Fully-gapped superconductivity in $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$: A low-temperature specific heat study

K. Gofryk,[*] J. C. Lashley, F. Ronning, D. J. Safarik, F. Weickert, and J. L. Smith
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

A. Leithe-Jasper, W. Schnelle, M. Nicklas, and H. Rosner
Max-Planck-Institut für Chemische Physik fester Stoffe, Nöthnitzer Straße 40, 01187 Dresden, Germany
(Received 29 April 2012; revised manuscript received 29 May 2012; published 4 June 2012)

We have studied the Fe-based superconductor $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ in order to identify the structure of the order parameter in this system by performing extensive low-temperature specific heat measurements in zero and in applied magnetic field. The pronounced superconducting jump at $T_c = 32.5$ K and $\Delta_0/(k_B T_c) = 2.57$ indicate strong-coupling superconductivity in this material. Here we provide evidence for fully gapped superconductivity in $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$. A linear magnetic field dependence of the low-temperature specific heat points to s-wave symmetry of the order parameter. Below T_c the superconducting electronic part of the specific heat can be described by the BCS α model with $\Delta_0 = 7.2$ meV.

DOI: 10.1103/PhysRevB.85.224504 PACS number(s): 74.25.Bt, 65.40.Ba, 74.20.Rp, 74.70.Dd

The discovery of superconductivity in Fe-based pnictides[1,2] opened a new chapter in superconductivity (SC) research.[3] Several types of superconducting families containing FeAs layers have been identified and studied, but the main focus has been on the "122" family of compounds,[4–6] for its favorable metallurgical properties and since large single crystals can be easily synthesized. In these materials the superconducting gap structure is often discussed within the nodeless isotropic and anisotropic $s_\pm$ model (extended s wave), with a sign reversal of the order parameter between the electron and the hole Fermi surfaces.[7–10] However, the nodal $s_\pm$ and $d_{x^2-y^2}$ models have also been theoretically suggested, and a possible change of the pairing symmetry upon doping has been proposed.[11–13] Despite the large theoretical and experimental efforts (see Refs. 14 and 15) the understanding of the nature of the superconductivity in these materials as well as the pairing mechanism and the symmetry of the order parameter are still under debate.

One way to elucidate the nature of the superconductivity is to study the low-temperature heat capacity since the temperature dependence of the specific heat and its magnetic response in the superconducting state give important information about the symmetry of the superconducting gap.[16–18] Introducing impurities into a superconductor is a good probe for determining the precise low-energy density of states and, hence, the nature of the superconducting order parameter. In multiband superconductors, it is expected that the impurity scattering within each band tends to make the gap on the corresponding FS sheet more isotropic and may result in lifting of the nodes and removal of the low-energy excitations. The superconducting temperature would also be reduced.[19,20] In optimally doped $BaFe_{2-x}Co_xAs_2$ specific heat studies[21–24] indicate the multiband nature of the superconductivity and an evolution of the gap structure with doping.[25,26] Moreover, the temperature and field dependence of $C_p(T,H)$ can be well explained by the $s_\pm$ model by taking into account intra- and interband interactions in the presence of disorder.[26,27] The situation is much less clear in $Ba_{1-x}K_xFe_2As_2$. At optimal doping specific heat studies suggest fully gapped superconductivity[29,30] and multiple gaps[31] but the possibility for a nodal gap in this material and its evolution upon doping or disorder remain a central question in the ongoing debate.[32–34]

Here we address this problem by investigating the specific heat of the $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ superconductor with $T_c = 32.5$ K. By substitution of K on the Ba site the sample is close to the optimal doping regime.[35] An additional disorder is introduced to the material by a direct doping into the "active" FeAs layers by Co. It has been shown in $BaFe_{2-x}Co_xAs_2$[25,26] that the doping into the FeAs layers strongly influences the superconducting order parameter and leads to the change of the gap structure from a fully gapped SC for optimally doped sample to a nodal SC upon doping by cobalt.[25–27] Initially, combined co-doping by K and Co aimed to enhance the high-field high-current performance of the superconductor, i.e., to achieve higher values of the upper critical field H_{c2}.[28] By using extensive low-temperature specific heat studies we show evidence for fully gapped superconductivity in the $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$. The size of the superconducting jump at T_c and the gap value indicate strong-coupling superconductivity in this sample. The normal state Sommerfeld coefficient is determined as 40.5 mJ mol^{-1} K^{-2}. By subtracting the lattice contribution we extract the full electronic T dependence. It can be described by the BCS α model with $\Delta_0 = 7.2$ meV. The field-induced change in the low-temperature specific heat shows a linear H dependence consistent with s-wave symmetry of the order parameter.

