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Angular-dependent magnetic torque in iron-pnictide $BaFe_{2-x}Ni_xAs_2$

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Angular-dependent torque measurements have been performed on the electron doped iron-pnictide superconductors $BaFe_{2-x}Ni_xAs_2$ with series of Ni concentrations. In the superconducting state, an irreversibility, as the evidence for the presence of vortex, is observed between the torque measured with increasing and decreasing angle. Our results in underdoped samples $x = 0.065$ show that the irreversible torque signal survives up to a temperature T_{irr} well above the superconducting transition temperature T_c, suggesting the existence of superconducting vortices above T_c, which is likely to originate from superconducting fluctuations.

Keywords: Iron-pnictide; magnetic torque; superconducting fluctuations.

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1. Introduction

Superconducting fluctuations (SCFs) above the superconducting transition temperature (T_c) have been demonstrated to exist in both conventional and unconventional superconductors.[1–4] Due to the small coherent length, large anisotropy and reduced charge carrier density, unconventional high-T_c superconductors exhibit strongly enhanced fluctuations of diamagnetism compared to conventional superconductors. In high-T_c cuprates, a large number of theoretical and experimental studies about SCFs have been performed, aiming at probing the boundary of SCF and understanding the relationship between the pseudogap and superconductivity. Up to date, theoretical calculations,[5] high-frequency conductivity measurements,[6] Nernst effect,[1,7,8] specific heat,[9] magnetization,[10,11] magnetic torque,[12–14] as well as magnetoresistance studies[15,16] all indicate that superconducting vortices can survive on a large temperature scale above T_c. The regime of SCFs has been traced out in the temperature-doping (T-x) based on these investigations.

After the initial discovery of superconductivity at 26 K in $LaFeAsO_{1-x}F_x$,[17] a large number of iron-based superconductors (FeSCs) with a common layered structure of FeAs (FeSe or Te) planes were reported with T_c up to 56 K.[18] In FeSCs, SCFs have also been detected by magnetization,[19–23] specific heat[24] and paraconductivity measurements.[25] These studies also imply that dimensionality plays an important role in the fluctuation effect. For example, a two-dimensional (2D) behavior[26] which is similar to the high-T_c cuprates, three-dimensional (3D) behavior[20,27] and even a 3D-2D transition are discussed in FeSCs.[28] In addition, similar to the case in cuprates, the origin of SCFs in FeSCs is also a matter of considerable debate. Specific heat studies indicate that SCFs above T_c in $SmFeAsO_{0.8}F_{0.2}$ are probably due to the presence of phase fluctuations.[21] Similar results have also been observed in $Ba_{2-x}K_xFe_2As_2$ and $BaFe_{2-x}Rh_xAs_2$,[19,23] whereas evidence for the absence of phase fluctuations was also reported in some other FeSCs.[25,29] In this sense, further investigations into the properties and nature of SCFs in FeSCs are indispensable.

Here, we perform angular-dependent torque measurements with magnetic field up to 9 T, a technique that is sensitive to superconducting vortices,[30] on a series of high quality $BaFe_{2-x}Ni_xAs_2$ single crystals. The hysteresis between increasing and decreasing angle in torque measurements indicates the presence of superconducting vortices. Our results in underdoped $BaFe_{2-x}Ni_xAs_2$ ($x = 0.065$) sample reveal an obvious irreversibility that persists up to a temperature $T_{\mathrm{irr}} = 15$ K, much higher than the superconducting transition temperature $T_c^{\mathrm{onset}}(9\ T) = 8.5$ K (hereafter we say T_c), signaling the presence of superconducting vortices above T_c, which may arise from SCFs. Furthermore, T_{irr} is suppressed by magnetic field in the same rate as T_c, which is also supportive of SCFs as the origin of the irreversibility.

