Nodeless superconducting gaps in Ca$_{10}$(Pt$_{4-\delta}$As)$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As)$_2$$_5$ probed by quasiparticle heat transport

X. Qiu, L. P. He, X. C. Hong, Z. Zhang, J. Pan, X. P. Shen, D. L. Feng, and S. Y. Li*
State Key Laboratory of Surface Physics, Department of Physics, and Laboratory of Advanced Materials, Fudan University, Shanghai 200433, P. R. China

(Dated: March 4, 2014)

The in-plane thermal conductivity of iron-based superconductor Ca$_{10}$(Pt$_{4-\delta}$As)$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As)$_2$$_5$ single crystal ("10-4-8", $T_c$ = 22 K) was measured down to 80 mK. In zero field, the residual linear term $\kappa_0/T$ is negligible, suggesting nodeless superconducting gaps in this multiband compound. In magnetic fields, $\kappa_0/T$ increases rapidly, which mimics those of multiband superconductor NbSe$_2$ and LuNi$_2$B$_2$C with highly anisotropic gap. Such a field dependence of $\kappa_0/T$ is an evidence for multiple superconducting gaps with quite different magnitudes or highly anisotropic gap. Comparing with the London penetration depth results of Ca$_{10}$(Pt$_3$As)$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As)$_2$$_5$ ("10-3-8") compound, the 10-4-8 and 10-3-8 compounds may have similar superconducting gap structure.

PACS numbers: 74.70.Xa, 74.25.fc

I. INTRODUCTION

To understand the electronic pairing mechanism of a superconductor, it is very important to know the symmetry and structure of its superconducting gap. For the iron-based high-temperature superconductors, there are many families, such as LaO$_{1-x}$F$_x$FeAs ("1111") $\downarrow$, Ba$_{1-x}$K$_x$Fe$_2$As$_2$ ("122") $\downarrow$, NaFe$_{1-x}$Co$_x$As ("111") $\uparrow$ and FeSe$_x$Te$_{1-x}$ ("11"). The most notable character of these families is the multiple Fermi surfaces, which may be the reason why their superconducting gap structure is so complicated $\downarrow$. Different from other families, the new compounds Ca$_{10}$(Pt$_3$As)$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As)$_2$$_5$ ("10-3-8") and Ca$_{10}$(Pt$_4$As)$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As)$_2$$_5$ ("10-4-8") consist of semiconducting [Pt$_3$As$_8$] layers or metallic [Pt$_4$As$_8$] layers sandwiched between [Fe$_{10}$As$_{10}$] layers, and show superconductivity with maximal $T_c \sim 15$ and 38 K, respectively. The metallic [Pt$_4$As$_8$] layers lead to stronger FeAs interlayer coupling in 10-4-8 compound, thus higher $T_c$ as compared to the 10-3-8 compound. The upper critical field of both 10-3-8 and 10-4-8 compounds show strong anisotropy $\downarrow$. For the 10-3-8 compound, the London penetration depth exhibits power-law variation, which suggests nodeless superconducting gap $\downarrow$. For the 10-4-8 compound, the angle-resolved photoemission spectroscopy (ARPES) experiments have revealed a multiband electronic structure $\uparrow$, but so far there is still no any investigation of its superconducting gap structure. As the 10-4-8 has a much higher $T_c$ than the 10-3-8 compound, it will be interesting to study its superconducting gap structure and compare with the 10-3-8 compound.

Low-temperature thermal conductivity measurement is a bulk technique to study the superconducting gap structure $\downarrow$. According to the magnitude of residual linear term $\kappa_0/T$ in zero field, one may judge whether there exist gap nodes or not. The field dependence of $\kappa_0/T$ can give further information on nodal gap, gap anisotropy, or multiple gaps $\uparrow$.

In this paper, we measure the thermal conductivity of Ca$_{10}$(Pt$_{4-\delta}$As)$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As)$_2$$_5$ ($T_c$ = 22 K) single crystal down to 80 mK. A negligible residual linear term $\kappa_0/T$ is found in zero magnetic field. The field dependence of $\kappa_0/T$ is very similar to those in multigap s-wave superconductor NbSe$_2$ and LuNi$_2$B$_2$C with highly anisotropic gap. Our data strongly suggest Ca$_{10}$(Pt$_{4-\delta}$As)$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As)$_2$$_5$ has nodeless superconducting gaps. The magnitudes of these gaps could be quite different, or some gap may be anisotropic.

