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Physica C 426–431 (2005) 234–239

PHYSICA C

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Superconducting gap structure of antiferromagnetic heavy-fermion superconductor UPd_2Al_3 studied by thermal conductivity measurements with rotating magnetic field

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Received 23 November 2004; accepted 28 December 2004
Available online 29 June 2005

Abstract

Heavy fermion superconductor UPd_2Al_3 exhibits intriguing behavior that superconductivity coexists with antiferromagnetic ordering in atomic scale. We investigated the superconducting gap structure of UPd_2Al_3 by thermal conductivity measurements with rotating magnetic field $\boldsymbol{H}$ in various directions relative to the crystal axes. Distinct two-fold oscillation of thermal conductivity was observed with rotating $\boldsymbol{H}$ within the *ac* plane, while no oscillation was observed within the basal plane. These angular variations indicate the superconducting gap function $\Delta(\boldsymbol{k})$ has a single line node orthogonal to the *c*-axis. Our experimental results deduce the superconducting gap function of UPd_2Al_3 as d-wave symmetry with a form $\Delta(\boldsymbol{k}) = \Delta_0\cos(\boldsymbol{k}_z c)$.

PACS: 74.20.Rp; 74.25.Fy; 74.25.Jb; 74.70.Tx

Keywords: Unconventional superconductivity; Superconducting gap symmetry; Thermal conductivity; UPd_2Al_3

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doi:10.1016/j.physc.2004.12.018

1. Introduction

Lanthanide and actinide compounds with elements including 4f- or 5f-electrons manifest variety of natures originated from the competition between itinerancy and localization of the f electrons. Unconventional superconductivity in heavy-fermion (HF) compounds is one of the intriguing phenomena in which the Cooper pairs are mostly characterized by the anisotropic superconducting (SC) order parameter with the presence of nodes [1]. A HF compound UPd_2Al_3 [2] with a large coefficient of the electronic specific heat $\gamma = 140$ mJ/K^2 mol is considered one of unconventional superconductors from various experimental studies. Specific heat [3] and NMR relaxation rate $1/T_1$ [4] show power-law behavior in the temperature dependence suggesting the presence of nodal SC gap structure. Especially the T^3 behavior of the NMR relaxation rate T_1^{-1} associated with the absence of the Hebel–Slichter coherence peak suggests existence of line node in the SC gap function [4]. Reduction of the NMR Knight shift [4] and μSR in spin susceptibility [5] below T_c favor the spin-singlet pairing in this compound.

The most interesting phenomenon in UPd_2Al_3 is the coexistence of antiferromagnetism and superconductivity. Well localized 5f electrons on the U sites with the local moments of $0.85\mu_B$ exhibit antiferromagnetic (AF) ordering below $T_N = 14.3$ K to coexist microscopically with the superconductivity below $T_c = 2.0$ K which are formed by heavy-mass conduction electrons [5]. Wave vector of the AF ordering is $\boldsymbol{Q} = (0, 0, \pi/C)$ with the ferromagnetic basal sheets of the U-site magnetic moments [6]. Evidence of the strong correlation between antiferromagnetism and superconductivity was observed in inelastic neutron scattering [7–9] and tunneling spectra [10]. Inelastic neutron scattering experiments around the wave vector $\boldsymbol{Q}$ observed spin-wave excitations with the energy of 1.5 meV below T_N, accompanied with a new resonance peak with the energy of 0.4 meV below T_c [7–9]. Strong coupling feature in the SC state corresponding to the energy of spin-wave excitations was observed in the tunneling spectra [10]. Therefore, possibility of superconductivity mediated by the observed spin-wave excitations is suggested theoretically [7]. In this scenario, the SC order parameter is expected to have a horizontal line node at boundary of the AF Brillouin zone in the cylindrical Fermi surface [11]. On the other hand, it is also theoretically pointed that the superconductivity in this compound should be dominated by in-plane spin fluctuations like high-T_c cuprates [12]. In this case, the SC order parameter with vertical line nodes is predicted.

To elucidate the pairing mechanism of superconductivity, and to understand the interplay between superconductivity and antiferromagnetism, it is crucial to identify the SC gap function of UPd_2Al_3. However the SC gap structure in momentum space $\Delta(\boldsymbol{k})$ has not been experimentally revealed yet. In the present work, thermal conductivity measurements with rotating magnetic field $\boldsymbol{H}$ in vortex state has been performed to determine the SC gap structure $\Delta(\boldsymbol{k})$ of UPd_2Al_3. This angle-sensitive technique is a quite powerful tool for determination of SC gap symmetry [13–23]. Theoretical heart of the $\boldsymbol{H}$-rotation method lies on so called Volovik effect [24]. In vortex state, QP density of states (DOS) $N(E)$ with nodal SC gap function is considered to experience modification of QP energies due to Doppler shift $E(\boldsymbol{p}) = E(\boldsymbol{p}) - \boldsymbol{p} \cdot v_s$, where $\boldsymbol{p}$ is QP momentum, and v_s is velocity of circulating supercurrent, respectively. As a result, QPs in the vicinity of nodes are excited due to the Doppler shift. Population of QPs excited by the Doppler shift depends on the direction of $\boldsymbol{H}$ relative to the position of nodes. Thus the angular variations of thermodynamics or thermal transport with rotating $\boldsymbol{H}$ can identify the SC gap symmetry by observing the anisotropy of such QP excitations by Volovik effect.

2. Experimental

Single crystals of UPd_2Al_3 with $T_c = 2.0$ K were grown by Czochralski pulling method in a tetra-arc furnace. The hexagonal crystal structure is shown in Fig. 1(a). The grown crystals are of the highest quality achievable with the residual resistivity ratio of 55 along the b-axis, and 40 along the c-axis. The upper critical magnetic field H_{c2} at 0.4 K for $\boldsymbol{H}\|a$, $\boldsymbol{H}\|b$, and $\boldsymbol{H}\|c$ are $H_{c2}^a = 3.2$ T,