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Physical Review B (2011), 83(18)
Nonmagnetic pair-breaking effect in La(Fe_{1−x}Zn_{x})AsO_{0.85} studied by ^{75}\text{As} and ^{139}\text{La} NMR and NQR

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(Received 9 March 2011; revised manuscript received 1 April 2011; published 6 May 2011)

75\text{As} and 139\text{La} NMR and nuclear quadrupole resonance (NQR) studies on Zn-substituted LaFeAsO_{0.85} have been performed to microscopically investigate the Zn-impurity effects. Although superconductivity in LaFeAsO_{0.85} disappears by 3% Zn substitution, we found that NMR/NQR spectra and NMR physical quantities in the normal state are hardly changed, indicating that the crystal structure and electronic states are not modified by Zn substitution. Our results suggest that the suppression of superconductivity by Zn substitution is not due to the change of the normal-state properties, but due to strong nonmagnetic pair-breaking effect to superconductivity.

DOI: 10.1103/PhysRevB.83.180501 PACS number(s): 74.70.Xa, 76.60.–k, 74.25.–q

The most important issues in iron-pnictide superconductors are to experimentally identify their superconducting (SC)-gap structure and pairing symmetry. Until now, it has become clear that iron-pnictide superconductors have a SC-gap structure and pairing symmetry.16 They showed that impurity effects are to experimentally identify their superconducting state.14 Theoretical treatments.16 They showed that impurity-3d levels of substituted Co and Ni are close to the Fe-3d level, so that the impurity effect is weak and the substitution dependence can be understood as a rigid band shift of the electronic structure. This is consistent with the experimental tendency.17 In addition, they pointed out that the Zn-d level is considerably deep, resulting in that the Zn site can be regarded as a simple vacancy without effective carrier doping. Therefore, Zn atoms are considered as ideal impurity for studying impurity effects. However, Zn-impurity effects reported in La1111 superconductors are controversial: substituted Zn does not suppress superconductivity in underdoped and optimally doped LaFeAs(O1−x)F_x.8 but significantly suppress T_c in LaFeAsO_{1−y} and La(Fe_{0.925}Co_{0.075})AsO.10 This discrepancy may originate from sample quality, and thus Zn substituted samples with careful characterization are required.

Here, we study the Zn-substitution effect in well-characterized LaFeAsO_{1−y}, in which superconductivity is completely suppressed by 3% Zn substitution.9 We have performed NMR and nuclear quadrupole resonance (NQR) measurements in order to identify the origin of the T_c suppression by Zn from the microscopic point of view. From our NMR/NQR measurements, we found that Zn impurities do not change crystal structure nor normal-state electronic structure significantly, and thus the strong suppression of T_c is considered to be due to nonmagnetic pair-breaking effect, which cannot be interpreted as conventional s-wave superconductivity.

Polycrystalline samples of Zn-substituted La(Fe_{1−x}Zn_{x})AsO_{0.85} (x = 0, 0.03, and 0.05) synthesized by solid-state reaction under high pressure9 are ground into powder for our NMR/NQR measurements. T_c was determined from the onset temperature of Meissner signal measured by an identical NMR coil. T_c of Zn-free x = 0 is 24 K, and the x = 0.03 and 0.05 samples do not show any Meissner signals as shown in Fig. 1(a). This is consistent with the previous report.9 Conventional spin-echo technique was utilized for the following NMR/NQR measurements.

Figure 1(b) shows ^{75}\text{As} NMR spectra for x = 0, 0.03, and 0.05 in La(Fe_{1−x}Zn_{x})AsO_{0.85} at 50 K obtained by sweeping magnetic field at a fixed frequency of 72.1 MHz. Compared with Zn-free x = 0, neither significant broadening...
spectra for $x = 0$, 0.03, and 0.05 at 1.5 K. Solid lines represent Gaussian fits. La(Fe$_{1-x}$Zn)$_x$AsO$_{0.85}$ peaks were observed in the Zn-substituted samples. Electron doping of our sample, which were obtained by the frequency-swept method. The peak frequencies ($\nu_Q$) of the $^{75}$As NQR spectra slightly increase, and the linewidth of each sample becomes broadened by Zn substitution, indicative of randomness of the electric field gradient introduced by Zn substitution.

