Thermal conductivity of overdoped BaFe_{1.73}Co_{0.27}As_2 single crystal: Evidence for nodeless multiple superconducting gaps and interband interactions

J. K. Dong, S. Y. Zhou, T. Y. Guan, X. Qiu, C. Zhang, P. Cheng, L. Fang, H. H. Wen, S. Y. Li

1Department of Physics, Surface Physics Laboratory (National Key Laboratory), and Laboratory of Advanced Materials, Fudan University, Shanghai 200433, China
2National Laboratory for Superconductivity, Institute of Physics and Beijing National Laboratory for Condensed Matter Physics, Chinese Academy of Sciences, Beijing 100190, China

(Dated: March 30, 2010)

The in-plane thermal conductivity $\kappa$ of overdoped FeAs-based superconductor BaFe$_{1.73}$Co$_{0.27}$As$_2$ ($T_c = 8.1$ K) single crystal was measured down to 80 mK. In zero field, the residual linear term $\kappa_0/T$ is negligible, suggesting a nodeless superconducting gap in the ab-plane. In magnetic field, $\kappa_0/T$ increases rapidly, very different from that of conventional s-wave superconductors. This anomalous $\kappa_0/T(H)$ may reveal an exotic superconducting gap structure in overdoped BaFe$_{1.73}$Co$_{0.27}$As$_2$: the vanishing hole ($\beta$) pocket has a much larger gap than the electron ($\gamma$ and $\delta$) pockets which contain most of the carriers. Such an exotic gap structure is an evidence for superconducting state induced by interband interactions, in which the band with the smaller density of states has a larger gap.

PACS numbers: 74.70.Xa, 74.25.fc, 74.20.Mn

I. INTRODUCTION

For the recently discovered FeAs-based high-$T_c$ superconductors the pairing symmetry of its superconducting gap remains the most important issue to resolve. Although extensive experimental and theoretical work have been done, there is still no consensus. While angle-resolved photoemission spectroscopy (ARPES) experiments clearly demonstrated nearly isotropic multigaps and the Andreev spectroscopy NMR and penetration depth experiments gave conflicting claims on whether there are nodes in the superconducting gaps. Low-temperature thermal conductivity measurement is a powerful bulk tool to probe the superconducting gap structure. The residual linear term $\kappa_0/T$ is very sensitive to the existence of gap nodes and the field dependence of $\kappa_0/T$ can give useful information on multi-gaps. Very recently, several heat transport studies have been done on this new family of FeAs-based and related superconductors. For the hole-doped Ba$_{1-x}$K$_x$Fe$_2$As$_2$ ($T_c \approx 30$ K) and electron-doped BaFe$_{1.9}$Ni$_{0.1}$As$_2$ ($T_c = 20.3$ K) a negligible $\kappa_0/T$ was found in zero field, indicating a single superconducting gap. By contrast, a large $\kappa_0/T$ was observed in BaFe$_{1.86}$Co$_{0.14}$As$_2$. For the prototype FeSe$_2$ ($T_c = 8.8$ K) superconductor, the thermal conductivity shows clear behavior of multiple nodeless superconducting gaps. In two superconductors with lower $T_c$, $\kappa_0/T$ of BaNi$_2$As$_2$ ($T_c = 0.7$ K) is consistent with a dirty fully gapped superconductivity while LaFePO ($T_c = 7.4$ K) appears to have a finite $\kappa_0/T$, suggesting the gap on some band may have nodes.

For the most interested hole- and electron-doped BaFe$_2$As$_2$ superconductors, all samples studied by heat transport so far are near optimal doping. It will be very interesting to study highly underdoped and overdoped samples to demonstrate its superconducting gap structure over the whole doping range. Furthermore, due to the high $T_c$ and $H_{c2}$ of optimally doped samples, magnetic field can only be applied up to about 30% of their $H_{c2}$. While for highly underdoped and overdoped samples with relatively lower $T_c$, one may get a complete $\kappa_0/T(H)$ behavior to see if it has the multigap character, as in FeSe$_2$.

