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To cite this article: Yuke Li et al 2010 New J. Phys. 12 083008

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Effect of a Zn impurity on $T_c$ and its implications for pairing symmetry in LaFeAsO$_{1-x}$F$_x$

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New Journal of Physics 12 (2010) 083008 (8pp)
Received 14 March 2010
Published 5 August 2010
Online at http://www.njp.org/
doi:10.1088/1367-2630/12/8/083008

Abstract. The effect of a non-magnetic Zn impurity on superconductivity in the LaFe$_{1-y}$Zn$_y$AsO$_{1-x}$F$_x$ system is studied systematically. In the presence of a Zn impurity, the superconducting (SC) transition temperature increases in the under-doped regime, remains unchanged in the optimally doped regime and is severely suppressed in the over-doped regime. Our results suggest a switch in the symmetry of the SC order parameters from an s-wave to $s_{±}$- or d-wave states as the charge carrier doping increases in FeAs-based superconductors.
1. Introduction

The discovery of iron-based superconductivity [1] has generated great interest in condensed-matter physics. Similar to the high-transition temperature superconducting (SC) copper oxides, the parent compounds of iron pnictide are antiferromagnets. Superconductivity emerges upon chemical doping, which introduces charge carriers and suppresses the antiferromagnetic (AFM) order. It is generally agreed that magnetism plays an important role in the superconductivity of both cuprates and pnictides. On the other hand, iron-based superconductors also show different behaviors from the cuprates. One of their major differences is the pairing symmetry. It has been well established that the SC pairing in cuprates is of nodal d-wave symmetry [2, 3]. In pnictides, the pairing symmetry continues to be an important and outstanding issue. There is a great deal of clear experimental evidence for full SC gaps in FeAs-based superconductors [4, 5]. Within the full gap scenario, because of the multi-Fermi surfaces [6], the relative phases of the SC order parameters in hole or electron pockets can be either positive (s-wave pairing) or negative (s±-pairing) [7]–[12], depending on the sign of the inter-Fermi pocket pair scattering amplitude or their Josephson coupling. The s± pairing is appealing with some experimental support [13]. In addition, there is also a great deal of evidence for d-wave SC gaps in FeP-based superconductors [14].

Non-magnetic impurities are an important probe for pairing symmetry. Non-magnetic impurities do not cause a severe pair-breaking effect in a conventional s-wave superconductor, according to Anderson’s theorem [15]. In the s± state, the order parameters in hole and electron pockets have opposite signs; non-magnetic impurities, such as Zn, can severely suppress the SC transition temperature \( T_c \), similar to the effect on high-\( T_c \) cuprates with d-wave pairing [16, 17].

The zinc element has a stable d\(^{10}\) configuration in the alloy [18] and can serve as the best non-magnetic impurity for this study. However, there is an apparent discrepancy between our early data on LaFeAsO\(_{0.9}\)F\(_{0.1}\) where \( T_c \) was essentially unaffected by a Zn impurity [19] and a following report that showed a severe suppression of \( T_c \) due to a Zn impurity in oxygen-deficient LaFeAsO\(_{1-\delta}\) samples [20]. In this paper, we report a systematic study of the effect of a Zn impurity on superconductivity in LaFeAsO\(_{1-\gamma}\)F\(_{\gamma}\) in different doping regimes. We have observed strong doping dependence of the Zn-impurity effect on \( T_c \). \( T_c \) is enhanced in the underdoped regime (\( x = 0.05 \)), remains essentially unchanged at optimal doping (\( x = 0.10 \)) and is severely suppressed in the overdoped regime (\( x = 0.15 \)). Our results suggest a switch in the symmetry of the SC order parameters from an s-wave to s±- or d-wave states as the charge carrier increases in FeAs-based superconductors. The increase in \( T_c \) at low electron doping may be explained as a result of the suppression of the magnetism upon Zn doping, which is in favor of the superconductivity.

New Journal of Physics 12 (2010) 083008 (http://www.njp.org/)
2. Experimental

Polycrystalline samples of LaFe$_{1-y}$Zn$_y$AsO$_{1-x}$F$_x$ ($x = 0.05$, $y = 0$, 0.02, 0.04, 0.06; $x = 0.15$, $y = 0$, 0.02) were synthesized by a solid-state reaction method. Details of the sample preparation can be found in the previous report [19]. The phase purity of the samples was investigated by powder x-ray diffraction (XRD) using a D/Max-rA diffractometer with Cu-K$_\alpha$ radiation and a graphite monochromator. Lattice parameters were calculated by a least-squares fit using at least 20 XRD peaks. Chemical analysis by energy-dispersive x-ray (EDX) microanalysis was performed on an EDAX GENESIS 4000 x-ray analysis system affiliated to a scanning electron microscope (SEM; model SIRION).