The samples were synthesized by a powder metallurgical technique as described in Ref. 28. The heat capacity was measured between 1.8 K and 300 K in a commercial system (PPMS, Quantum Design) using a thermal-relaxation technique.

The temperature dependence of the specific heat of $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ is shown in Fig. 1. At low temperature no sign of any upturns or Schottky-like anomalies are observed at zero or in any applied magnetic fields. At the transition a pronounced anomaly is observed in the $C_p(T)$ curve and the entropy-conserving construction gives $T_c = 32.5$ K (see the dashed lines in the upper inset of Fig. 1). This T_c is consistent with a zero resistance value of the

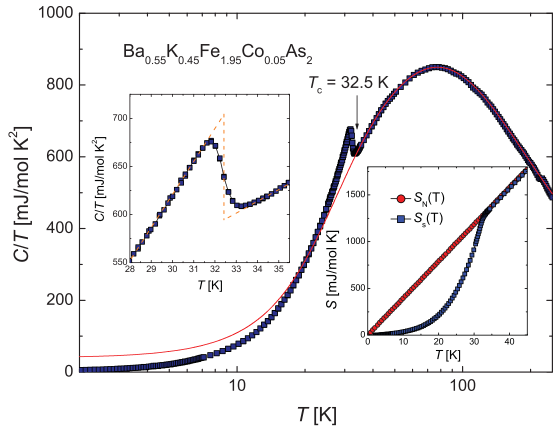

FIG. 1. (Color online) Temperature dependence of the specific heat C/T of $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ at zero magnetic field. The solid line is the estimated normal state specific heat (see text). The arrow marks T_c at 32.5 K. Left inset: The specific heat in the vicinity of the superconducting transition. The dashed line is an entropy conservation construction (see text). Right inset: The temperature dependence of the electronic entropy in the normal $S_n(T)$ (circles) and superconducting $S_s(T)$ (squares) states.

electrical resistivity.[28] At T_c the specific heat jump, determined at zero field, is $\frac{\Delta C}{T}|_{T_c} = 118$ mJ mol^{-1} K^{-2}. It is comparable to the previous specific heat studies of the optimally doped $Ba_{1-x}K_xFe_2As_2$.[29–31,36] By taking into account $\gamma_N = 40.5$ mJ mol^{-1} K^{-2} (see below) the normalized C_p jump $\frac{\Delta C}{T\gamma_N}|_{T_c} = 2.9$ is much larger than the expected weak coupling Bardeen-Cooper-Schrieffer (BCS) value of 1.43, indicating strong-coupling superconductivity in $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$. As seen in Fig. 2(a) an applied magnetic field depresses the superconducting anomaly and gradually shifts the transition down to lower temperatures. At $\mu_0H = 9$ T the T_c is reduced by only 0.8 K, pointing to the large critical field in this system. As shown in Fig. 2(b), T_c decreases linearly upon applied magnetic field with the slope of $\frac{dH_{c2}}{dT} = -10$ T K^{-1}. This agrees well with the electrical resistivity data,[28] and it is close to the one observed for optimally doped $Ba_{1-x}K_xFe_2As_2$.[31] From the slope of the

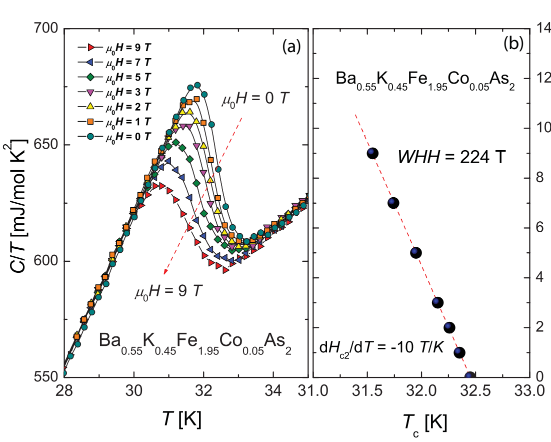

FIG. 2. (Color online) (a) Temperature dependence of the specific heat of $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ near T_c measured at different magnetic fields. (b) Magnetic field dependence of T_c (see in text).