In this paper, we measure the thermal conductivity $\kappa$ of a highly overdoped BaFe$_{1.73}$Co$_{0.27}$As$_2$ single crystal with $T_c = 8.1$ K down to 80 mK. In zero field, the residual linear term $\kappa_0/T$ is negligible, suggesting a nodeless superconducting gap, at least in ab-plane. In magnetic field, $\kappa_0/T(H)$ increases sharply, very different from the Ba$_{1-x}$K$_x$Fe$_2$As$_2$ and BaFe$_{1.9}$Ni$_{0.1}$As$_2$ samples near optimal doping. Such an anomalous $\kappa_0/T(H)$ likely results from an exotic superconducting gap structure in overdoped BaFe$_{1.73}$Co$_{0.27}$As$_2$: the vanishing hole ($\beta$) pocket has a much larger gap than the electron ($\gamma$ and $\delta$) pockets which contain most of the carriers. Our finding of this exotic gap structure supports the s$_{\pm}$-wave superconducting state induced by interband interactions in FeAs-based superconductors.

II. EXPERIMENTAL

Single crystals with nominal formula BaFe$_{1.7}$Co$_{0.3}$As$_2$ were prepared by self flux method. The diamagnetic superconducting transition was measured by a vibrating sample magnetometer (VSM) based on a physical property measurement system (PPMS of Quantum Design) with the magnetic field perpendicular to the ab-plane of the crystals. Energy Dispersive of X-ray (EDX) microanalysis (Hitach S-4800) show that the actual Co content is 0.27. The sample was cleaved to a rectangular shape of dimensions $2.1 \times 1.4$ mm$^2$ in the ab-plane, with 25 $\mu$m thickness along the c-axis. Contacts were made directly...
FIG. 1: (Color online) In-plane resistivity $\rho(T)$ of BaFe$_{1.73}$Co$_{0.27}$As$_2$ single crystal in $H = 0$ and 14.5 T. The zero-resistance point of the resistive transition is at $T_c = 8.1$ K in zero field. The solid line is a fit of the $H = 14.5$ T data between 10 and 30 K to the Fermi liquid form $\rho = \rho_0 + AT^2$, which gives residual resistivity $\rho_0 = 64.8 \mu\Omega$ cm. Inset: normalized magnetization which shows the diamagnetic superconducting transition.

FIG. 2: (Color online) Low-temperature thermal conductivity of BaFe$_{1.73}$Co$_{0.27}$As$_2$ in magnetic fields applied along the $c$-axis ($H = 0$, 1, 2, 4, 9, and 14.5 T). The solid lines are $\kappa/T = a + bT^\alpha$ fits (see text). The dashed line is the normal state Wiedemann-Franz law expectation $L_0/\rho_0$, with $L_0$ the Lorenz number $2.45 \times 10^{-8} \text{W} \text{K}^{-2} \text{cm}$. Thermal conductivity for BaFe$_{1.73}$Co$_{0.27}$As$_2$ in $H = 0$, 1, 2, 4, 9, and 14.5 T magnetic fields are plotted as $\kappa/T$ vs $T$. All the curves are roughly linear, therefore we fit the data to $\kappa/T = a + bT^\alpha$ (refs. 35 and 36) with $\alpha$ fixed to 2. The two terms $aT$ and $bT^\alpha$ represent electronic and phonon contributions, respectively. In the phonon term, the value of $\alpha$ is usually between 2 and 3, due to specular reflection of phonons at the smooth crystal surfaces in the boundary scattering limit at low temperature. Previously, $\alpha = 2.22$ and 2.02 were observed in BaFe$_2$As$_2$ and BaFe$_{1.9}$Ni$_{0.1}$As$_2$ single crystals, respectively. Here we only focus on the electronic term.

