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# Fluctuation conductivity of single-crystalline BaFe1.8 Co0.2As2 in the critical region


**Abstract**

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**Keywords**

Fluctuation, conductivity, single, crystalline, BaFe1, Co0, 2As2, critical, region

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# Fluctuation conductivity of single-crystalline $BaFe_{1.8}Co_{0.2}As_2$ in the critical region

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The magnetofluctuation conductivity, called excess conductivity, originated from the forming of the superconducting droplet near to the mean-field transition temperature, was measured for the optimally doped $BaFe_{1.8}Co_{0.2}As_2$ single crystals with a critical temperature, $T_c$, of 24.6 K. This measurement of the excess conductivity for magnetic fields up to 9 T was compared with the thermodynamic scaling theory in the critical region, in which not only the Gaussian fluctuation but also fourth order terms of the order parameter are included. An analysis of the excess conductivity showed that the superconductivity followed three-dimensional scaling rather than two-dimensional scaling even though the sample had a layered structure. © *2010 American Institute of Physics*. [doi:10.1063/1.3478716]

## I. INTRODUCTION

The recent discovery of superconductivity in F-doped LaFeAsO (FeAs-1111) at 26 K (Ref. 1) has stirred interested in the community of strongly correlated electron systems and has accelerated further investigations to increase the superconducting transition temperature. In a similar structure, superconductivity was also discovered when La was replaced by Ln=Sm, Ce, Nd, Pr, Gd, Tb, or Dy (Refs. 2–7) with the highest $T_c$, up to 56 K, having been discovered for Nd substitution.[8] Also, a $T_c$ of 43 K was achieved by applying pressure to FeAs-1111.[9] Soon after the discovery of these oxypnictides, oxygen-free iron pnictides, such as K- or Co-doped $BaFe_2As_2$ and $SrFe_2As_2$ (FeAs-122) (Refs. 10–12) with a $T_c$ up to 38 K, were discovered. The common feature of these compounds is the possession of a FeAs layer that is similar to the $CuO_2$ plane in high-temperature cuprate superconductors (HTSC). In fact, FeAs-1111 has one FeAs layer in a unit cell while the FeAs-122 phase contains two FeAs layers.

For conventional superconductors, superconductivity appears suddenly at the superconducting transition temperature, $T_c$, defined as the point at which the free energies of the superconducting and the normal states of a material become equal. However, for some superconductors, near the transition regions, thermodynamic fluctuations give rise to an anomalous increase in the superconducting properties even at temperatures above $T_c$. This fluctuation effect is very important because it may provide valuable information on the superconductivity once we measure physical quantities such as the conductivity, the magnetization, and the thermoelectricity. This is of theoretical significance in that it would provide a stringent test of scaling theories in phase transitions while approaching the critical region.

The quantity called the Ginzburg number, Gi, defines the order of thermal fluctuations in a superconductor. The derived Gi number[13] is $[8\pi^2 k_B T_c \lambda_{ab}^2(0)/\xi_c \Phi_0^2]^2/2$ for anisotropic superconductors, where $k_B$ is the Boltzmann constant, $\lambda_{ab}(0)$ is the London penetration depth along the ab plane, $\xi_c$ is the c-axis coherence length, and $\Phi_0$ is the flux quantum. A value of $\sim 10^{-2}$ for this quantity is known to be quite large for HTSC and indicates a quite enhanced fluctuation effect even for bulk single crystals. This number is several orders of magnitude larger than that, $10^{-9}$, for a conventional superconductor. This is the reason why the fluctuation effect has been observed for conventional superconductors only in the forms of thin films or one-dimensional (1D) wires not for these in a bulk form. Even though the $T_c$ is lower than that of HTSC, a quite pronounced fluctuation effect is also observed in intermetallic superconductors, for example in $YNi_2B_2C$, and in the $MgB_2$ superconductor. This can be understood from the magnitude of the Ginzburg number, Gi, which governs how strong the fluctuation effect is. This number is $\sim 10^{-6}$ for $YNi_2B_2C$ (Ref. 14) and for $MgB_2$,[15,16] which is between the value of $\sim 10^{-9}$ for a conventional superconductor and $\sim 10^{-2}$ for a HTSC.

Since both the Fe–As and the HTSC are characterized by a high $T_c$, a layered structure, and a short $\xi_c$, an enhanced thermal fluctuation effect is also expected in Fe–As-based superconductors. It is well known that a quite large thermal fluctuation effect is observed in HTSC. However, so far, a conductivity fluctuation effect in the Fe–As superconductor has not been well documented.

