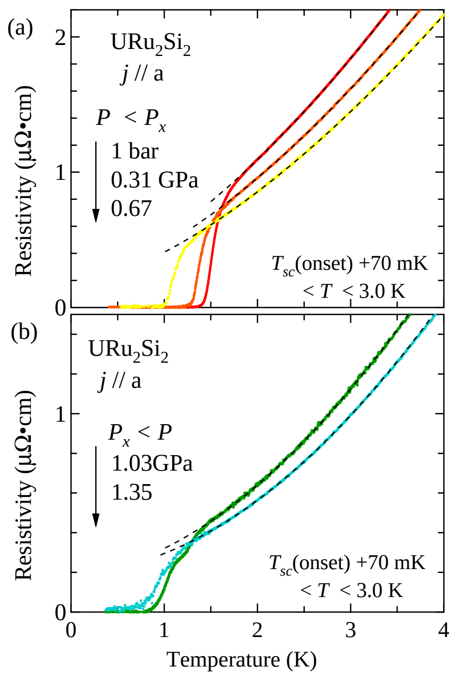


**Figure 1.** Temperature dependence of the electrical resistivity in $URu_2Si_2$ at (a)1 bar, 0.31, and 0.67 GPa below $P_x$ and (b) 1.03 and 1.35 GPa above $P_x$. The dotted lines represent the fit of a expression $\rho = \rho_0 + \alpha_1 T + \alpha_2 T^2$ to the resistivity.

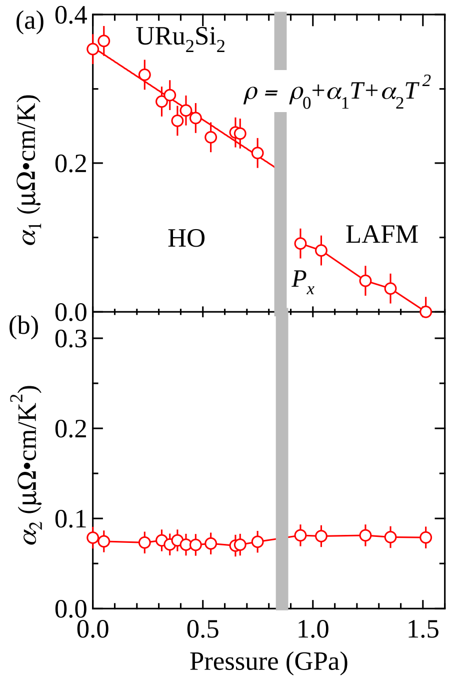


**Figure 2.** Pressure dependences of (a) the coefficient $\alpha_1$ and (b) $\alpha_2$ obtained by fitting the expression to the resistivity in $URu_2Si_2$.

## 3. Results and Discussions

Figure 1 shows the low temperature electrical resistivity $\rho_a$ at (a)1 bar, 0.31, and 0.67 GPa below $P_x$, and (b) 1.03 and 1.35 GPa above $P_x$. The readers refer to the ref. 11 for the pressure phase diagram in $URu_2Si_2$. $P_x$ is located between 0.75 and 0.94 GPa in the present study. At 1 bar, the clear SC transition was observed at $T_{sc} = 1.43$ K. The transition temperature decreases with increasing pressure. The previous studies clarified that the bulk-SC state exists only below $P_x$ and that the broad SC transition in the resistivity seen in the pressure region above $P_x$ seems to be related to residual HO phase well above $P_x$ [7, 8]. In the present study, the SC transition temperature depends on the applied electrical current above 0.94 GPa. Zero resistivity was not observed at 1.35 and 1.51 GPa (data not shown). These results reflects the filamentary SC above $P_x$.

The data in the temperature regions from $T_l = T_{sc}(\text{onset}) + 70$ mK to 3.0 K have been analyzed using the expression $\rho = \rho_0 + \alpha_1 T + \alpha_2 T^2$ used in the analysis of the anomalous electrical transport in the strongly correlated electron superconductors [12, 13, 14]. Figure 2 (a) and (b) show the pressure dependences of $\alpha_1$ and $\alpha_2$. The contribution to the resistivity from the term $\alpha_1 T$ is far larger than that from $\alpha_2 T^2$ in the HO phase below $P_x$. With increasing pressure, the value of $\alpha_1$ decreases monotonously and shows a discontinuous decrease at $P_x$.

