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The interplay between weak ferromagnetism and superconductivity in $RuSr_2EuCu_2O_8$

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Abstract

The magnetic field dependence of the low-temperature specific heat (LTSH) and *I–V* characteristics measurements on $RuSr_2EuCu_2O_8$ were systematically carried out. It is found that the linear-*T* term γ decreases with increasing *H*, in contrast to the predicted result for the clean d-wave superconductivity. This finding suggests that the interaction between quasiparticles and magnons be weakened by magnetic field. In addition, the LTSH data exhibits a remarkably large T^2 term for both $H = 0$ and $H \neq 0$. The T^2 term might be predominately associated with weak ferromagnetism in the Ru sublattice. Furthermore, the effective flux pinning energy $E(H,T)$ determined from fitting the nonlinear region of the *I–V* curves follows a power-law dependence on magnetic field with an exponent close to −0.5 at a fixed temperature, indicating that the vortex lines of $RuSr_2EuCu_2O_8$ is quasi-two-dimensional.

Keywords: Low-temperature specific heat; d-wave superconductivity; Weak ferromagnetism

1. Introduction

Coexistence of superconductivity (SC) and weak ferromagnetism (WFM) has been reported in ruthenate-cuprates $RuSr_2RCu_2O_8$ (Ru-1212) with R = Gd, Eu, Y, and Sm [1,2]. Neutron measurements show that the WFM originates from a canted *G*-type antiferromagnetic order of Ru moments, which gives rise to a small net moment in the RuO_2 basal planes [3]. Up to date, how SC and WFM of Ru-1212 accommodate each other is still an open issue. To shed a light on understanding of interplay between SC and WFM in Ru-1212, low-energy quasiparticle excitations and vortex dimensionality of $RuSr_2EuCu_2O_8$ were studied by LTSH and *I–V* characteristic measurements. The advantage of $RuSr_2EuCu_2O_8$ is that $\mu_{Eu^{3+}} \approx 0$ makes electronic specific heat not be overshadowed by a decent upturn associated with entropy change of magnetic ordering of other R^{3+} at low temperatures and local magnetic field associated with Eu^{3+} be negligible.

2. Experimental

The samples investigated were prepared by the solid-state reaction method. Stoichiometric powders of Eu_2O_3, $SrCO_3$, RuO_2, and CuO were ground thoroughly and calcined at 960 °C in air for 12 h, followed by sintering at 1010 °C in N_2 for 10 h then annealing at 1060 °C in flowing oxygen for 7 days. The crystal structure of the samples was characterized by X-ray diffraction with CuK_α radiation. LTSH measurements were made by a thermal-relaxation microcalorimeter and *I–V* characteristics measurements were done with PPMS in fields up to 8 T.

3. Results and discussion

Fig. 1 shows $C(T)/T$ versus T^2 plot from 1.5 K to 10 K under various fields. It is clear that all plots exhibit a deviation from $\gamma T + \beta T^3$ behavior at low temperatures, where

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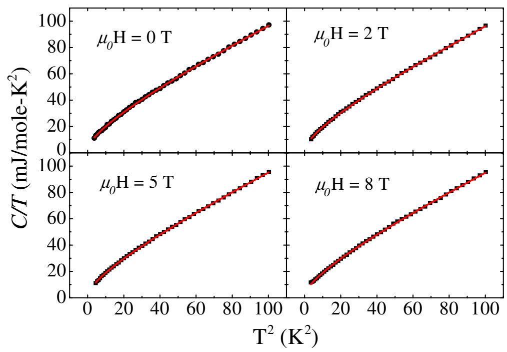

Fig. 1. C/T versus T^2 plot under different fields for $RuSr_2EuCu_2O_8$. The solid line is a fitting curve of $C/T = \gamma(H) + \beta T^2 + \alpha(H)T$.

