Essential difference between scatterings by Zn and Pt on superconductivity of BaFe$_{1.92}$Pt$_{0.08}$As$_2$ single crystal

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**Abstract.** We report a Zn-doping effect on BaFe$_{1.92}$Pt$_{0.08}$As$_2$ ($T_c$ =24.5 K) single crystal. $T_c$ rapidly decreases with increasing the Zn content in the lattice, revealing a distinct feature which is highly contrasted with the intrinsic scattering feature induced by Pt. Doped Zn completely kills the superconductivity by no more than 8 atomic %, while intrinsic scattering induced by doped Pt shows a good coexistence with the superconductivity. The results are discussed in connection with the $s_\pm$ and $s_{++}$-wave models.

1. Introduction

Symmetry of the superconducting order parameter is always a central topic toward the establishment of physics for novel superconductors. The issue in iron pnictides superconductors, being unfortunately complicated by those contradicting results derived both theoretically and experimentally, has not yet been well settled. At the early stage, the answer converged quickly to the $s_\pm$-wave state with the parameter being nodeless and sign-reversing on different sheets of the Fermi surface [1, 2], while it subsequently has faced challenges mainly from a competing $s_{++}$-wave model [3].

Traced a theory proposed by Anderson in 1959 [4], superconductivity of isotropic $s$-wave superconductors should be robust to non-magnetic impurities, whereas those with an anisotropic gap generally suffered a Cooper pair-breaking effect due to the existence of nodes, such as in $d$-wave YBCO [5]. However, the case of a multiband iron pnictides superconductor is more complicated, where intra-band and inter-band impurity scatterings likely play distinct roles for the superconducting state [6]. So far substitutions indeed showed different responses to species of impurities, where superconductivity in LaFeAsO$_{1-x}$F$_x$ showed very slow $T_c$ suppression against a number of $d$-metals such as Co and Ru [7], while in either LaFeAsO$_{0.85}$ ($T_c$~26 K), or LaFeAs(O, F) or BaFe$_{1.93}$Co$_{0.13}$As$_2$
(\(T_c\approx 25\) K) [8-10], it was clearly suppressed with incorporation of nonmagnetic Zn. BaFe_{1.92}Pt_{0.08}As_2 shows a relative high \(T_c\) of about 25 K, regardless of the rather strong intrinsic impurity scattering introduced by doped Pt [11, 12], thus likely challenging the \(s_\pm\)-wave model since it predicates a fragile \(T_c\) against strong impurity scattering [13]. We herein carried out a Zn-doping study on BaFe_{1.92}Pt_{0.08}As_2 to discriminate the scattering effects of Zn and Pt on the superconductivity.

2. Experimental
The growth of BaFe_{1.92-x}Pt_{0.08}Zn_xAs_2 (\(x=0, 0.04, 0.08, 0.12, 0.16\)) crystals on a belt-type high-pressure apparatus has already been described elsewhere [12]. Resulted crystals are typically of a dimension of \(~0.6\times0.4\times0.02\) mm\(^3\), shown by the picture of BaFe_{1.92}Pt_{0.08}As_2 inserted in Figure 1.

![Figure 1. XRD pattern of BaFe_{1.92}Pt_{0.08}As_2 single crystal. Inset shows a photograph of the crystal.](image1)

Room temperature powder x-ray diffraction was performed on an X-ray diffractometer with Cu K\(\alpha\) radiation (2\(\theta\)=5°-100°). Resistivity (\(\rho\)) was measured in a Quantum Design Physical Properties Measurements System by a four-probe method. Hall coefficient was measured on a laboratory made apparatus via employing a standard van der Pauw four-probe geometry applied to samples.