The electrical resistivity was measured on bar-shaped samples using a standard four-probe method. The measurements of resistance and Hall effect were performed on a Quantum Design Physical Property Measurement System (PPMS-9). Dc magnetization was measured on a Quantum Design Magnetic Property Measurement System (MPMS-5).

3. Results and discussion

Figure 1 shows a characterization of LaFe$_{1-y}$Zn$_y$AsO$_{1-x}$F$_x$ samples by using the XRD experiments. The inset shows the variation in lattice constants with Zn content for both F-underdoped and F-overdoped samples. All the XRD peaks can be indexed with the tetragonal ZrCuSiAs-type structure, indicating that all the samples are single phase without foreign phases. The $a$-axis shrinks slightly with Zn doping, while the $c$-axis increases, similarly to
Figure 2. Temperature dependence of resistivity ($\rho$) for the LaFe$_{1-y}$Zn$_y$AsO$_{1-x}$F$_x$ samples. Inset: diamagnetic transitions under a magnetic field of 10 Oe with field-cooling (FC) mode. (a) $x = 0.05$, $y = 0, 0.02, 0.04$ and $0.06$; (b) $x = 0.15$, $y = 0$ and $0.02$.

the previous report [19]. The EDX measurements found that the actual Zn content ($x$) is very close to the nominal composition, and the variation in Zn content in the samples is less than 5%. These results indicate that Zn has successfully replaced Fe.

Figure 2 shows the temperature dependence of resistivity ($\rho$) for LaFe$_{1-y}$Zn$_y$AsO$_{1-x}$F$_x$ from 2 to 300 K and the inset shows the temperature dependence of dc susceptibility for the same samples. For the zinc-free LaFeAsO$_{0.95}$F$_{0.05}$ sample, the resistivity shows an SC transition at 16.8 K (defined as the midpoint), consistent with the previous report [21]. In the underdoped regime, as shown in figure 2(a), with the increase in Zn content, to our surprise, $T_c$ increases to 19.2 and 22.7 K for $y = 0.02$ and 0.06, respectively. The $T_c$ values determined from the magnetic susceptibility exhibit consistent variation with resistivity data. The estimated Meissner volume fraction indicates bulk nature for superconductivity. Obviously, the above result is in contrast to the case of Zn-doped high-$T_c$ cuprates [22], where $T_c$ always decreases sharply with Zn doping.

The resistivity and dc susceptibility of overdoped LaFe$_{1-y}$Zn$_y$AsO$_{0.85}$F$_{0.15}$ ($y = 0$ and $0.02$) samples are shown in figure 2(b). Without Zn doping, $T_c$ (midpoint) is about 9.6 K. With only 2% Zn doping, $T_c$ is severely suppressed to below 2 K. We did not observe the diamagnetism in susceptibility in this sample, consistent with the resistivity measurement. These results are in contrast to the case of the underdoped LaFe$_{1-y}$Zn$_y$AsO$_{0.95}$F$_{0.05}$ sample and indicate that Zn doping in the overdoped region does sharply suppress superconductivity. A similar sharp suppression of $T_c$ with Zn doping was also reported in the oxygen-deficient LaFeAsO$_{1-\delta}$, where the sample is apparently overdoped according to the oxygen content [20].
Figure 3 shows the temperature dependence of the Hall coefficient $R_H$ for LaFe$_{1-y}$Zn$_y$AsO$_{1-x}$F$_x$ samples. For all the samples, the negative $R_H$ signal indicates that electron-type charge carrier is dominant in the whole temperature region. For the underdoped LaFe$_{1-y}$Zn$_y$AsO$_{0.95}$F$_{0.05}$ samples, $R_H$ of the Zn-free sample exhibits a strong $T$ dependence and drops sharply below 100 K, which may be attributed to the residual spin-density-wave (SDW) order or fluctuations. $R_H$ finally goes to zero as the samples enter the SC state. In the parent compound LaFeAsO, $R_H$ drops sharply due to the opening of SDW gap below the structural/magnetic transition temperature [23]. With increasing Zn content, the sharp drop in $R_H$ is gradually suppressed, indicating that the residual SDW order or fluctuations are further suppressed by Zn impurities. Such an effect of Zn impurities on the SDW order has also been observed in the parent compound LaFeAsO [19]. Meanwhile, the room-temperature $R_H$ remains almost unchanged with Zn doping, indicating that Zn doping does not change the charge carrier density. This is consistent with the band calculation result, which predicts that Zn 3d electrons are deep below the Fermi level [18]. For the overdoped LaFe$_{1-y}$Zn$_y$AsO$_{0.88}$F$_{0.15}$ samples (figure 3(b)), $R_H$ of both the Zn-free and 2% Zn-doped samples exhibit very weak $T$ dependence and again the change in the room-temperature $R_H$ is very small, indicating that the charge carrier density essentially does not change with Zn doping. It should be noted that $R_H$ drops quickly due to SC transition for the Zn-free sample, whereas it remains constant for the Zn-doped sample as $T$ goes to zero.

