Correlation between anomalous quasiparticle scattering and superconductivity in URu_2Si_2

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- The pressure dependent electrical resistivity of URu_2Si_2 has been studied at high pressure. The electric transport property deviates from Fermi liquid theory in the "hidden order" phase.
- We find a linearity between the coefficient of the T-linear resistivity and the superconducting transition temperature T_{sc} that indicates the strong correlation between the anomalous electric transport and superconductivity.
- The present study suggests a universality of the "hidden order" phase inherent in strongly correlated electron superconductors near quantum criticality.

Abstract

Since the discovery of the superconductivity in 1985, URu_2Si_2 has been the focus of many theoretical and experimental studies. The compound shows a second order phase transition at T_0 = 17.5 K, and this ordered state coexists with unconventional superconductivity T_{sc} = 1.4 K at ambient pressure. The nature of the phase below T_0, known as "hidden order", is still not understood, despite many studies for a long time. In this study, we have measured the electrical resistivity under high pressure and found a correlation between the anomalous quasiparticle scattering and the unconventional superconductivity. The present study clarifies a universality of the "hidden order" phase inherent in strongly correlated electron superconductors.

This work has been done in collaboration work with Prof. Z. Fisk, Drs. Y. Haga, and T. D. Matsuda at Advanced Science Research Center (JAEA), and with Prof. Y. Onuki at Osaka University. The part of this work was published in Journal of Physics.: Conference Series [1].

1. Background

Superconductivity (SC) is a macroscopic quantum mechanical phenomenon first observed in mercury (Hg) by Kammerlingh Onnes at 1911. Bardeen, Cooper, and Schrieffer showed theoretically in 1957 that the SC arose because the electrons experienced an attractive interaction brought about by the vibrations of the crystal lattice. Their theory, called "BCS theory", can explain various experimental results in superconducting materials such as lead (Pb).

Since the end of 1970's, "unconventional SC" has been discovered in the strongly correlated electron systems of the rare earth and actinide compounds, the organic materials, and the cuprate oxides. Lattice vibration may not play an important role for these SC. The superconducting properties of these compounds are not explained by the BCS theory.

The SC in URu_2Si_2 has attracted much attention due to its novel superconducting properties [2]. Unconventional type SC has been suggested from unusual temperature dependencies of physical quantities such as the heat capacity and the thermal conductivity. The compound shows a second order phase transition at T_0 = 17.5 K and SC co-exists with the ordered state below the superconducting transition temperature T_{sc} = 1.4 K. The nature of this ordered phase has not been resolved for more than 25 years, despite many experimental and theoretical efforts. The phase is known as "hidden order" (HO). A recent study shows that rotational symmetry breaking occurs in the "hidden order" phase [3]. There is no information for what kind of interaction between electrons mediates the SC in URu_2Si_2.

2. History of our studies

We have focused on the electrical resistivity ρ in URu_2Si_2 since ρ reflects the electronic properties of the "hidden order" phase through the scattering process of conduction electrons. The behavior of electrons in a metal is well described by Landau's Fermi-liquid theory where the electrons can be treated as well-defined fermions called “quasiparticles”. In the theory, the usual electron-electron scattering gives a T^2-term in the resistivity. To obtain reliable information from the resistivity data, a high quality single crystal sample is required since the scattering of electrons by impurities, dislocations, and lattice defects may mask the intrinsic electric property. It is important to establish a technique to grow a high-quality single crystal. We succeeded in growing high purity single crystals of URu_2Si_2 by the combination of the solid-state electro-transport and the Czochralski-pulling methods [4]. We have carefully measured the resistivity of these ultra-clean single crystal sample whose quality is the highest among those used in previous studies and found that ρ shows $T^{1.5}$-dependence at low temperatures. This anomalous behavior cannot be explained by the usual electron-electron scattering as mentioned before. This may be related to the unusual electric properties of “hidden-order” phase.