Figure 3 shows temperature dependence of $1/T_1 T$ for $x = 0$, 0.03, and 0.05. $1/T_1 T$ in the normal state hardly changes by Zn substitution. (Inset) Temperature dependence of the anisotropy of $1/T_1 T$, $r \equiv (1/T_1)_{H_{ab}}/(1/T_1)_{H_{c2}}$ for $x = 0$ and 0.05. $(1/T_1)_{H_{ab}}$ is estimated from $(1/T_1)_{H_{ab}}$ and $(1/T_1)_{H_{c2}}$. $(1/T_1)_{H_{ab}}(1/T_1)_{H_{c2}} \simeq 1.5$ does not change by Zn substitution.

The decrease of $1/T_1 T$ is not due to superconductivity, but can be ascribed to the characteristic band dispersion around the Fermi energy. The pseudogap like behavior observed in $1/T_1 T$ can be interpreted by the presence of high density of states just below the Fermi energy, and continues down to low temperatures in the Zn-substituted samples. However, $1/T_1 T$ above 30 K hardly changes by Zn substitution, suggesting that Zn substitution modifies neither carrier doping level nor FS properties.

Although we tried to align the samples as we performed previously in LaFeAs(O$_{1-x}$F$_x$), we could not align them. Alternatively, we measured $1/T_1 T$ at the peak corresponding to $H || c$ [$\theta$] shown in Fig. 1(b)] to derive $1/T_1$ along the $c$ axis. Here $\theta$ is an angle between a magnetic field and the principal axis of the electric field gradient ($c$ axis). In general, the angle dependence of $1/T_1$ in axial symmetric crystals can be described as

$$1/T_1(\theta) = (1/T_1)_{H_{c2}} \cos^2 \theta + (1/T_1)_{H_{ab}} \sin^2 \theta .$$

Therefore $(1/T_1)_{H_{c2}}$ and the anisotropy of $1/T_1 [r \equiv (1/T_1)_{H_{ab}}/(1/T_1)_{H_{c2}}]$ can be estimated from $(1/T_1)_{H_{ab}}$ and $1/T_1$ measured at $\theta = 41.8^\circ$ by using the above relation. The inset of Fig. 3 shows the temperature dependence of $r$. The value of $r$ is approximately 1.5 at $x = 0$ and 0.05 above 50 K, suggesting that the local stripe correlations are unchanged by Zn substitution, since $r \simeq 1.5$ can be understood by the presence of the local stripe correlations related with the nesting between the hole and electron FSs.

Now we discuss the Zn-substitution effect in LaFeAs(O$_{0.85}$). Several effects which suppress $T_c$ can be pointed out; variations of (i) crystal structure and (ii) electronic structure and (iii) induction of staggered magnetism by nonmagnetic impurities. It was reported that the Fe-As-Fe bond angle and/or pnictogen height are important parameters for determination of $T_c$. NQR studies on LaFeAs(O$_{1-x}$F$_x$) and LaFeAsO$_{1-\delta}$...
have shown that $v_Q$ is related to the hybridization between the Fe and As orbitals, and thus related to the As-Fe-As bond angle.18,25,26 With increasing F content in LaFeAs(O$_{1-x}$F$_x$), $v_Q$ in LaFeAs(O$_{1-x}$F$_x$) increases by 1.5 MHz and As-Fe-As bond angle increases by 0.8° from undoped to overdoped samples.25,27 Following this relation, observed $v_Q$ change of 0.28 MHz by 5% Zn substitution corresponds to 0.15° increase of As-Fe-As bond angle, which is consistent with the XRD result.9 The tiny change in $v_Q$ with Zn substitution indicates that the hybridization between the Fe and As bonds is almost unchanged, and thus the $T_c$ suppression by Zn substitution cannot be attributed to variations of the Fe-As-Fe bond angle and/or pnictogen height.

