Evidence of anisotropic phase correlations above T_c in single crystalline $\text{Ba}_{0.54}\text{K}_{0.46}\text{Fe}_2\text{As}_2$

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Abstract

Isofield magnetization curves have been recorded and analyzed in optimally doped $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ single crystal in two main crystallographic directions ($H\parallel c$ -axis and $H\parallel ab$ -planes). Near transition temperature (T_c), magnetization exhibits temperature dependence $\sqrt{-M} \propto [T_a(H) - T]^m$, where T_a is the apparent transition temperature and represents onset of phase coherence of the superconducting order parameter. We have shown that T_a behaves differently in two main crystallographic directions: $dT_a(H)/dH > 0$ for $H\parallel ab$ -planes and $dT_a(H)/dH < 0$ for $H\parallel c$ -axis. In $H\parallel ab$ -planes we have observed $T_a(H) > T_c$ which implies that magnetic field can probe a region above T_c where phase correlation persists. We suggest that multiband character may be the possible reasons for anomalous behavior of T_a . The obtained values of fitting exponents (m) are larger than 0.5 and increase with magnetic field.

Keywords: Pnictides; single crystal; fluctuation phenomena; magnetization.

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1. Introduction

Superconducting fluctuations are very important near the transition temperature (T_c) and affects many physical properties near T_c [1-4]. The effect of superconducting fluctuations is more in the case of layered high T_c superconductors compared to conventional BCS system. There are theories predicting many physical properties with magnetic field and temperature in presence of enhanced fluctuations [5, 6]. In Ref. 6 it has been explained that phase coherence is pronounced near T_c as a consequence of small phase stiffness in the case of underdoped cuprates having very low superfluid density. Recently discovered iron based superconductors [7, 8] are very much interesting since many important things like pairing mechanism, gap symmetry are not yet known like high T_c cuprates. In this work we study the phase correlations that persist above T_c in the region of reversible magnetization of single crystal iron pnictide $\text{Ba}_{0.54}\text{K}_{0.46}\text{Fe}_2\text{As}_2$ system [8]. This system acquires low anisotropy ($\gamma \sim 2-3$) and shows multiband nature in contrast to cuprates. Some experiments show that this system has an s-wave multiband pairing symmetry [9]. In other experiments, [10] s-wave gap with nodes is also claimed in this system and a recent theoretical work [11] shows multiband s-wave gap can have nodes. Three-dimensional fluctuation magnetization of the lowest-Landau-level type has been observed in under-doped $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ system in a temperature window exceeding 3 K above T_c in Ref. 12. They also examined asymptotic behavior of the gap near $T_c(H)$ and value of the exponent was larger than 0.5. Fluctuation diamagnetism has been observed with magnetic field applied along the two main crystallographic directions in the single crystal of $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ [13]. This work was motivated by the fact that whether the nature of phase correlations is different in two main crystallographic directions of the single crystal of iron based superconductors with low

anisotropy under application of magnetic field or it shows similar fluctuation behavior in two different directions. Here we address the existence of phase correlation above T_c under the application of magnetic field along two main crystallographic directions in the single crystal of $\text{Ba}_{0.54}\text{K}_{0.46}\text{Fe}_2\text{As}_2$ (BaK122) and observe different behavior in the two above mentioned directions which has not been clearly explored in the literature.

Isofield magnetization curves (M vs T) were obtained for BaK122 in magnetic field applied parallel and perpendicular to the c axis. We study isofield curves of $\sqrt{-M}$ vs T , since $\sqrt{-M}$ is directly proportional to the amplitude of the order parameter $|\psi|$ near T_c . The energy gap is proportional to the modulus of the order parameter. Below $T_c(H)$ the curve ($\sqrt{-M}$ vs T) shows an asymptotic behavior of the form $(T_a - T)^m$, where $T_a(H)$ is an apparent transition temperature representing the onset of phase correlations and m is a fitting exponent.

2. Experimental details

We have taken optimal-doped $\text{Ba}_{0.54}\text{K}_{0.46}\text{Fe}_2\text{As}_2$ (BaK122) single crystal ($\text{RRR} \approx 10$) with $T_c = 38.5\text{K}$ for measurements and this single crystal is grown at Rice University, USA. The single crystals were prepared by self-flux method [14]. The studied single crystal shows sharp superconducting transition with $\Delta T_c \approx 1.5\text{K}$ which has been demonstrated in our previous study [15]. The sample with dimensions of the order $1 \times 1 \times 0.2 \text{ mm}^3$ has been taken for all the measurements. Crystallographic c axis was perpendicular to the largest plane of the samples. Isofield measurements (M vs T curves) were recorded by using a commercial magnetometer based on superconducting quantum interference device (SQUID, Quantum Design). All data have been recorded after cooling the sample above T_c under the earth magnetic field to the

desired temperature below T_c . Then we have recorded the data by heating the sample slowly (small temperature ramp rate) after applying the desired magnetic field without overshoot using high precision PID temperature controller (Lakeshore, Model 340). We have carried out measurements to record field cooled (FC) curves which provides reversible magnetization. Data have been taken by applying the magnetic field in the two main crystallographic directions (H||c-axis and H||ab-planes).

