



## Linear decrease of critical temperature with increasing Zn substitution in the iron-based superconductor $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$

Jun Li,<sup>1,2,\*</sup> Yanfeng Guo,<sup>3</sup> Shoubao Zhang,<sup>3</sup> Shan Yu,<sup>1</sup> Yoshihiro Tsujimoto,<sup>3</sup> Hiroshi Kontani,<sup>5</sup> Kazunari Yamaura,<sup>1,2,4,†</sup> and Eiji Takayama-Muromachi<sup>2,3,4</sup>

<sup>1</sup>*Superconducting Properties Unit, National Institute for Materials Science, 1-1 Namiki, Tsukuba, Ibaraki 305-0044, Japan*

<sup>2</sup>*Department of Chemistry, Graduate School of Science, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan*

<sup>3</sup>*International Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science, 1-1 Namiki, Tsukuba, Ibaraki 305-0044, Japan*

<sup>4</sup>*JST, Transformative Research Project on Iron Pnictides (TRIP), 1-1 Namiki, Tsukuba, Ibaraki 305-0044, Japan*

<sup>5</sup>*Department of Physics, Nagoya University, Furo-cho, Nagoya 464-8602, Japan*

(Received 26 June 2011; published 29 July 2011)

The nonmagnetic impurity effect is studied on the Fe-based  $\text{BaFe}_{1.89-2x}\text{Co}_{0.11}\text{As}_2$  superconductor ( $T_c = 25$  K) with Zn substitution for Fe up to 8 at. %, which is achieved by means of high-pressure and high-temperature heating.  $T_c$  decreases almost linearly with increasing Zn content and disappears at  $\sim 8$  at. %. It is different in the shared phenomenology of the early Zn doping studies, where  $T_c$  decreased little. The decreasing  $T_c$  rate, however, remains much lower (3.63 K/%) than what is expected for the  $s_{\pm}$ -wave model, implying the model is inaccurate. Another symmetry model such as the non-sign-reversal  $s$ -wave model may better account for the result.

DOI: [10.1103/PhysRevB.84.020513](https://doi.org/10.1103/PhysRevB.84.020513)

PACS number(s): 74.70.Xa, 74.62.Bf, 74.25.Dw

Discovery of a Fe-based superconductor in 2008 raised a fundamental question about the pairing symmetry of its superconductivity (SC).<sup>1,2</sup> In the compound, fully gapped multiband superconductivity has been realized, according to NMR,<sup>3</sup> angle-resolved photoemission spectroscopy,<sup>4</sup> London penetration depth measurements,<sup>5</sup> and muon spin rotation, relaxation and resonance ( $\mu$ SR) studies.<sup>6</sup> Several independent groups theoretically predicted a sign-reversal  $s$ -wave model ( $s_{\pm}$  wave) for the SC,<sup>2</sup> and recent half-flux quantum experiments on  $\text{NdFeAsO}_{0.88}\text{F}_{0.12}$  supported the model.<sup>7</sup> Meanwhile, a non-sign-reversal  $s$ -wave model ( $s_{++}$  wave) was proposed to account for the hump structure observed in neutron-scattering measurements below  $T_c$ .<sup>8</sup> The  $s_{++}$ -wave model is highly developed and is competitive with the  $s_{\pm}$ -wave model.<sup>9-11</sup> In addition, a  $d$ -wave model is still competing with the  $s_{++}$ - and  $s_{\pm}$ -wave models.<sup>12</sup>

The  $s_{++}$  and  $s_{\pm}$  waves share the same sign for the hole-Fermi pockets but not for the electron-Fermi pockets. The  $d$ -wave state has opposite signs for the nearest-neighbor electron-Fermi pockets. Because nonmagnetic impurity (NMI) causes pair breaking in different ways depending on the pairing symmetry, the NMI study is expected to greatly help to answer the open question.<sup>13-16</sup> Anderson's theorem predicts that a NMI does not break pairing in an isotropic non-sign-reversal SC state but does in an anisotropic state.<sup>16</sup> The theorem describes well the results for the cuprate superconductor, which quickly loses the SC by a small amount of NMI.<sup>13</sup>

