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Effect of antiferromagnetic ordering on temperature dependent superconducting gap in $ErNi_2B_2C$: Laser-photoemission spectroscopy

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ABSTRACT

We have performed temperature (T)-dependent laser-photoemission spectroscopy of antiferromagnetic (AF) superconductor $ErNi_2B_2C$ to study the electronic structure, especially the effect of AF ordering in T-dependent superconducting (SC) gap. To estimate the values of T-dependent SC gap, we fitted the experimental data by Dynes function having an anisotropic s-wave SC gap. From the fitting results, we find a sudden deviation from the BCS prediction just below T_N. This observation can be well explained by the theoretical model, indicating that the origin of anomalous T-dependence is competition between rapid evolution of AF molecular field and SC condensation energy.

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1. Introduction

Since the publication of Ginzburg's pioneering works [1], the competition between superconductivity and magnetism has been one of the most profound and interesting problems in solid state physics. The discovery of the first antiferromagnetic (AF) superconductors, where superconductivity and long-range AF order coexist at low temperature (T), in Chevrel phase compounds and rhodium tetra-borides motivated further experimental and theoretical studies [2]. Neutron study identified their magnetic structures as a sinusoidal spin density wave (SDW) structure of localized 4f electrons. Theoretically, it was considered that these local moments interact very weekly with conduction electrons mainly originating from d bands via the indirect-exchange-RKKY (Ruderman-Kittel-Kasuya-Yoshida) type interaction. Moreover, the upper critical field H_{c2} anomaly near the Néel T (T_N) observed experimentally in the Chevrel phase compounds was explained by a theory by Machida et al. for AF superconductors in which a SDW ordering with a wave vector Q may coexist with superconductivity [3]. This theory suggests that the superconducting (SC) order parameter suddenly drops below T_N due to the competition between the rapid evolution of AF molecular field and the increase of SC condensation energy. However, because of their very low transition temperatures ($T_N < 1.6$ K), no direct experimental observation of the electronic structure of the AF SC phase has been made yet.

The discovery of AF SC borocarbides RNi_2B_2C (R = Dy, Ho, Er, and Tm) in 1994 [4] has activated the field. Because of their relatively high SC transition temperature's (T_c's) and T_N's, we can easily investigate the interplay of superconductivity and antiferromagnetism. Especially, $ErNi_2B_2C$ has higher $T_c \sim 11$ K and $T_N \sim 6$ K. Below T_N, Er^{3+} magnetic moments order in a transversely polarized incommensurate sinusoidal SDW structure with a wave vector $Q \sim (0.55, 0, 0)$. This wave vector is consistent with the predicted nesting vector, where the calculated generalized susceptibility $\chi(q)$ for $LuNi_2B_2C$ shows a pronounced peak [5]. Furthermore, another transition, like a reentrant transition of superconductivity in $HoNi_2B_2C$ [4], is not occurred until 2.3 K where the system becomes weak ferromagnetic [6]. Thus, $ErNi_2B_2C$ is ideal for investigating the interplay of superconductivity and antiferromagnetism in AF SC borocarbides. In fact, the effect of magnetic order for

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superconductivity has been observed near T_N in several experiments, *e.g.* a dip structure in T-dependence of H_{c2}, an increase of the SC coherence length and a decrease of the SC penetration depth measured using the flux line form factor in a small-angle neutron scattering, and a slight depression of the superfluid density calculated from the magnetic penetration depth measurements. In addition, scanning tunneling spectroscopy has been performed to study the electronic structures of the AF SC phase of $ErNi_2B_2C$ by several groups [7,8]. Most probably due to their surface sensitivity, however, the obtained results were not consistent with each other, leaving the need of further experimental studies for the magnetic ordering effect on superconductivity.

Laser- photoemission spectroscopy (PES) enables us to measure the electronic structures near the Fermi level (E_F) with a sub-meV energy resolution down to 2.9 K, with sufficient bulk sensitivity due to low energy photons used [9]. So, we performed Laser-PES on $ErNi_2B_2C$ to study the electronic structure and reported bulk electronic structure of AF SC $ErNi_2B_2C$, *i.e.* broadened spectral shape and dip structure in T-dependent SC gap [10]. In the analysis of SC gap, we use Dynes function [11] with isotropic *s*-wave SC gap for simplicity [10]. But, nonmagnetic borocarbide superconductors YNi_2B_2C and $LuNi_2B_2C$ have anisotropy in SC gap [12].

In this paper, we report T-dependent SC gap of AF SC $ErNi_2B_2C$ analyzed by Dynes function using anisotropic *s*-wave SC gap [13]. The T-dependence of the SC gap also exhibits a sudden deviation from the BCS prediction just below T_N. This behavior is well reproduced by the Machida's theory.

2. Experimental

Single crystals of $ErNi_2B_2C$ were prepared with a floating zone method. The dc susceptibility measurements confirmed T_c = 9.3 K (midpoint) and T_N = 6.0 K. The estimated residual resistivity ratio from resistivity measurements are 9.3. Laser-PES measurements were performed with 800 μeV energy resolution. All the PES measurements were done for *in situ* fractured surfaces. T-dependent spectral changes were confirmed by cycling T across T_c. Repeated measurements of gold E_F during the present study confirmed the energy drift of ±0.05 meV, which determined the energy accuracy of data points.