One of the quantities related to the fluctuation effect that

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we like to investigate is the conductivity fluctuation in single-crystalline $BaFe_{1.8}Co_{0.2}As_2$. Since the Gi number is $\sim 10^{-5}$ for our single-crystalline $BaFe_{1.8}Co_{0.2}As_2$, which is higher than that of $YNi_2B_2C$, we expect to observe a conductivity fluctuation effect in our single crystals. Up to now, excess fluctuation conductivity has never been reported in Co-doped FeAs-122 superconductor although the Gi number of our sample is in a range comparable to that for the intermetallic superconductors mentioned above. The Gi number for another FeAs-based 1111 superconductor, NdFeAs (O and F) is reported to be $10^{-2}$,[16] which is the same order of magnitude as the value for HTSC. On the other hand, (Ba and K) $Fe_2As_2$ shows $Gi \sim 10^{-4}$,[17] which implies that even for the same family of Fe–As superconductors, the Gi number can vary by more than one order of magnitude.

In this paper, we present the fluctuations of the magnetoconductivity for optimally Co-doped $BaFe_{1.8}Co_{0.2}As_2$ superconducting single crystals with a $T_c$ of 24.6 K. The thermodynamic scaling functions of the magnetoconductivity, including the critical fluctuations, were analyzed. We found that the excess conductivity followed a three-dimensional (3D) scaling form quite well, but poorly matched the two-dimensional (2D) scaling form, so we conclude that this material is a 3D superconductor.

## II. EXPERIMENTS

The single crystals of $BaFe_{2-x}Co_xAs_2$ were grown by using the high-temperature self flux method. FeAs and CoAs were prepared by placing a mixture of As powder and Fe/Co powder in a quartz tube and reacting it at 600 °C for 10 h after it had been heated to 600 °C for 17 h. A mixture of FeAs/CoAs and Ba pieces was then placed in an alumina crucible. The whole assembly was sealed in a large quartz tube and heated to 1180 °C for 15 h, which was followed by a reaction at 1180 °C for 10 h. The detailed procedure of crystal growth is described in Ref. 18. The onset resistive transition temperature was 24.6 K. Several platelike crystals were used in this measurement.

The four-probe configuration was used to measure the magnetoresistivity for magnetic fields up to 9 T with the field direction parallel to the c-axis. The temperature for the resistivity measurement was varied up to 70 K, which is more than $2T_c$. A temperature interval of 0.05 K was used for detailed measurement of the fluctuation conductivity.

## III. THEORY

In Ginzburg–Landau (GL) theory, physical quantities are obtained with the assumption that the free energy has a minimum at $\Psi_0$. But the thermodynamic fluctuation allows the system to have another order parameter $\Psi(\mathrm{r})$ which considerably raise the free energy by $\sim k_BT$. Due to this fluctuation, the superconducting droplets are formed and annihilated near to the mean-field transition temperature and produce excess conductivity. To explain this, simple theory of the fluctuation, called Gaussian fluctuation theory, is suggested. In this theory, only square term, not fourth order term of the order parameter is included in the free energy. This theory works quite well for temperature above and below $T_c$ but poorly for temperature near $T_c$ in the critical fluctuation region. To overcome this disagreement, we should consider other theories that include square term and fourth order term, as well. When the fluctuation order parameter is comparable to the mean value of the order parameter, the fluctuations become critical. The boundary separating the critical fluctuation region from the Gaussian mean-field region is called the Ginzburg criterion. The critical region is related to the Gi number through the condition of $(\Delta\Psi)^2 \sim |\Psi|^2$. Ullah and Dorsey[19,20] treated this fourth order term within the Hartree approximation and predicted the scaling form of physical quantities. Ikeda *et al.*[21] treated this fourth order term within the renormalization method, which includes interactions between higher Landau levels while considering the layer structure in a strong field. Tesanovic *et al.*[22] used a nonperturbative approach to the GL free energy functional, and predicted the scaling functions, even in a closed form, for the free energy and, thus, for the magnetization, entropy, and specific heat in the high-field and quasi-2D limits.