Since  $\text{Zn}^{2+}$  has a tightly closed  $d$  shell, a doped Zn normally works as a better NMI. A few atomic percentage points of Zn in fact act as a strong scattering center in a superconductor, though it has little influence on the magnetism and transport properties.<sup>13-15</sup> Because the doped Zn actually plays a crucial role of the pairing symmetry determination, we may expect that it works as well in the Fe-based superconductor. In early studies, Cheng *et al.* reported that the doped Zn hardly affects the SC of the  $p$ -type  $\text{Ba}_{0.5}\text{K}_{0.5}\text{Fe}_2\text{As}_2$ ,<sup>17</sup> and Li *et al.* reports the same for the  $n$ -type  $\text{LaFeAsO}_{0.85}\text{F}_{0.15}$ .<sup>18</sup> However,

the SC is completely suppressed by at most 3 at. % of Zn for  $\text{LaFeAsO}_{0.85}$  in our study.<sup>19</sup> These early results seem to contradict each other. It is possible that the Zn substitution suffered from the high volatility of Zn, resulting in an overestimation of the net Zn content.<sup>13,20</sup> Our recent studies showed that more than 2 at. % of Zn is hardly doped into  $\text{Ba}(\text{Fe},\text{Co})_2\text{As}_2$  under regular conditions of synthesis.<sup>21</sup>

Recently, we succeeded in doping a large amount of Zn into a crystal of  $\text{BaFe}_{1.89-2x}\text{Co}_{0.11}\text{As}_2$  ( $T_c = 25$  K) using a high-pressure and high-temperature heating method. Magnetic and electrical properties of the Zn-doped crystal indicate a notable  $T_c$  decrease in proportional to the Zn content. Because early studies showed smaller  $T_c$  decreases (except for Ref. 19), the  $T_c$  decrease is remarkable. Thus, it is significant to investigate the role of Zn in the crystals of  $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$  ( $0 \leq x \leq 0.08$ ).

The nominal composition of the crystals was  $\text{BaFe}_{1.87-2x}\text{Zn}_{2x}\text{Co}_{0.13}\text{As}_2$  ( $x = 0-0.07$ ); mixtures of BaAs (prepared as in Ref. 19), FeAs (Ref. 19), Fe (99.9%, Rare Metallic Co.), Co (99.5%, Rare Metallic Co.), and Zn (99.99%, Rare Metallic Co.) were each placed in a boron-nitride cell, which was installed in a Ta capsule. The loaded capsule was treated at 3 GPa in a belt-type pressure apparatus at 1300 °C for 2 h, and the temperature was slowly decreased to 1100 °C for 2 h. The capsule was quenched to room temperature, and the pressure was released. The prepared samples were kept in a vacuum for 3-5 days, resulting in isolation of thin crystals ( $\sim 0.3 \times 0.2 \times 0.1$  mm<sup>3</sup> or smaller).

The crystal structure was investigated by powder x-ray diffraction (XRD). The tetragonal  $\text{ThCr}_2\text{Si}_2$ -type structure was found to form over the compositions from  $x = 0$  to 0.08 without traces of impurities.<sup>22</sup> The lattice constants were estimated from analysis of the XRD patterns (Table I); a nearly isotropic expansion of both  $a$  and  $c$  was found, reflecting difference between the Zn-As and the Fe-As bonds as discussed in Ref. 18. In addition, a magnetic effect is possibly included

TABLE I. The net Zn and Co contents, lattice parameters,  $T_c$ , residual resistivity, and Hall coefficient of crystals of  $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$  ( $x = 0-0.08$ ).