II. EXPERIMENT

Single crystals of Ca$_{10}$(Pt$_{4-\delta}$As)$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As)$_2$$_5$ ($T_c$ = 22 K) were grown by the flux method $\uparrow$. The composition of the sample was determined as Ca:Fe:Pt:As = 2:1.73:0.79:3.39 by wavelength-dispersive spectroscopy (WDS), utilizing an electron probe microanalyzer (Shimadzu EPMA-1720). The doping level is close to the $T_c = 26$ K sample with Ca:Fe:Pt:As = 2:1.8:0.9:3.5 in Ref. 8, which has the chemical formula Ca$_{10}$(Pt$_4$As)$_8$)((Fe$_{0.97}$Pt$_{0.03}$)$_2$As)$_2$$_5$ ($\delta = 0.26$) determined by single crystal structure refinement. The dc magnetization was measured at $H = 20$ Oe, with zero-field cooling process, using a SQUID (MPMS, Quantum Design).

The sample was cleaved to a rectangular shape with dimensions of 1.5 × 0.74 mm$^2$ in the $ab$ plane and ~25 μm along the $c$ axis. Contacts were made directly on the fresh sample surfaces with silver paint, which were used for both resistivity and thermal conductivity measurements. In-plane thermal conductivity was measured in a dilution refrigerator using a standard four-wire steady-
state method with two RuO$_2$ chip thermometers, calibrated in situ against a reference RuO$_2$ thermometer. Magnetic fields are applied along the $c$ axis. To ensure a homogeneous field distribution in the samples, all fields are applied at a temperature above $T_c$.

III. RESULTS AND DISCUSSION

Figure 1(a) shows the in-plane resistivity of Ca$_{10}$(Pt$_{4-x}$As$_x$)((Fe$_{1-x}$Pt$_x$)$_2$As$_2$)$_5$ single crystal in zero field. Defined by $\rho = 0$, $T_c = 22.2$ K is obtained. The solid line is a fit of the data between 50 and 125 K to $\rho = \rho_0 + AT^\alpha$, which gives residual resistivity $\rho_0 = 82.5$ $\mu\Omega$ cm and $\alpha = 1.15$. The dc magnetization is shown in Fig. 1(b), and a slightly lower $T_c = 21.7$ K is found. Blow we take $T_c = 22$ K. This value is lower than the $T_c = 38$ K at optimal doping. Since the phase diagram, $T_c$ vs $x(\delta)$, of 10-4-8 system has not been well studied, it is not sure that our sample is underdoped or overdoped.

Figure 2(a) shows the low-temperature resistivity of Ca$_{10}$(Pt$_{4-x}$As$_x$)((Fe$_{1-x}$Pt$_x$)$_2$As$_2$)$_5$ single crystal in magnetic fields ($H = 0$, 3, 6, 9, 12, and 14.5 T) along the $c$ axis. (b) Temperature dependence of the upper critical field $H_{c2}(T)$. The solid line is a fit to the two-band model, which points to $H_{c2}(0) \approx 52$ T.
giving $H_{c2}^{\parallel}(0) \approx 90$ T. Taking the same process as in Ref. 11, we also fit the $H_{c2}(T)$ data in Fig. 2(b) with the two-band model, and get $H_{c2}(0) = 52$ T for our Ca$_{10}$(Pt$_4$-xAs$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As$_2$)$_5$ ($T_c = 22$ K) sample. Note that a slightly different $H_{c2}(0)$ does not affect our discussion on the field dependence of normalized $\kappa_0/T$ blow.

In Fig. 3, the temperature dependence of the in-plane thermal conductivity for Ca$_{10}$(Pt$_4$-xAs$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As$_2$)$_5$ in $H = 0, 2, 3, 6, 9,$ and $12$ T magnetic fields are plotted as $\kappa/T$ vs $T$. To get the residual linear term $\kappa_0/T$, we fit the curves to $\kappa/T = a + bT^{n-1}$ blow 0.4 K, in which the two terms $aT$ and $bT^n$ come from contributions of electrons and phonons, respectively. The power $n$ of the phonon term is typically between 2 and 3, due to the specular reflections of phonons at the sample surfaces. In zero field, the fitting gives $\kappa_0/T = 0.005 \pm 0.013$ mW K$^{-2}$ cm$^{-1}$ and $\alpha = 2.57 \pm 0.03$. Such a tiny value of $\kappa_0/T$ is within our experimental error bar $\pm 0.005$ mW K$^{-2}$ cm$^{-1}$. Therefor it is negligible, comparing to the normal-state Wiedemann-Franz law expectation $L_0/\rho_0 = 0.297$ mW K$^{-2}$ cm$^{-1}$, with $L_0 = 2.45 \times 10^{-8}$ WΩ K$^{-2}$ and $\rho_0 = 82.5 \mu$Ω cm. The absence of $\kappa_0/T$ in zero field means that there are no fermionic quasiparticles to conduct heat as $T \to 0$, which provides bulk evidence for nodeless superconducting gaps in Ca$_{10}$(Pt$_4$-xAs$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As$_2$)$_5$, at least in the $ab$ plane. The data in magnetic fields $H = 2, 3, 6, 9,$ and $12$ T are also fitted, as seen in Figs. 3(b)-3(f). The $\kappa_0/T$ increases significantly with increasing field, although the maximum applied field $H = 12$ T is only about 23% of the $H_{c2}(0) = 52$ T. To see the field dependence of $\kappa_0/T$ more clearly, the normalized $\kappa_0/T$ of Ca$_{10}$(Pt$_4$-xAs$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As$_2$)$_5$ as a function of $H/H_{c2}$ is plotted in Fig. 4. Similar data are shown for the clean s-wave superconductor Nb, the dirty s-wave superconducting alloy InBi, the multiband s-wave superconductor NbSe$_2$, the s-wave superconductor LuNi$_2$B$_2$C with highly anisotropic gap, an overdoped d-wave cuprate superconductor Ti-2201, and the iron-based superconductor BaFe$_{1.73}$Co$_{0.27}$As$_2$.

