Evidence of Point Nodes in Superconducting Gap of Borocarbide Superconductor YNi_2B_2C

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Abstract

In order to determine the superconducting gap structure of the borocarbide superconductor YNi_2B_2C, we have measured the angular variation of the *c*-axis thermal conductivity κ_{zz} in magnetic field rotated within the *ab*-planes. A clear fourfold symmetry with narrow cusps was observed in the angular variation of κ_{zz}. These results provide a strong evidence that the gap function has *point nodes* which are located along the *a*- and *b*-axes of the crystal.

Key words: borocarbides; superconducting gap structure; thermal conductivity

The borocarbide superconductor YNi_2B_2C with a relatively high T_c of 15.5 K [1] has attracted much attention because of a variety of interesting physical properties. In particular, the superconducting gap structure is one of the fascinating issues. Recent measurements of temperature and magnetic-filed dependence of the heat capacity indicate the presence of a large anisotropy in the superconducting gap function [2,3]. Moreover the impurity effect suggests an anisotropic *s*-wave order parameter [2]. Despite these studies, the detailed structure of the gap function remains unresolved. Since the gap structure is closely related to the pairing interaction, its clarification is crucial for understanding the mechanism of superconductivity. In addition to that, the transition between triangular and square vortex lattice observed in this compound [4] should be related to the gap structure.

Here in order to determine the superconducting gap structure, we have measured the angular dependence of the *c*-axis thermal conductivity κ_{zz} by rotating the applied magnetic filed $\boldsymbol{H}$ within the basal plane. This method has recently been demonstrated to be a powerful means for determining the gap structure. In fact, the superconducting gap functions were successfully determined by this method in high-T_c cuprate $YBa_2Cu_3O_{7-\delta}$ [5,6], heavy fermion $CeCoIn_5$ [7], ruthenate Sr_2RuO_4 [8], and organic κ-$(ET)_2Cu(NCS)_2$ [9]. All of these superconductors have line nodes. Here we show that the results of the thermal conductivity in YNi_2B_2C indicates the existence of *point nodes* which are located along the [100] and [010] directions.

In the superconductor with nodes, the thermal transport is governed by the delocalized quasiparticles (QPs) arising from the nodes [3,2]. The Doppler shift of the delocalized QPs energy spectrum [10], which gives rise to a finite density of states (DOS) at the Fermi surface, causes a steep increase of the thermal conductivity with $\boldsymbol{H}$. Since the magnitude of the

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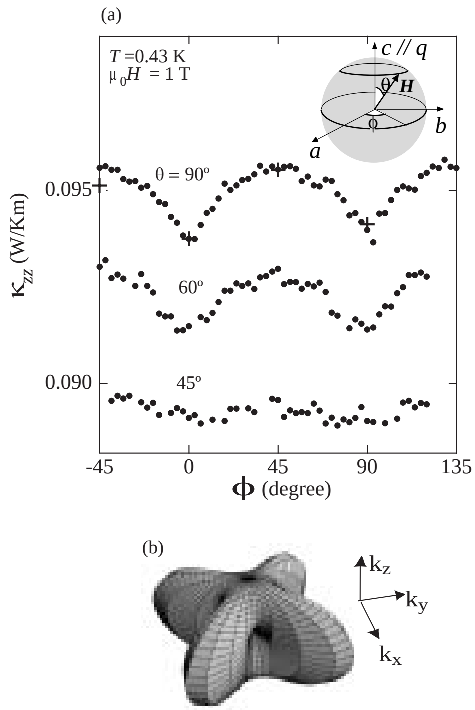

Fig. 1. (a) Angular variation of the c-axis thermal conductivity κ_{zz} at H=1 T and T=0.43 K (thermal current $\boldsymbol{q}\parallel c$). κ_{zz} are measured by rotating $\boldsymbol{H}$ conically as a function of ϕ at fixed θ (see the inset). The crosses represent the data obtained under the field cooling condition at each angle. (b) The gap function $\Delta(\boldsymbol{k})$ of the $s+g$-wave model.

Doppler shift is sensitive to the relative orientation between $\boldsymbol{H}$ and node [11], the thermal conductivity can be a probe of the nodal structure.

