Critical and Gaussian conductivity fluctuations in a BaFe$_{1.9}$Ni$_{0.1}$As$_2$ superconductor

S Salem-Sugui Jr$^1$, A D Alvarenga$^2$, R I Rey$^3$, J Mosqueira$^3$, H-Q Luo$^4$ and X-Y Lu$^4$

$^1$ Instituto de Física, Universidade Federal do Rio de Janeiro, 21941-972, Rio de Janeiro, RJ, Brazil
$^2$ Instituto Nacional de Metrologia Qualidade e Tecnologia, 25250-020 Duque de Caxias, RJ, Brazil
$^3$ LBTS, Universidade de Santiago de Compostela, E-15782, Spain
$^4$ Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, People’s Republic of China

E-mail: said@if.ufrj.br

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Abstract

We study fluctuation conductivity in a single crystal of BaFe$_{1.9}$Ni$_{0.1}$As$_2$ superconductor ($T_c = 20$ K) as a function of temperature and applied magnetic field. Magneto-conductivity curves, $\Delta \sigma$ versus $T$, were analyzed in terms of $-1/(d \ln(\Delta \sigma)/dT)$ versus $T$ plots, which allow us to study different fluctuation regimes and to estimate exponent values and temperature widths of each regime. The analysis of magneto-conductivity curves evidences the existence of only two fluctuation regimes, a possible critical one (of glass-like type) going from the irreversible temperature to above $T_c(H)$, followed by Aslamazov–Larkin fluctuations in the Gaussian regime.

(Some figures may appear in colour only in the online journal)

1. Introduction

The study of superconducting fluctuations above the superconducting transition temperature, $T_c$, in iron-based superconductors [1] has gained increasing attention [2–20], as these effects extend up to relatively large temperatures above $T_c$, when compared with low-$T_c$ superconductors [21]. These enhanced fluctuations as observed in pnictides are due to their layered structure in conjunction with their relatively large $T_c$, large values of the Ginzburg–Landau (GL) parameter, $\kappa$, and large values of the upper critical field, $H_{c2}(0)$ (low values of the coherence length). Studies of superconducting fluctuations, near and above $T_c$, allow us to compare experiments with available theoretical predictions for critical and Gaussian fluctuations in superconductors. As fluctuations are sensitive to the pairing symmetry, it is of particular interest to study pnictides, for which multi-band (inter-band) levels participate in the pairing [22, 23] producing an $s\pm$ symmetry (the symmetry is still not clear, and seems to depend on the doping [8]). For instance, a recent theoretical work taking into account the characteristic inter-band pairing of the pnictides and an $s\pm$ symmetry [8] predicted that conductivity fluctuations should exhibit only one critical regime, while two critical regimes are expected near $T_c$ for an $s$-wave pairing (a static one, followed by a dynamic) [24]. Superconducting fluctuations can also provide information on the system dimensionality. Analysis of critical and Gaussian fluctuations in the studied pnictides in the literature appears to support a three-dimensional, 3D, behavior [4–7, 10, 14], but two-dimensional behavior was observed for higher fields (above 8 T) in the SmFeAs system [3] and in LiFeAs [19], and a recent theory of critical fluctuations was specially developed for pnictides considering an intermediate dimensionality between two and three for high applied magnetic fields, which seems to explain high-field experimental data as well [9].

The Ginzburg criterion which defines the temperature width of critical fluctuations close to $T_c$ can be estimated by the relation $|T - T_c| < 1.07 \times 10^{-9}(\kappa^2 T_c^2/H_{c2}(0))$ K [24] where $H_{c2}(0)$ is the field obtained by extrapolating the linear region near $T_c$ in the $H$ versus $T$ diagram to $T = 0$ K.
Values for conventional superconductors are [24] \(|T - T_c| < 10^{-6}\) K, \(|T - T_c| \leq 1\) K for high-\(T_c\) cuprates [25–27], but of the order of \(10^{-3}\) K for pnictides [7]. This predicted narrow critical region, difficult to be resolved experimentally, can increase by orders of magnitude under the effect of a high magnetic field that constricts the pairs to the lowest Landau level, lowering the system dimensionality [28]. The latter explains the considerably large critical fluctuation regime that has been observed in pnictides under high applied magnetic fields [3–7, 10–14].