In zero field, the fitting gives residual linear term $\kappa_0/T = -3 \pm 9 \mu\text{W K}^{-2} \text{cm}^{-1}$. This value of $\kappa_0/T$ is within the experimental error bar $\pm 5 \mu\text{W K}^{-2} \text{cm}^{-1}$ although the fitting error bar is a little high due to the slight noise of the data. Even after considering these error bars, the $\kappa_0/T$ is still less than 3% of the normal-state Wiedemann-Franz law expectation $L_0/\rho_0 = 0.378 \text{mW} \text{K}^{-2} \text{cm}^{-1}$, with $L_0$ the Lorenz number $2.45 \times 10^{-8} \text{W} \text{K}^{-2}$. Such a negligible $\kappa_0/T$ in zero field suggests a nodeless (at least in $ab$-plane) superconducting gap in overdoped BaFe$_{1.73}$Co$_{0.27}$As$_2$, which is consistent with previous results on Ba$_{1-x}$K$_x$Fe$_2$As$_2$ and BaFe$_{1.9}$Ni$_{0.1}$As$_2$ and different from BaFe$_{1.86}$Co$_{0.14}$As$_2$. It has been noted that the large $\kappa_0/T$ in zero field observed in BaFe$_{1.86}$Co$_{0.14}$As$_2$ by Machida et al. may be extrinsic.

In $H = 9$ and 14.5 T magnetic fields, $\kappa_0/T = 0.365 \pm 0.009$ and $0.366 \pm 0.009$ mW K$^{-2}$ cm$^{-1}$ were obtained from the fittings, respectively. For both values, one gets the Lorenz ratio $L = \rho_0\kappa_0/T = 0.97 \pm 0.03 L_0$, which shows that Wiedemann-Franz law is roughly sat-
In Fig. 3, the rapid increase of $\kappa_0/T$ of BaFe$_{1.73}$Co$_{0.27}$As$_2$ as a function of $H/H_{c2}$. Similar data of the clean s-wave superconductor NbSe$_2$ the dirty s-wave superconducting alloy InBi$^{21}$ the multi-band s-wave superconductor NbSe$_2$$^{22}$ an overdoped sample of the d-wave superconductor Tl-2201$^{23}$ and BaFe$_{1.9}$Ni$_{0.1}$As$_2$$^{24}$ are also shown for comparison.

satisfied within the experimental error bar. Note that in the non-superconducting parent BaFe$_2$As$_2$ single crystal, the Wiedemann-Franz law was found to be satisfied as $T \to 0$.\textsuperscript{37}$\,$\textsuperscript{37}

The saturation of thermal conductivity in $H > 9$ T suggests that the bulk $H_{c2}$ has been reached at $H = 9$ T, although the resistive transition is not completely suppressed until $H_{c2} = 17$ T. Similar situation happened in overdoped cuprate superconductor Tl-2201 with $T_c = 15$ K, in which $H_{c2} = 13$ T was obtained from the resistivity data, while bulk $H_{c2} = 7$ T was determined from the thermal conductivity data.\textsuperscript{24} Here we take bulk $H_{c2} = 9$ T for overdoped BaFe$_{1.73}$Co$_{0.27}$As$_2$. To choose a slightly different bulk $H_{c2}$ does not affect our discussions below.

In Fig. 3, the normalized $\kappa_0/T$ of BaFe$_{1.73}$Co$_{0.27}$As$_2$ is plotted as a function of $H/H_{c2}$, together with the clean s-wave superconductor Nb$^{44}$ the dirty s-wave superconducting alloy InBi$^{21}$ the multi-band s-wave superconductor NbSe$_2$$^{22}$ an overdoped sample of the d-wave superconductor Tl-2201$^{23}$ and BaFe$_{1.9}$Ni$_{0.1}$As$_2$$^{24}$ As seen in Fig. 3, the rapid increase of $\kappa_0/T$ at low field for overdoped BaFe$_{1.73}$Co$_{0.27}$As$_2$ is clearly different from the optimally doped BaFe$_{1.9}$Ni$_{0.1}$As$_2$. In fact, it looks more like the typical behavior of d-wave superconductors, due to the Volovik effect.\textsuperscript{24} However, the negligible $\kappa_0/T$ in zero field, which means nodeless superconducting gap, has excluded d-wave gap in BaFe$_{1.73}$Co$_{0.27}$As$_2$.