The fluctuation effect become much more enhanced when a magnetic field is applied because the spatial correlation is reduced from $\xi$ to $(\xi^{-2}+2\pi H/\Phi_0)^{-1/2}$. In this case, the scaling forms of the fluctuation conductivity, $\Delta\sigma$, calculated by Ullah and Dorsey[19,20] while including the fourth order term in the GL free energy, within a self-consistent Hartree approximation are given by

$$\Delta[1/\rho(T,H)]_{2D} = \Delta\sigma(T,H)_{2D} = \left(\frac{T}{H}\right)^{1/2} F_{2D}\left[A\frac{T-T_c(H)}{(TH)^{1/2}}\right] \quad \text{for 2D}, \tag{1}$$

$$\Delta[1/\rho(T,H)]_{3D} = \Delta\sigma(T,H)_{3D} = \left(\frac{T^2}{H}\right)^{1/3} F_{3D}\left[B\frac{T-T_c(H)}{(TH)^{2/3}}\right] \quad \text{for 3D}, \tag{2}$$

where $F_{2D}$ and $F_{3D}$ are scaling functions and $A$ and $B$ are field and temperature-independent constants. The $T_c(0)$ and the $T_c(H)$ are the mean-field transition temperature for magnetic fields of zero and $H$, respectively. It is noticed that $T$ need not to be lower than $T_c$,[15] because critical region contains $|T-T_c|/T_c < \mathrm{Gi}$. This excess conductivity, $\Delta\sigma$, was analyzed for the temperature up to $2T_c$ for the HTSC.[23]

## IV. RESULTS AND DISCUSSION

Figure 1 shows the dc resistivity of $BaFe_{1.8}Co_{0.2}As_2$ single crystals as a function of temperatures near $T_c$. Field values for this measurement were between 0 to 9 T. Figure 1 shows a broadening of the transition, which is quite different from a conventional superconductor and indicates the existence of a fluctuation effect. This broadening of the conductivity is not as large as HTSC but is still quite pronounced in this graph. The $T_c$ onset and the temperature of zero resistivity also decrease as the magnetic field is increased. From the graph, the fluctuation conductivity of this crystal in the presence of a magnetic field can be analyzed by including a

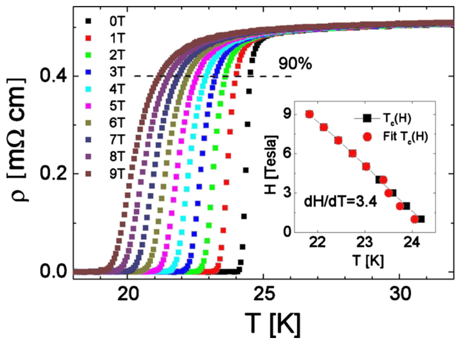


FIG. 1. (Color online) The resistivity of the $BaFe_{1.8}Co_{0.2}As_2$ single crystal for magnetic fields from 0 to 9 T. Inset shows the $H_{c2}$ obtained from the scaling fitting and resistivity measurement with the criterion of $\rho=0.9\rho$ (26 K).

critical fluctuation region in the framework of 2D or 3D scaling behaviors. First, we assume that the total conductivity, $\sigma$, is a sum of the normal conductivity, $\sigma_n$, and the excess conductivity, $\Delta\sigma$, $\sigma=\sigma_n+\Delta\sigma$. Then, the fluctuation conductivity can be calculated. The derivation of $\Delta\sigma$ within the scaling forms predicted by Ullah and Dorsey was adapted.

In Fig. 2, the scaled magnetoconductivity $\Delta\sigma$ for $BaFe_{1.8}Co_{0.2}As_2$ single crystals is given for the case of 3D scaling. For the correct form of the excess conductivity, the normal conductivity is subtracted from the total conductivity for each magnetic field. The total conductivity, with $\sigma_n$ of the form $1/(aT+b)$, was used while adjusting $a$, $b$, and $T_c(H)$ in the scaling functions for each magnetic field. To obtain the best 3D scaling function, we fitted the normal-state conductivity mentioned above. The obtained values of $a$ and $b$ were almost field independent and $a=(1.16\pm0.02)\times10^{-6}[\Omega\ \mathrm{cm/K}]$ and $b=(4.75\pm0.02)\times10^{-4}[\Omega\ \mathrm{cm}]$.