critical field the value of H_{c2} may be evaluated by the Werthammer-Helfand-Hohenberg (WHH) model.[37,38] In this approach (taking into account the orbital effect only; Maki parameter $\alpha = 0$) the critical field may be expressed as $H_{c2}^{orb} = 0.69 \times T_c[\frac{dH_{c2}}{dT}]_{T_c}$ and for $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ it gives 224 T. As has been shown recently the actual H_{c2} for this material is about 70 T (see Ref. 28). This could point to the multiband SC in this material. Moreover, the Pauli field estimated as $H_{c2}^P = 1.84 \times T_c = 60$ T could indicate the importance of Pauli paramagnetism as a pair breaking mechanism in this material.

Now we evaluate the possible gap scenario in $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$. The magnetic field and temperature dependencies of the low-temperature specific heat are excellent probes of the gap structure in superconductors. For a fully gapped SC the number of Caroli–de Gennes bound states increases linearly with field due to the linear increase in the number of vortices entering the sample. Therefore $\gamma_{el}(H) \propto H$ (see Ref. 39). On the other hand, an anisotropic gap will cause the specific heat to deviate from the H-linear dependence.[40] In a clean d-wave superconductor the quasiparticle excitation spectrum is shifted by the superfluid velocity, giving $\gamma_{el}(H) \propto \sqrt{H}$ (Ref. 41) where the quasiparticles contributing to the density of states are coming from regions away from vortex cores, close to the nodes.[41] In the presence of disorder the $\gamma_{el}(H) \propto \sqrt{H}$ behavior changes to $\gamma_{el}(H) \propto H \ln H$ (Ref. 42).

Figure 3(a) shows C_p/T of $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ measured in magnetic fields of up to 9 T. The specific heat

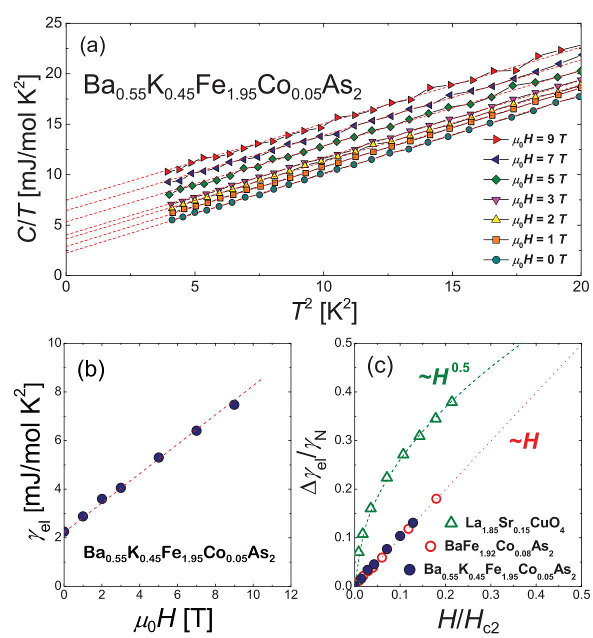

FIG. 3. (Color online) (a) Low-temperature dependence of the specific heat of $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$, plotted as C/T vs T^2 and measured at different magnetic fields. Dashed lines are fits of $C/T = \gamma_{el}(H) + \beta T^2$ (see text). (b) Field dependence of the field-induced electronic specific heat $\gamma_{el}(H)$ obtained at 0 K. (c) Normalized field-induced change in low-temperature specific heat vs normalized magnetic field. The dashed and dotted lines show the predicted H dependence for d- and s-wave scenarios. The specific heat data for $La_{1.85}Sr_{0.15}CuO_4$ (green triangles) and $BaFe_{1.84}Co_{0.16}As_2$ (red circles) are taken from Refs. 43,44 and Ref. 26 respectively.