2. Experimental Detail

Single crystals of $BaFe_{2-x}Ni_xAs_2$ with a series of Ni concentrations were grown by the self-flux method.[31] In-plane resistivity were measured as a function of temperature in a physical property measurements system (PPMS-9, Quantum Design) by using standard four-electrodes method. Out-of-plane angular dependent torque were measured over a large range of temperatures and in the magnetic field up to

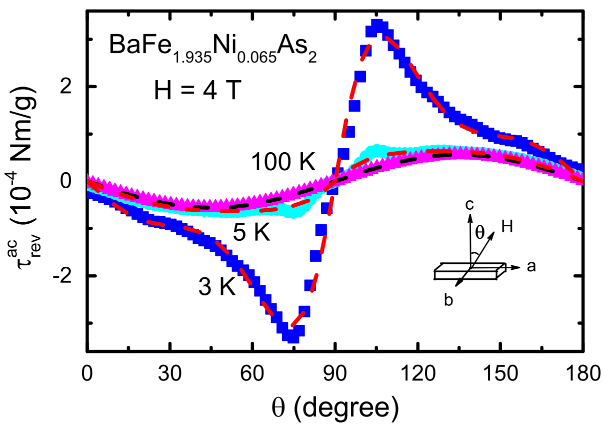

Fig. 1. (Color online) Angular dependent reversible torque $\tau^{ac}_{rev} = (\tau_{In} + \tau_{De})/2$ measured at $T =$ 3 K, 5 K, 100 K with $H = 4\ T$ for $BaFe_{1.935}Ni_{0.065}As_2$ single crystal. The red and black dashed lines are the fitting results with equation $\tau^{ac}_{irr} = \frac{\tau_{In} - \tau_{De}}{2} H^2 \sin 2\theta$ and $\tau^{ac}_{PM} = \frac{\chi_c - \chi_a}{2} H^2 \sin 2\theta$, respectively. θ is the angle between H and c-axis, where H is in the ac-plane.

9 T through a piezoresistive torque magnetometer. Here, we define θ as the angle between the applied field H and the crystallographic c-axis of the single crystal as shown in the inset of Fig. 1. The typical sample size used for torque measurements in this work are approximately $1.0 \times 1.0 \times 0.1\ mm^3$. The torque signal from the puck was measured and subtracted as previously reported.[32]

3. Results and Discussion

We first present in Fig. 1, the angular-dependent out-of-plane reversible torque $\tau^{ac}_{rev} = (\tau_{In} + \tau_{De})/2$ measured at 3, 5 and 100 K with $H = 4\ T$ for $x = 0.065$ single crystal, which exhibits superconducting transition at $T_c^{onset}(0\ T) = 10.8$ K using electrical resistivity measurements (Fig. 3(e)). τ_{In} and τ_{De} are the torque signal measured at increasing and decreasing angle, respectively. Pure paramagnetic torque signal is observed at 100 K, with the amplitude reflecting the anisotropy between the susceptibility χ_a and χ_c, χ_a and χ_c are the susceptibility parallel and perpendicular to ab-plane. The black dashed line is a fitting curve with a paramagnetic equation $\tau^{ac}_{PM} = \frac{\chi_c - \chi_a}{2} H^2 \sin 2\theta$. With decreasing temperature, the superconducting diamagnetism shows an influence on the torque signal. As shown in Fig. 1, the data at 5 K and 3 K consist of the torque signal of paramagnetic τ^{ac}_{PM} and τ^{ac}_{sc} due to superconducting diamagnetism, τ^{ac}_{sc} is originated from the Abrikosov vortex matter and it can be expressed by Kogan's model:[33] $\tau^{ac}_{sc} = \frac{\Phi_0 H V}{16\pi\mu_0\lambda^2} \frac{\gamma^2 - 1}{\gamma} \frac{\sin 2\theta}{\epsilon(\theta)} \ln\{\frac{\gamma\eta H_{c2}}{H\epsilon(\theta)}\}$, where Φ_0 is flux quantum, V is the sample volume, μ_0 is vacuum permeability, λ is the in-plane penetration, γ is the anisotropic parameter, η is a numerical parameter of order unity, H_{c2} is the upper critical field along the c-axis, and $\epsilon(\theta) = (\sin^2\theta + \gamma^2\cos^2\theta)^{1/2}$. The red dashed line at 3 K and 5 K are the fitting results by using the equation $\tau^{ac}_{rev} = \tau^{ac}_{PM} + \tau^{ac}_{sc}$, with $\lambda(T = 3\ K) \approx 340$ nm taken