In most of the cases the study of high-field critical fluctuations is possible by checking if experimental curves follow specific scaling laws derived from the GL theory developed for layered systems within the lowest Landau level approximation (LLL) and taking into account interactions in the fluctuation regime [29, 30]. These scalings laws when applied to experimental data may allow us to estimate many values of GL intrinsic parameters [28], but unfortunately, do not provide even qualitative information regarding the temperature width where these fluctuations are important.

Conductivity fluctuations above the superconducting transition temperature, also known as excess conductivity or paraconductivity, have been widely theoretically and experimentally studied in most of the known superconductors [21, 28], including earlier works studying Gaussian fluctuations at zero magnetic field within the well-known Aslamazov–Larkin (AL) theory [31, 21]. In more recent experimental works performed in the presence of magnetic fields, fluctuation effects are interpreted in terms of extensions of the AL theory [2, 32] when in the Gaussian regime, and near the transition temperature, by scaling laws derived from GL theories which include correlations in the fluctuation regime, then critical [29, 28]. For pnictides, magnetoconductivity studies were performed in SmFeAsO [13], BaFe2As2 [7], LaOFeAs [14], LiFeAs [19] and in BaFe2As2 single crystal [33] with \(T_c \approx 20.0\) K and \(\Delta T_c \approx 0.3\) K (electron-doped 122 system). We focus our analysis on the width of the critical regime above the superconducting transition, the associated critical exponents, and the evolution of this regime with the applied magnetic field. As will be shown, the results resolved for the first time the width of the critical region under applied magnetic field and its associated critical exponent.

2. Experimental details

As detailed in [2], precise isofield resistivity, \(\rho\), measurements were obtained as a function of temperature, for magnetic fields running from 0 to 9 T applied parallel to the \(c\)-axis of the sample. The excess conductivity, \(\Delta\sigma\), above the superconducting temperature transition is obtained from each isofield resistivity curve by subtracting the normal state resistivity, \(\rho_0\), extrapolated to lower temperatures. The lower inset shows \(d\rho/dT\) for \(H = 0\).

\[ \Delta\sigma \propto A(T - T_c)^{-\alpha} \]

where \(A\) is a constant and \(\alpha\) an exponent which assumes different values depending on the regime of fluctuations. This equation is expected to hold in the presence of a magnetic field by just replacing \(T_c\) by \(T_c(H)\). In the absence of magnetic fields, the expected values of the exponent \(\alpha\) are as follows: \(\alpha = 1/2\) in the mean field regime, crossing over to \(\alpha \approx 0.67\) as temperature approaches \(T_c\) corresponding to a static critical exponent, crossing over to \(\alpha \approx 0.33\) even closer to
Figure 2. $-1/(d \ln(\Delta \sigma)/dT)$ is plotted against $T$ for (a) $H = 0$, and (b) $H = 1$ T. The inset in (a) shows $\ln(\Delta \sigma)$ versus $T$ for $H = 0$ and a 3D-AL theory fitting extracted from [2]; the inset in (b) shows $\delta T(H)$ versus $H$.

$T_c$, corresponding to a dynamical critical exponent [24]. The equation above can also be written as $-1/(d \ln(\Delta \sigma)/dT) = (1/\alpha)(T - T_c)$, and analysis of experimental conductivity curves in terms of plots of $-1/(d \ln(\Delta \sigma)/dT)$ versus $T$ may allow us to estimate exponent values and temperature widths in the fluctuation regime [26]. Here, we apply this approach, among others, to analyze the conductivity curves presented in figure 1.