$x$	$x$ by EPMA	Co/Ba by EPMA	$a$ (Å)	$c$ (Å)	$T_c$ (K) by $\chi$	$T_c$ (K) by $\rho$	$\rho_0$ ( $\text{m}\Omega \cdot \text{cm}$ )	$R_H$ ( $\text{m}^3/\text{C}$ ) at 150 K
0	0	0.113(1)	3.955(2)	12.976(9)	25.0	25.26	0.26	$-2.92 \times 10^{-9}$
0.01	0.008(2)	0.114(2)	3.957(3)	12.980(11)	20.0	19.31	0.42	
0.02	0.021(2)	0.109(1)	3.963(3)	12.983(9)	18.5	18.33	0.40	$-2.82 \times 10^{-9}$
0.03	0.033(1)	0.105(3)	3.967(1)	12.989(4)	17.0	15.48	0.48	
0.04	0.044(1)	0.112(1)	3.968(2)	13.002(6)	11.0	11.46	0.57	$-4.57 \times 10^{-9}$
0.05	0.052(5)	0.117(4)	3.968(1)	13.001(4)	8.0	9.82	0.59	
0.07	0.073(4)	0.106(5)	3.972(2)	13.026(7)	5.5	7.86	0.76	$-4.81 \times 10^{-9}$
0.08	0.082(6)	0.107(8)	3.977(4)	13.033(12)	<2	< 2	1.02	

in the  $c$ -axis expansion.<sup>23</sup> In addition, a shining surface of the platelike crystal ( $\sim 0.5$  mm long) was studied by XRD (Fig. 1). An orientation toward  $[002n]$  ( $n$  is integer) is obvious, indicating that the  $c$  axis is perpendicular to the crystal plane.<sup>24</sup> The Zn substitution was again confirmed in an electron probe microanalysis (EPMA, JXA-8500F, JEOL) conducted on the surface (Table I). The Co content is almost constant at  $\sim 0.11$  over the compositions, while the Zn content monotonically increases with increasing  $x$ . Hereafter, the crystals are labeled as  $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$  with  $x = 0, 0.01, 0.02, 0.03, 0.04, 0.05, 0.07$ , and  $0.08$ . Note that the high-pressure method was probably essential to overcoming the difficulties regarding the Zn doping.

We attempted to measure the magnetic susceptibility ( $\chi$ ) of an individual crystal; however, accurate measurements were not achieved. Thus, we loosely gathered crystals into a sample holder ( $\sim 30$  mg each composition) in a magnetic properties measurement system, Quantum Design, for an alternative measurement. Figure 2 shows temperature dependence of  $\chi$  in a magnetic field ( $H$ ) of 10 Oe for the crystals of  $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$  ( $x = 0-0.08$ ). The host crystal ( $x = 0$ ) was confirmed to show the SC transition at 25 K as reported.<sup>22,25</sup> With increasing the Zn content,  $T_c$  monotonically decreases, and the SC disappears at  $x = 0.08$  ( $>2$  K) (Table I).

Each crystal was carefully cleaved to a thickness of approximately 20–100  $\mu\text{m}$  along the  $c$  axis, and the  $ab$ -plane electrical resistivity ( $\rho$ ) was measured by a standard four-point method in a physical properties measurement system, Quantum Design. Figure 3 shows  $T$  vs  $\rho$  for  $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$  ( $x = 0-0.08$ );  $T_c$  by  $\rho$  goes down with increasing the Zn content as much as  $T_c$  by  $\chi$  (Table I). This supports that the doped Zn is evenly distributed into the crystal since  $T_c$  by  $\rho$  is rather sensitive to the surface matter. Note that  $T_c$  by  $\rho$  was defined by a peak position of the  $d\rho/dT$  curve (not shown). Besides, we define the residual resistivity  $\rho_0$  by extrapolation of the linear part of  $T$  to zero temperature (the upturned region is excluded). Because the upturn of the resistivity curve in the highly Zn-doped crystals indicates the occurrence of localization, we tested several definitions of  $\rho_0$  to avoid influence of the upturn on the  $\rho_0$  estimation. However,  $\rho_0$  remained essentially large in any cases. The  $\rho_0$  (Table I) gradually increases with increasing Zn content at a rate of  $\sim 76 \mu\Omega \text{cm}/\%$ . Such a large  $\rho_0$  indicates that the potential for Zn impurities is very strong, as predicted by the first principle calculation.<sup>23</sup> Note that the theoretical residual resistivity per 1% impurity with  $\delta$ -functional strong potential is just  $\sim 20 \mu\Omega \text{cm}$ .<sup>8,9</sup> This suggests that the impurity scattering cross section is enlarged by the many-body effect.<sup>26</sup>