Next, we have an interest in pressure effects on the electrical resistivity and the superconducting transition temperature T_{sc}. Figure 1 shows the temperature-pressure phase diagram in URu_2Si_2 [1,5]. The horizontal axis indicates the pressure (GPa) and the vertical one the temperature (K). 1 GPa corresponds to approximately 10000 atmospheres. At ambient pressure, URu_2Si_2 shows a second order phase transition from the paramagnetic to the “hidden order” phase at T_0 = 17.5 K and subsequently a superconducting transition at T_{sc} = 1.4 K. Applying pressure induces a first order phase transition from the “hidden order” to a large moment antiferromagnetic phase at a critical pressure of $T_x(P)$. The superconducting transition temperature decreases with increasing pressure and the bulk superconductivity exist only in the “hidden order” phase. We have measured the electrical resistivity under high pressure to investigate the pressure effect on the electrical transport in the “hidden order” phase.

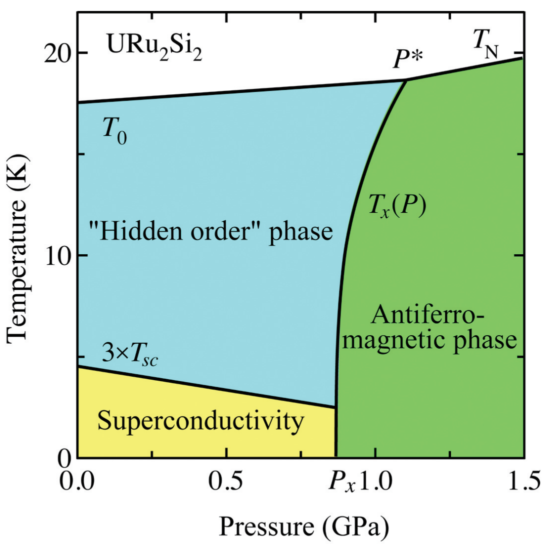

Fig.1. Pressure-temperature phase diagram in URu_2Si_2. (To show the boundary between the “hidden order” and superconducting phases clearly, a line of 3 × T_{sc} is shown)

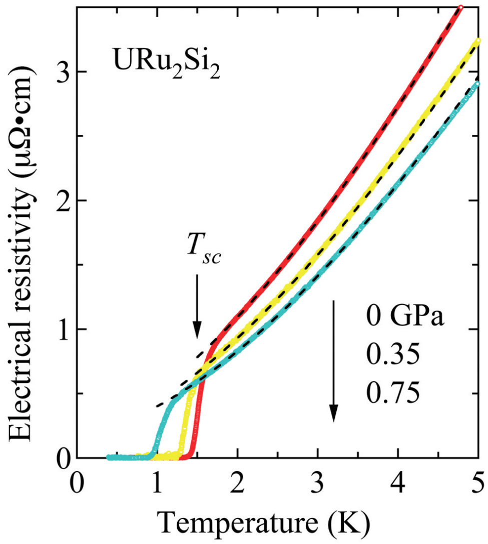

Fig.2. Temperature dependences of the electrical resistivity at 0, and 0.35, and 0.75 GPa in URu_2Si_2.

3. Results and discussions

Figure 2 shows the temperature dependence of the electrical resistivity ρ at ambient pressure (~ 0 GPa), 0.35, and 0.75 GPa. The value of ρ decreases with decreasing temperature and goes to zero below the superconducting transition temperature T_{sc}. The application of pressure reduces T_{sc}. The temperature dependence of ρ was analyzed with the generalized power law

$$\rho = \rho_0 + A_n T^n \quad (1)$$

in the temperature region from T_{sc} to 3.0 K shown as the dotted lines in the figure. Figure 3 (a) shows the pressure dependence of the resistivity exponent n in the eq. (1) obtained from the analysis. The value of n shows a weak pressure dependence with approximately n = 1.5 below P_x in the “hidden ordered” phase. There seems to be a discontinuous increase of n at P_x and the value of n at 1.51 GPa becomes 2.0, that expected in Landau’s Fermi liquid theory. This analysis finds that the deviation of the electric transport property from the Landau’s Fermi liquid theory is intrinsic to the “hidden order” phase.