For s-wave superconductor NbSe$_2$, $\kappa_0/T$ is zero in $H = 0$, but it also increases rapidly at low field, unlike Nb and InBi. This has be explained by its multi-gap structure: the gap on the $\Gamma$ band is approximately one third of the gap on the other two Fermi surfaces, and magnetic field first suppresses the superconductivity on the Fermi surface with smaller gap (given that $H_{c2}(0) \propto \Delta_0^2$). Therefore, the even sharper increase of $\kappa_0/T$ in BaFe$_{1.73}$Co$_{0.27}$As$_2$ may result from an extreme case of multigap structure, in which the gap of one band is much smaller than others (e.g., 1/4 or 1/5). However, there is an apparent difference between NbSe$_2$ and BaFe$_{1.73}$Co$_{0.27}$As$_2$. For NbSe$_2$, after the smaller gap was suppressed, $\kappa_0/T$ shows a slight downward curvature at high field due to the larger gap. Similar curvature of $\kappa_0/T$ was found in MgB$_2$. In Fig. 3, $\kappa_0/T$ of BaFe$_{1.73}$Co$_{0.27}$As$_2$ increases so rapidly and it does not show downward curvature at high field. Such an anomalous $\kappa_0/T$ has never been seen before. If it indeed results from multiple nodeless gaps, the bands with smaller gaps must contain most of the carriers so that $\kappa_0/T$ can increase so rapidly all the way to high field.

To investigate this possibility, we have examined the band structure and superconducting gaps in doped BaFe$_2$As$_2$ system, revealed by ARPES experiments.\textsuperscript{8,12,13,45} From the hole doped side, in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ ($T_c = 37$ K), the average gap values $\Delta(0)$ for the two hole ($\alpha$ and $\beta$) pockets at the $\Gamma$ point are 12.5 and 5.5 meV, respectively, while for the electron ($\gamma$ and $\delta$) pockets at the $M$ point, the gap value is about 12.5 meV.\textsuperscript{46,47} For electron-doped BaFe$_{1.85}$Co$_{0.15}$As$_2$ ($T_c = 25.5$ K) at optimal doping, the inner hole ($\alpha$) pocket disappears, and the average gap values $\Delta(0)$ of hole ($\beta$) and electron ($\gamma$ and $\delta$) pockets are 6.6 and 5.0 meV, respectively.\textsuperscript{26} Such nearly isotropic multigaps with similar size has been used to explain the slow field dependence of $\kappa_0/T$ up to 30% $H_{c2}$ in BaFe$_{1.9}$Ni$_{0.1}$As$_2$ as seen in Fig. 3. With further electron doping, in heavily doped non-superconducting BaFe$_{1.7}$Co$_{0.3}$As$_2$ the $\beta$ hole pocket is absent or very small, while the two electron ($\gamma$ and $\delta$) pockets at the $M$ point significantly expand.\textsuperscript{25} This is consistent with the band structure calculation, which shows that the $\beta$ band disappears at $\sim 26.5\%$ electron doping.\textsuperscript{25} Based on this trend of band structure evolution, in our superconducting BaFe$_{1.73}$Co$_{0.27}$As$_2$ sample there should be a very small hole ($\beta$) pocket, together with two large electron ($\gamma$ and $\delta$) pockets which contain most of the carriers. To explain its anomalous $\kappa_0/T(H)$, the gap on hole ($\beta$) pocket must be much larger, 4 to 5 times, than the gaps on electron ($\gamma$ and $\delta$) pockets.

