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# High-resolution ARPES study of electron-doped Fe-based superconductor $BaFe_{1.85}Co_{0.15}As_2$

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ABSTRACT

We have performed high-resolution angle-resolved photoemission spectroscopy of an electron-doped iron-based superconductor $BaFe_{1.85}Co_{0.15}As_2$, and experimentally determined the Fermi-surface, the band structure and the superconducting gap. We found an isotropic *s*-wave-like superconducting gap on a hole pocket centered at the $\Gamma$ point and on electron pockets at the $M$ point. The superconducting gap magnitude is significantly enhanced on the Fermi-surfaces connected by the antiferromagnetic wave vector, suggesting the importance of an interband interaction on the pairing mechanism.



## 1. Introduction

The recent discovery of iron-based superconductor $LaFeAsO_{1-x}F_x$ ($T_c = 26$ K) [1] has triggered intensive debates on its superconducting (SC) mechanism. There are mainly four types of crystal structures in iron-based superconductors, called the 1111, 122, 111 and 11 systems. The electronic structure has been actively studied in the 122 system since large high-quality single crystalline samples are available. The parent compound of the Ba122 system ($BaFe_2As_2$) is an antiferromagnetic metal and it becomes a superconductor by both electron- and hole-doping. Investigation of the electronic structure in the hole- and electron-doped systems plays an important role to understand the mechanism of high-$T_c$ superconductivity. So far, angle-resolved photoemission spectroscopy (ARPES) studies have been mainly carried out on the hole-doped system, and they have revealed (i) the isotropic nodeless SC gaps, (ii) the Fermi-surface (FS) dependence of the SC gap and (iii) the strong pairing on the nearly nested FS pockets [2,3]. On the other hand, very few ARPES studies have been reported on the electron-doped counterpart. It is of particular importance to perform ARPES measurements on the electron-doped system to find the universality of the electronic structure responsible for the occurrence of superconductivity.

In this paper, we report ARPES results on the optimally electron-doped $BaFe_{1.85}Co_{0.15}As_2$. We observed the *k*- and *T*-dependences of the SC gap on each FS. We compare the ARPES results between the electron- and hole-doped compounds to discuss the universality of the SC mechanism.

## 2. Material and methods

High-quality single crystals of $BaFe_{1.85}Co_{0.15}As_2$ were grown by the self-flux method. ARPES measurements were performed using a VG-SCIENTA SES2002 spectrometer with a high-flux discharge lamp and a toroidal grating monochromator. We used the He I$\alpha$ resonance line (21.218 eV). The energy resolution was set to 4 and 15 meV for the measurement of the SC gap and the band dispersion, respectively. The angular resolution was set to 0.2°.

## 3. Results and discussion

The ARPES intensity at the Fermi level ($E_F$) of $BaFe_{1.85}Co_{0.15}As_2$ plotted as a function of the in-plane wave vector is shown in Fig. 1a. A circular and an elongated intensity pattern centered at the $\Gamma$ and $M$ points are observed, and they are attributed to hole- and electron-like bands [4]. In Fig. 1b, we show an ARPES intensity

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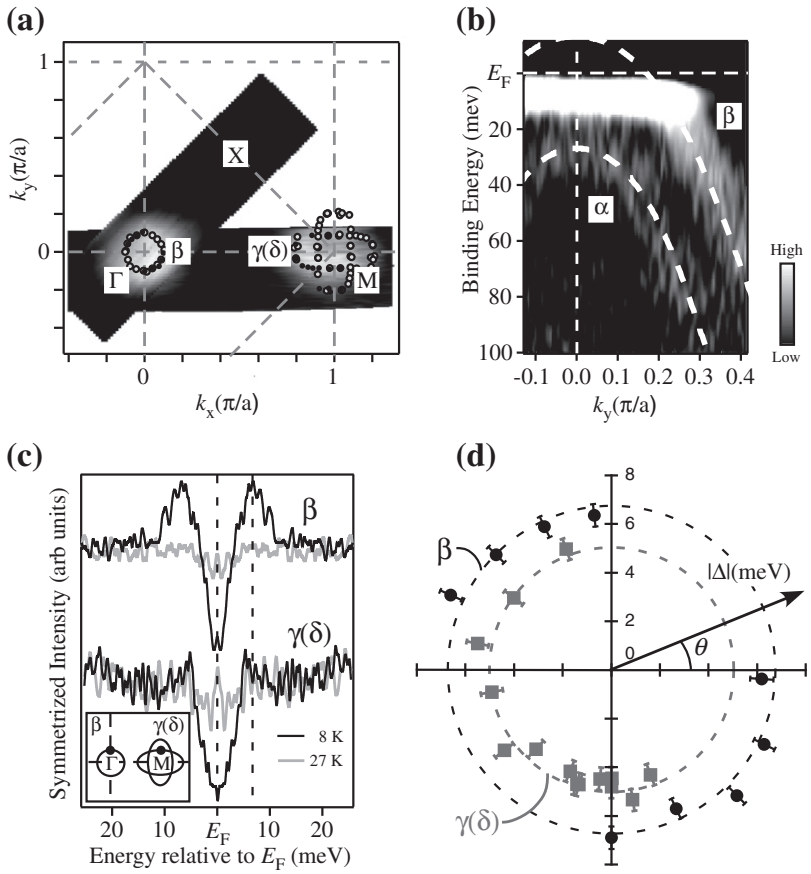