The Hall coefficient ( $R_H$ ) at 150 K of the selected  $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$  crystals ( $x = 0, 0.02, 0.04$ , and

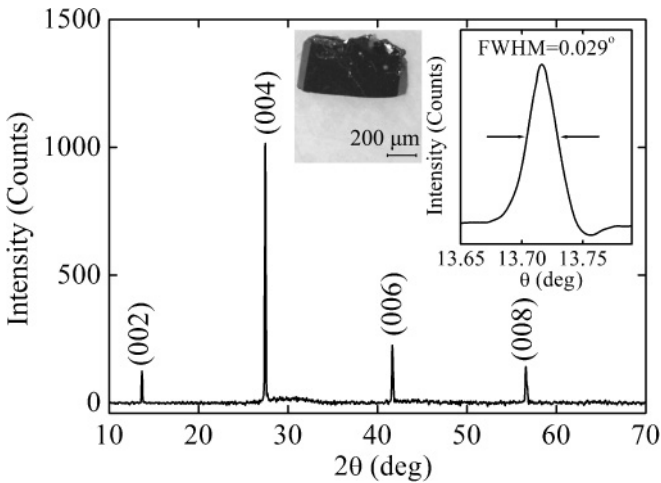


FIG. 1. XRD pattern of a crystal of  $\text{BaFe}_{1.81}\text{Zn}_{0.08}\text{Co}_{0.11}\text{As}_2$  (EPMA). Insets are a photograph of the crystal and the rocking curve of the (004) peak.

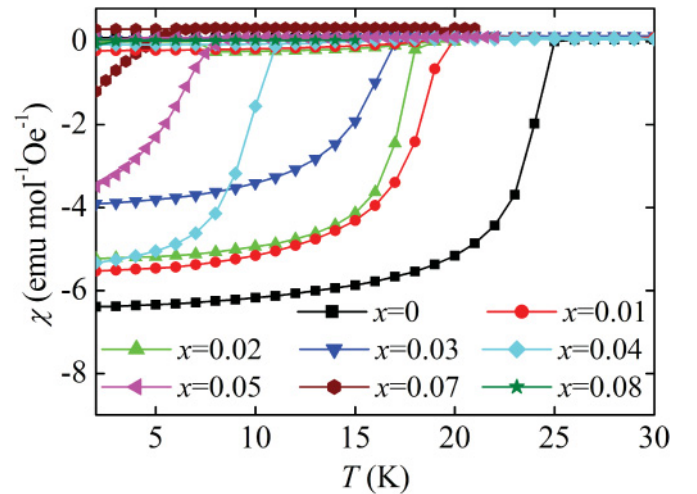


FIG. 2. (Color online)  $\chi$  vs  $T$  for  $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$  ( $x = 0-0.08$ ) at  $H = 10$  Oe.

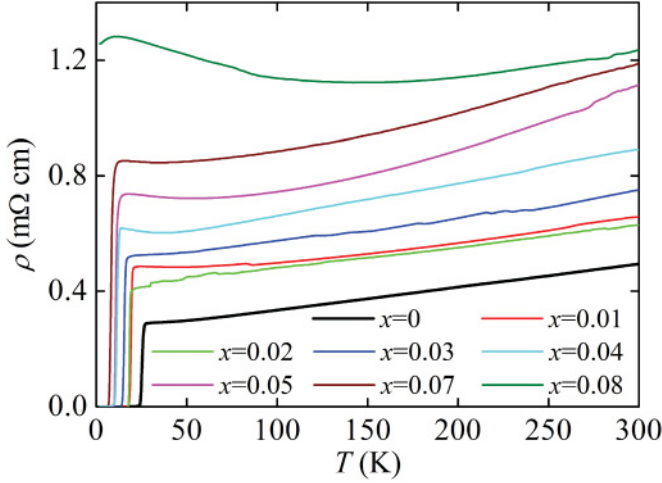


FIG. 3. (Color online) The  $ab$  plane  $\rho$  vs  $T$  for the  $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$  ( $x = 0-0.08$ ).

