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Angular dependent torque measurements on $CaFe_{0.88}Co_{0.12}AsF$

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Abstract
Out-of-plane angular dependent torque measurements were performed on $CaFe_{0.88}Co_{0.12}AsF$ (Ca1 1 1 1) single crystals. In the normal state, the torque data shows $\sin 2\theta$ angular dependence and H^2 magnetic field dependence, as a result of paramagnetism. In the mixed state, the torque signal is a combination of the vortex torque and paramagnetic torque, and the former allows the determination of the anisotropy parameter γ. At $T = 11.5$ K, γ (11.5 K $\simeq$ 0.5 T_c) = 19.1, which is similar to the result of $SmFeAsO_{0.8}F_{0.2}$, $\gamma \simeq 23$ at $T \simeq 0.4T_c$. So the 11 1 1 is more anisotropic compared to 11 and 122 families of iron-based superconductors. This may suggest that the electronic coupling between layers in 1 1 1 1 is less effective than in 11 and 122 families.

Keywords: torque, anisotropy parameter, superconductivity

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

1. Introduction

In 2006, the first iron-based superconductor (FeSC) LaFePO (1 1 1 1) is reported by Hosono's group [1]. In 2008, the breakthrough came with the fluoride doped arsenide $LaFeAsO_{1-x}F_x$ (1 1 1 1) with the superconducting transition temperature up to 26 K [2]. After that many families of FeSCs were discovered but among which $SmFeAsO_{1-x}F_x$ (1 1 1 1) keep the record high of the superconducting transition temperature $T_c \sim 55$ K [3]. CaFeAsF is another 1 1 1 1-type of FeSC but is oxygen-free. It has a ZrCuSiAs-type tetragonal structure in which LaO layers in LaFeAsO are replaced by CaF layers [4]. This parent compound exhibits pressure-induced superconductivity and the maximum T_c is higher than that in LaFeAsO, making it a promising candidate as a parent compound for high T_c superconductor [5]. Electrons doped into FeAs layers by partial replacement of Fe with Co suppress the antiferromagnetic state and superconductivity arises. In addition, the electronic and magnetic properties of this compound are intermediate between those of $LaFeAsO_{1-x}F_x$ and $Ba(Fe_{1-x}Co_x)_2As_2$ [6]. All these features make CaFeAsF different from other FeSCs. However, the investigation on this new 1 1 1 1 type of FeSC are greatly restricted due to the difficulties in obtaining sizable single crystals.

Knowledge of the anisotropy parameter γ is essential to clarify the nature of superconductivity. For the 1 1 1 1 family, limited reports are found on oxypnictides $LaFeAsO_{1-x}F_x$ [7] and $SmFeAsO_{0.8}F_{0.2}$ [7, 8] and there is a discrepancy in the value of γ and also the tendency of temperature dependence. In this paper, we performed detailed torque measurements on $CaFe_{0.88}Co_{0.12}AsF$ and found that this 1 1 1 1 system is more anisotropic compared to 11 and 122 families of iron-based superconductors where γ stays in the range of 2–3. In addition, we estimated the penetration depth λ_{ab}, which is an important characteristic length scale of a superconductor, which parameterizes the ability of a superconductor to screen an applied field by the diamagnetic response of the superconducting condensate [9].

2. Methods

High quality single crystal samples of $CaFe_{0.88}Co_{0.12}AsF$ were grown using the self-flux method with CaAs as the flux. The details about sample growth and characterization can be found

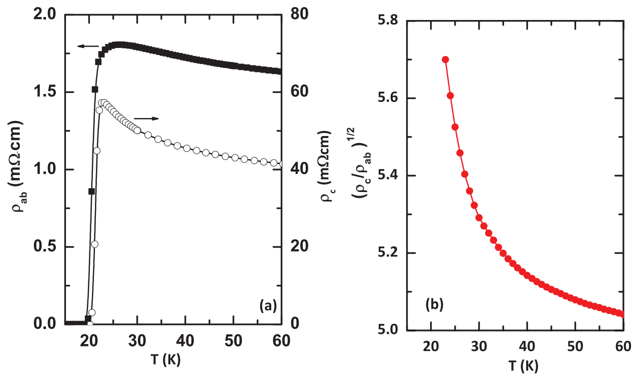

Figure 1. (a) Temperature T dependent in-plane and out-of-plane resistivity data, ρ_{ab} (left axis), rho_c (right axis). (b) T dependent resistivity anisotropy $(\rho_c/\rho_{ab})^{1/2}$.