3. Results and discussion
XRD pattern of BaFe_{1.92}Pt_{0.08}As_2 is shown in Figure 1. All peaks could be well indexed by the tetragonal unit cell with a ThCr\(_2\)Si\(_2\)-type structure (space group: \(I4/mmm\)), indicating formation of the expected 122-type phase. Zn doping within the range of 0-0.16 had not changed the crystal structure, confirmed by the same structure symmetry of all studied specimens. Zn variations in all crystals were minimized to \(\pm\)0.002 as examined by an energy dispersive X-ray spectrometer. These facts ambiguously indicate the successful incorporation of Zn into BaFe_{1.92}Pt_{0.08}As_2.

Figure 2 plots the \(\rho\) vs. \(T\) of BaFe_{1.92}Pt_{0.08}As_2 single crystal, and inset shows the \(T_c\) of BaFe_{2-x}Pt_xAs_2 (\(x=0\)-0.20) and the \(RRR\) ratio vs. Pt concentration.

![Figure 2. \(\rho\) vs. \(T\) of BaFe_{1.92}Pt_{0.08}As_2 single crystal, and inset shows the \(T_c\) of BaFe_{2-x}Pt_xAs_2 (\(x=0\)-0.20) and the \(RRR\) ratio vs. Pt concentration.](image2)
Despite the $RRR$ values fluctuate in the range of 1.33-2, $T_c$ in the under-doped and over-doped regimes changes nearly independently, thus possibly suggesting there is no intimate relation between them. Coexistence of relative high $T_c$ and strong scattering seems exceptionally within the framework of the $s_\pm$-wave model, whereas it could be alternatively interpreted by the $s_+$-wave state with $T_c$ being robust to impurities.

However, understanding $T_c$ suppression by impurities in terms of $s_\pm$-wave model could not be so dogmatically, where complexities arising from the strength of interband scattering [15], or possible fragile $s_\pm$-wave states to impurities [16], should be carefully taken into account. The work of doping Zn in BaFe$_{1.92}$Pt$_{0.08}$As$_2$ is expected to show a comparison with the intrinsic impurity scattering effect.

**Figure 3.** (a) $\rho$ vs. $T$ for BaFe$_{1.92}$Zn$_x$Pt$_{0.08}$As$_2$, (b) $T_c$ vs. Zn for BaFe$_{1.92}$Zn$_x$Pt$_{0.08}$As$_2$, LaFe$_{1.87}$Zn$_x$Co$_{0.13}$As$_2$, and BaFe$_{1.87}$Zn$_x$Co$_{0.13}$As$_2$, and (c) shows the Hall coefficient of the selected crystals of $x$ = 0, 0.04, and 0.16.

$\rho(T)$ of BaFe$_{1.92}$Pt$_{0.08}$Zn$_x$As$_2$ is presented in Figure 3a. $T_c$ is clearly pushed to low temperatures in response to Zn substitution, and it eventually almost disappears at $x=0.16$. $T_c$ as functions of Zn concentration is summarized in Figure 3b. The yielding $T_c$ suppression rate for BaFe$_{1.92}$Pt$_{0.08}$Zn$_x$As$_2$, $\sim$3K/%, is comparable to that of BaFe$_{1.87}$Zn$_x$Co$_{0.13}$As$_2$, $\sim$3.6 K/%, while distinguishably smaller than that of LaFe$_{1.87}$Zn$_x$AsO$_4$, $\sim$11.2 K/%. The behavior is reminiscent of that in the $d$-wave YBa$_2$Cu$_{3-y}$Zn$_y$O$_{6.93}$ [17], where doped Zn can also drastically decrease the $T_c$ in a rate of $\sim$11K/%. Moreover, to exclude the possibility of carriers change caused by Zn, Hall coefficient $\rho_H$ for $x=0, 0.04, 0.16$ was also presented in Figure 3c. With the doping of Zn, $\rho_H$ is almost independent over the temperature range, suggesting that Zn substitution actually does not substantially affect the conducting carriers. $T_c$ suppression should be caused by Zn-doping itself.