Next we consider the variations of electronic state from the viewpoint of low-energy magnetic fluctuations. In LaFeAs(O$_{1-x}$F$_x$) and LaFeAsO$_{1−δ}$, low-energy magnetic fluctuations probed with 1/$T_1$ measurements are dramatically suppressed by F (electron) doping due to variations of the nesting condition.28–30 Therefore, the variations of the electronic state with Zn substitution should be detected with 1/$T_1$ measurements. As seen in Fig. 3, 1/$T_1$T in the normal state remains unchanged, indicating that Zn substitution does not modify the FS properties. This result is in good agreement with the Hall coefficient and specific-heat results, in which normal-state data are identical between Zn-free and substituted samples.9 Moreover, the stripe antiferromagnetic (AF) spin correlations, which originate from the nesting between electron and hole FSSs, are essentially unchanged, since the anisotropy of 1/$T_1$ is the same in the $x = 0$ and 0.05 samples.21

Magnetism potentially induced by nonmagnetic impurities is also investigated by $^{139}$La NMR measurements. Since the hyperfine coupling constant at the La site is smaller than at the As site, the wipe out effect due to induced magnetism is expected to be weak at the La site even if it exists. Figure 4 shows temperature dependence of the full width at half maximum (FWHM) of the central peaks shown in the inset of Fig. 4 and the Knight shift derived from $^{139}$La NMR spectra. The FWHM of all samples becomes broader with decreasing temperature, but the temperature dependence in the normal state remains unchanged, indicating that Zn substitution does not modify the FS properties. This result is in good agreement with the Hall coefficient and specific-heat results, in which normal-state data are identical between Zn-free and substituted samples.9 Moreover, the stripe antiferromagnetic (AF) spin correlations, which originate from the nesting between electron and hole FSSs, are essentially unchanged, since the anisotropy of 1/$T_1$ is the same in the $x = 0$ and 0.05 samples.21

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FIG. 4. (Color online) (Upper panel) Temperature dependence of the full width at half maximum (FWHM) of $^{139}$La NMR spectra for $x = 0$, 0.03, and 0.05. All samples show similar behavior. (Inset) Field swept $^{139}$La NMR spectra at 50 K at 72.1 MHz. (Lower panel) Temperature dependence of $^{139}$La NMR Knight shift for $H \parallel ab$.
variation of residual-resistivity value is difficult to be observed experimentally in polycrystalline La$_{1111}$ with impurities.

Finally, we comment on the previous reports on the Zn-substitution effect in LaFeAsO$_{1-x}$F$_x$. In the previous reports, the normal-state resistivity in Zn-substituted samples is smaller than that in the Zn-free samples, which is quite unusual and different from the results of our samples. The decrease of the normal-state resistivity by Zn substitution is hard to understand because substituted Zn does not change carrier content as clarified in this paper. We point out that the carrier content might be changed in the Zn-substitution process, which can be checked by $^{75}$As NMR/NQR measurements as shown in this Rapid Communication. We claim that microscopic NMR and NQR studies play a crucial role to discuss the impurity effect in the iron-pnictide superconductors.

In conclusion, from the microscopic NMR and NQR measurements, we show that the Zn substitution neither changes carrier content nor modifies the electronic state in LaFeAsO$_{1-x}$. In addition, temperature dependence of $^{139}$La NMR spectra indicates that the substituted Zn does not induce any static moments around the impurity in contrast to underdoped cuprates. Superconductivity is suppressed by only a few percent of nonmagnetic Zn substitution, which cannot be expected in conventional superconductors, but strongly suggests unconventional nature of superconductivity in LaFeAsO$_{1-x}$. The Zn-substitution effect revealed by the present study gives a strong constraint to theoretical models for the iron-pnictide superconductors.

We are grateful to S. Yonezawa, H. Ikeda, and Y. Maeno for valuable discussions. This work was supported by a Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” from MEXT, and for Scientific Research from JSPS. This was also supported in part by “Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)”.

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