3. Results and discussion

In Fig. 1, we show the T-dependent laser-PES spectra of $ErNi_2B_2C$ measured from 4.2 K (AF SC phase) to 12 K (normal phase) across T_c of 9.3 K and T_N of 6.0 K. At the normal phase of 12 K, the spectrum has a Fermi edge whose midpoint is located at E_F. With decreasing T, the spectral edge shifts to higher binding energy with a piling up of a small quasiparticle peak. To see the difference in T-dependence of spectra between above and below T_N, we show the energy-enlarged normalized spectra of $ErNi_2B_2C$ at $T_N < T < T_c$ and $T < T_N$ in Fig. 2a and b, respectively. At $T_N < T < T_c$, the PES intensity at E_F gradually decreases, giving rise to a systematic shift of the leading edge and a gradual increase in the PES intensity at higher binding energy. However, at $T < T_N$, the intensity of DOS at E_F hardly changes with decreasing T. This is not due to the drift of E_F, because we have checked E_F just before and after the T-dependent measurements and found the shift of E_F was within 0.1 meV. This anomalous T-dependence of laser-PES spectra of AF SC $ErNi_2B_2C$ is quite different from nonmagnetic superconductors, showing a characteristic electronic-structure evolution of $ErNi_2B_2C$.

To see how the SC gap behaves as a function of T, we try to fit the spectra by Dynes function [11] using an anisotropic *s*-wave SC gap $\Delta(\theta)$ and the phenomenological broadening parameter Γ defined by $D(E,\Delta(\theta),\Gamma) = \mathrm{Re}\{(E-i\Gamma)/\sqrt{(E-i\Gamma)^2-\Delta(\theta)^2}\}$, $\Delta(\theta) = \Delta_{max} + (\Delta_{max} + \Delta_{min})|\cos 2\theta|$ [12]. Here, we used the ratio of anisotropy $\Delta_{max}/\Delta_{min}$ = 3.24 from the analysis of T-dependent laser-photoemission spectra of YNi_2B_2C [13] and assumed that the ration of anisotropy does not change for all the T. The fitting results are shown in Fig. 3a–j as solid curves. We could also fit all the T-dependent spectra reasonably well with value sets (Δ_{max}, Γ) shown in each panel.

Fig. 4 shows obtained T-dependent Δ_{max} and Γ values as open and filled circle, respectively. We define the error bar as 100% variation of the residual of showed energy range in changing values of Δ_{max} or Γ with a 0.01 meV interval while keeping the other parameters constant. The dotted curve is the theoretical T-dependence of the SC gap. Above T_N, T-dependence of SC gap follows simple BCS

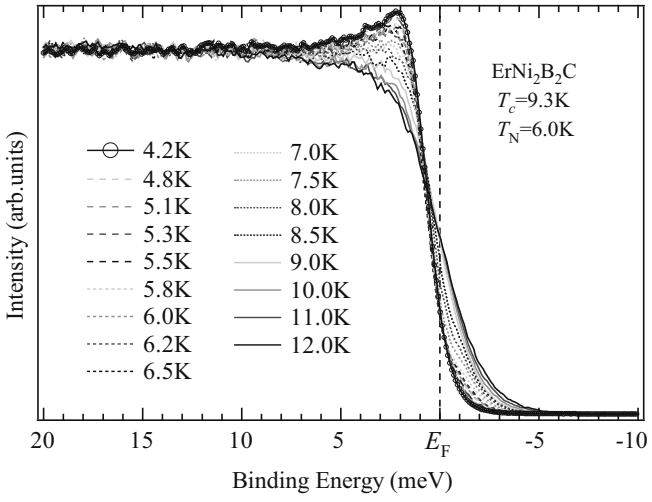

Fig. 1. T-dependent laser-PES spectra of AF SC $ErNi_2B_2C$. The normalization of the spectra was done with the area under the curve from 20 meV to −10 meV.

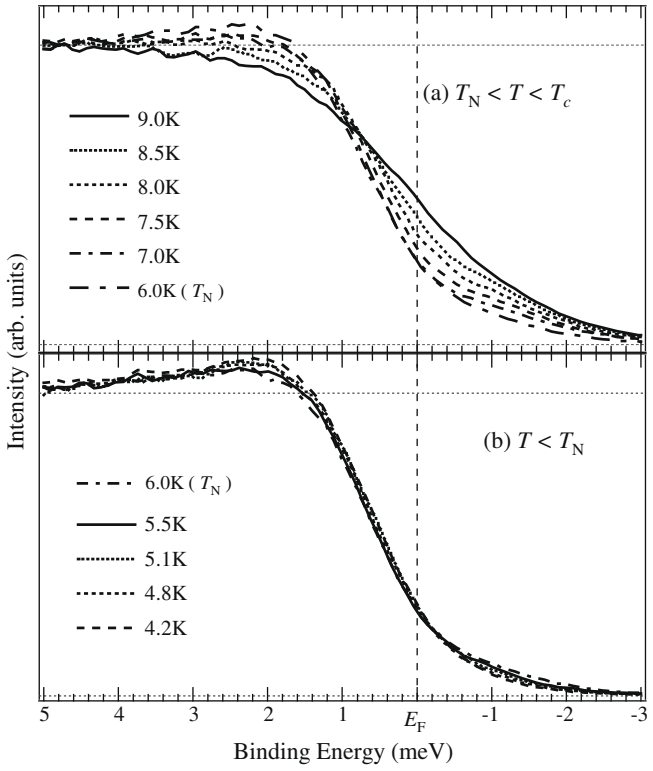

Fig. 2. Energy-enlarged spectra of Fig. 1 for two temperature regions (a) $T_N < T < T_c$ and (b) $T < T_N$.

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