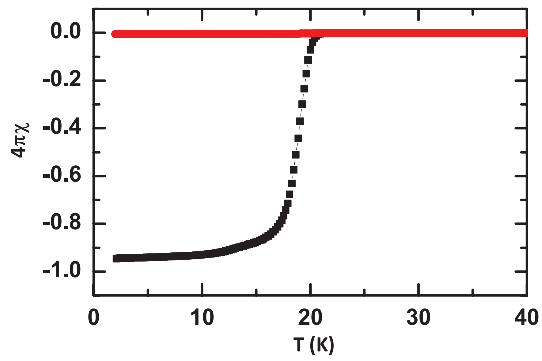

Figure 2. Temperature T dependent normalized magnetization data for $H = 10$ Oe under both zero-field-cooled (ZFC) and field cooled (FC) conditions.

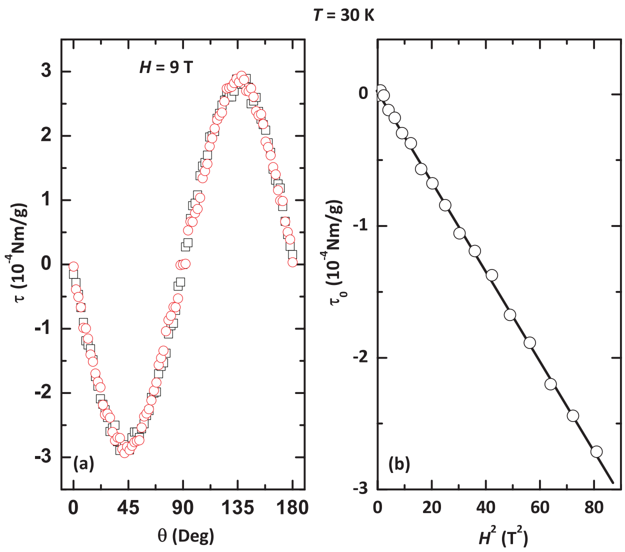

Figure 3. (a) Typical angular θ dependent torque τ at temperature $T = 30$ K with a magnetic field $H = 9$ T. (e) τ_0 versus H^2 at $T = 30$ K.

elsewhere[10]. The actual Co level was determined to be 0.12 through the energy dispersive x-ray (EDX) measurements on the as-grown single crystals. The sample for which the data is shown in this paper has a mass $m = 0.12 \pm 0.02$ mg. Electrical resistivity measurements were performed in a physical property measurement system (PPMS). Magnetization measurements were performed by using a superconducting quantum interference device (SQUID). Out-of-plane torque measurements were performed using a piezoresistive torque magnetometer in PPMS. The angle θ is defined as the angle between the magnetic field and the c axis of the single crystal.

3. Results and discussion

Figure 1(a) shows the temperature T dependent in-plane and out-of-plane resistivity data ρ_{ab}, ρ_c. An upturn behavior shows up before the transition to the superconducting state for both curves. The onset of the superconducting transition appears at 21.7 K and the zero resistivity is reached at 20.4 K. The anisotropy parameter γ calculated from the normal state resistivity, $\gamma = \sqrt{\rho_c/\rho_{ab}}$, is plotted in figure 1(b), which is about 5–6 in the temperature range from 23 to 60 K. This value of γ is similar to the anisotropy of normal state resistivity in $Ba_{1-x}K_xFe_2As_2$, which is about 3–6 [11]. The magnetization M curves were measured under field-cooled (FC) and zero-field-cooled (ZFC) conditions with a magnetic field H of 10 Oe applied along the ab-plane of the crystal, as shown in figure 2. T_c determined from magnetization measurements is 20.5 K, which is the same as T_{c0} of resistivity measurements.

Figure 3(a) shows the typical angular θ dependent torque curve $\tau(\theta)$ of $CaFe_{0.88}Co_{0.12}AsF$ at temperature above T_c with an applied magnetic field H of 9 T. The superconducting transition temperature is $T_c(9\text{ T}) = 15$ K and the data shown here is for $T = 30$ K. Note that the torque data is reversible with increasing (τ_{inc}) and decreasing (τ_{dec}) angles. Torque τ has a $\sin 2\theta$ angular dependence and can be well fitted by $\tau_0 \sin 2\theta$. It is found that τ_0 has a H^2 magnetic field dependence at $T = 30$ K, as shown in figure 3(b). These two features, $\sin 2\theta$ angular dependence and H^2 magnetic field dependence, are typical behaviors for paramagnetic response τ_p, since $\tau_p = \frac{\chi_c - \chi_a}{2} H^2 \sin 2\theta$, where χ_c and χ_a are the susceptibility along the c and a axes of the crystal [12, 13]. Since χ_c is smaller than χ_a in FeSCs, [14] the coefficient of $\sin 2\theta$ term is negative, which is opposite to the case of the heavy fermion superconductor $CeCoIn_5$ [15] and the cuprate superconductor $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$, [16] where $\chi_c > \chi_a$.