0.07) was measured in the same apparatus, where  $H$  was applied parallel to the  $c$  axis. The data for the Zn-free crystal accesses the early data (Table I).<sup>27</sup> The  $R_H$  changes little over the Zn substitution, reflecting the isoelectronic substitution of Zn for Fe. Thus, the net carrier density change is unlikely responsible for the  $T_c$  decrease.

Since the potential for Zn impurity is very strong, the Zn impurity works as the unitary scattering potential comparable to the bandwidth. According to Ref. 8, the reduction in  $T_c$  due to strong impurity ( $I > 1$  eV) in the  $s_{\pm}$ -wave state is  $\sim 50z$  K/%, where  $z$  is the renormalization factor ( $z = m/m^*$ ;  $m$  and  $m^*$  are the band mass and the effective mass, respectively). Since  $m^*$  was estimated to be between approximately  $2m$  and  $3m$  by angle-resolved photoemission spectroscopy (ARPES) for the 122 superconductor,<sup>28</sup> we obtain 25 K/% (17 K/%) for  $z = 0.5$  ( $z = 0.33$ ). However, the rate for  $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$  is much smaller: 3.63 K/% is estimated by a linear fitting to  $T_c$  (by  $\rho$ ) vs  $x$ . The result quantitatively contradicts the expectation from the  $s_{\pm}$ -wave model. Meanwhile, the  $s_{++}$ -wave model better accounts for the result;  $T_c$  is weakly suppressed by impurities due to (i) suppression of the orbital fluctuations and (ii) the strong localization effect in which the mean free path is comparable to the lattice spacing.<sup>8</sup> Point (i) results from the violation of the orbital degeneracy near the impurities and is a possible origin of the  $s_{++}$ -wave state.<sup>8</sup>

To further study the  $T_c$  suppression, it is significant to calculate the pair-breaking rate  $\alpha = 0.88z\Delta\rho_0/T_{c0}$  ( $z\hbar\gamma/2\pi k_B T_{c0}$ ), where  $\gamma$  is the electron scattering rate and  $T_{c0}$  is the  $T_c$  of the Zn-free crystal. On basis of the five-orbital model for the 122 system, a relation between  $\gamma$  and  $\Delta\rho_0$  was proposed as  $\Delta\rho_0$  ( $\mu\Omega$  cm) =  $0.18\gamma$  (K), where  $\Delta\rho_0$  is the gap between  $\rho_0$  with and without Zn. In this study, we estimated  $\alpha$  using  $z = 0.33$  and  $0.50$  ( $\equiv \alpha_1$ ) as depicted in Fig. 4. To obtain the elastic scattering rate, we also calculated  $\alpha$  by deriving  $\gamma = ne^2\Delta\rho_0/2m$  ( $\equiv \alpha_2$ ), where  $n$  is the carrier number estimated from the Hall data. Both  $\alpha_1$  and  $\alpha_2$  data change in roughly linearly;  $\alpha$  is thereby estimated to be 7.64, 11.49, and 6.76 for  $\alpha_1$  ( $z = 0.33$ ),  $\alpha_1$  ( $z = 0.05$ ), and  $\alpha_2$ , respectively. For the  $s_{\pm}$ -wave state, the SC is expected to vanish in the range  $\alpha > 0.22$  ( $\alpha_c^{\pm}$ ),<sup>8</sup> which

