Laser-excited ultrahigh-resolution photoemission study of anisotropic s-wave superconductor YNi$_2$B$_2$C

T. Baba$^a$,*, T. Yokoya$^b$, S. Tsuda$^a$, T. Kiss$^c$, T. Shimojima$^a$, S. Shin$^a,c$, T. Togashi$^c$, C.T. Chen$^d$, C.Q. Zhang$^d$, S. Watanabe$^a$, T. Watanabe$^a$, M. Nohara$^e$, H. Takagi$^e$

$^a$Institute for Solid State Physics (ISSP), University of Tokyo, Kashiwa 277 8581, Japan
$^b$The Graduate School of Natural Science and Technology, Okayama University, Okayama, Okayama 700 8530, Japan
$^c$The Institute of Physical and Chemical Research (RIKEN), Sayo-gun, Hyogo 679 5143, Japan
$^d$Beijing Center for Crystal R&D, Chinese Academy of Science Zhongguancun, Beijing 100080, China
$^e$Department of Advanced Materials Science, University of Tokyo, Kashiwa 277 8581, Japan

Abstract

We have performed laser-excited ultrahigh-resolution photoemission spectroscopy of Y(Ni$_{1-x}$Pt$_x$)$_2$B$_2$C ($x=0.0$, 0.2) and numerical simulation using s, anisotropic s and even s+g symmetry to study the superconducting gap anisotropy in borocarbide superconductors. We observed the reduction of gap anisotropy in the $x=0.2$ sample in comparison to the $x=0.0$ sample, confirming the anisotropic s-wave gap. We also found that the spectrum of $x=0.0$ at 3.5 K cannot be fitted well with the s+g-wave symmetry, implying that the s+g symmetry is too simple to describe over all superconducting gap electronic structure of borocarbides.

PACS: 74.25.Jb; 74.70.Dd; 79.60.–i

Keywords: Anisotropic s-wave superconductor; Antiferromagnetic superconductor; Photoemission spectroscopy

1. Main text

In nonmagnetic borocarbide superconductor RNi$_2$B$_2$C ($R=\text{Lu, Y}$), various experimental results [1,2] have shown the existence of a large superconducting (SC) gap anisotropy with s-wave SC gap symmetry, in spite of phonon-mediated superconductivity [3,4]. Recently, even the direction and type of node have been discussed from field-angle-dependent thermal conductivity and ultrasonic attenuation for all the symmetrically independent elastic modes [5,6]. But the mechanism of SC gap anisotropy has not been clarified, yet.

In this paper, utilizing laser-excited ultrahigh-resolution photoemission spectroscopy [7] enabling us to measure with higher-energy resolution, more bulk sensitivity, and lower sample temperature, we study anisotropic s-wave superconductor YNi$_2$B$_2$C and discuss its SC gap anisotropy.

Single crystals of Y(Ni$_{1-x}$Pt$_x$)$_2$B$_2$C ($x=0.0$ and 0.2) were prepared from a floating zone method [8]. The DC susceptibility measurement indicated that SC transition temperature $T_c$ of the crystals ($x=0.0$ and 0.2) are 15.4 and 12.1 K, respectively. The energy resolution of all PES measurements was set to 1.5 meV. All the photoemission measurements have been done for in situ fractured surfaces.

Figure 1 shows normalized SC PES spectra of Y(Ni$_{0.8}$Pt$_{0.2}$)$_2$B$_2$C and YNi$_2$B$_2$C near $E_F$ at 3.5 K plotted as a function of binding energy/peak position. The spectrum of $x=0.0$ has a lower peak intensity and a gentler slope of the leading edge with a larger intensity at $E_F$ compared with those of $x=0.2$. The variation of SC spectra are more clearly observed than those of our previous study [2].

To verify SC gap function of Y(Ni$_{0.8}$Pt$_{0.2}$)$_2$B$_2$C and YNi$_2$B$_2$C, we have tried numerical simulations. In Figure 2 (a), we show Y(Ni$_{0.8}$Pt$_{0.2}$)$_2$B$_2$C spectrum at 3.5 K (open...
circles) and fitting results with an isotropic s-wave Dynes function [9] (connected line). With the values of $\Delta = 1.75 \text{ meV}$ and $\Gamma = 0.14 \text{ meV}$, the fitting result well reproduces the spectrum, indicating that Y(Ni$_{0.8}$Pt$_{0.2}$)$_2$B$_2$C has a s-wave SC gap symmetry. In Fig. 2 (b)–(d), YNi$_2$B$_2$C spectra at 3.5 K are shown together with numerical calculation results with (b) isotropic s-wave, (c) anisotropic s-wave ($\Delta(0) = \Delta_{\text{min}} + (\Delta_{\text{max}} - \Delta_{\text{min}}) \cos 2\theta$ ($\Delta_{\text{min}} = 0$)) and (d) s+g-wave ($\Delta(0,\phi) = 1/2\Delta(1 + \sin^2 \theta \cos 4\phi)$) [10]. Calculated spectra are shown with the best fitting values of (b) $\Delta = 2.35 \text{ meV}$ and $\Gamma = 0.30 \text{ meV}$, (c) $\Delta = 2.80 \text{ meV}$ and $\Gamma = 0.04 \text{ meV}$ and (d) $\Delta = 4.20 \text{ meV}$ and $\Gamma = 0.03 \text{ meV}$. We find that the calculated spectra using anisotropic s-wave can reasonably reproduce the experimental results than using an isotropic s-wave. This indicates a reduction of SC gap anisotropy in Y(Ni$_{0.8}$Pt$_{0.2}$)$_2$B$_2$C in comparison to YNi$_2$B$_2$C due to disorder and thus provides experimental evidence for anisotropic s-wave SC gap symmetry of borocarbide superconductors [11], consistent with our previous study [2]. On the other hand, we found that the fitting results using s+g-wave symmetry cannot explain the measured spectrum successfully. This implies that the s+g symmetry might not be a suitable one to describe over all SC gap electronic structure of borocaribdes. This implies importance of taking the complicated electronic structures of borocaribdes into consideration when the s+g wave symmetry is used for analyzing the anisotropic SC gap.

Acknowledgments

This study was supported by Grant-in-aid from the Ministry of Education, Science, and Culture of Japan. T. B. thanks center of excellence for applied physics on strong correlation for financial support.

References