We also carefully obtained the $T_c(H)$ while varying the temperature in steps of 0.05 K to fit the excess conductivity to the scaling form. The obtained values of the $T_c(H)$ from the scaling analysis are shown in Fig. 1. The change in the upper critical threshold field per unit temperature, the slope $\Delta H_{c2}/\Delta T$, was about $-3.42$ T/K for the 3D scaling analysis. The excellent scaling behavior of the fluctuations is obtained for the 3D case. On the other hand, as is seen from the graph, the 2D scaling plot gives rather poor results, especially at low temperatures. Since Fig. 2 shows quite small excess conductivity, we redraw the fluctuation conductivity in log scale as shown in inset. Both of the linear and logarithmic scale, excess conductivity fit very well to the 3D scaling relation, but 2D scaling does not fit very well at the low and high-temperature region. The $T_c(H)$ is also measured from the $R(T)$ for the given $H$ with the criterion of $R=0.9\ R$ (26 K) and found to be consistent from the value obtained from the scaling analysis. The Gi number of $10^{-5}$ was estimated from the value of $\lambda_{ab}(0)\sim200$ nm (Ref. 24) and $\xi_c(0)\sim2.08$ nm from $\xi_c(0)=[\Phi_0/(2\pi H_{c2}\Gamma^{1/2})]^{1/2}$ with our estimated value of $H_{c2}=54$ T and anisotropic ratio of about $\Gamma=2$.[25] This upper critical field parallel to c-axis $H_{c2}(0)$ was estimated by using the formula of Werthamer, Helfand, and Hohenberg (WHH): $H_{c2}(0)=-0.69T_c(dH_{c2}/dT)$. Since $\xi_c(T)>\xi_c(0)$ near $T_c$ and $\xi_c(0)$ is larger than that for a c-axis lattice constant of 1.3 nm,[26] and second distance 0.8 nm between two FeAs layers, it is quite natural, to expect the 3D scaling of the excess conductivity. We also expect any quantity related to the fluctuation effect to show a 3D behavior.

It is interesting to notice that the observed spread in the scaled conductivity for the low-temperature in the critical fluctuation region for a HTSC is almost not observed in the 3D scaling of $BaFe_{1.8}Co_{0.2}As_2$ single crystals, which implies that our scaling is quite remarkable. This spread is also not negligible in the 3D scaling for $YNi_2B_2C$ (Ref. 14) or $MgB_2$ (Ref. 15) even though the Gi numbers of these two superconductors are in a range similar to that for our $BaFe_{1.8}Co_{0.2}As_2$ single crystals. In our $BaFe_{1.8}Co_{0.2}As_2$ single crystals, the broadening of the conductivity originating from the field-induced fluctuation conductivity in the critical region near the transition is quite pronounced.

## V. CONCLUSION

In conclusion, in addition to cuprate HTSC and R (R=Y and Lu) $Ni_2B_2C$ single-crystalline superconductors, we have observed fluctuation conductivity in $BaFe_{1.8}Co_{0.2}As_2$ single crystals. Including the critical fluctuation region, the scaling behavior for $BaFe_{1.8}Co_{0.2}As_2$ is well described by using a 3D theory, which is quite in contrast to the rather poor scaling for the 2D theory. Our sample's Gi was $10^{-5}$. This value is between the value of $10^{-9}$ for a conventional superconductor and the value of $10^{-2}$ for a HTSC. The analysis of the excess fluctuation conductivity showed that the superconductivity followed 3D fluctuations rather than 2D fluctuations even though the superconductor had a layered structure.

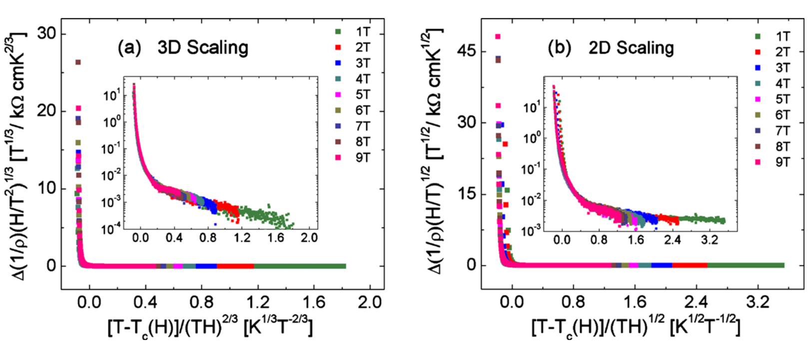


FIG. 2. (Color online) (a) Best fit of the 3D scaling and (b) that for 2D scaling.