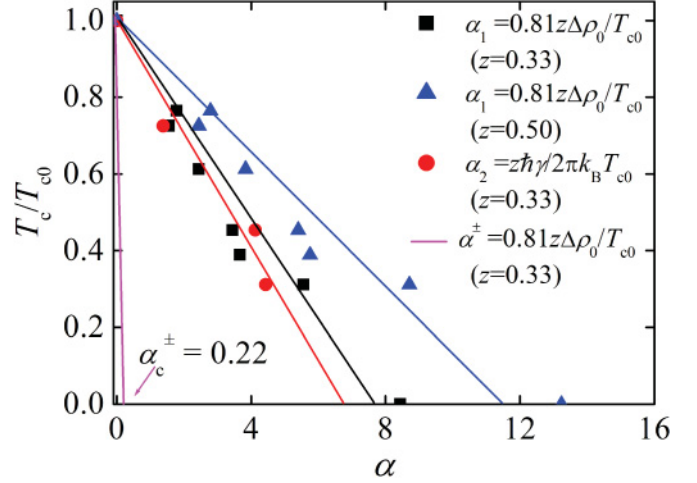


FIG. 4. (Color online)  $T_c/T_{c0}$  vs  $\alpha$  with various calculations for  $\text{BaFe}_{1.89-2x}\text{Zn}_{2x}\text{Co}_{0.11}\text{As}_2$  ( $x = 0-0.08$ ).

is remarkably much lower than the experimental values. In addition, using the relation  $\alpha_3 = \hbar\Delta\rho_0/4\pi T_{c0}\mu_0\lambda_0^2$ , we obtain  $\alpha_3 = 2.58$  for  $\lambda_0 = 195$  nm,<sup>5</sup> which is still very far from  $\alpha_c^{\pm}$ . Obviously, any pair-breaking parameter for the present superconductor is too far from  $\alpha_c^{\pm}$  to support the  $s_{\pm}$ -wave model, indicating realization of the  $s_{++}$ -wave state.

It is possible that  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  are slightly overestimated if  $\Delta\rho_0$  is overestimated due to influences from the grain boundaries and undetected factors. For further clarification, we make additional estimates using the critical impurity concentration for the  $s_{\pm}$ -wave state ( $n_{\text{imp}}^{\pm}$ ). According to the discussion in Ref. 8, Zn ( $I > 1$  eV) corresponds to  $n_{\text{imp}}^{\pm} \sim 0.5z/T_c$  (K). Thus, we predict  $n_{\text{imp}}^{\pm}$  to be 0.01 (0.015) for  $z = 0.5$  (0.33); however, the experimentally determined  $n_{\text{imp}}$  of 0.08 ( $T_c = 0$ ) is much higher than the theoretical values. Thus, the discussion for  $n_{\text{imp}}^{\pm}$  does not support the  $s_{\pm}$ -wave model for  $\text{BaFe}_{1.89-2x}\text{Co}_{0.11}\text{As}_2$  either.

The pair-breaking parameters for the  $\alpha$ -particle-irradiated  $\text{NdFeAs}(\text{O},\text{F})$ <sup>29</sup> and the proton-irradiated  $\text{Ba}(\text{Fe},\text{Co})_2\text{As}_2$ <sup>30</sup> are larger than  $10\alpha_c^{\pm}$  ( $= 2.2$ ) and  $17\alpha_c^{\pm}$  ( $= 3.8$ ), respectively, implying that the  $s_{\pm}$ -wave model is unlikely for the superconductors. Recent NMR studies on P-doped  $\text{BaFe}_2\text{As}_2$ <sup>31</sup> and theoretical studies on the local structure of the  $\text{Fe}_2\text{As}_2$  layer<sup>32</sup> suggest a possible change of the gap symmetry depending on minute factors. Besides, a change from  $d$  to  $s$  wave was predicted theoretically to depend on degree of disorder.<sup>33</sup> To understand the pair-breaking effect comprehensively on the Fe-based superconductor, additional Zn studies over varieties of the Fe-based superconductors, including the 11, 111, 122, and 1111 systems, would be helpful from  $p$  doped to  $n$  doped.