Figures 2(a) and (b) show plots of the quantity $-1/(d \ln(\Delta \sigma)/dT)$ versus $T$ as obtained from the conductivity curve for $H = 0$ and $H = 1$ T respectively. The derivatives $d \ln(\Delta \sigma)/dT$ were calculated by using the commercial program Origin 8. As shown in figure 2(a), it is possible to identify two distinct linear regions above $T \approx 19.9$ K. The first region with a width $\Delta T \approx 0.6$ K has an exponent $\alpha \approx 0.42$, which is close to the mean field value $\alpha = 0.5$ and it appears to be associated with three-dimensional AL fluctuations, as discussed above. An extrapolation of this region to the $T$ axis, suggests the value of $T_c = 20.2$ K. The region below 20.2 K in figure 2(a) is likely to be associated with the transition width $\approx 0.3$ K. As expected, the experiment cannot resolve any critical region near $T_c$, which would occur within a $10^{-3}$ K width. A second region with $\alpha \approx 3$ starts at $T \approx 21.1$ K and seems to extend up to higher temperatures although a large spread of the data is observed above 23–24 K (not shown). The inset of figure 2(a) shows the original $\ln(\Delta \sigma)$ versus $T$ curve of the main figure and the dashed line is the fitting of the data following the 3D AL theory presented in [2]. Arrows in this inset give a rough indication of the exponents $\alpha$ in the curve. Between these two regions, the plot in figure 2(a) shows a small region with decreasing curvature from which one can barely resolve an exponent $\alpha \approx 0.85$. Probably this small region has no associated exponent and just represents a decay in the amplitude of AL fluctuations, which is physically expected to occur as temperature increases above $T_c$ (entering in the region with $\alpha \approx 3$). Such a decay in the amplitude fluctuations is related to the well-known short-wavelength effects occurring well above $T_c$ [34, 35], and explains the rather large value of the exponent $\alpha \approx 3$ associated with AL Gaussian fluctuations in the corresponding region [2].

Figure 2(b) shows the same plot as figure 2(a), but with a magnetic field $H = 1$ T, which exhibits a totally different scenario. It is possible to resolve three different linear regions in this figure. The first region, with $\alpha \approx 2.4$, starts just above the irreversible temperature, $T_{irr}$ ($T_{irr}$ is defined here as the temperature below which a critical current $J_c > 0$ is established), and ends close to the mean field transition temperature, $T_c(H)$, which is estimated by extrapolating the second regime with $\alpha \approx 0.88$ to the $T$-axis (marked with an arrow). Above $T_c(H)$ there are two distinct regions, the first, with $\alpha \approx 0.88$, is most likely to be related to the mean field AL fluctuations under a magnetic field (similar to the AL fluctuations with $\alpha \approx 0.42$ observed in figure 2(a) with $H = 0$), and the second one, with $\alpha \approx 1.4$, is likely to be associated with AL fluctuations with short-wavelength effects since data in this region lies in the same region where the amplitude fluctuations decay to zero as temperature increases [2].

Figure 3 shows plots of $-1/(d \ln(\Delta \sigma)/dT)$ versus $T$ for magnetic fields running from 3 to 9 T. It is interesting to observe in this figure that all curves exhibit only two different regions, each one with approximately the same exponent (the exponent of the region starting at $T_{irr}$ varies between 2.1 for $H = 3$ T and 2.6 for $H = 9$ T, similar to the region starting at $T_{irr}$ for $H = 1$ T in figure 2(b), and the exponent of the second region varies between 1.3 and 1.4) similar to the second region above $T_c(H)$ in figure 2(b)), which appears to be a clear effect of the high magnetic field. The absence of a linear region occurring between these two regions, as observed for $H = 1$ T in figure 2(b) with $\alpha \approx 0.88$, impedes us from estimating a value for $T_c(H)$ in each curve of figure 3. The second region in the curves of figure 3 with $\alpha \approx 1.3$ is likely to be associated with AL fluctuations with short-wavelength effects (in analogy to the region with $\alpha \approx 1.3$ in figure 2(b)) [2]. The first linear regions starting at $T_{irr}$ in the curves of figure 3 (and of figure 2(b)) with exponents $\alpha$ varying between 2.1 and 2.6 correspond to the reversible (flux–flow) regions observed.
in the resistivity curves which show a rounding effect (as resistivity approaches the normal region) due to thermal fluctuations.