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[1]Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono, J. Am. Chem. Soc. **130**, 3296 (2008).
[2]X. H. Chen, T. Wu, G. Wu, R. H. Liu, H. Chen, and D. F. Fang, Nature (London) **453**, 761 (2008).
[3]G. F. Chen, Z. Li, D. Wu, G. Li, W. Z. Hu, J. Dong, P. Zheng, J. L. Luo, and N. L. Wang, Phys. Rev. Lett. **100**, 247002 (2008).
[4]Z. A. Ren, J. Yang, W. Lu, W. Yi, X. L. Shen, Z. C. Li, G. C. Che, X. L. Dong, L. L. Sun, F. Zhou, and Z. X. Zhao, EPL **82**, 57002 (2008).
[5]Z. A. Ren, J. Yang, W. Lu, W. Yi, G. C. Che, X. L. Dong, L. L. Sun, and Z. X. Zhao, Mater. Res. Innovations **12**, 105 (2008).
[6]J. Yang, Z. C. Li, W. Lu, W. Yi, X. L. Shen, Z. A. Ren, G. C. Che, X. L. Dong, L. L. Sun, F. Zhou, and Z. X. Zhao, Supercond. Sci. Technol. **21**, 082001 (2008).
[7]J. A. Rodgers, G. Penny, A. Marcinkova, J. Bos, D. Sokolov, A. Kusmartseva, A. Huxley, and J. Attfield, Phys. Rev. B **80**, 052508 (2009).
[8]P. Cheng, B. Shen, G. Mu, X. Zhu, F. Han, B. Zeng, and H. H. Wen, EPL **85**, 67003 (2009).
[9]H. Takahashi, K. Igawa, K. Arii, Y. Kamihara, M. Hirano, and H. Hosono, Nature (London) **453**, 376 (2008).
[10]M. Rotter, M. Tegel, and D. Johrendt, Phys. Rev. Lett. **101**, 107006 (2008).
[11]A. S. Sefat, R. Jin, M. A. McGuire, B. C. Sales, D. J. Singh, and D. Mandrus, Phys. Rev. Lett. **101**, 117004 (2008).
[12]K. Sasmal, B. Lv, B. Lorenz, A. M. Guloy, F. Chen, Y. Y. Xue, and C. W. Chu, Phys. Rev. Lett. **101**, 107007 (2008).
[13]G. Blatter and V. Geshkenbein, *The Physics of Superconductors*, edited by K. H. Bennerman and J. B. Ketterson (Springer, Berlin, 2003), Vol. 1, p. 800.
[14]M. O. Mun, S.-I. Lee, and W. C. Lee, Phys. Rev. B **56**, 14668 (1997).
[15]W. N. Kang, K. J. Kim, H. J. Kim, E. M. Choi, M. S. Park, M. S. Kim, Z. Du, C. U. Jung, K. H. Kim, S.-I. Lee, and M.-O. Mun, J. Korean Phys. Soc. **40**, 949 (2002).
[16]Z. Pribulova, T. Klein, J. Kacmarcik, C. Marcenat, M. Konczykowski, S. L. Bud'ko, M. Tillman, and P. C. Canfield, Phys. Rev. B **79**, 020508 (2009).
[17]J. Kacmarcik, C. Marcenat, T. Klein, Z. Pribulova, C. J. Beek, M. Konczykowski, S. L. Budko, M. Tillman, N. Ni, and P. C. Canfield, Phys. Rev. B **80**, 014515 (2009).
[18]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).
[19]S. Ullah and A. T. Dorsey, Phys. Rev. Lett. **65**, 2066 (1990).
[20]S. Ullah and A. T. Dorsey, Phys. Rev. B **44**, 262 (1991).
[21]R. Ikeda, T. Ohmi, and T. Tsuneto, J. Phys. Soc. Jpn. **60**, 1051 (1991).
[22]Z. Tešanović, L. Xing, L. Bulaevskii, Q. Li, and M. Suenaga, Phys. Rev. Lett. **69**, 3563 (1992).
[23]M.-O. Mun, S.-I. Lee, S.-H. Suck Salk, H. J. Shin, and M. K. Joo, Phys. Rev. B **48**, 6073 (1993).
[24]N. Ni, M. E. Tillman, J.-Q. Yan, A. Kracher, S. T. Hannahs, S. L. Bud'ko, and P. C. Canfield, Phys. Rev. B **78**, 214515 (2008).
[25]R. T. Gordon, N. Ni, C. Martin, M. A. Tanatar, M. D. Vannette, H. Kim, G. D. Samolyuk, J. Schmalian, S. Nandi, A. Kreyssig, A. I. Goldman, J. Q. Yan, S. L. Bud'ko, P. C. Canfield, and R. Prozorov, Phys. Rev. Lett. **102**, 127004 (2009).
[26]Q. Huang, Y. Qiu, W. Bao, M. A. Green, J. W. Lynn, Y. C. Gasparovic, T. Wu, G. Wu, and X. H. Chen, Phys. Rev. Lett. **101**, 257003 (2008).