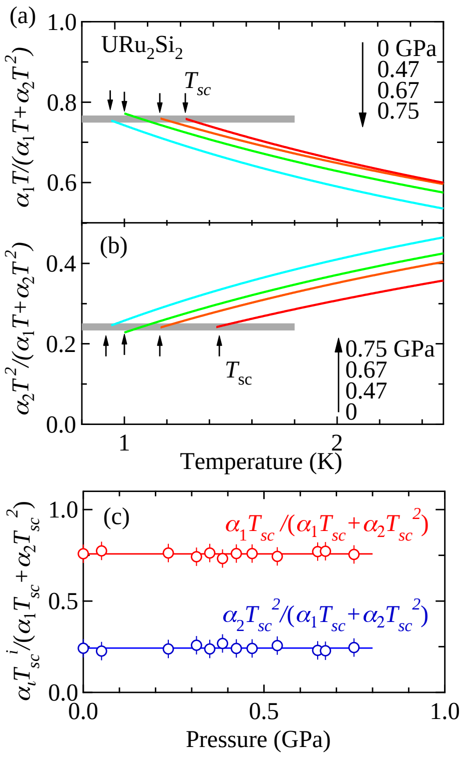


**Figure 3.** Temperature dependences of (a) $\alpha_1 T/(\alpha_1 T + \alpha_2 T^2)$ and (b) $\alpha_2 T^2/(\alpha_1 T + \alpha_2 T^2)$ calculated using the values of the coefficients $\alpha_1$ and $\alpha_2$ obtained from the fits of the data. (c) Pressure dependences of $\alpha_1 T_{sc}/(\alpha_1 T_{sc} + \alpha_2 {T_{sc}}^2)$ and $\alpha_2 {T_{sc}}^2/(\alpha_1 T_{sc} + \alpha_2 {T_{sc}}^2)$ in $URu_2Si_2$.

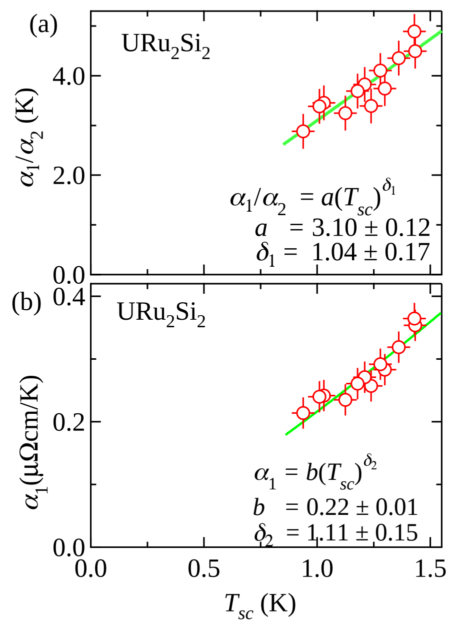


**Figure 4.** Relations between (a)the superconducting transition temperature $T_{sc}$ and $\alpha_1/\alpha_2$, and (b) $T_{sc}$ and $\alpha_1$ in $URu_2Si_2$.

The value of $\alpha_1$ remains finite up to 1.35 GPa even though the ground state changes to the LAFM phase. This may be due to the residual HO phase in the LAFM phase as mentioned above. The coefficient $\alpha_2$ shows only weak pressure dependence, indicating that the Fermi liquid contribution to the electrical resistivity does not change greatly across $P_x$. This is consistent with recent Fermi surface studies by the de Haas-van Alphen experiments which showed no substantial change in the topology of the Fermi surfaces across $P_x$ [15, 16]. It is suggested that the scattering process of the quasiparticles in specific regions of the Fermi surfaces deviates from the Fermi liquid theory in the HO phase and anomalous quasiparticle scattering around the "hot area" gives the anomalous electrical transport.

Next, we show the temperature dependences of $\alpha_1 T/(\alpha_1 T+\alpha_2 T^2)$ and $\alpha_2 T^2/(\alpha_1 T+\alpha_2 T^2)$ in Fig. 3 (a) and (b). Those correspond to the ratios of the terms $\alpha_1 T$ and $\alpha_2 T^2$ to the resistivity due to the electron correlations $\Delta\rho$ ($= \rho$ - $\rho_0$). The contribution from $\alpha_1 T$ to $\Delta\rho$ increases with decreasing pressure and becomes dominant just above $T_{sc}$. It is interesting to note that $\alpha_1 T/(\alpha_1 T+\alpha_2 T^2)$ and $\alpha_2 T^2/(\alpha_1 T+\alpha_2 T^2)$ show almost pressure-independent values of 0.74 $\pm$ 0.05 and 0.25 $\pm$ 0.05, respectively, at just above $T_{sc}$ as shown in Fig. 3 (c). This suggests the relation $\alpha_1/\alpha_2 \propto T_{sc}$. The relation between $T_{sc}$ and $\alpha_1/\alpha_2$ is shown in Fig. 4 (a). The line is a fit with the relation $\alpha_1/\alpha_2 = a(T_{sc})^{\delta_1}$, where the values of $a$ and $\delta_1$ are determined as 3.10 $\pm$ 0.12 and 1.04 $\pm$ 0.17, respectively. This suggests a linearity between $T_{sc}$ and $\alpha_1/\alpha_2$. Since the pressure dependence of the coefficient $\alpha_2$ is very weak as shown in Fig. 2 (b), the value of $T_{sc}$ depends primarily on the coefficient $\alpha_1$ as shown in Fig. 4 (b). The relation $\alpha_1 = c{T_{sc}}^{\delta_1}$ is obtained, where $c$ and $\delta_1$ are determined to be 0.22 $\pm$ 0.01 and 1.11 $\pm$ 0.15, respectively, suggesting an almost linear relation between $\alpha_1$ and $T_{sc}$. These results suggest the strong correlation between anomalous quasiparticle scattering and unconventional superconductivity in the HO phase of $URu_2Si_2$. The almost same results are obtained when the the resistivity data between $T_l$ to 3.4 K are analyzed.

As summarized in the ref. 14, similar correlation between the $T$-linear resistivity and $T_{sc}$ has been found in the organic superconductors, the iron pnictide superconductors and the high-$T_c$ cuprate superconductors [14]. The correlation may be universal in the unconventional superconductors.

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