Search for the chiral superconducting state in Sr_2RuO_4-Ru eutectic

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Abstract

Sr_2RuO_4 has become one of the most intensely studied transition metal oxides displaying unconventional superconductivity ($T_c = 1.5$ K). It is known that its eutectic system Sr_2RuO_4-Ru shows an inteface superconductivity with an enhanced onset of $\sim$3 K. It is predicted that in the 3-K phase, a second transition to a chiral state occurs at a temperature between 1.5 and 3 K. The transition is thought to be observable by ac-susceptibility measurements. We report the low-frequency ac-susceptibility of Sr_2RuO_4-Ru eutectic measured with a SQUID ac magnetometer.

Key words: Sr_2RuO_4; Sr_2RuO_4-Ru eutectic; chiral state; SQUID

1. Introduction

Several recent experiments have firmly established unconventional superconductivity in the layered perovskite Sr_2RuO_4 [1]. There is strong evidence for spin-triplet pairing with broken time reversal symmetry (chiral state), a pairing state with the basic form $\boldsymbol{d}(\hat{\boldsymbol{k}}) = \hat{z}\Delta_0(k_x + ik_y)$ [2,3]. While the transition temperture T_c of Sr_2RuO_4 is 1.5 K, its eutectic system Sr_2RuO_4-Ru shows a superconducting transition with an enhanced onset of $\sim$3 K [4,5]. The enhanced superconductivity is called the 3-K phase. Because pure Ru is a superconductor with $T_c = 0.5$ K and the 3-K phase does not show bulk superconductivity, it has been suggested that the enhanced superconductivity most probably originates in the interface region between Ru inclusions and Sr_2RuO_4.

Sigrist and Monien theoretically treat the 3-K phase from a phenomenological point of view [6]. The basic assumptions are that the interface region has an enhanced transition temperture and that the pairing state of 3-K phase is represented by a two-component order parameter, reflecting the symmetry of Sr_2RuO_4. They predict that the superconducting state of the 3-K phase has only a one-component order parameter near 3 K, so that it is invariant under time reversal. Consequently, there is a further second transition to a time reversal symmetry breaking state (chiral state) above the onset of the bulk superconductivity. The interface superconducting chiral state shows a spontaneous magnetic moment along the c-axis of Sr_2RuO_4. It shows hysteretic reversal with field and may exihibit enhanced absorption in the ac-susceptibility.

2. Experimental

Single crystals of Sr_2RuO_4-Ru eutectic were grown by a floating zone technique. The dimensions were about 1×1 mm^2 in the ab-plane and 1 mm along the c-axis. Figure 1 shows an optical microscopy picture of the ab-plane of a 3-K phase single crystal used in the present study. We measured the ac-susceptibility of 3-K phase single crystals at 2, 10 and 100 Hz from 1.3 K to 4.2 K using a SQUID ac magnetometer as a preamplifier. The applied ac-field (5 mOe) was along the c-axis. The use of a SQUID ac technique with a superconducting transformer enables low-frequency ac-susceptibility to be measured without loss of the

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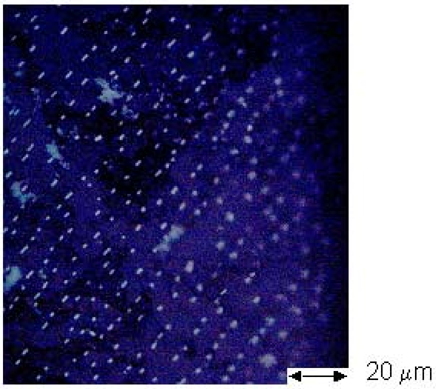

Fig. 1. The optical microscopy picture of the ab-plane of 3-K phase single crystal. The bright part represents ruthenium inclusions, which are needlelike. The dark part corresponds to Sr_2RuO_4.

signal amplitude.

3. Results and Discussion

Figure 2 represents the imaginary and real parts of the ac-susceptibility of one of the crystals investigated. The superconducting transition occurs at a temperature substantially higher than 1.5 K (T_c of Sr_2RuO_4), indicating the 3-K phase. While the superconducting transition to the 3-K phase is seen, no signal attributable to a second transition to the chiral state is observed. This is possibly because the spontaneous moment is too small to pick up and/or the transition temperture for the chiral state is very close to the bulk T_c of Sr_2RuO_4, so that the singnal is obscured by the bulk superconducting state. The overall results are consistent in other crystals as well. It is worth mentioning that the onset of superconductivity and the magnitude of dissipation are strongly frequency dependent, clearly seen in the imaginary part of ac-susceptibility. We have ensured that pure Sr_2RuO_4 also has strong frequency dependence, while the conventional superconductor indium ($T_c = 3.4$ K) does not. We suggest that the frequency dependent ac-susceptibility could be connected with the weak vortex pinning potential of Sr_2RuO_4.

4. Summary

In order to probe the chiral state, we have measured the ac-susceptibility of 3-K phase single crystals using a SQUID ac magnetometer. While we did not observe any sign of the second transition to the chiral state, we observed strongly frequency dependent ac-susceptibility.

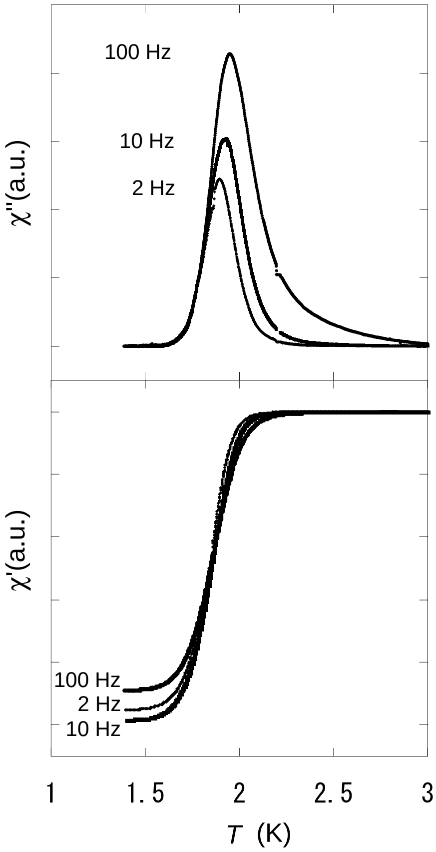

Fig. 2. Ac-susceptibility $\chi' + i\chi''$ of Sr_2RuO_4-Ru eutectic. Top and bottom panels show the imaginary and real parts of the ac-susceptibility, respectively.

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References

[1] Y. Maeno *et al.*, Nature **372** (1994) 532.

[2] K. Ishida *et al.*, Nature **396** (1998) 658.

[3] G.M. Luke *et al.*, Nature **394** (1998) 558.

[4] Y. Maeno *et al.*, Phys. Rev. Lett. **81** (1998) 3765.

[5] T. Ando *et al.*, J. Phys. Soc. Jpn. **68** (1999) 1651.

[6] M. Sigrist and H. Monien, J. Phys. Soc. Jpn. **70** (2001) 2409.