3. Results and Discussions

Fig. 1 shows the isofield magnetization curves in H||c orientation. We have not shown the data for H||ab-planes which is similar to the H||c orientation. The background magnetization, M_{back} , due to normal electrons were obtained and removed from each data set by fitting the curves with $M_{back} = a + bT + c/T$ to the raw data in the temperature interval well above T_c . Similar temperature dependence for M_{back} for background corrections has been previously used by ref. 13. We have calculated T_c using the linear extrapolation of the reversible magnetization for each isofield magnetization curve and have been shown later on.

The reversible magnetization data are plotted as $\sqrt{-M}$ vs T in Fig. 2 and 3 for H||c-axis and H||ab-planes, respectively. In the case of H||ab-planes as shown in Fig. 3, there exists a crossing point where magnetization is independent of magnetic field. This interesting feature has been observed in two-dimensional (2D) systems [16] and in three-dimensional (3D) systems [17,18] and it can be explained in terms of vortex fluctuations. We did not observe any crossing point for BaK122 single crystal when H||c-axis. It is interesting to note that in one orientation (H||ab-planes) of magnetic field, crossing point is observed but in other orientation (H||c-axis) there is no crossing point. In Fig. 4 we have shown the variation of apparent transition

temperature (T_a) with magnetic field. T_a increases with magnetic field when magnetic field is parallel to ab - planes in contrast to the conventional trend followed by T_c . This prevents all analyzed data to be shown in one figure.

According to the conventional theory of upper critical field, magnetic induction B can be written from Ginzburg-Landau equation as follows [3]

$$B = H - \frac{4\pi e\hbar}{mc} |\psi|^2, \quad (1)$$

where ψ is the order parameter. The magnetization $M = (B - H)/4\pi$ is

$$M = -\frac{e\hbar}{mc} |\psi|^2 \quad (2)$$

and follows that $\sqrt{-M}$ is directly proportional to the average amplitude of the order parameter. Then near the superconducting transition temperature T_c , $\sqrt{-M}$ can be expressed as $\sqrt{-M} \propto [T_c(H) - T]^m$, where $T_c(H)$ denotes mean field transition temperature and m is the critical exponent. The mean field value of m is $1/2$ for s-wave BCS superconductor [3] and for d-wave superconductor within a Ginzburg-Landau theory [19]. Here we have fitted the isofield magnetization data using $\sqrt{-M} \propto [T_a(H) - T]^m$, where $T_a(H)$ denotes the apparent transition temperature and m is the fitting exponent. Using the above analysis we infer the existence of phase correlations above the mean field transition temperature (T_c) and anisotropic nature of phase correlations in the two main crystallographic directions. The superconducting order parameter has two degrees of freedom: phase and amplitude. The superconducting transition (T_c) represents the temperature at which phase coherence is lost [6]. The phase mediated

behavior is a long standing debate since the era of cuprates. For underdoped high- T_c cuprates with a d-wave order parameter symmetry, phase fluctuations have an important effect on the superfluid density of states and reduce the gap in the vicinity of T_c [5]. In Fig. 3, we have observed a crossing point where magnetization is independent of applied magnetic field. We have shown the crossing point using extrapolated lines in the figure. We did not observe any such point in the isofield curves when $H||c$ -axis. In Ref. 12, Sugui *et al.* also observed similar behavior of isofield curves of K doped 122 iron based superconductor. But they used different doping concentrations with smaller T_c and carried out measurements only in $H||c$ -axis. The crossing point has been seen in two dimensional (2D) [15] and three dimensional (3D) systems [17,18]. High T_c superconductors like cuprates have high anisotropic parameter, strong two dimensionality and single band character. In iron based superconductors, all five Fe 3d-orbitals contribute to the electronic structure near Fermi level and also anisotropy is low ($\gamma \sim 2-3$) in contrast to cuprates. Since we have observed different behaviors in the different orientations of magnetic field, we can infer that anisotropy plays an important role in phase correlations near T_c . Another important parameter is the apparent transition temperature T_a which represents the onset of phase coherence in this scenario. We have determined magnetic field dependence of apparent transition temperature (T_a) from this analysis. Figs. 4(a) and 4(b) show the variation of T_a with magnetic field in two magnetic field orientations. We have also shown the variation of transition temperature (T_c) in two magnetic field orientations in Figs. 4(a) and 4(b). The resulting values of T_a follow the conventional trend $dT_a(H)/dH < 0$ as followed by T_c when $H||c$ -axis. When magnetic field is parallel to the ab-plane, T_a does not follow the conventional trend $dT_a(H)/dH < 0$ and $T_a(H) > T_c$. This result is indeed very interesting. So the onset of phase