can be fitted by $C(T) = \gamma T + \beta T^3$ as shown in Fig. 3. For the zero-field data the parameters obtained are $\gamma_{el}(0) = 2.24$ mJ mol^{-1} K^{-2} and $\beta = 0.78$ mJ mol^{-1} K^{-4}. It's worth noting that γ_0 is one of the smallest values observed within the K-doped Ba122 systems and indicates a very good quality and purity of the polycrystalline sample. The ratio of the residual specific heat to its normal-state value results in an upper estimate of the non-superconducting fraction $\gamma_0/\gamma_N \approx 5\%$ (assuming that no low-energy electronic excitations are coming from pair-breaking effects). To derive the magnetic field dependence of $\gamma_{el}(H)$ the same procedure as for zero field has been applied [see Fig. 3(a)]. For all fits the parameter β has a very similar value indicating independence of the phonon contribution to the magnetic field. The obtained $\gamma_{el}(H)$ is presented in Fig. 3(b). As seen γ_{el} increases linearly with the magnetic field as anticipated for fully gapped superconductivity.[45] The total increase of $\gamma_{el}(H)$ at 9 T is 5.3 mJ mol^{-1} K^{-2}. A linear slope a marked as a dashed line in Fig. 3(b) is related to the normal state Sommerfeld coefficient and critical field by $a = \gamma_N/H_{c2}$. Taking $H_{c2} = 70$ T as derived from high-field measurements[28] the estimated γ_N is 42 mJ mol^{-1} K^{-2}, which agrees well with the value obtained from the temperature dependence (see below). Figure 3(c) shows a normalized field-induced change in low-temperature specific heat $\frac{\Delta\gamma_{el}}{\gamma_N}$ versus normalized magnetic field $\frac{H}{H_{c2}}$ where $\Delta\gamma_{el} = \gamma_{el}(H) - \gamma_0$. In the same figure data obtained for the d-wave superconductor $La_{1.85}Sr_{0.15}CuO_4$[43,44] and the fully gapped s-wave superconductor $BaFe_{1.84}Co_{0.16}As_2$[26] are shown for comparison.

To estimate the electronic contribution to the total specific heat the phonon part of C_p has to be reliably determined. However, it is challenging to directly measure the normal state in $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ due to the very high H_{c2} in this material. Therefore, we model the specific heat above the superconducting transition temperature and extrapolate it to below T_c (see Ref. 30). As shown by the solid line in Fig. 1, above T_c, the $C_p(T)$ curve can be fitted by the expression

$$C_{\mathrm{p}}(T) = \gamma_N T + (1-k)C_{\mathrm{D}}(T) + kC_{\mathrm{E}}(T), \tag{1}$$

in which the lattice contribution to the specific heat is accounted for by considering both Debye $C_D(T)$ and Einstein $C_E(T)$ functions with the k parameter ensuring the proper quantity of oscillator modes involved. The least-squares fit of this formula to the experimental data above 35 K yields the following parameters: $\gamma_n = 40.5$ mJ mol^{-1} K^{-2}, $\Theta_{\mathrm{D}} = 195$ K, $\Theta_{\mathrm{E}} = 348$ K, and $k = 0.47$. It is worth noting that the value of the normal state Sommerfeld coefficient is very similar to the one obtained from the field dependence and agrees well with γ_N derived for optimally doped $Ba_{1-x}K_xFe_2As_2$ (see Refs. 29 and 30). The normal state electronic specific heat is larger than the value obtained from DFT calculations, $\gamma_n = 10.1$ mJ mol^{-1} K^{-2}, obtained for $Ba_{0.68}K_{0.38}Fe_2As_2$.[31] This could point towards the strong mass renormalization by a factor of 4 in $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$. The Debye and Einstein temperatures are close to those obtained for $Ba_{1-x}K_xFe_2As_2$ samples.[30] Moreover, the normal state γ_N obtained provides an accurate entropy balance for the electronic specific heat below T_c. As shown in the lower inset in Fig. 1 the electronic entropies in the superconducting and normal states are equal at T_c satisfying the entropy constraint. Furthermore, the superconducting characteristics that we obtain from the resulting analysis are consistent with each other and with other measurements (see Refs. 46–48). Using the normal state specific heat we derive the condensation energy [obtained by integrating the entropy difference $U = \frac{H_c^2}{2\mu_0} = \int \{S_n(T) - S_s(T)\}\, dT$ in normal $S_n(T)$ and superconducting state $S_s(T)$] and relate it to the thermodynamical critical field H_c. The obtained values are $U = 9.6$ J mol^{-1} and $H_c = 0.63$ T, respectively. Taking $H_{c2} = 70$ T the Ginzburg-Landau (GL) parameter $K = 78$ can be obtained from $H_{c2} = \sqrt{2}K H_c$. Its large value clearly points to type-II superconductivity in $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$. The GL coherence length $\xi = 2.2$ nm, lower critical field $H_{c1} = 24$ mT, and penetration depth $\lambda = 170$ nm can be derived from $\xi = [\frac{\phi}{2\pi H_{c2}}]^{1/2}$, where ϕ is the magnetic flux quanta and $H_{c1}H_{c2} = H_c^2 \ln K$. The parameters are similar to the ones obtained for optimally doped BaK-122 system,[48] providing additional confidence in our phonon substraction.

