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Heat capacity measurements on UBe_{13} in rotated magnetic fields: Anisotropic response in the normal state and absence of nodal quasiparticles

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ABSTRACT

In order to gain insight into the superconducting (SC) gap of UBe_{13}, we studied its quasiparticle excitations by means of heat-capacity measurements. Quite unexpectedly, we found the isotropic $C(H) \propto H$ behavior in low fields at low temperatures, implying the absence of nodal quasiparticle excitations. This result indicates that the SC gap in UBe_{13} is fully open over the Fermi surfaces. Furthermore, we observed a characteristic oscillation of heat capacity both in the SC and non-Fermi-liquid normal states above ~2 T, and the angular variation of heat capacity possibly originates from anisotropic magnetic response of the heavy-electron state. Our result regarding the low-energy quasiparticle excitations in the SC and normal states will be a clue to understand the unusual nature of UBe_{13}.

1. Introduction

Since the discovery of the heavy-fermion superconductivity in Ce and U based materials three decades ago [1,2], intensive studies have been done in order to explore the nonphononic unconventional pairing mechanisms in the strongly correlated electron systems. So far, it has widely been believed that itinerant heavy *f* electrons favor anisotropic nodal pairing to avoid the strong Coulomb repulsion. It is of primary importance to investigate the SC gap function because it reflects the pairing interaction between the Cooper pairs. Although the uranium heavy-fermion superconductors are fascinating because of their unusual SC nature, there exist few compounds of which the SC gap symmetry has been completely elucidated.

In the present work, we focus on the oldest uranium heavy-fermion superconductor UBe_{13}, which has a $NaZn_{13}$ cubic (O_h^6) crystal structure (Fig. 1). In spite of numerous experimental and theoretical works, true nature of the superconductivity of UBe_{13} has remained elusive. Since the NMR Knight shift does not decrease at the SC transition temperature with cooling [3,4], the possibility of an odd-parity state has been discussed so far. Furthermore, as for the SC gap structure, point or line nodal gap functions have been discussed from power-law temperature dependence of physical quantities, such as heat capacity [6], magnetic penetration depth [7], NMR spin-relaxation rate [8], and ultrasound attenuation [9], however, no consensus has been achieved at present.

In order to obtain further information about the SC gap symmetry of UBe_{13}, we investigated the low-energy quasiparticle excitations by means of heat capacity measurements using a single crystal. In our recent paper [10], we have reported the precise angle-resolved heat capacity measurements in rotating magnetic fields in the cubic $(1\bar{1}0)$ plane, which includes the three principal cubic axes, i.e., [001], [111], and [110]. In the present paper, we also report the angular dependence of C/T in the (001) plane, which includes [100] and [110] axes. This angle resolved heat capacity measurement is a powerful tool to probe a nodal structure of SC gap in unconventional superconductors, in which a few percent of heat-capacity oscillation arising from anisotropic nodal gap is usually expected [11].

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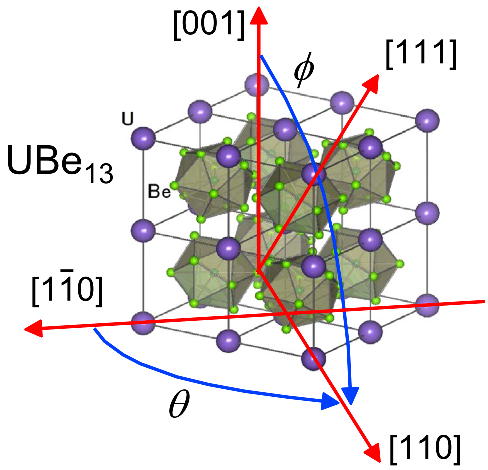

Fig. 1. The cubic $NaZn_{13}$ crystal structure of UBe_{13} with the space group $O_h{}^6$. As indicated in the figure, we define the angles ϕ and θ in the $(1\bar{1}0)$ and (001) planes, respectively.

2. Experimental procedures

The single crystal of UBe_{13} was grown by an Al-flux method [16]. The heat capacity (C) has been measured by a standard quasi-adiabatic method at low temperatures down to ~70 mK in magnetic fields up to 5 T. Angular dependencies of heat capacity $C(H, \phi, \theta)$ were measured in rotating magnetic fields in the $(1\bar{1}0)$ and (001) crystal planes. The angle ϕ is defined from the [001] axis in the $(1\bar{1}0)$ plane, and θ is defined from the $[1\bar{1}0]$ axis in the (001) plane as indicated in Fig. 1.

3. Results and discussion

Fig. 2(a) shows the temperature dependence of the heat capacity of UBe_{13} measured at zero and several magnetic fields up to 5 T for $H \parallel [001]$. Since the nuclear spin-relaxation time of ^{9}Be nuclei of the order of $\sim 10^3$ s is much longer than our measuring time of heat capacity ($\sim 10^2$ s) [8], we can assume that the nuclear Schottky contribution is virtually absent at low magnetic fields. In Fig. 2(a), we also plot the obtained entropy at 0 T divided by $R \ln 2$, where R is the gas constant. At the SC transition, the entropy of $\sim 0.15\, R \ln 2$ is resolved. Fig. 2(b) shows C/T as a function of T^2. Below ~0.6 K, $C(T)$ is nearly proportional to T^3 as reported previously [6]. It should be noted that C/T approaches zero as $T \to 0$, indicating that all parts of the sample become the SC state.

