Field-temperature phase diagram of the 3-K phase of Sr_2RuO_4

Hiroshi Yaguchi [a,1], Masahiko Wada [a], Yoshiteru Maeno [a,b] and Takehiko Ishiguro [a]

[a] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

[b] *International Innovation Center, Kyoto University, Kyoto 606-8501, Japan*

Abstract

We have investigated the field-temperature phase diagram of the 3-K phase (Sr_2RuO_4-Ru eutectic) for two field directions ($H//$ab and $H//$c) using resistivity data. We have found an upturn curvature in the $H_{c2}(T)$ curve for $H//$c and a rather gradual temperature dependence of H_{c2} close to T_c. We propose that these characteric features can be explained, at least in a qualitative fashion, on the basis of a theory that assumes surface superconductivity with a two-component order parameter at the interface between Sr_2RuO_4 and Ru inclusions.

Key words: Sr_2RuO_4; surface superconductivity; spin-triplet pairing; eutectic

1. Introduction

The layered perovskite superconductor Sr_2RuO_4 has been of great interest owing to its unconventional spin-triplet pairing [1]. Its symmetry is believed to be represented by the two-component order parameter $\boldsymbol{d}(\boldsymbol{k}) = \boldsymbol{z}\Delta_0(k_x + ik_y)$. Another remarkable feature related to Sr_2RuO_4 is an enhancement of T_c in the Sr_2RuO_4-Ru eutectic system, where lamellar microdomains of ruthenium metal are embedded in Sr_2RuO_4 [2]. The eutectic system shows a broad superconducting transition with an onset of about 3 K. On further cooling, this transition is followed by the original superconducting transition of Sr_2RuO_4 at 1.5 K. The higher T_c superconductivity is called the 3-K phase and the original lower T_c superconductivity is referred to as the 1.5-K phase. Although the mechanism of the enhanced superconductivity still remains unknown, it probably originates from the triplet pairing of Sr_2RuO_4 [3].

Earlier work of resistive measurements has revealed that the field-temperature phase diagram of the 3-K phase has intriguing properties [4]. When the applied field is parallel to the ab-plane, the upper critical field H_{c2} is accompanied by clear hysteresis at low temperatures. Also the $H_{c2}(T)$ curve for $H//$ c looks rather peculiar. In the present work, we have studied the field-temperature phase diagram to higher precision for a further discussion.

[1] Corresponding author. Present address: Department of Physics, Kyoto University, Kyoto 606-8502, Japan E-mail: yag@scphys.kyoto-u.ac.jp

2. Experiment

The Sr_2RuO_4-Ru eutectic sample used was grown by a floating zone method [5], which was cut from the crystal rod into a size of $0.96 \times 1.04 \times 0.58$ mm^3 with the shortest dimension along the c-axis. We have measured the resistivity to determine $H_{c2}(T)$ and $T_c(H)$. We have used a lock-in technique at 137 Hz with a current of 0.5 mA along the c-axis. Low temperatures down to 60 mK were reached by means of a ^{3}He cryostat or a dilution refrigerator. Magnetic fields of up to 5 T were generated by a superconducting solenoid.

3. Results and discussion

Figure 1 shows the field-temperature phase diagram of the 3-K phase of Sr_2RuO_4 for the field parallel to the ab-plane and the c-axis. The transition points have been defined as the onset of the transition to the 3-K phase. That there are two branches at low temperatures for $H//$ ab corresponds to the hysteretic H_{c2} mentioned in the introduction. Apart from this feature, we note two prominent features in the phase diagram. (1) The temperature dependence of H_{c2} in the vicinity of T_c is rather gradual. (2) An upward curvature is seen at relatively low temperatures in the $H_{c2}(T)$ line for $H//$ c.

We propose that these two features may be explained, at least in a qualitative manner, by a theory recently proposed by Sigrist and Monien [6]. They have constructed a phenomelogical theory based on a Ginzburg-Landau formalism with the following two reasonable assumptions: First, the 3-K superconductivity occurs at the interface between Sr_2RuO_4 and Ru inclusions. (For simplicity, they treat the interface as a single flat plane.) Second, the superconducting order parameter is represented by a two-component order parameter with a relative phase of $\pi/2$, similar to Sr_2RuO_4.

The theory suggests that H_{c2} is proportional to $(1-T/T_c)^{0.5}$ in the vicinity of T_c, which is common to surface superconductivity in a field applied parallel to the surface. This is in contrast to the standard $(1-T/T_c)$ dependence. In fact, fitting the functional form $H_{c2}(T) = A(1-T/T_c)^n$ to the gradual temperature dependence in the vicinity of T_c shown in Fig.1 yields $n = 0.65$ and $n = 0.66$ for $H//$ ab and for $H//$ c, respectively. These powers of 0.65 and 0.66 appear to be in reasonable agreement with the prediction of Sigrist and Monien's theory.

The theory also provides a qualitative explanation for the anomalous behaviour of the $H_{c2}(T)$ curve for $H//$ c [6]. According to Sigrist and Monien's prediction, of the two-components of a superconducting order parameter such as $(k_x + ik_y)$, only one of the two is stabilised at T_c in zero applied field owing to the lowered symmetry at the Sr_2RuO_4-Ru interface. However, the application of a magnetic field parallel to the c-axis will induce the other component with a relative phase of $\pi/2$ and thus the coupling between the two components results in an enhancement of H_{c2} at low temperatures. This is consistent with our observation of the upward curvature.

4. Summary

We have investigated the field-temperature phase diagram in detail using resistivity measurements and have found two prominent features. One is rather gradual temperature dependence of the upper critical field H_{c2} close to T_c. The other is an enhancement of H_{c2} for $H//$ c at low temperatures. Taken together with the phenomelogical theory by Sigrist and Monien, these observations support that the 3-K phase is surface superconductivity with a two-component order parameter occurring at Sr_2RuO_4-Ru interfaces.

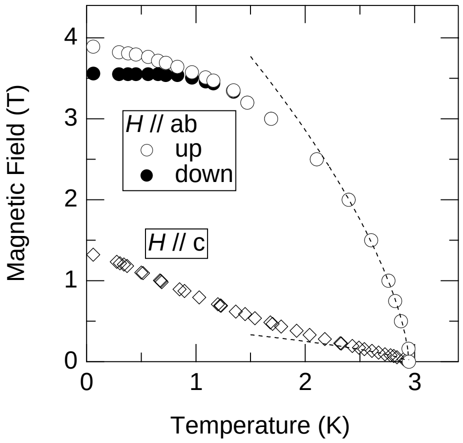

Fig. 1. Field-temperature phase diagram for $H//$ ab and $H//$ c. The dashed lines represent fits of $(1-T/T_c)^n$ dependence to the data. The two branches for $H//$ ab correspond to the hysteretic H_{c2} at low temperatures.

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