Figure 4 shows the electronic specific heat at zero field after subtracting the lattice contribution. In order to analyze the C_{el}/T data we use the BCS α model[49] for specific heat:

$$C_{el}^{\mathrm{BCS}} = t\frac{d}{dt}\int_0^\infty dy\left(-\frac{6\gamma\Delta_0}{k_B\pi}\right)[f\ln f + (1-f)\ln(1-f)], \tag{2}$$

where $t = T/T_c$, f is the Fermi function $f = (e^{E/k_BT} + 1)^{-1}$, $E = \sqrt{\epsilon^2 + \Delta^2}$, and $y = \epsilon/\Delta$ (see Ref. 50), plus a residual normal state component.

The results of our analysis using a single s-wave gap (solid red line) and two separate s-wave gaps (dashed blue line) are shown in Fig. 4. The normal state Sommerfeld coefficient and $T_c = 32.5$ K were fixed during the fitting procedure. The gap value obtained from the single gap fit is 7.2 meV. Taking $\Delta_0 = 7.2$ meV and $T_c = 32.5$ K gives $\Delta_0/(k_BT_c) = 2.57$, much larger than the weak coupling limit of 1.76. As can be seen from Fig. 4 a better description (especially above 15 K)

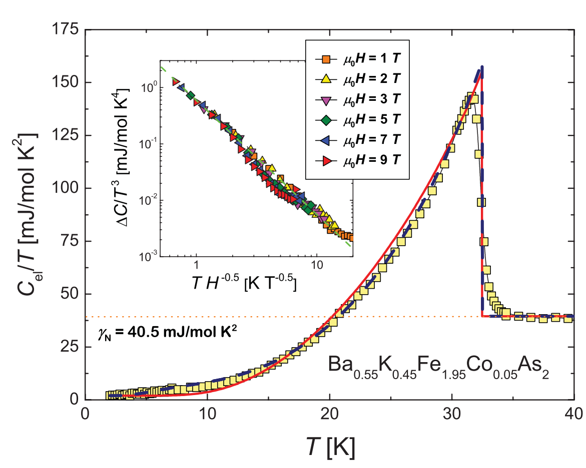

FIG. 4. (Color online) Temperature dependence of the electronic specific heat of $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$. The solid and dashed lines are theoretical curves based on BCS theory by taking into account one and two s-wave gaps, respectively (see text). Inset: Scaling of the experimental data according to the s-wave gap scenario (see text). In this plot $\Delta C = C(H) - C(0)$.

is obtained by fitting the data to $C_{el}(T) = (1 - A)C_{el}^{\mathrm{BCS}}\Delta_1 + AC_{el}^{\mathrm{BCS}}\Delta_2$ which gives the dashed blue line and the parameters $\Delta_1 = 7.9$ meV, $\Delta_2 = 2.4$ meV, and $A = 0.14$. This can be compared with $\Delta_1 = 11$ meV, $\Delta_2 = 3.5$ meV obtained by the specific heat studies of $Ba_{0.68}K_{0.32}Fe_2As_2$ with $T_c = 38.5$ K (see Ref. 31). This is also consistent with ARPES and STM measurements obtained for optimally doped $Ba_{1-x}K_xFe_2As_2$ samples (see Refs. 51 and 52) but similar measurements are not available for co-doped samples. However, even though the two-gap description represents the data somewhat better than the one-gap approach, there is still some discrepancy between the model and the experimental data observed below 15 K (see Fig. 4). Therefore, taking into account the ambiguity of the phonon substraction it is difficult to draw any firm conclusion on the multiband nature of the superconductivity in $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ by specific heat measurements only.

