Specific Heat of the Spin-Triplet Superconductor Sr_2RuO_4 with Nonmagnetic Impurities

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Abstract

We report the substitution effect of *nonmagnetic* Ti^{4+} for Ru^{4+} on the specific heat of $Sr_2Ru_{1-x}Ti_xO_4$ from $x = 0$ (spin-triplet superconductor) to 9% (magnetically ordered phase with glassy behavior) via magnetic instability point at $x_c \sim 2.5\%$. We found that specific heat divided by temperature C_P/T around x_c deviates from the conventional Fermi-liquid behavior seen in pure Sr_2RuO_4 and shows the logarithmic behavior at x_c. Such critical enhancement is attributable to the diverging two-dimensional antiferromagnetic fluctuation, which arises mainly from the nesting within one of the three Fermi-surface sheets.

Key words: Sr_2RuO_4; nonmagnetic impurity effect; specific heat; non-Fermi Liquid

1. Introduction

The superconductivity of Sr_2RuO_4 with a layered perovskite structure has attracted much attention both experimentally and theoretically. First, the superconductivity with the intrinsic transition temperature $T_{c0} = 1.5$ K is of unconventional pairing symmetry, most probably spin triplet [1]. Second, physical properties in the normal state is well described in terms of the quasi two-dimensional Fermi liquid [2] based on the detailed Fermi surface topography, where the Fermi surface is composed of three nearly cylindrical sheets (α, β, γ) [3].

Systematic study of substitution effect of nonmagnetic and/or magnetic impurities is a useful method in order to understand such unconventional superconductivity. For instance, the substitution effects by the *nonmagnetic* Zn^{2+} impurity and the *magnetic* Ni^{2+} impurity for Cu^{2+} ions in the high-T_c cuprates have been extensively studied to detect the unusual features [4].

By the analogy of the high-T_c cuprates, we reported the substitution effect of *nonmagnetic* impurity Ti^{4+} (the electron configuration $3d^0$) for Ru^{4+} ($4d^4$ in the low spin configuration) [5]. In that study, it has been revealed that local moment, which has Ising anisotropy with an easy axis perpendicular to the RuO_2 planes, is induced. Moreover, magnetic ordering with glassy behavior is observed for $x \geq 2.5\%$ in $Sr_2Ru_{1-x}Ti_xO_4$. In order to understand in more detail the effect of the nonmagnetic impurity on the thermodynamic properties, we measured the specific heat of $Sr_2Ru_{1-x}Ti_xO_4$ from $x = 0$ (the spin-triplet superconductor) to $x =$ 9% (the magnetically ordered phase) across the critical point at $x_c \sim 2.5\%$.

2. Experimental

A series of single-crystalline $Sr_2Ru_{1-x}Ti_xO_4$ with x up to 9% were grown by a floating-zone method

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with an infrared image furnace (NEC Machinery, SC-E15HD) [5,6]. The specific heat C_P was measured by a thermal relaxation method between 0.5 K and 30 K (Quantum Design, model PPMS).

3. Results and Discussion

Figure 1 shows the specific heat divided by temperature C_P/T for $x = 0$, 1, 2.5 and 9% plotted as functions of T^2. The data for $x = 0$ was obtained by applying the magnetic field of 0.2 T perpendicular to the conductive RuO_2 planes in order to suppress the superconductivity ($T_c = 1.44$ K). There is no evidence for magnetic field dependence of the C_P/T at $T \geq T_c$ within the experimental resolution, consistent with the previous report [7]. We can clearly see the gradual enhancement of the C_P/T toward $x_c = 2.5\%$ as shown in Fig. 2. The enhancement can not be explained by the induced impurity band, because C_P/T decreases for $x \geq 2.5\%$. In addition, a logarithmic upturn behavior, which deviates from the simple Fermi liquid behavior in pure Sr_2RuO_4 [3], becomes remarkable near x_c as demonstrated in the inset of Fig. 1, where $\Delta C_P/T = C_P/T(x = 1,\ 2.5\%) - C_P/T(x = 0)$.

Incommensurate magnetic ordering with the wave vector $\boldsymbol{Q}_{\rm ic} \sim (2\pi/3,\ 2\pi/3,\ 0)$, which is close to the position of the incommensurate spin fluctuations [8] in pure Sr_2RuO_4 resulting mainly from the nesting of the β band [9], is detected by an *elastic* neutron scattering for $x = 0.09$ [10]. This magnetic ordering is interpreted as the two-dimensional antiferromagnetic fluctuations at $\boldsymbol{Q}_{\rm ic}$ observed in Sr_2RuO_4 becoming static by Ti substitution. Thus, the enhancement of the C_P/T near x_c can be explained by the diverging two-dimensional antiferromagnetic fluctuations, which is in agreement with the logarithmic behavior in C_P/T, observed in the heavy fermion systems in the vicinity of the magnetic instability [11].

4. Summary

We found an enhancement of C_P/T and deviation from the Fermi liquid behavior around the border of the magnetically ordered phase. This result suggests that the diverging two-dimensional antiferromagnetic fluctuations, originating from the nesting of the Fermi-surface sheets, plays an essential role in the non-Fermi Liquid behavior.

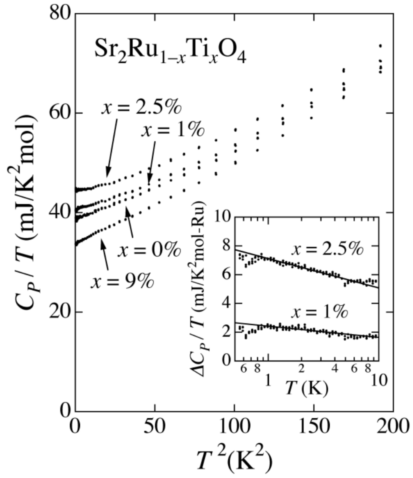

Fig. 1. Specific heat divided by temperature C_P/T for $x = 0$, 1, 2.5 and 9% plotted against T^2. The inset displays $\Delta C_P/T$ vs log$T$ for $x = 1$ and 2.5%. The solid lines are guide to the eye.

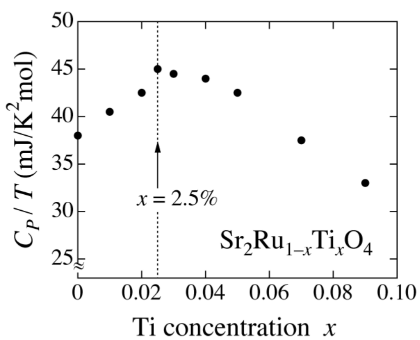

Fig. 2. The value of C_P/T at 0.5 K as a function of *nonmagnetic* Ti concentration x in $Sr_2Ru_{1-x}Ti_xO_4$.

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