Anomalous temperature dependences of the physical quantities, the deviations from the Landau's Fermi liquid theory, have been reported in strongly correlated electron systems. These phenomena, referred to as "non-Fermi liquid behavior", have recently attracted a great deal of attention. Although many studies have been done for the phenomena in the rare earth cerium and ytteribium compounds, non-Fermi liquid behavior has been rarely observed in uranium compounds. This interesting finding in URu_2Si_2 provides a key for further studies on the "hidden order" phase.

We explain details of the high pressure physical properties in URu_2Si_2. The "hidden order" phase below P_x does not break the crystal-lattice and the time reversal symmetries. Meanwhile, the phase above P_x is antiferromagnetically ordered phase with the propagating vector Q_0 = (1,0,0). The "strange hidden order" phase adjoins the "ordinary antiferromagnetic phase" across the first order phase boundary $T_x(P)$.

The "Fermi energy" of electrons in a metal gives us information about the velocities of the electrons which participate in ordinary electrical conduction. The "Fermi surface" is a constant energy surface defined by the Fermi energy in the k-space containing the wave vectors of states of individual fermion. The Fermi surface topology reflects the behavior of the conduction electrons in a metal. One may consider

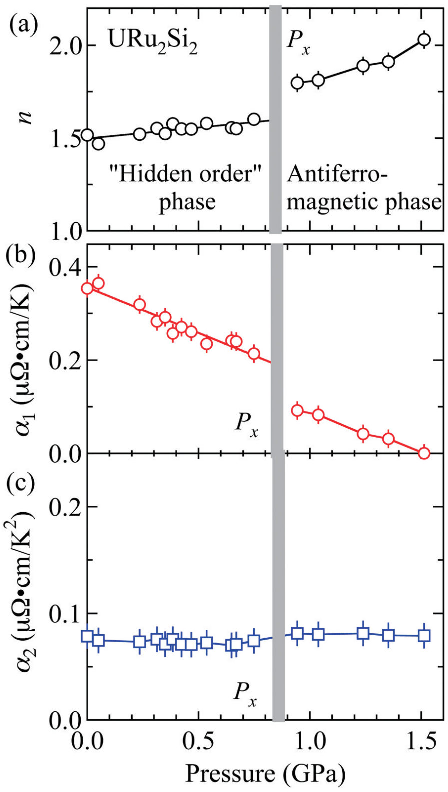

Fig.3. Pressure dependences of (a)the resistivity exponent n , and (b) the coefficients α_1, and (c) α_2 in URu_2Si_2.

the "hidden order" phase has different Fermi surfaces from those in the antiferromagnetic phase. However, a previous study showed the similarity of the Fermi surface topology between the two phases [6]. A recent photoemission experiment revealed that the periodicity of the electric state in the "hidden order" phase is the same as that (= Q_0) in the antiferromagnetic state [7]. We note that our single crystals have been used in these studies.

Then, how we can understand results shown in Fig. 3(a)? We speculate that the scattering process of quasiparticles in specific regions of the Fermi surfaces deviates from Fermi liquid theory and that the anomalous scattering around these regions gives the anomalous electrical transport. Meanwhile, the scattering process on most regions of the Fermi surfaces obeys the theory, which gives the conventional T^2 term in the resistivity. Indeed, neutron scattering experiments show the existence of low energy excitations at Q_0 = (1, 0, 0), Q_1 = (1.4, 0, 0) in the non magnetic hidden order phase [5]. In particular, the excitation at Q_0 appears only in the hidden order phase. Assuming the anomalous quasiparticles scattering gives a T-linear resistivity, we re-analyze the resistivity data with

$$\rho = \rho_0 + \alpha_1 T + \alpha_2 T^2 \quad (2).$$

Roughly speaking, we assume that the resistivity consists of the "unusual component" expressed as $\alpha_1 T$ and the "unusual one" as $\alpha_2 T^2$.