In the s-wave superconductors, quasiparticle excitations are governed by the inner-core states. Taking into account the specific heat of the quasiparticles induced by magnetic field (γ_{qp}) and that coming from the vortex cores (γ_{core}), a straightforward scaling behavior $\gamma_{\mathrm{core}}/T^2 \sim \gamma_{qp}/T^2 = \frac{\gamma_N}{H_{c2}}[\frac{T}{\sqrt{H}}]^{-2}$ is observed.[29,53] As seen in the inset in Fig. 4 all the data obtained for $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ can roughly be scaled to the straight line being in agreement with the field data above.

To summarize, we have studied the co-doped Fe-based superconductor $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ in order to identify the structure of the order parameter in this system by performing extensive low-temperature specific heat measurements in zero and in applied magnetic fields. It is a superconductor at 32.5 K as marked by a pronounced jump in $C_p(T)$ at the transition temperature. At T_c the superconducting jump $\frac{\Delta C}{T\gamma_N}|_{T_c} = 2.9$ and the normalized gap $\Delta_0/(k_B T_c) = 2.57$ indicate strong-coupling superconductivity in this material. It could suggest strong interaction with interband spin fluctuations as a potential pairing mechanism.[31] Using the phonon part of the specific heat obtained from the high-temperature fit, we determine the normal state Sommerfeld coefficient to be 40.5 mJ mol^{-1} K^{-2}. All the results obtained point to a fully gapped nature of the superconducting gap. The field-induced change in the low-temperature specific heat shows a linear H dependence consistent with s-wave symmetry of the order parameter. Below T_c the electronic part of the specific heat of $Ba_{0.55}K_{0.45}Fe_{1.95}Co_{0.05}As_2$ is described well by the BCS α model with $\Delta_0 = 7.2$ meV.

We gratefully acknowledge fruitful discussions with Tomasz Durakiewicz. We are grateful to Norman Phillips for discussion on approaches to estimate the lattice contribution of the specific heat in this material. Work at Los Alamos National Laboratory was supported in part by the Department of Energy Laboratory Directed Research and Development Program. The work at MPI CPfS was supported by the DFG through SPP 1458.

*gofryk@lanl.gov

[1] Y. Kamihara *et al.*, J. Am. Chem. Soc. **130**, 3296 (2008).
[2] X. H. Chen *et al.*, Nature (London) **453**, 761 (2008).
[3] M. R. Norman, Physics **1**, 21 (2008).
[4] M. Rotter, M. Tegel, and D. Johrendt, Phys. Rev. Lett. **101**, 107006 (2008).
[5] A. S. Sefat, R. Jin, M. A. McGuire, B. C. Sales, D. J. Singh, and D. Mandrus, Phys. Rev. Lett. **101**, 117004 (2008).
[6] A. Leithe-Jasper, W. Schnelle, C. Geibel, and H. Rosner, Phys. Rev. Lett. **101**, 207004 (2008).
[7] I. I. Mazin, D. J. Singh, M. D. Johannes, and M. H. Du, Phys. Rev. Lett. **101**, 057003 (2008).
[8] A. V. Chubukov, D. V. Efremov, and I. Eremin, Phys. Rev. B **78**, 134512 (2008).
[9] K. Seo, B. A. Bernevig, and J. Hu, Phys. Rev. Lett. **101**, 206404 (2008).
[10] V. Cvetkovic and Z. Tesanovic, Europhys. Lett. **85**, 37002 (2009).
[11] K. Kuroki, H. Usui, S. Onari, R. Arita, and H. Aoki, Phys. Rev. B **79**, 224511 (2009).
[12] S. Graser *et al.*, New J. Phys. **11**, 025016 (2009).
[13] H. Ikeda, R. Arita, and J. Kunes, Phys. Rev. B **81**, 054502 (2010).
[14] I. I. Mazin and J. Schmalian, Physica C **469**, 614 (2009).
[15] K. Ishida *et al.*, J. Phys. Soc. Jpn. **78**, 062001 (2009).
[16] N. E. Hussey, Adv. Phys. **51**, 1685 (2002).
[17] F. Bouquet, R. A. Fisher, N. E. Phillips, D. G. Hinks, and J. D. Jorgensen, Phys. Rev. Lett. **87**, 047001 (2001).
[18] Y. Nakajima, T. Nakagawa, T. Tamegai, and H. Harima, Phys. Rev. Lett. **100**, 157001 (2008).
[19] V. Mishra, G. Boyd, S. Graser, T. Maier, P. J. Hirschfeld, and D. J. Scalapino, Phys. Rev. B **79**, 094512 (2009).
[20] V. Mishra, A. Vorontsov, P. J. Hirschfeld, and I. Vekhter, Phys. Rev. B **80**, 224525 (2009).
[21] K. Gofryk *et al.*, New J. Phys. **12**, 023006 (2010).
[22] F. Hardy *et al.*, Phys. Rev. B **81**, 060501(R) (2010).
[23] G. Mu *et al.*, Chin. Phys. Lett. **27**, 037402 (2010).
[24] K. Gofryk, A. S. Sefat, M. A. McGuire, B. C. Sales, D. Mandrus, J. D. Thompson, E. D. Bauer, and F. Ronning, Phys. Rev. B **81**, 184518 (2010).
[25] J. P. Reid, M. A. Tanatar, X. G. Luo, H. Shakeripour, N. Doiron-Leyraud, N. Ni, S. L. Budko, P. C. Canfield, R. Prozorov, and L. Taillefer, Phys. Rev. B **82**, 064501 (2010).
[26] K. Gofryk, A. B. Vorontsov, I. Vekhter, A. S. Sefat, T. Imai, E. D. Bauer, J. D. Thompson, and F. Ronning, Phys. Rev. B **83**, 064513 (2011).
[27] D-J. Jang *et al.*, New J. Phys. **13**, 023036 (2011).
[28] F. Weickert *et al.*, J. Appl. Phys. **110**, 123906 (2011).
[29] G. Mu, H. Luo, Z. Wang, L. Shan, C. Ren, and H. H. Wen, Phys. Rev. B **79**, 174501 (2009).
[30] C. Kant, J. Deisenhofer, A. Gunther, F. Schrettle, A. Loidl, M. Rotter, and D. Johrendt, Phys. Rev. B **81**, 014529 (2010).
[31] P. Popovich, A. V. Boris, O. V. Dolgov, A. A. Golubov, D. L. Sun, C. T. Lin, R. K. Kremer, and B. Keimer, Phys. Rev. Lett. **105**, 027003 (2010).
[32] T. Goko *et al.*, Phys. Rev. B **80**, 024508 (2009).
[33] S. W. Zhang, L. Ma, Y. D. Hou, J. Zhang, T. L. Xia, G. F. Chen, J. P. Hu, G. M. Luke, and W. Yu, Phys. Rev. B **81**, 012503 (2010).