![FIG. 4. (Color online) Normalized residual linear term $\kappa_0/T$ of Ca$_{10}$(Pt$_4$-xAs$_8$)((Fe$_{1-x}$Pt$_x$)$_2$As$_2$)$_5$ as a function of $H/H_{c2}$](image)

For the multiband s-wave superconductor NbSe$_2$, 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. For the s-wave superconductor LnNi$_2$B$_2$C with highly anisotropic gap, the gap minimum $\Delta_{\text{min}}$ is at least 10 times smaller than the gap maximum, $\Delta_{\text{min}} \leq \Delta_0/10$. The nearly identical field dependence of normalized $\kappa_0/T$ between NbSe$_2$ and LnNi$_2$B$_2$C indicates that bulk thermal conductivity measurement can not distinguish these two kinds of superconducting gap structures. Nevertheless, the field dependence of $\kappa_0/T$ suggests that the nodeless superconducting gaps in multiband 10-4-8 compound may have quite different magnitudes, or some gap may be anisotropic. Note that similar field dependence of $\kappa_0/T$ was also observed in iron-based superconductors BaFe$_{1.73}$Co$_{0.27}$As$_2$ and FeSe$_{2}$.

In a theoretical calculation of $\kappa_0(H)/T$ with unequal size of isotropic s$_\pm$-wave gaps, the shape of $\kappa_0(H)/T$ changes systematically with the gap size ratio $\Delta_S/\Delta_L$. In case of isotropic s-wave gaps with unequal size, the ratio $\Delta_S/\Delta_L \approx 1/4$ is estimated for our 10-4-8 compound, by comparing with the theoretical curves. However, we can not rule out that some gap may be anisotropic. In fact, the robust power-law variation of London penetration depth observed in 10-3-8 compound was interpreted in terms of strongly anisotropic gap, which may be similar to that of Ca$_{10}$Pt$_3$As$_8$ single crystal down to 80 mK. The absence of $\kappa_0/T$ in zero field gives strong evidence for nodeless superconducting gaps in such a multiband compound. The rapid field dependence of $\kappa_0/T$ suggests multiple superconducting gaps with quite different magnitudes or highly anisotropic gap, which may be similar to that of Ca$_{10}$Pt$_3$As$_8$ single crystal.

### IV. SUMMARY

In summary, we have measured the thermal conductivity of Ca$_{10}$(Pt$_4$−δAs$_8$)(Fe$_{1-x}$Pt$_x$)$_2$As$_2$ single crystals down to 80 mK. The absence of $\kappa_0/T$ in zero field gives strong evidence for nodeless superconducting gaps in such a multiband compound. The rapid field dependence of $\kappa_0/T$ suggests multiple superconducting gaps with quite different magnitudes or highly anisotropic gap, which may be similar to that of Ca$_{10}$Pt$_3$As$_8$ single crystal.

### ACKNOWLEDGEMENTS

This work is supported by the Natural Science Foundation of China, the Ministry of Science and Technology of China (National Basic Research Program No. 2012CB821402), and the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning.