In summary, we studied the Zn doping effect on the  $T_c$  optimized superconductor  $\text{BaFe}_{1.89-2x}\text{Co}_{0.11}\text{As}_2$  ( $T_c = 25$  K). The highest Zn level of 8 at. % was achieved by a high-pressure and high-temperature technique, resulting in a complete suppression of SC, which is remarkable. The surface Zn content by EPMA truly reflects the bulk Zn content because (i) the SC transition in the  $\chi$  measurements is as sharp as that for the non-Zn-doped crystal, (ii)  $T_c$  by  $\chi$  and  $T_c$  by  $\rho$  are almost comparable over the Zn content, and (iii) the XRD lattice parameters systematically change as a bulk nature. However,

the  $T_c$  suppression rate (3.63 K/%) is too low to support the  $s_{\pm}$ -wave model. In contrast, the  $s_{++}$ -wave model may better account for the result.<sup>8,9,29,30</sup> We note here that early Zn studies by others reached the same conclusion because there was little  $T_c$  decrease by Zn. However, this was likely due to an overestimation of the net Zn content of the regularly synthesized polycrystalline samples.

We thank M. Miyakawa, K. Kosuda, and M. Sato for valuable discussions. This research was supported in part by the World Premier International Research Center from MEXT, Grant-in-Aid for Scientific Research No. 22246083 from JSPS, and the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program) from JSPS.

\*LI.Jun@nims.go.jp

†YAMAURA.Kazunari@nims.go.jp

<sup>1</sup>Y. Kamihara *et al.*, *J. Am. Chem. Soc.* **130**, 3296 (2008); M. Rotter, M. Tegel, and D. Johrendt, *Phys. Rev. Lett.* **101**, 107006 (2008); Z. A. Ren *et al.*, **25**, 2215 (2008).

<sup>2</sup>I. I. Mazin, D. Singh, M. D. Johannes, and M. H. Du, *Phys. Rev. Lett.* **101**, 057003 (2008); K. Kuroki, S. Onari, R. Arita, H. Usui, Y. Tanaka, H. Kontani, and H. Aoki, *ibid.* **101**, 087004 (2008); V. Cvetkovic and Z. Tesanovic, *Phys. Rev. B* **80**, 024512 (2009); I. I. Mazin, *Nature (London)* **464**, 183 (2010).

<sup>3</sup>A. Kawabata *et al.*, *J. Phys. Soc. Jpn.* **77**, 103704 (2008); K. Matano *et al.*, *Europhys. Lett.* **83**, 57001 (2008).

<sup>4</sup>H. Ding *et al.*, *Europhys. Lett.* **83**, 47001 (2008); K. Nakayama *et al.*, *ibid.* **85**, 67002 (2009).

<sup>5</sup>R. T. Gordon *et al.*, *Phys. Rev. Lett.* **102**, 127004 (2009); *Phys. Rev. B* **82**, 054507 (2010); H. Kim *et al.*, *ibid.* **82**, 060518 (2010).

<sup>6</sup>H. Lutkens *et al.*, *Phys. Rev. Lett.* **101**, 097009 (2008).

<sup>7</sup>C.-T. Chen *et al.*, *Nature Phys.* **6**, 260 (2010).

<sup>8</sup>S. Onari and H. Kontani, *Phys. Rev. Lett.* **103**, 177001 (2009).

<sup>9</sup>S. Onari, H. Kontani, and M. Sato, *Phys. Rev. B* **81**, 060504(R) (2010); T. Saito, S. Onari, and H. Kontani, *ibid.* **82**, 144510 (2010); H. Kontani and M. Sato, e-print [arXiv:1005.0942](https://arxiv.org/abs/1005.0942).

<sup>10</sup>M. Sato *et al.*, *J. Phys. Soc. Jpn.* **79**, 014710 (2010); S. C. Lee *et al.*, *ibid.* **79**, 023702 (2010).

<sup>11</sup>D. V. Efremov *et al.*, e-print [arXiv:1104.3840](https://arxiv.org/abs/1104.3840).

<sup>12</sup>K. Kuroki, S. Onari, R. Arita, H. Usui, Y. Tanaka, H. Kontani, and H. Aoki, *Phys. Rev. Lett.* **101**, 087004 (2008); W. Q. Chen, K. Y. Yang, Y. Zhou, and F. C. Zhang, *ibid.* **102**, 047006 (2009); Y. Yanagi *et al.*, *J. Phys. Soc. Jpn.* **77**, 123701 (2008).