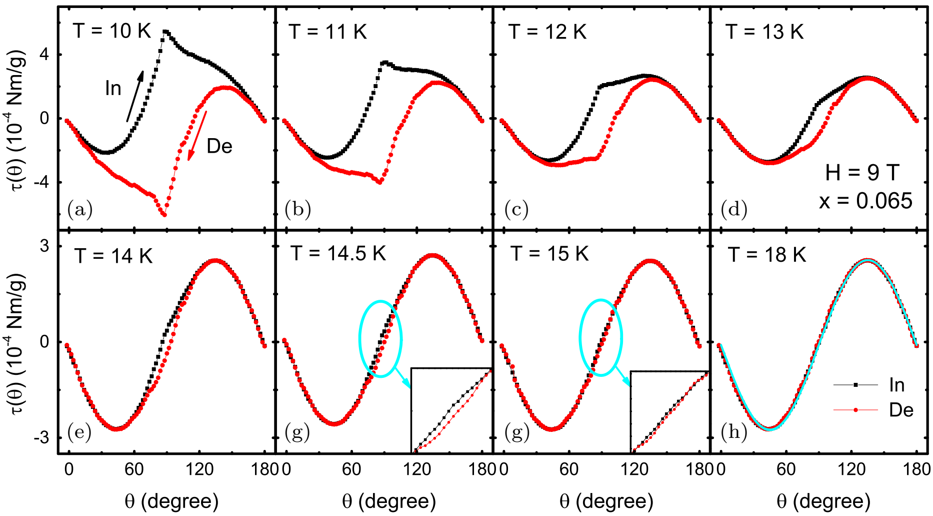

Fig. 2. (Color online) $\tau_{\rm In}(\theta)$ (black squares) and $\tau_{\rm De}(\theta)$ (red circles) curves with $H = 9\ T$ for underdoped $BaFe_{1.935}Ni_{0.065}As_2$ sample. (a)–(h) $T = 10$, 11, 12, 13, 14, 14.5, 15 and 18 K. The insets at $T = 14.5$ K and 15 K display the enlarged view of $\tau(\theta)$.

from Ref. 34. It shows a good consistency between experimental data and fitting results. From the fitting, we get the anisotropic parameter $\gamma \sim 2.86$ at 3 K and $\gamma \sim 2.13$ at 5 K, which is close to the values reported in the previous studies in 122 FeSCs.[29,35–37]

Figure 2 shows the $\tau(\theta)$ curves for $x = 0.065$ sample measured at $H = 9\,T$ at different temperatures. The black (squares) and the red (circles) curves are the torque data measured with increasing angle $\tau_{\rm In}$ and decreasing angle $\tau_{\rm De}$, respectively. As mentioned before, the irreversibility between $\tau_{\rm In}$ and $\tau_{\rm De}$ is originated from vortex, which normally only exists in the superconducting state. However, in our results, we find that the hysteresis still exists obviously up to 13 K, which is above the T_c of 8.5 K at 9 T. And with increasing temperature, the hysteresis become smaller at 14 K and 14.5 K (the inset at $T = 14.5$ K shows a clear hysteresis). At $T = 15$ K, which is far above T_c, $\tau_{\rm In}$ and $\tau_{\rm De}$ overlap each other, indicating the vanishment of the pinning of superconducting vortex. With further increasing temperature, the curves at 18 K show an obvious paramagnetic torque signal and can be well fitted by the expression $\tau^{\rm ac}_{\rm PM} = \frac{\chi_c - \chi_a}{2} H^2 \sin 2\theta$ (cyan solid line in Fig. 2(h)). The hysteresis observed in the temperature up to 14.5 K suggests that the superconducting vortex can exist above the $T_c = 8.5$ K. This provides evidence for the presence of SCFs above T_c. Meanwhile, the irreversible torque $\tau^{\rm ac}_{\rm irr} = \frac{\tau_{\rm In} - \tau_{\rm De}}{2}$ decreases obviously as the temperature increases from 10 K to 14.5 K. This may be due to the number of superconducting vortices decreases as the temperature increases away from T_c. The disappearance of irreversibility can be used as a criteria to determine $T_{\rm irr}$, the temperature up to which superconducting vortices exist. By this way, we find $T_{\rm irr} \sim 15$ K which is much larger than $T_c = 8.5$ K.