Traced a recent theory developed by Efremov et al. [18], superconducting properties in the presence of disorder strongly depend on the inter- to intra-band paring coupling constant $\lambda_{ij}$. When the intra-band scattering is dominated, even in the $s_\pm$-wave scenario with $<\lambda_{ij}>$ being positive, $T_c$ suppression rate should be far below that predicated by Abikosov-Gor’kov theory [19], which therefore could be used to interpreted the rather weak $T_c$ suppression by most substitutions like Co and Ru etc, being also possibly in line with the coexistence of high $T_c$ and strong intrinsic impurity

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scattering induced by Pt. Also proposed by the same theory, depending on the strength enhanced disorder, the \( s_\pm \) superconductivity may eventually transit to the \( s_{++} \)-wave state. However, the exceptional \( T_c \) suppression, not only in 1111 LaFeAsO\(_{0.85}\), but also reproduced in 122-BaFe\(_{1.87}\)Co\(_{0.13}\)As\(_2\) and BaFe\(_{1.93}\)Pt\(_{0.08}\)As\(_2\) single crystals despite the somewhat different suppression rate, seems hard to be understood by this theory. Before more solid experimental evidences could be obtained, the paring symmetry of the superconducting order parameter thus remains an open question.

In summary, throughout the Zn-doping study on BaFe\(_{1.92}\)Pt\(_{0.08}\)As\(_2\) single crystal, the essential differences between Zn and Pt induced intrinsic scattering were clearly observed. Doped Zn results in a remarkable \( T_c \) suppression, while intrinsic scattering induced by Pt does not. This possibly provides a universal trend regarding impurity scattering in the Fe-based superconductor, and may help to test so-far proposed paring symmetry models.

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References
[1] Mazin I I, Singh D J, Johannes M D, and Du M H 2008 Phys. Rev. Lett. \textbf{101} 057003
[2] Kuroki K, \textit{et al}. 2008 Phys. Rev. Lett. \textbf{101} 087004
[3] Onari S and Kontani H 2009 Phys. Rev. Lett. \textbf{103} 177001
[4] Anderson P W1959 J. Phys. Chem. Solids \textbf{11}, 26
[5] Xiao G \textit{et al}.1988 Phys. Rev. Lett. \textbf{60} 1446
[6] Senga Y, Kontani H 2008 J. Phys. Soc. Jpn. \textbf{77} 113710
[7] Lee S C, \textit{et al}. 2009 J. Phys. Soc. Jpn. \textbf{78} 043703; Satomi E, \textit{et al}. 2010 J. Phys. Soc. Jpn. \textbf{79} 023702
[8] Guo Y F, Shi Y G, \textit{et al}.2010 Phys. Rev. B \textbf{82} 054506
[9] Y. K. Li, \textit{et al}. 2010 New J. Phys. \textbf{11} 053008
[9] Li J J, Guo Y F, \textit{et al}.2011 Phys. Rev. B \textbf{84} 020513(R)
[10] Saha S R \textit{et al}. 2010 J. Phys.:Condens. Matter \textbf{22} 072204; Zhu X Y \textit{et al}. 2010 Phys. Rev. B \textbf{81} 104525
[11] Guo Y F, \textit{et al}., submitted
[12] Cvetkovic V, Tesanovic Z 2009 Europhys. Lett. 85 37002
[13] Mu G, \textit{et al}. 2010 Chin. Phys. Lett. \textbf{27} 037402
[14] Ng T K 2009 Phys. Rev. Lett.\textbf{103} 236402
[15] Hanaguri T, Niitaka S, Kuroki K, Takagi H 2010 Science \textbf{328} 474
[16] Ishida K, \textit{et al}. 1993 J. Phys. Soc. Jpn. 62 2803
[17] Efremov D V, \textit{et al}., 2011 arXiv:11043.3840
[18] Abrikosov A A, Gor’kov L P 1961 Sov. Phys. JETP 12 1234