The effect of Zn impurity in the different doping levels is summarized in a phase diagram of $T_c$ versus Zn content, as shown in figure 4. In the underdoped regime, i.e. 5% F-doped samples,
Figure 4. SC transition temperatures versus Zn content in LaFe\(_{1-y}Zn\_y\)AsO\(_{1-x}F_x\). Solid and open symbols refer to \(T_c\) determined from the measurements of resistivity (midpoint) and susceptibility (onset point), respectively. The data for \(x = 0.1\) were taken from the previous report [19].

\(T_c\) remarkably increases with increasing Zn-doped concentration, while in the nearly optimally doped regime, LaFe\(_{1-y}Zn\_y\)AsO\(_{0.9}F_{0.1}\), \(T_c\) almost does not change with Zn doping, or it is even enhanced slightly at low Zn content. In the overdoped regime, i.e. LaFe\(_{1-y}Zn\_y\)AsO\(_{0.85}F_{0.15}\), \(T_c\) sharply decreases to below 2 K even with only 2% Zn doping.

Recently, the Zn doping effect has also been studied in the hole-type pnictide superconductor (Ba,K)Fe\(_2\)As\(_2\) [24]. Wen and co-workers [24] confirmed that superconductivity is robust against the non-magnetic Zn doping in the nearly optimally doped Ba\(_{0.6}\)K\(_{0.4}\)Fe\(_2\)As\(_2\), consistent with our result in the optimally doped regime. Meanwhile, a severe suppression of \(T_c\) was reported in an oxygen-deficient 1111 phase LaFe\(_{1-y}Zn\_y\)AsO\(_{0.85}\), which is apparently overdoped according to the oxygen content [20], in agreement with our result in the overdoped regime. It should also be noted that the partial substitution of other transition metal elements such as Co, Ni, Ru, Rh, Pd and Ir not only has negligible pair-breaking effect but also can induce superconductivity. The 3d electrons of these ions (such as Co, Ni and Ru) are believed to be itinerant according to the first-principle calculations [25]. In contrast, the 3d electrons of Zn ions are localized without any local moments [18].

Since the impurity effect is very sensitive to the symmetry of the SC order parameter, the contrastive difference in the Zn impurity effect between the underdoped and overdoped regimes cannot be easily explained within the same pairing symmetry state. Instead, our result strongly suggests a switch in the pairing symmetry from an impurity-insensitive pairing state to an impurity-sensitive pairing state. Since other experimental results such as the angle-resolved photoemission spectroscopy (ARPES) measurements [5] have found that the underdoped or optimally doped FeAs-based superconductors should have full SC gaps, our present data suggest an s-wave pairing in the underdoped and optimally doped regimes. Meanwhile, \(s_{\pm}\) or d-wave pairings are strongly suggested in the overdoped regime. Iron-based SC compounds have hole Fermi pockets centered at the Γ point in the Brillouin zone and electron pockets centered at...
the zone corner (M point). The s-wave and $s_{\pm}$-wave states correspond to the same and opposite signs of the relative order parameters between the hole and electron Fermi pockets, which is determined by the sign of the Josephson coupling between the Fermi pockets. A switch from the s-wave to $s_{\pm}$-wave states is in accordance with the sign change of the Josephson coupling from attractive at the underdoped regime to repulsive at over-doped regimes.

Below, we shall further elaborate the scenario of a switch between pairing states. The impurity effect in the $s_{\pm}$-wave state was studied by Bang et al [16] and by Onari and Kontani [17]. Theoretical calculations have shown that, in the strong scattering limit, the non-magnetic impurity effect on the $s_{\pm}$-wave state is severe and similar to the effect on the d-wave SC state [16]. Their theory should apply to Zn impurity located in the Fe planes, where the scattering is strong. The severe suppression of $T_c$ in the overdoped regime may thus be well explained within the scenario of $s_{\pm}$-wave symmetry. Moreover, the d-wave pairing is unlikely according to the ARPES studies in the overdoped regimes [26, 27]. On the other hand, the insensitivity of the impurity effect in the under-doped and optimally doped regimes is not compatible with the $s_{\pm}$ pairing. Note that the suppression of $T_c$ by impurities in the $s_{\pm}$-wave is not dependent on the charge carrier doping level. Our data strongly suggest that, in the underdoped and optimally doped regimes, the SC pairing is likely s-wave, essentially unaffected by the Zn impurity according to the Anderson theorem [15]. The enhancement of $T_c$ with a Zn impurity in the underdoped regime may be explained as the result of the suppression of AFM order, which in turn enhances superconductivity.