**Fig. 1.** (a) ARPES intensity at $E_F$ of $BaFe_{1.85}Co_{0.15}As_2$ ($T_c$ = 25.5 K) plotted as a function of the two-dimensional wave vector measured at 8 K. The intensity at $E_F$ is obtained by integrating the spectra within 5 meV with respect to $E_F$. Filled circles in (a) show the $k_F$ positions determined by tracing the experimental band dispersion, while open circles are symmetrized $k_F$ points obtained by assuming a four-fold symmetry with respect to the $\Gamma$ and $M$ point, respectively. (b) Second derivative plot of EDCs along the $\Gamma$–$M$ direction at 8 K as a function of wave vector and binding energy. Dashed lines are guidelines for the energy dispersion. (c) Temperature dependence of the ARPES spectrum measured at $T$ = 8 and 27 K at the $k_F$ point on the $\beta$ and $\gamma(\delta)$ FS (black dots in inset). Symmetrized EDCs were divided by those at $T$ = 33 K. (d) SC gap values at 8 K as a function of FS angle $\theta$ extracted from the EDCs shown on the polar plot, for the $\beta$ and $\gamma(\delta)$ FSs (black and gray dots, respectively). Dashed circles represent the averaged gap value.

plot measured along the $\Gamma$–$M$ direction. Two holelike bands are clearly visible. The inner band, which is assigned to the $\alpha$ band [2,3], sinks significantly (~30 meV) and does not create a small FS pocket as observed in the hole-doped samples, confirming the electron doping by the Co substitution. The outer band (the $\beta$ band) crosses $E_F$, creating a hole pocket at the $\Gamma$ point. As clearly seen in Fig. 1a, the $\beta$ hole pocket is nearly nested with the electron pockets, in sharp contrast to the observation of a good FS nesting between the $\alpha$ hole pocket and the electron pockets in the hole-doped $Ba_{0.6}K_{0.4}Fe_2As_2$.

As seen in Fig. 1c, we clearly observe a SC gap below $T_c$ on each FS. The spectral shapes on each FS are basically similar whereas there are some important differences: the SC gap on the $\gamma(\delta)$ FS has a weaker coherence-peak weight and a smaller SC-gap size as compared to those on the $\beta$ FS, demonstrating the FS-sheet dependence of the SC gap. We also notice that the weight of the coherence peak is much weaker than that of the hole-doped $Ba_{0.6}K_{0.4}Fe_2As_2$ [2,3], possibly owing to a lower superfluid density due to a lower $T_c$ value (25.5 vs. 37 K) and disorder scattering induced by the Co substitution.

The estimated $k$-dependence of the SC gap magnitude is shown in Fig. 1d, where the FS angle $\theta$ denotes the angle between the $k_F$–$\Gamma$(or $M$) line and the $\Gamma M$ line. The SC gap on each FS is nearly constant, indicating an isotropic $s$-wave nature. On the other hand, the average gap values of the hole and electron pockets are different (6.6 and 5.0 meV, respectively), again confirming the FS-dependent nature of the SC gap.

From a direct comparison of the ARPES data on the electron- and hole-doped SC samples, we conclude that (i) the SC gap opens on multiple FSs centered at the $\Gamma$ and $M$ points, (ii) the SC gap is nodeless and exhibits a nearly isotropic behavior on each FS, and (iii) the pairing strength, as reflected by the ratio of $2\Delta/k_BT_c$, is related to the FS nesting condition between the electron and hole pockets. In hole-doped $Ba_{0.6}K_{0.4}Fe_2As_2$ [2,3] the interband scattering *via* the wavevector $Q \sim (\pi, \pi)$ would enhance the pairing amplitude of the $\alpha$ and $\gamma(\delta)$ FSs, resulting in large $2\Delta/k_BT_c$ values of 7.2–7.7, while the poorly-nested $\beta$ FS has a value of 3.6, close to the weak-coupling regime. Remarkably, in electron-doped $BaFe_{1.85}Co_{0.15}As_2$, the $\beta$ (but not $\alpha$) is connected to the $\gamma(\delta)$ FSs by the same $Q$ vector and possess strong-coupling $2\Delta/k_BT_c$ values of 5.9, suggesting an enhancement of the pairing amplitude due to inter-pocket scattering on the nearly nested FSs. The observation that the pairing strength of the $\beta$ band increases from 3.6 in the optimally hole-doped sample to 5.9 in the optimally electron-doped sample strongly suggests that the coupling strength is more related to the nesting condition among the FSs than to the orbital characters themselves. All these experimental observations suggest that inter-pocket scattering and FS nesting are critical aspects of the pairing mechanism of the iron-based superconductors.

## 4. Conclusion

We have performed high-resolution ARPES on optimally electron-doped $BaFe_{1.85}Co_{0.15}As_2$ ($T_c$ = 25.5 K) and revealed FS-dependent isotropic nodeless SC gaps and strong pairing on nearly nested FS-sheets.

## References

[1] Y. Kamihara et al., J. Am. Chem. Soc. 130 (2008) 3296.
[2] H. Ding et al., Europhys. Lett. 83 (2008) 47001.
[3] K. Nakayama et al., Europhys. Lett. 85 (2009) 67002.
[4] K. Terashima et al., Proc. Nat. Acad. Sci. 106 (2009) 7330.