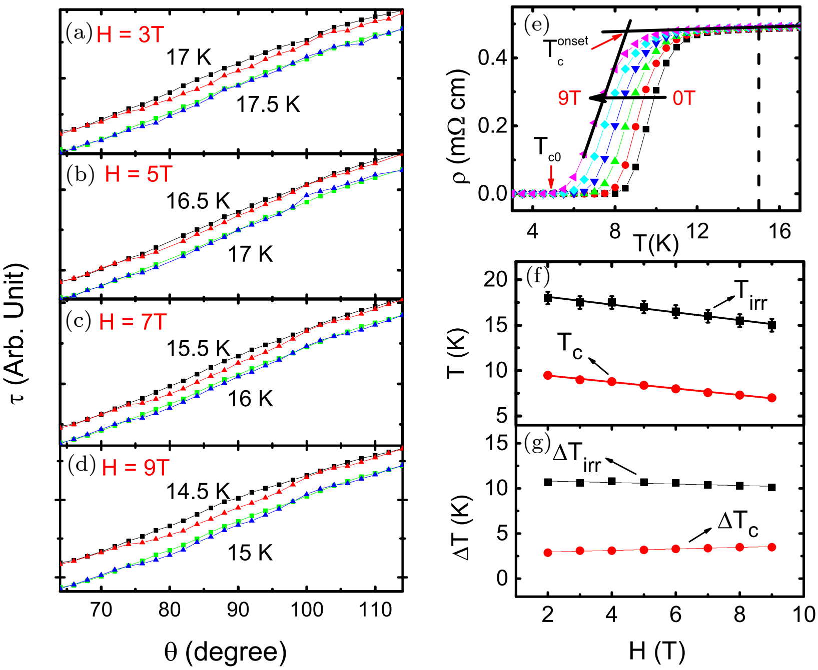

Fig. 3. Amplified $\tau_{\rm In}(\theta)$ (squares) and $\tau_{\rm De}(\theta)$ (up triangles) curves for underdoped $BaFe_{1.935}Ni_{0.065}As_2$ with H = (a) 3 T, (b) 5 T, (c) 7 T and (d) 9 T. Data were offset vertically to separate the overlapped curves at different temperatures. (e) Broadening resistivity curves for $H \parallel ab$ configurations. (f) Field dependence of $T_{\rm irr}$ and T_c curves. (g) Field dependence of $\Delta T_{\rm irr}$ and ΔT_c.

In order to reveal the influence of magnetic field on SCFs, we plot in Figs. 3(a)–3(d), $\tau_{\rm In}(\theta)$ and $\tau_{\rm De}(\theta)$ obtained from the torque data at different fields above T_c. To make the observed phenomenon more clear, we choose an enlarged curve with the angle ranging from 65° to 115° (as the inset in Figs. 3(f) and 3(g)). It is noticed that the $\tau(\theta)$ curves measured at increasing and decreasing angle are irreversible at 17, 16.5, 15.5 and 14.5 K with $H = 3$, 5, 7 and 9 T, respectively. Upon increasing the temperature at each magnetic field, the irreversibility disappears from 17.5 K at 3 T to 15 K at 9 T. This indicates that the applied field suppresses the fluctuation effect above T_c. However, the previous results in high-T_c cuprate showed that the magnetic field suppresses the diamagnetism signal below T_c and enhances the fluctuating diamagnetism above T_c,[12,38] but no evidence has been shown that the external magnetic field will influence the temperature $T_{\rm irr}$ of SCFs.