The anisotropy parameter is an important quantity for characterization and is essential to clarify the nature of superconductivity. We examine the anisotropy of $CaFe_{0.88}Co_{0.12}AsF$ by studying in detail the torque data for $T < T_c$. Figure 4(a) shows the torque data measured at $T = 16$ K and $H = 6$ T. A sharp peak around 90° is found and there is large hysteresis between the torque data measured with increasing and decreasing angles (τ_{inc} and τ_{dec}) as indicated by the arrows. The reversible part of the torque can be obtained by $\tau_{rev} = \frac{1}{2}(\tau_{inc} + \tau_{dec})$. Note that only τ_{rev} reflects equilibrium states, which allows the determination of the thermodynamic parameters. Figures 4(b)

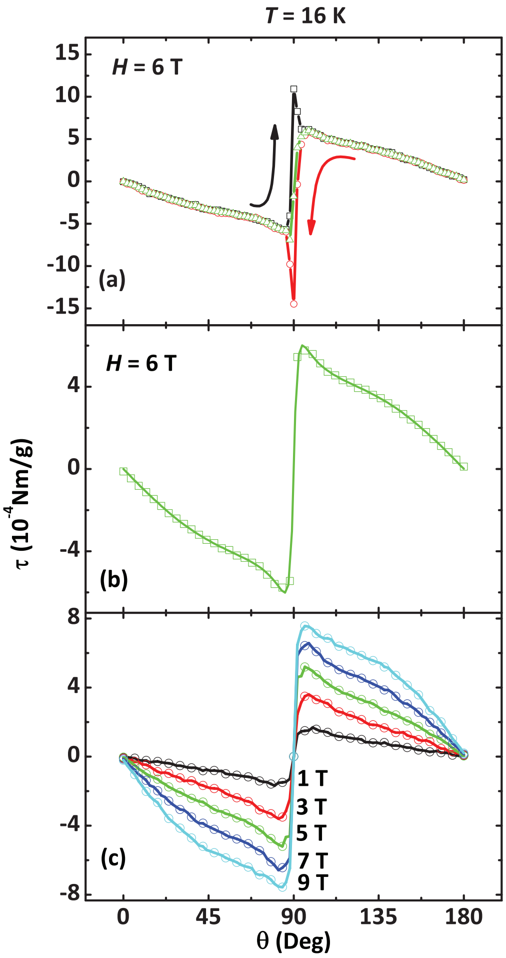

Figure 4. Torque data at $T = 16$ K. (a) Angular θ dependent torque data measured at $H = 6$ T. (b) Reversible part of the torque data τ_{rev} at $H = 6$ T. (c) τ_{rev} for $H = 1, 3, 5, 7, 9$ T. In (b), (c) the solid lines are fitting curves by equation (1).

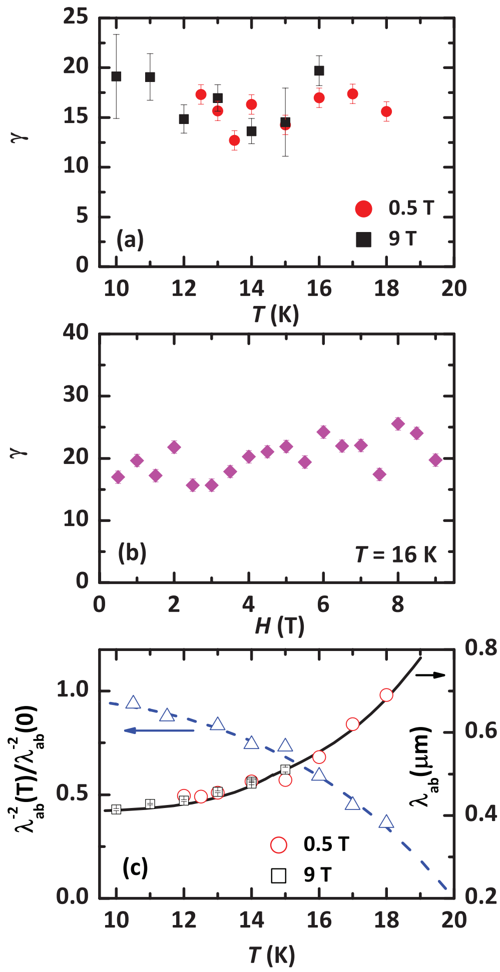

Figure 5. (a) Temperature T dependence of anisotropy parameter γ. (b) The magnetic field H dependence of γ. (c) Right axis: temperature dependence of penetration depth λ_{ab}. Left axis: temperature dependence of the normalized superfluid density $\lambda_{ab}^{-2}(0)/\lambda_{ab}^{-2}(T)$. The dashed line is a fitting curve by equation (2).