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

---

1. Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono, J. Am. Chem. Soc. 130, 3296 (2008).
2. M. Rotter, M. Tegel, and D. Johrendt, Phys. Rev. Lett. 101, 107006 (2008).
3. D. R. Parker, M. J. P. Smith, T. Lancaster, A. J. Steele, I. Franke, P. J. Baker, F. L. Pratt, M. J. Pitcher, S. J. Blundell, and S. J. Clarke, Phys. Rev. Lett. 104, 057007 (2010).
4. B. C. Sales, A. S. Sefat, M. A. McGuire, R. Y. Jin, D. Mandrus, and Y. Mozharivskiy, J. Phys. Rev. B 79, 094521 (2009).
5. P. J. Hirschfeld, M. M. Korshunov, and I. I. Mazin, Rep. Prog. Phys. 74, 124508 (2011).
6. Fa Wang and D.-H. Lee, Science 332, 200 (2011).
7. C. Löhnhert, T. Stürzer, M. Tegel, R. Frankovsky, G. Friederichs, and D. Johrendt, Angew. Chem. Int. Ed. 50, 9195 (2011).
8. N. Ni, J. M. Allred, B. C. Chan, and R. J. Cava, Proc. Natl. Acad. Sci. USA 108, E1019 (2011).
9. S. Kakiya, K. Kudo, Y. Nishikubo, K. Oku, E. Nishibori, H. Sawa, T. Yamamoto, T. Nozaka, and M. Nohara, J. Phys. Soc. Jpn. 80, 093704 (2011).
10. Z. J. Xiang, X. G. Luo, J. J. Ying, X. F. Wang, Y. J. Yan, A. F. Wang, P. Cheng, G. J. Ye, and X. H. Chen, Phys. Rev. B 85, 224527 (2012).
11. E. Mun, N. Ni, J. M. Allred, R. J. Cava, O. Ayala, R. D. McDonald, N. Harrison, and V. S. Zapf, Phys. Rev. B 85, 100502(R) (2012).
12. K. Cho, M. A. Tanatar, H. Kim, W. E. Straszheim, N. Ni, R. J. Cava, and R. Prozorov, Phys. Rev. B 85, 020504(R) (2012).
13. X. P. Shen, S. D. Chen, Q. Q. Ge, Z. R. Ye, F. Chen, H. C. Xu, S. Y. Tan, X. H. Niu, Q. Fan, B. P. Xie, and D. L. Feng, Phys. Rev. B 88, 115124 (2013).
14. S. Thirupathaiah, T. Stürzer, V. B. Zabolotnyy, D. Johrendt, B. Büchner, and S. V. Borisenko, Phys. Rev. B 88, 140505(R) (2013).
15. H. Shakeripour, C. Petrovic, and L. Taillefer, New J. Phys. 11, 055006 (2009).
16. N. R. Werthamer, E. Helfand, and P. C. Hohenberg, Phys. Rev. 147, 295 (1966).
17. A. Gurevich, Phys. Rev. B 67, 184515 (2003).
18. M. Sutherland, D. G. Hawthorn, R. W. Hill, F. Ronning, S. Wakimoto, H. Zhang, C. Proust, E. Boaknin, C. Lupien, L. Taillefer, R. Liang, D. A. Bonn, W. N. Hardy, R. Gagnon, N. E. Hussey, T. Kimura, M. Nohara, and H. Takagi, Phys. Rev. B 67, 174520 (2003).
19. S. Y. Li, J.-B. Bonnemaison, A. Payeur, P. Fournier, C. Xu, S. Y. Tan, X. H. Niu, Q. Fan, B. P. Xie, and D. L. Feng, Phys. Rev. B 115124 (2013).
20. A. Gurevich, Phys. Rev. B 67, 184515 (2003).
21. J. O. Willis and D. M. Ginsberg, Phys. Rev. B 67, 174520 (2003).
22. J. Lowell and J. B. Sousa, J. Low. Temp. Phys. 3, 65 (1970).
23. J. O. Willis and D. M. Ginsberg, Phys. Rev. B 14, 1916 (1976).
24. E. Boaknin, M. A. Tanatar, J. Paglione, D. Hawthorn, F. Ronning, R. W. Hill, M. Sutherland, L. Taillefer, J. Sonier, S. M. Hayden, and J. W. Brill, Phys. Rev. Lett. 90, 117003 (2003).
25. E. Boaknin, R. W. Hill, C. Proust, C. Lupien, L. Taillefer, and P. C. Canfield, Phys. Rev. Lett. 87, 237001 (2001).
24 C. Proust, E. Boaknin, R. W. Hill, L. Taillefer, and A. P. Mackenzie, Phys. Rev. Lett. 89, 147003 (2002).
25 J. K. Dong, S. Y. Zhou, T. Y. Guan, X. Qiu, C. Zhang, P. Cheng, L. Fang, H. H. Wen, and S. Y. Li, Phys. Rev. B 81, 094520 (2010).
26 G. E. Volovik, JETP Lett. 58, 469 (1993).
27 J. K. Dong, T. Y. Guan, S. Y. Zhou, X. Qiu, L. Ding, C. Zhang, U. Patel, Z. L. Xiao, and S. Y. Li, Phys. Rev. B 80, 024518 (2009).
28 Y. Bang, Phys. Rev. Lett. 104, 217001 (2010).