Next, we plot the in-plane resistivity $\rho_{ab}(T)$ curves with $H \parallel ab$ for different magnetic fields in Fig. 3(e). $T_c^{\rm onset}$ and T_{c0} are determined as shown in the figure. T_c, $T_{\rm irr}$, $\Delta T_c = T_c^{\rm onset} - T_{c0}$ and $\Delta T_{\rm irr} = T_{\rm irr} - T_{c0}$ are extracted and plotted in Figs. 3(f) and 3(g). In Fig. 3(f), T_c and $T_{\rm irr}$ decrease with increasing magnetic field, and the linear fitting data show an almost equivalent slope (-0.42 K/T at $T_{\rm irr}(H)$ and -0.35 K/T at $T_c(H)$ curves) between these two curves. This means that $T_{\rm irr}$ and

T_c are suppressed in the same rate by an external magnetic field, pointing to a close relation between the irreversible torque and superconductivity. In Fig. 3(g), it is observed that ΔT_c and $\Delta T_{\rm irr}$ are basically unchanged with increasing magnetic field. This suggests that the magnetic field suppresses the SCFs temperature $T_{\rm irr}$, while it has no influence on the fluctuation region in underdoped $BaFe_{1.935}Ni_{0.065}As_2$.

Since large irreversibility was observed far above T_c in the underdoped $x = 0.065$ sample, question arises as to whether this effect exists in other dopings. In order to address this question, we have done the same measurements at $H = 9\ T$ for a series of Ni-doped $(0.03 \le x \le 0.3)$ $BaFe_{2-x}Ni_xAs_2$ single crystals. Our results in the underdoped $x = 0.075$ sample (not shown) also show an irreversibility at 14 K above $T_c = 10.3$ K, suggesting that the irreversibility found in $x = 0.065$ is by no means fortuitous, but exists intrinsically in this system. However, as shown in Figs. 4(a) and 4(b), we give the results of an optimally doped ($x = 0.10$, $T_c^{\rm onset}(9\ T) = 19.1$ K) and a heavily overdoped sample ($x = 0.15, T_c^{\rm onset}(9\ T) = 13.2$ K). At $H = 9\ T$, the hysteresis are observed at 17 K and 11.5 K in the optimally doped and overdoped samples, respectively. With increasing temperature, the irreversibility vanishes at $T_{\rm irr} = 18$ K and 12 K, respectively, both are slightly lower than T_c in these two samples. Considering that magnetic measurements always yield a slightly lower T_c than transport measurements, this small discrepancy is reasonable. The absence of irreversible torque signal above T_c in these two samples indicates that the vortices may only survive up to T_c and the SCFs are much weaker in these two samples than that in underdoped $x = 0.065$ and 0.075 samples.