In Fig. 1(a), we show the angular variation of κ_{zz}, which was measured by rotating $\boldsymbol{H}$ conically around the c-axis as a function of the azimuthal angle ϕ. The thermal current $\boldsymbol{q}$ was applied parallel to the c-axis. Here, the polar angle θ=($\boldsymbol{q}$, $\boldsymbol{H}$) is fixed constant, and ϕ is measured from a-axis. The field trapping effect is negligibly small at H=1 T. At $\theta = 90^\circ$, a clear fourfold symmetry with narrow cusps at $\phi = 0^\circ$ and 90° was observed. Moreover, the amplitude of fourfold symmetry is strongly suppressed at $\theta = 45^\circ$. We stress that the fourfold symmetry is not a result of the anisotropies of the upper critical field H_{c2} and the Fermi velocity v_F for the following reasons. First, the anisotropy of H_{c2} within the basal plane shows a sinusoidal ϕ-dependence, which is very different from Fig. 1(a). Second, the amplitude of fourfold oscillation of H_{c2} at $\theta = 45^\circ$ is nearly 1/3 of that at $\theta = 90^\circ$, while the amplitude of κ_{zz} at $\theta = 45^\circ$ is less than 1/5 of that at $\theta = 90^\circ$, showing the different θ dependence. Third, according to the calculation based on the Kubo formula, the anisotropy of v_F will only enter as a secondary effect in the ϕ-variation of κ_{zz}. These consideration lead us to conclude that *the fourfold symmetry originates from the anisotropy of the superconducting gap structure*.

We next discuss the detailed nodal structure. According to prediction of the Doppler shift, the DOS shows the maximum (minimum) when $\boldsymbol{H}$ is applied to the antinodal (nodal) directions. Therefore the minimum of κ_{zz} at $\phi = 0^\circ$ and 90° indicates that *the nodes are located along the [100] and [010] directions*. The narrow cusp structure and the rapid suppressoin of the amplitude of fourfold symmetry with decreasing θ are crucial for identifying the type of nodes. For the point node, we adopt a gap function s+g-wave order parameter $\Delta(\boldsymbol{k}) = \frac{1}{2}\Delta_0\{1-\sin^4\theta\cos(4\phi)\}$ (see Fig. 1(b)) [12]. According to the calculation in Ref.[13], both the cusp structure and θ-dependence in $\kappa_{zz}(H, \phi, \theta)$ are well reproduced [14]. On the other hand, the same calculation for d-wave order parameter with line node is inconsistent with the experimental results. Therefore we can conclude that the superconducting gap function of YNi_2B_2C has *point nodes* located along the [100] and [010] directions.

In summary, we measured the c-axis thermal conductivity of YNi_2B_2C as a function of the magnetic field rotated to various directions relative to the crystal axis. On the basis of these results, we arrived at a conclusion that the superconducting gap function of YNi_2B_2C has *point nodes* which are located along the [100] and [010] directions. The determination of the gap structure would give important information on the pairing mechanism and the unusual superconducting properties of YNi_2B_2C.

References

[1] R.J. Cava *et al.*, Nature (London) **367** (1994) 146.
[2] M. Nohara *et al.*, J. Phys. Soc. Jpn. **68** (1999) 1078; M. Nohara *et al.*, Physica C **341-348** (2000) 2177.
[3] K. Izawa *et al.*, Phys. Rev. Lett. **86** (2001) 1327.
[4] M. Eskildsen *et al.*, Phys. Rev. Lett. **86** (2001) 5148.
[5] F. Yu *et al.*, Phys. Rev. Lett. **74** (1995) 5136.
[6] H. Aubin *et al.*, Phys. Rev. Lett. **78** (1997) 2624.
[7] K. Izawa *et al.*, Phys. Rev. Lett. **87** (2001) 057002.
[8] K. Izawa *et al.*, Phys. Rev. Lett. **86** (2001) 2653.
[9] K. Izawa *et al.*, Phys. Rev. Lett. **88** (2002) 027002.
[10] G.E. Volovik, JETP Lett. **58** (1993) 469.
[11] I. Vekhter *et al.*, Phys. Rev. B **59** (1999) R9023.
[12] K. Maki, P. Thalmeier, H. Won, Phys. Rev. B **65** (2002) 140502.
[13] P. Thalmeier, K, Maki, proceeding of SCES (2002).
[14] K. Izawa *et al.*, cond-mat/0205178.