In order to establish the SC gap structure by locating node positions, it is important to investigate the magnetic field dependence of C/T and its anisotropy at low fields, all of which reflect the nodal quasiparticle excitations. If there is nodal structure for the SC gap function, $C(H)$ is predicted to exhibit a convex upward curvature; in the case of line node, $C(H) \propto H^{1/2}$ is expected in low magnetic fields [17,18,11,19,20]. In addition, we expect quasiparticle excitations to be anisotropic, resulting from the field-orientation dependence of the Doppler-shift effect arising from the nodal structure. Fig. 3(a) shows C/T vs H below 2 T for $H \parallel [001]$ and [111]. Quite surprisingly, C/T is linear in H with *no* angular dependence. The observed C/T is rather similar to the behavior of s-wave superconductors [11]. This behavior suggests that the SC gap of UBe_{13} is fully open over the Fermi surface, conflicting starkly with a nodal SC gap as has been believed so far. We will come back to the discussion about the SC gap structure in UBe_{13} later.

Fig. 3(b) shows the field dependence of $C(H)/T$ and its

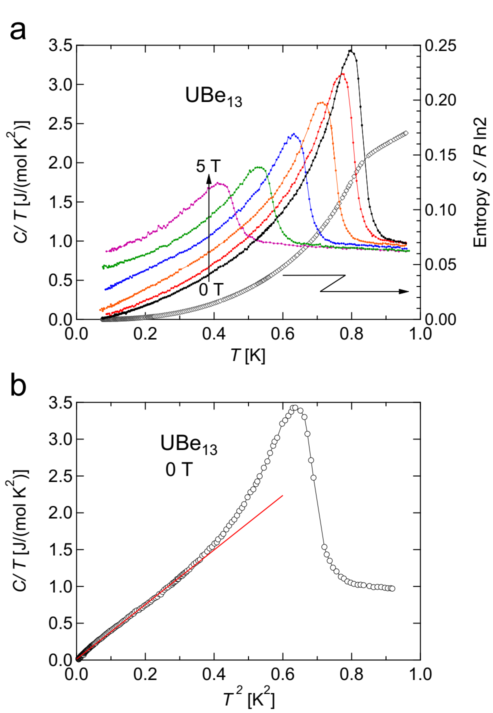

Fig. 2. (a) Temperature dependence of C/T for UBe_{13}, measured at 0, 1, 2, 3, 4, and 5 T for $H \parallel [001]$. The entropy at 0 T divided by $R \ln 2$ is also plotted for the right axis. (b) C/T as a function of T^2 at 0 T. The solid line indicates the result of linear fitting below 0.56 K.

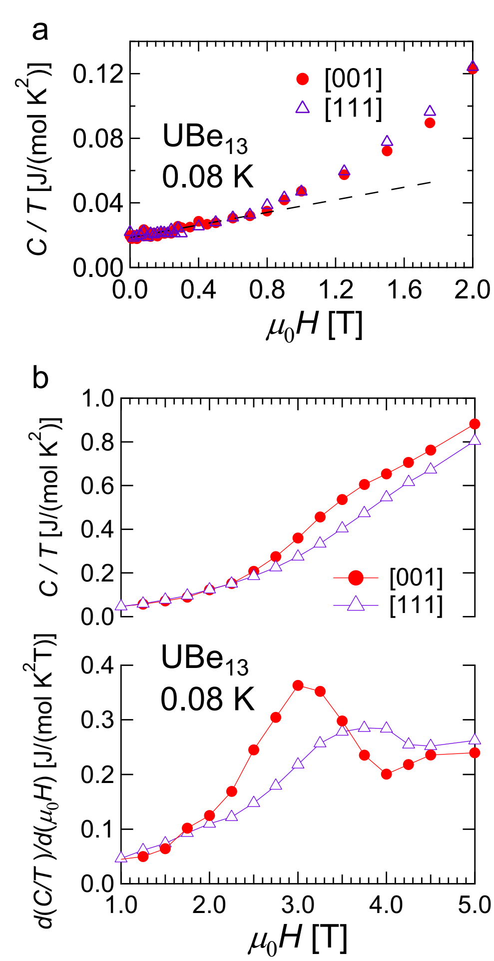

Fig. 3. (a) Magnetic-field dependence of $C(H)/T$ at 0.08 K in low fields for $H \parallel [001]$ and [111]. The dashed line indicates the result of linear fitting below ~0.8 T. (b) $C(H)/T$ and its derivative at 0.08 K up to 5 T for $H \parallel [001]$ and [111].