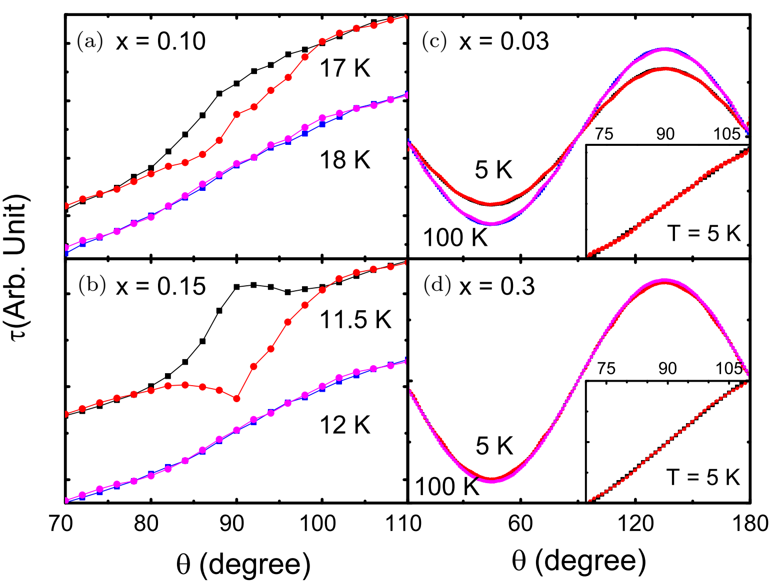

Fig. 4. $\tau_{\rm In}(\theta)$ (squares) and $\tau_{\rm De}(\theta)$ (circles) curves at selected temperatures for $BaFe_{2-x}Ni_xAs_2$ samples with $H = 9\ T$, (a) $x = 0.10$, (b) $x = 0.15$, (c) underdoped $x = 0.03$, (d) overdoped $x = 0.3$. The insets in 3(c) and 3(d) display the enlarged view of $\tau(\theta)$.

We would like to point out that the presence of magnetic impurity and inhomogeneity in a material may also lead to an irreversibility in the magnetic torque measurements. However, a careful comparison between different samples rules out these two possible contributions. If magnetic impurities exist in the underdoped $x = 0.065$ sample, it's reasonable to expect that they should also appear in other doped samples, and have an even higher density in overdoped compounds. Following this line, we performed the same measurements on the nonsuperconducting underdoped ($x = 0.03$) and heavily overdoped ($x = 0.3$) $BaFe_{2-x}Ni_xAs_2$. As shown in Figs. 4(c) and 4(d), no irreversibility is observed from 5 K to 100 K, suggesting that the irreversibility is associated with superconductivity rather than magnetic impurities. As to the inhomogeneity, we extract the superconducting transition width (ΔT_c) of the samples, which is believed to reflect the homogeneity of a sample. We found that the underdoped ($x = 0.075$) and an overdoped ($x = 0.18$) sample are characterized by $\Delta T_c \approx 1.3$ K and 1.4 K, respectively, meaning that the homogeneity of these two samples is indeed identical. But irreversibility above T_c is only observed in the underdoped $x = 0.075$ sample, suggesting that sample inhomogeneity is unlikely the origin of the irreversibility.

Moreover, we realized that the superconducting transition temperature T_c increases from $x = 0.065$ to 0.075, while the SCFs temperature $T_{\rm irr}$ decreases. This opposite doping dependence of T_c and $T_{\rm irr}$ was also reported by Nernst effect and magnetoresistance studies in underdoped copper-oxide superconductors.[1,16] Their results further showed that phase fluctuations play an important role in the SCFs regime above the superconducting critical temperature where preformed Cooper pairs without phase coherence appears. In analogy to copper oxides, the observed SCFs above T_c in underdoped $BaFe_{2-x}Ni_xAs_2$ could be related to phase fluctuations of superconducting order parameter. Preformed Cooper pairs without long-range coherence may also exist in the SCFs region.

Interestingly, our observations are consistent with several previous works by different techniques in other systems. An optical conductivity study in underdoped $Ba_{1-x}K_xFe_2As_2$ revealed a pseudogap opening at a temperature T^* above T_c,[39] which has been attributed to preformed Cooper pairs. Andreev reflection studies on electron-doped $BaFe_{2-x}Co_xAs_2$ provided evidence for phase-incoherent superconducting pairs above T_c,[40] and ^{75}As nuclear-quadrupole-resonance measurements on electron-doped $Ca(Fe_{1-x}Co_x)_2As_2$ also showed that a pseudogap-like phase exists above T_c as a precursor state for the coherent superconducting phase.[41] These studies all provided evidence for the existence of superconducting pairs without rigid phase coherence above T_c.

4. Conclusion

In summary, angular-dependent torque measurements have been carried out on a series of $BaFe_{2-x}Ni_xAs_2$ single crystals. An irreversible $\tau(\theta)$ above T_c is observed in two underdoped samples, which has been associated with SCFs. A comparison between our observations and studies in other systems suggests that the SCFs in underdoped $BaFe_{2-x}Ni_xAs_2$ might be related to phase fluctuations of superconducting order parameter.

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