coherence temperature behaves differently in the two main crystallographic directions under magnetic field. It has been observed for underdoped cuprates that T_a behaves differently with magnetic field in two different directions [20]. In $H \parallel ab$ -planes, $T_a(H)$ is essentially constant with no resolvable slope and in $H \parallel c$ -axis, $T_a(H)$ shows anomalous behavior with $dT_a(H)/dH > 0$ [20]. They have suggested that this anomalous behavior is due to the anisotropic nature of the symmetry of order parameter: s-wave along c-axis vs d-wave in the ab planes [20]. In iron pnictides pairing mechanism is still under debate, whether it is a fully gaped s-wave [21] or unconventional with nodes [11]. Presence of nodes in the order parameter plays an important role in controlling the behavior of phase and amplitude fluctuation above T_c [5]. Unconventional pairing with sign changing s-wave has been proposed for iron pnictides [22]. But till now there has been no observation of presence of different symmetry of the order parameter in two different directions in iron pnictides. So, by observing the anomalous behavior of $T_a(H)$ we can conclude that magnetization can probe a regime where phase correlations persist above T_c . The anisotropic nature of symmetry of order parameter and multiband nature may be the possible reasons for this anomalous behavior of $T_a(H)$ in 122 type hole doped superconductors. To establish clearly more experimental work is required on other iron based superconductors. Another important parameter can be extracted from the fitting: the value of exponent m . For s-wave BCS superconductors [3] and d-wave superconductors within a Ginzburg-Landau theory [19] the value of mean field exponent (m) is $1/2$. The extracted values of m are written inside the figure. The values of m are larger than 0.5 and increases with magnetic field for both orientations. We have got large value for 30 kOe magnetic field. This deviation might be related to the spreading of the data points. Since we have used only optimal doped materials we can

anticipate that the value of m strongly depends on magnetic field for a particular field orientation. In Ref. 12, the values of m were larger than 0.5 and were increasing with field for the same system but with different K doping. So our result is consistent with the earlier observations [12]. This result is an evidence of phase fluctuations. It is shown in Ref. 5 that phase fluctuation play an important role when there is a node in the order parameter and change the shape of the gap near T_c . In conclusion, above values of m are consistently larger than 0.5 similar to the previous observations [12,20].

4. Conclusion

In conclusion, we have clearly observed anisotropic phase correlations that persist above T_c in $\text{Ba}_{0.54}\text{K}_{0.46}\text{Fe}_2\text{As}_2$ single crystal and it is more prominent in the orientation of $\text{H}\parallel\text{ab}$ -planes. Apparent transition temperature (T_a) that represents the onset of phase coherence behaves differently in two main crystallographic directions: $dT_a(H)/dH > 0$ for $\text{H}\parallel\text{ab}$ -planes and $dT_a(H)/dH < 0$ for $\text{H}\parallel\text{c}$ -axis. We have suggested that multiband nature may be the possible reasons for this anomalous behavior of $T_a(H)$ in 122 type hole doped superconductors. The values of m are larger than 0.5 and increases with magnetic field. This confirms the dominant effects of phase correlations above T_c . More theoretical and experimental works on other iron based superconductors are required to understand clearly the nature of order parameter symmetry in two different directions for explaining the phase correlations above T_c .

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Figure Caption

Fig. 1. Isofield magnetization curves (M vs T) for $\text{Ba}_{0.54}\text{K}_{0.46}\text{Fe}_2\text{As}_2$ single crystal with $T_c=38.5$ K for H||c-axis: zfc curves for 0.1, 0.5, 1, 5, 10, 20, 30 kOe.

Fig. 2. Isofield curves of $\sqrt{-M}$ vs T for $\text{Ba}_{0.54}\text{K}_{0.46}\text{Fe}_2\text{As}_2$ single crystal for H||c-axis.

Fig. 3. Isofield curves of $\sqrt{-M}$ vs T for $\text{Ba}_{0.54}\text{K}_{0.46}\text{Fe}_2\text{As}_2$ single crystal for H||ab-planes. Inset: $\sqrt{-M}$ vs T curve for 30 kOe in the same orientation mentioned above.

Fig. 4 (a) Variation of phase correlation temperature $T_a(H)$ and transition temperature T_c with magnetic field H for H||c-axis. (b) Variation of phase correlation temperature $T_a(H)$ and transition temperature T_c with magnetic field H for H||ab-planes.