The pressure dependences of α_1 and α_2 were determined from the fit of the data to eq. (2). The results are shown in Fig. 3(b) and (c). The contribution to the resistivity from the term $\alpha_1 T$ is far larger than that from $\alpha_2 T^2$ in the "hidden order" phase below P_x. The value of α_1 shows a discontinuous decrease at P_x and it decreases strongly with increasing pressure going to 0 at 1.51 GPa. The value of α_1 remains finite up to 1.35 GPa even though the ground state changes to the antiferromagnetic phase. This may be due to the residual "hidden order" phase in the antiferromagnetic phase as pointed out in previous studies [5]. The coefficient α_2 shows only weak pressure dependence, indicating that the Fermi liquid contribution to the resistivity does not change significantly across P_x. This is consistent with the Fermi surface studies under high pressure as mentioned before. The analysis with the eq. (2) gives us a comprehensive picture which is compatible with other experimental results.

We find an interesting fact from the analysis using eq. (2). The ratio of the first term $\alpha_1 T$ to the second one $\alpha_2 T^2$ shows a pressure independent value of about 3 just above T_{sc}, although T_{sc} depends on the pressure. This indicates a linear relation of $\alpha_1/\alpha_2 \propto T_{sc}$. Figure 4 shows the relation between the two

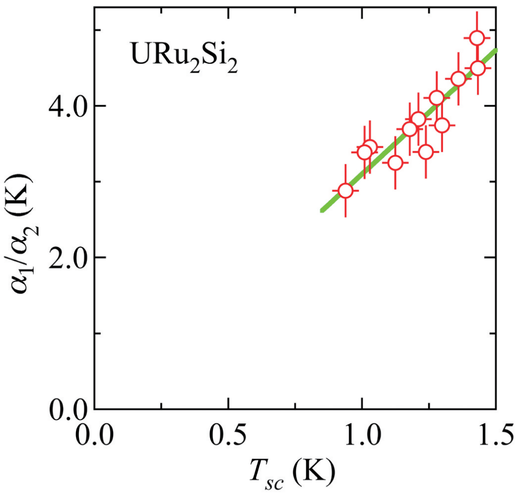

Fig.4. Relation between the superconducting transition temperature T_{sc} and α_1/α_2 in URu_2Si_2.

quantities. A line in the figure is the result of the fit to the data with an equation $\alpha_1/\alpha_2 = a(T_{sc})^{\delta_1}$. The values of a and δ_1 are determined as 3.10 ± 0.12 and 1.04 ± 0.17, respectively, suggesting a linearity between them. Since the pressure dependence of the coefficient α_2 is very weak, the superconducting transition temperature T_{sc} depends primarily on the coefficient α_1. The term $\alpha_1 T$ reflects the "anomalous component" of the resistivity. The present result suggests a strong correlation between the anomalous electrical transport and the unconventional superconductivity in the "hidden" phase of URu_2Si_2 and that both have a common origin.

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 [8]. It is surprising that this simple correlation has been observed in the strongly correlated electron superconductors where crystal structures and dimensionality of the electric state are completely different from each other. This correlation may be a universality common to the unconventional superconductors.

4. Summary

We have found a correlation between the anomalous electrical transport and the unconventional superconductivity in URu_2Si_2. This same correlation has been found in other strongly correlated electron superconductors. There have been reported unidentified mysterious phases in the strongly correlated electron system such as "pseudo-gap phase" in the cuprate superconductors. We suggest that the "hidden order phase shares a universality with these other unidentified phases. A recent study revealed rotational symmetry breaking of the electronic state in the "hidden order" phase as mentioned in the introduction. Similar symmetry breaking has been reported in the pseudo-gap phase in the cuprate superconductors [9]. These phenomena have been compared with the assembly of large molecules liquid crystals and are referred as "electronic nematicity". Our study provides a different point of view for existing and future theories of the HO phase.

5. Future plans

We will continue to study the "hidden order" phase by the measurements of other physical quantities such as the heat capacity and the Hall coefficient. A final goal is to understand how the electronic state switches from the mysterious "hidden order" to the conventional magnetic phase.

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