[34] H. Kim *et al.*, arXiv:1105.2265.
[35] H. Chen *et al.*, Europhys. Lett. **85**, 17006 (2009).
[36] C. R. Rotundu *et al.*, J. Phys.: Conf. Ser. **273**, 012103 (2011).
[37] E. Helfand and N. R. Werthamer, Phys. Rev. **147**, 288 (1966).
[38] N. R. Werthamer *et al.*, Phys. Rev. **147**, 295 (1966).
[39] C. Caroli *et al.*, Phys. Lett. **9**, 307 (1964).
[40] N. Nakai, P. Miranović, M. Ichioka, and K. Machida, Phys. Rev. B **70**, 100503(R) (2004).
[41] G. E. Volovik, JETP Lett. **58**, 469 (1993).
[42] C. Kübert and P. J. Hirschfeld, Solid State Commun. **105**, 459 (1998).
[43] Y. Wang and H.-H. Wen, Europhys. Lett. **81**, 57007 (2008).
[44] S. J. Chen, C. F. Chang, H. L. Tsay, H. D. Yang, and J. Y. Lin, Phys. Rev. B **58**, 14753(R) (1998).
[45] F. R. Drymiotis *et al.*, Phys. Rev. B **72**, 024543 (2005).
[46] T. Shibauchi *et al.*, Physica C **469**, 590 (2009).
[47] A. Bharathi *et al.*, Physica C **470**, 8 (2010).
[48] J. G. Storey *et al.*, arXiv:1001.0474.
[49] H. Padamsee *et al.*, J. Low Temp. Phys. **12**, 387 (1973).
[50] M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1975).
[51] K. Nakayama *et al.*, Phys. Rev. B **83**, 020501(R) (2011).
[52] L. Shan, Y. L. Wang, J. Gong, B. Shen, Y. Huang, H. Yang, C. Ren, and H. H. Wen, Phys. Rev. B **83**, 060510(R) (2011).
[53] Z. Y. Liu *et al.*, Europhys. Lett. **69**, 263 (2005).