and (c) plots τ_{rev} for the data measured at $T = 16$ K and with different applied magnetic field. The symbols are data points and the solid lines are fitting curves by the following equation,

$$\tau_{\text{rev}}(\theta) = a\sin 2\theta + \frac{\phi_0 HV}{16\pi\mu_0\lambda_{ab}^2}\frac{\gamma^2-1}{\gamma}\frac{\sin 2\theta}{\epsilon(\theta)}\ln\left\{\frac{\gamma\eta H_{c2}^{\parallel c}}{H\epsilon(\theta)}\right\}. \tag{1}$$

In the above equation, the first term represents the $\sin 2\theta$ contribution to the torque signal. The second term describes the vortex torque according to Kogan's model [17] which is derived in the frame of the anisotropic Ginzburg–Landau regime, where μ_0 is the vacuum permeability, λ_{ab} is the penetration depth in the ab-plane, $\gamma = \sqrt{m_c/m_a}$ is the anisotropy parameter (m_c and m_a is the effective mass along the c and a axes), $\epsilon(\theta) = (\sin^2\theta + \gamma^2\cos^2\theta)^{1/2}$, η is a numerical parameter of the order of unity, and $H_{c2}^{\parallel c}$ is the upper critical field parallel to the c-axis.

We use γ, a and λ_{ab} as fitting parameters to fit the torque data and figures 4(b) and (c) shows the fitting results. Note that the contribution from the $\sin 2\theta$ term becomes more evident as the magnetic field increases. We summarize the temperature and magnetic field dependence of the anisotropy parameter γ in figures 5(a) and (b). It is found that γ shows weak temperature and magnetic field dependence. At $T = 11.5$ K, $\gamma(11.5\text{ K} \simeq 0.5T_c) = 19.1$, which is similar to the result of $SmFeAsO_{0.8}F_{0.2}$, $\gamma \simeq 23$ at $T \simeq 0.4T_c$ [8]. So, the 1 1 1 1 is more anisotropic in the superconducting state compared to 11 and 122 families of FeSCs, where γ stays in the range of 2–3 as evidenced by μSR measurements, [18] despite the fact that the normal state anisotropy parameter is about the same in the 1 1 1 1 and 122 compounds (γ is 5–6 for the former and 3–6 for the latter). This might suggest that in the superconducting state, the electronic coupling between layers in 1 1 1 1 is less effective than in the 11 and 122 families.

Figure 5(c) (right axis) shows temperature dependence of the penetration depth λ_{ab}, which is obtained from fits of equation (1) to the torque data. The left axis shows the temperature dependence of normalized superfluid density $\lambda_{ab}^{-2}(T)/\lambda_{ab}^{-2}(0)$. It is found that $\lambda_{ab}^{-2}(T)/\lambda_{ab}^{-2}(0)$ decreases with increasing temperature and vanishes when approaching T_c. We use the empirical equation,

$$\lambda_{ab}^{-2}(T)/\lambda_{ab}^{-2}(0) = 1 - (T/T_c)^n \quad (2)$$

with $n = 4$ to fit our data (see the dashed line) and obtain $\lambda(0) = 400$ nm. Lower critical field measurements on $PrFeAsO_{1-y}$ give $\lambda(0) = 280$ nm [19]. From μSR measurements, $\lambda(0) = 189$ and 195 nm for $SmFeAsO_{0.85}$ and $NdFeAsO_{0.85}$ [20]; $\lambda(0) = 254$ and 364 nm for $LaFeAsO_{1-x}F_x$ $x = 0.1$ and 0.075 [21]. Our result of λ_{ab} here is comparable with that of other 1 1 1 1 families.

4. Conclusions

In summary, we performed detailed angular dependent torque measurements on $CaFe_{0.88}Co_{0.12}AsF$. A large paramagnetic effect is observed in the normal state. After subtracting this paramagnetic contribution to the mixed state, we obtain the anisotropy parameter from the mixed state torque data and summarized its temperature and magnetic field dependence. The value of γ is comparable with other 1 1 1 1 families of FeSCs, but much larger than 11 and 122 families of FeSCs. The zero temperature penetration depth of $CaFe_{0.88}Co_{0.12}AsF$ is also estimated, which is reasonable when compared to the value reported for other 1 1 1 1 FeSCs.

Acknowledgments

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