We remark that the possible changes in pairing symmetry with doping level were also proposed in a recent nuclear magnetic resonance study on the P-doped BaFe$_2$As$_2$ system [28], in a theoretical proposal for the time reversal symmetry breaking state [29] and in a theory for a possible switch between nodeless and nodal pairings by changing the pnictogen height measured from the Fe plane [30].

4. Conclusion

In summary, we have studied systematically the effect of a non-magnetic Zn impurity on superconductivity in various doping regimes of LaFeAsO$_{1-x}$F$_x$ systems. The Zn impurities do not suppress superconductivity in the underdoped and optimally doped regimes, but severely suppress superconductivity in the overdoped regime. Our results suggest a switch in the pairing symmetry from Zn-impurity-insensitive s-wave at underdoped and optimally doped regimes to the impurity-sensitive pairing state (likely $s_{\pm}$-wave) at the overdoped regime. The enhancement of $T_c$ with increasing Zn content at the low-F-doping regime could result from the suppression of AFM order or fluctuation in FeAs layers, which competes with superconductivity.

Acknowledgments

This work was supported by the National Science Foundation of China (grant nos 10634030 and 10931160425), PCSIRT (IRT-0754) and the National Basic Research Program of China (grant no. 2007CB925001). We also acknowledge partial support from Hong Kong RGC GRF grant HKU 7068/09P and RGC/NSFC grant N_HKU 726/09.
References

[1] Kamihara Y, Watanabe T, Hirano M and Hosono H 2006 J. Am. Chem. Soc. 130 3296
[2] Tsuei C C, Kirtley J R and Chi C C 1994 Phys. Rev. Lett. 73 593
[3] Wollman D A, Van Harlingen D J, Lee W C, Gingsberg D M and Leggett A J 1993 Phys. Rev. Lett. 71 2134
[4] Chen T Y, Tesanovic Z, Liu R H, Chen X H and Chien C L 2008 Nature 453 1224
[5] Ding H et al 2008 Europhys. Lett. 83 47001
[6] Singh D J and Du M H 2008 Phys. Rev. Lett. 100 237003
[7] Mazin I I, Singh D J, Johannes M D and Du M H 2008 Phys. Rev. Lett. 101 057003
[8] Kuroki K, Onari S, Arita R, Usui H, Tanaka Y, Kontani H and Aoki H 2008 Phys. Rev. Lett. 101 087004
[9] Seo K, Bernevig B A and Hu J 2008 Phys. Rev. Lett. 101 206404
[10] Cvetkovic V and Tesanovic Z 2009 Europhys. Lett. 85 37002
[11] Wang F, Zhai H, Ran Y, Vishwanath A and Lee D H 2009 Phys. Rev. Lett. 102 047005
[12] Chen W Q, Yang K Y, Zhou Y and Zhang F C 2009 Phys. Rev. Lett. 102 047006
[13] Chen C T, Tsuei C C, Ketchen M B, Ren Z A and Zhao Z X 2010 Nat. Phys. 6 260
[14] Hicks C W, Lippman T M, Huber M E, Analytis J G, Chu J H, Erickson A S, Fisher I R and Moler K A 2009 Phys. Rev. Lett. 103 127003
[15] Anderson P W 1959 J. Phys. Chem. Solids 11 26
[16] Bang Y, Choi H and Won H 2009 Phys. Rev. B 79 054529
[17] Onari S and Kontani H 2009 Phys. Rev. Lett. 103 177001
[18] Zhang L J and Singh D J 2009 Phys. Rev. B 80 214530
[19] Li Y K, Lin X, Tao Q, Wang C, Zhou T, Li L J, Wang Q B, He M, Cao G H and Xu Z A 2009 New J. Phys. 11 053008
[20] Guo Y F et al 2009 arXiv:0911.2975
[21] Luetskens H et al 2009 Nat. Mater. 8 305
[22] Xiao G, Cieplak M Z, Gavrin A, Streit A F H, Bakhtshai A and Chien C L 1988 Phys. Rev. Lett. 60 1446
[23] McGuire M A et al 2008 Phys. Rev. B 78 094517
[24] Cheng P, Shen B, Hu J P and Wen H H 2010 Phys. Rev. B 81 174529
[25] Xu G, Ming W, Yao Y, Dai X, Zhang S C and Fang Z 2008 Europhys. Lett. 82 67002
[26] Terashima K et al 2009 Proc. Natl. Acad. Sci. USA 106 7330
[27] Sekiba Y et al 2009 New J. Phys. 11 025020
[28] Nakai Y, Iye T, Kitagawa S, Ishida K, Kasahara S, Shibauchi T, Matsuda Y and Terashima T 2010 Phys. Rev. B 81 020503
[29] Lee W C, Zhang S C and Wu C J 2009 Phys. Rev. Lett. 102 217002
[30] Kuroki K, Usui H, Onari S, Arita R and Aoki H 2009 Phys. Rev. B 79 224511