Many types of fluctuations have been proposed to explain the flux–flow region in type II superconductors, including glass-like fluctuations occurring near (above) the glass transition temperature \( T_g(H) \) \([36]\), low-field 3DXY fluctuations (driven by phase fluctuations of the complex order parameter as in superfluid \(^4\)He) \([24]\) and high-field LLL fluctuations \([29, 28]\). In the case of LLL fluctuations, the high magnetic field constrains the pairs to the lowest Landau level which acquires an effectively 1D dimension enhancing the importance of fluctuations. As it is shown in \([29]\) the inclusion of the quartic \( \beta \Delta^4 \) term in the GL Hamiltonian within the LLL-approximation (this term is only important in the critical region near \( T_c(H) \)) removes the divergence at the mean field \( T_c(H) \) and as a consequence the mean field \( H_{c2}(T) \) line becomes a crossover line. Since fluctuations of the 3DXY type have been used to explain the vortex-liquid phase in resistivity and magnetization curves in the low-field regime \([37, 38]\), we applied a 3DXY scaling for conductivity to our isofield \( \sigma(T) \) curves of figure 1, where a plot of \( \log_{10}(\sigma(T)H^{0.5}) \) versus \( (1 - T/T_c)H^{-0.743} \) (where \( T_c \) is the only adjustable parameter, and \( 1/2\nu = -0.743 \) where \( \nu_{xy} = -0.669 \)) is expected to collapse in to a single curve. Figure 4(b) shows this plot with the parameter \( T_c = 20 \) K, evidencing that the lower field curve for \( H = 1 \) T fails to follow the scaling, which excludes this type of fluctuations. For the case of glass-like fluctuations occurring near (above) \( T_g(H) \) \([36]\), the conductivity is expected to follow \( \sigma \equiv A(T - T_g)^{-\alpha} \) with the critical exponent \( \alpha = \nu(2 + z - d) \) where \( \nu \) is the coherence length exponent, \( z \) is the dynamical critical exponent and \( d \) is the dimensionality. This type of fluctuations has been considered in the 3D ‘gauge glass’ model (in the vortex representation) presented in \([39]\) where it is obtained \( \nu = 1.3 \) and \( z \approx 3.1 \) producing \( \alpha \approx 2.7 \) \((d = 3)\), which value is close to the values of the exponent \( \alpha \) found in figures 3 and 2(b). This agreement suggests that the first linear regions of figures 2(b) and 3 can be explained in terms of gauge glass fluctuations \([39]\) occurring around (above) \( T_{irr} \). In that case, a second order phase transition (possibly a glass phase) should take place at some temperature very close to \( T_{irr} \).

Since the glass transition is driven by disorder, it is important to compare the irreversibility line obtained from \( T_{irr} \) values extracted from the curves of figures 2(b) and 3 with the expression developed in \([40]\) for the (glass line) irreversibility line which considers the effect of disorder:

![Figure 3](image1.png)

**Figure 3.** \(-1/d \ln(\Delta \sigma)/dT\) is plotted against \( T \) for \( H \geq 3 \) T. Vertical arrows up show the position of \( T_c(H) \), obtained from the 3D-LLL scaling, in each respective curve.

![Figure 4](image2.png)

**Figure 4.** (a) \( H \) versus \( T \) phase diagram for the studied sample. The solid line is a fitting of the irreversibility line to the theory in \([40]\). (b) Results of the 3DXY scaling. (c) Results of the 3D-LLL scaling. The \( Y \)-axis is in units of \((Oe^{-1/3} \Omega^{-1} m^{-1} K^{-2/3})\).
with values of $T_{irr}$ in figure 4(a). To better visualize the results of this work, we added an arrow in each curve of figures 3 and 1 indicating the position of $T_c(H)$ obtained from the scaling approach, and a line linking the values of conductivity at the virtual points separating critical and Gaussian regimes in figure 3 (dotted line) and in figure 1 (solid line named $T^*$ line).

4. Conclusions

In conclusion, analysis of high-field conductivity curves evidences the existence of only two fluctuation regimes, a possible critical one going from the irreversible temperature to above $T_c(H)$, followed by Aslamazov–Larkin fluctuations in the Gaussian regime. Our analysis suggests that critical fluctuations emerge above $T_{irr}$ under high applied magnetic fields. These critical fluctuations, not resolved for zero magnetic field, appear to account for the excess conductivity above $T_c(H)$, which extends more than 1 K for 9 T. The analysis allowed us to estimate with certain accuracy the width of the critical region as well as its associated critical exponent.

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