<sup>13</sup>H. Alloul *et al.*, *Rev. Mod. Phys.* **81**, 45–108 (2009).

<sup>14</sup>T. R. Chien, Z. Z. Wang, and N. P. Ong, *Phys. Rev. Lett.* **67**, 2088 (1991); B. Nachumi *et al.*, *ibid.* **77**, 5421 (1996).

<sup>15</sup>D. L. Sisson, S. G. Doettinger, A. Kapitulnik, R. Liang, D. A. Bonn, and W. N. Hardy, *Phys. Rev. B* **61**, 3604 (2000).

<sup>16</sup>P. W. Anderson, *J. Phys. Chem. Solids* **11**, 26 (1959).

<sup>17</sup>P. Cheng, B. Shen, J. Hu, and H. H. Wen, *Phys. Rev. B* **81**, 174529 (2010).

<sup>18</sup>Y. Li *et al.*, *New J. Phys.* **12**, 083008 (2010).

<sup>19</sup>Y. F. Guo *et al.*, *Phys. Rev. B* **82**, 054506 (2010).

<sup>20</sup>B. vom Hedt, W. Lisseck, K. Westerholt, and H. Bach, *Phys. Rev. B* **49**, 9898 (1994); Y. K. Kuo, C. W. Schneider, M. J. Skove, M. V. Nevitt, G. X. Tessema, and J. J. McGee, *ibid.* **56**, 6201 (1997).

<sup>21</sup>J. J. Li *et al.*, *Physica C* **471**, 213 (2011).

<sup>22</sup>N. Ni, M. E. Tillman, J. Q. Yan, A. Kracher, S. T. Hannahs, S. L. Budko, and P. C. Canfield, *Phys. Rev. B* **78**, 214515 (2008).

<sup>23</sup>L. J. Zhang and D. J. Singh, *Phys. Rev. B* **80**, 214530 (2009).

<sup>24</sup>X. F. Wang, T. Wu, G. Wu, H. Chen, Y. L. Xie, J. J. Ying, Y. J. Yan, R. H. Liu, and X. H. Chen, *Phys. Rev. Lett.* **102**, 117005 (2009).

<sup>25</sup>N. R. Werthamer *et al.*, *Phys. Rev.* **147**, 295 (1966).

<sup>26</sup>H. Kontani and M. Ohno, *Phys. Rev. B* **74**, 014406 (2006).

<sup>27</sup>E. D. Mun, S. L. Budko, N. Ni, A. N. Thaler, and P. C. Canfield, *Phys. Rev. B* **80**, 054517 (2009).

<sup>28</sup>D. V. Evtushinsky *et al.*, *New J. Phys.* **11**, 055069 (2009); K. Nakayama *et al.*, *Europhys. Lett.* **85**, 67002 (2009); V. Brouet, M. Marsi, B. Mansart, A. Nicolaou, A. Taleb-Ibrahimi, P. LeFevre, F. Bertran, F. Rullier-Albenque, A. Forget, and D. Colson, *Phys. Rev. B* **80**, 165115 (2009).

<sup>29</sup>C. Tarantini *et al.*, *Phys. Rev. Lett.* **104**, 087002 (2010).

<sup>30</sup>Y. Nakajima, T. Taen, Y. Tsuchiya, T. Tamegai, H. Kitamura, and T. Murakami, *Phys. Rev. B* **82**, 220504(R) (2010).

<sup>31</sup>Y. Nakai, T. Iye, S. Kitagawa, K. Ishida, S. Kasahara, T. Shibauchi, Y. Matsuda, and T. Terashima, *Phys. Rev. B* **81**, 020503 (2010).

<sup>32</sup>K. Kuroki, H. Usui, S. Onari, R. Arita, and H. Aoki, *Phys. Rev. B* **79**, 224511 (2009).

<sup>33</sup>B. Spivak *et al.*, *Physica B* **404**, 462 (2009).