In the BCS theory, larger DOS usually leads to a larger superconducting gap $\Delta(0)$. Therefore it is counterintuitive that the vanishing $\beta$ pocket with much smaller DOS ends up with a much larger gap. However, in the theory of interband superconductivity,\textsuperscript{25} this is exactly the result of the interband-only pairing, since the pairing amplitude on one band is generated by the DOS on the other.

Right after the discovery of $T_c = 26$ K superconductivity in LaFeAs$_{1-x}$F$_x$,\textsuperscript{48} the importance of interband pairing interaction has been emphasized due to the multiband fermiology.\textsuperscript{48,49} The interaction, possibly via antiferromagnetic spin fluctuations, connects the well-
separated Fermi surface pockets located around Γ and around M, and gives extended s-wave pairing symmetry whose order parameter has opposite sign on the electron and hole pockets. Although the relative strength of interband and intraband pairing interactions is still under debate, the experimentally observed different $2\Delta/k_BT_c$ values on different Fermi surface pocket in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ and BaFe$_{1.9}$Co$_{0.15}$As$_2$ prefer the interband pairing mechanism.

Quantitatively, in the interband-only pairing model, the gap ratio $\Delta_2/\Delta_1 = \sqrt{N_1/N_2}$, with $N_1$ and $N_2$ the Fermi-level density of states. In this sense, our overdoped BaFe$_{1.73}$Co$_{0.27}$As$_2$ sample has provided the best testing ground for the theory of interband superconductivity, due to its biggest difference of DOS between the hole and electron pockets in doped BaFe$_2$As$_2$ superconductors so far. Indeed, the results of our current work have given strong support for the interband superconductivity in FeAs-based superconductors. It will be very interesting to directly measure the superconducting gaps in our overdoped BaFe$_{1.73}$Co$_{0.27}$As$_2$ sample with ARPES, which needs to be done at temperature below the $T_c = 8.1$ K.

IV. SUMMARY

In summary, we have used low-temperature thermal conductivity to clearly demonstrate nodeless superconducting gap in overdoped iron-arsenide superconductor BaFe$_{1.73}$Co$_{0.27}$As$_2$. Furthermore, the $\kappa_0/T(H)$ increases sharply at low field, very different from Ba$_{1-x}$K$_x$Fe$_2$As$_2$ and BaFe$_{1.9}$Ni$_{0.1}$As$_2$ near optimal doping. It may reveal an exotic superconducting gap structure in overdoped BaFe$_{1.73}$Co$_{0.27}$As$_2$: the vanishing hole ($\beta$) pocket has a much larger gap than the electron ($\gamma$ and $\delta$) pockets, although the electron pockets have much larger density of states. Such an exotic gap structure is an evidence for the theory of interband superconductivity, thus of great importance to understand the superconducing state in FeAs-based superconductors.

V. NOTE ADDED

During preparation of this manuscript, a similar work on BaFe$_{1.73}$Co$_{0.27}$As$_2$ was posted online [arXiv:0908.2209]. In ref. 52, the results of overdoped BaFe$_{1.72}$Co$_{0.22}$As$_2$ ($T_c = 10.1$ K) are consistent with ours, but the anomalous increase of $\kappa_0/T(H)$ at low field was explained by highly anisotropic superconducting gap with deep minima. While this debate needs to be resolved by low-temperature ARPES experiments, we note a very recent calculation of $\kappa_0/T(H)$ with unequal size of isotropic $s_\pm$-wave gaps has successfully fit the experimental data, thus supports our interpretation.

ACKNOWLEDGEMENTS

We thank Y. Chen, D. L. Feng, and J. P. Hu for useful discussions. This work is supported by the Natural Science Foundation of China, the Ministry of Science and Technology of China (National Basic Research Program No:2009CB929203 and 2006CB601000), Program for New Century Excellent Talents in University, and STCSM of China (No: 08dj140200 and 08PJ1402100).

* E-mail: shiyan_li@fudan.edu.cn

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