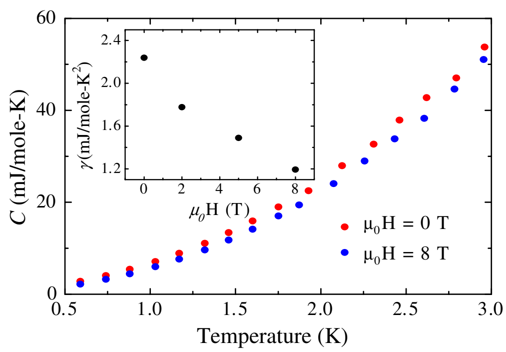

Fig. 2. Low-temperature specific heat as a function of temperature at $\mu_0 H = 0$ T and 8 T. The inset displays the linear-T term γ as a function of magnetic field.

the slope β is the coefficient of the lattice T^3 term and the intercept γ is the coefficient of the linear electronic specific heat and proportional to density of states near Fermi level E_F. The data are best fitted to $C(T,H) = \gamma(H)T + \beta T^3 + \alpha(H)T^2$. In zero-field, $\gamma(0) = 2.24$ mJ/mol K^2 is as large as that of YBCO, $\beta = 0.549$ mJ/mol K^4 corresponds to Debye temperature $\theta_D = 367$ K, and $\alpha = 3.95$ mJ/mol K^3. It should be noted that the αT^2 term of $RuSr_2EuCu_2O_8$ is 64% of total zero-field specific heat and much larger than the phonon contribution βT^3 at 2 K, in contrast to YBCO with αT^2 term less than or comparable to 5% of βT^3 term at 2 K [4]. More interestingly, the $\alpha(H)$ appears to have the same order of magnitude as the zero-field α. The remarkably large T^2 term for both $H = 0$ and $H \neq 0$ might predominately arise from anomalous spin wave excitations of the weak ferromagnetism in the Ru sublattice.

The representative magnetic field dependence of the LTSH from 0.5 K to 3.0 K is plotted in Fig. 2. It is striking that a decrease of the specific heat is observed under magnetic field. The linear-T term γ decreases with increasing H

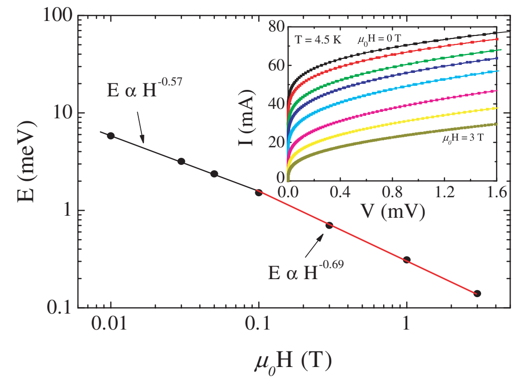

Fig. 3. E versus $\mu_0 H$ plot at 4.5 K in a logarithmic scale. The inset displays I–V curve at 4.5 K under different fields.

as shown in the inset of Fig. 2, in contrast to $\gamma(H) \propto H^{1/2}$ predicted for superconductivity with lines of nodes in the gap function [5]. This finding suggests that the interaction between quasiparticles and magnons associated with the WFM be weakened by magnetic field. As a result, it leads to a reduction of density of states at Fermi level.

The magnetic field dependence of the effective flux pinning energy E at 4.5 K, determined from fitting the nonlinear region of I–V curves displayed in the inset of Fig. 3 with $V \propto I \exp(-E(H,T)/k_B T)$, is shown in Fig. 3. E follows a power-law dependence on H with an exponent of -0.57 for $H < 1000$ G and -0.69 for $H > 1000$ G, respectively. It has been demonstrated that E varies as $H^{-0.5}$ in 2D vortices and with a smaller value of E compared with 3D vortices [6]. The deduced value of the exponent is close to -0.5 and E is on the order of magnitude of 10 meV, comparable to what is observed in BSCCO, strongly suggesting that the vortex lines of $RuSr_2EuCu_2O_8$ is quasi-two-dimensional caused by the WFM in the RuO_2 basal planes.

Acknowledgment

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