Thermally activated energy and critical magnetic fields of SmFeAsO$_{0.9}$F$_{0.1}$

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Abstract

Thermally activated flux flow and vortex glass transition of the recently discovered SmFeAsO$_{0.9}$F$_{0.1}$ superconductor are studied in magnetic fields up to 9.0 T. The thermally activated energy is analyzed in two analytic methods, of which one is conventional and generally used, while the other is closer to the theoretical description. The thermally activated energy values determined from both methods are discussed and compared. In addition, several critical magnetic fields determined from resistivity measurements are presented and discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The recently discovered FeAs-based superconductors inspired study, as their superconducting transition temperatures and upper critical magnetic fields reach values which are higher than those of MgB$_2$ and comparable to those of the cuprate-based superconductors (CBS) [1–11]. One of the interesting characteristics is that they show a layered structure with conducting layers of FeAs and charge reservoir layers of ReO, where Re is a rare earth element [3]. This layered structure is very similar to that of CBS and suggests that the superconducting behaviors may have similarities to those of CBS.

The vortex dynamics of CBS have been widely studied in theory and experiments [12–31]. According to the theory, the thermally activated flux flow (TAFF) resistivity is expressed as

$$\rho = (2\nu_0 LB/J) \exp(-J_{00} BVL/T) \sinh(J_{00} BVL/T)$$

where $\nu_0$ is an attempt frequency for a flux bundle hopping, $L$ is the hopping distance, $B$ the magnetic induction, $J_{00}$ the applied current density, $J_{00}$ the critical current density in the absence of flux creep, $V$ the bundle volume and $T$ the temperature. If $J$ is small enough and $J_{00} BVL/T \ll 1$, we have

$$\rho = (2\nu c U/T) \exp(-U/T),$$

where $U = J_{00} BVL$ is the thermally activated energy (TAE) and $\nu c = \nu_0 LB/J_{00}$. Equation (1) simply means that the prefactor $2\nu c U/T$ is temperature-and magnetic-field-dependent.

Generally, the TAE of CBS is analyzed by equation (1) using an assumption that the prefactor $2\nu c U/T$ is temperature-independent and $\ln \rho(H, T)$ linearly depends on $1/T$ with the form

$$\ln \rho(H, T) = \ln \rho(0) - U_0 / T$$

where $H$ is the magnetic field strength, $\rho(0)$ is the normal state resistivity, $U_0$ is the TAE for $T = 0$, $\nu c$ the constant, $T_c$ the superconducting transition temperature. The importance is that the analysis leads to $U = U_0(1 - t)$ and the apparent activation energy $-\partial \ln \rho(0) / \partial T^{-1} = U_0$, where $t = T/T_c$ [22–31]. By drawing resistivity data in the so-called Arrhenius plot with a relation $\ln \rho(H, 1/T)$, one can easily determine $U_0(H)$ with its corresponding slope in a low resistivity range. However, $U = U_0(1 - t)$ may not be true in reality, when a local slope of $\ln \rho$ versus $1/T$ in the Arrhenius plot shows a round curvature. As a result, the corresponding apparent activated energy $-\partial \ln \rho(H, T) / \partial T^{-1}$ shows a sharp increase with decreasing temperature. The phenomena mean $U \neq U_0(1 - t)$, $\rho(T) \neq$ const, and the determination of $U_0(H)$ from the slopes is a problem. In the early stage of the discovery of CBS, the experimental observation of the abnormal phenomena had been reported by Palstra et al. [22] without solution.

Zhang et al. [23] suggested that the temperature-dependent of the prefactor in equation (1) must be taken into account in the analysis. By using this suggestion to equation (1) with $U = U_0(1 - t)^q$, the derivative is

$$-\partial \ln \rho(\partial T^{-1} = (1 - T/U)(U - T \partial U / \partial T)$$

$$= [U_0(1 - t)^q - T[1 + qt/(1 - t)]],$$

where $q$ has a value in the range from 0.5 to 2 and $t = T/T_c$. 

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In this paper, TAFF resistivity of SmFeAsO$_{1−δ}$F$_{0.1}$ (SFAOF) is studied with magnetic fields up to 9.0 T. By using the assumption $\rho_{0f}/U/T = \text{const}$ and $U = U_0 (1 − t)$, the TAFF behaviors were first analyzed in the Arrhenius plot. After that, by using the assumption of the prefactor $2\rho_0 U/T$ is temperature-dependent, and $\rho_0$ is not temperature-dependent, the TAFF resistivity is analyzed in the other method in which equation (2) is employed to determine $U_0 (H)$. The $U_0 (H)$ determinations from both methods are discussed and compared. We suggest that the second method shall be used instead of the first in the analysis of TAFF characteristics of other superconductors. In addition, the vortex glass transition, zero resistivity temperature and the temperature dependence of the critical fields determined from different resistivity criteria values in the superconducting transition regime are presented.

2. Experiments

The SFAOF sample was prepared by a high pressure synthesis method. SmAs powder (pre-sintered) and As, Fe, Fe$_2$O$_3$ and FeF$_2$ powders (the purities of all starting chemicals are better than 99.99%) were mixed together in the nominal stoichiometric ratio of Sm[O$_{1−x}$F$_x$]FeAs, then ground thoroughly and pressed into small pellets. The pellet was sealed in boron nitride crucibles and sintered in a high pressure synthesis apparatus under a pressure of 6.0 GPa and temperature of 1250°C for 2 h. The x-ray diffraction analysis showed that the main phase is an LaOFeAs structure with some impurity phases [2, 3]. It was cut into a rectangular shape with dimensions of 4.20 mm (length) × 1.60 mm (width) × 1.08 mm (thickness). The standard four-probe technique was used for resistivity $\rho (T, H)$ measurements. Bipolar pulsed dc current with an amplitude of 5.0 mA (corresponding to a current density of about $\sim$0.29 A cm$^{-2}$) was applied to it. The measurements were performed on a physical property measurement system (PPMS, Quantum Design) with the magnetic field up to 9 T. From the zero-field $\rho (T, 0)$ data, we find that the superconducting transition width is about 1.7 K (defined by the superconducting transition from 10% to 90% of the normal resistivity) and the zero resistance temperature $T_\alpha$ is 52.2 K (determined by the criterion of 0.1 $\mu$Ω cm).

3. Results and discussion

Figure 1(a)–(c), respectively, show $\rho (T, H)$, $−\partial \ln \rho (T, H)/\partial T^{-1}$ and $\partial T/\partial \ln \rho (T, H)$ data in magnetic fields of $\mu_0 H = 0.0, 0.5, 1.0, 3.0, 5.0, 7.0$ and $9.0$ T with different symbols. The solid lines in (a) and short horizontal lines in (b) correspond to the regressions with the fitting parameters of $U_0 (H)$ and $\rho_{0f}$ determined from the first analytic method. The dashed lines are regression curves with the fitting parameters $U_0 (H)$ and $\rho_0 (H)$ determined from the second analytic method (see text). The dashed lines in (c) plot a linear fitting.

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Figure 2 shows the Arrhenius plot of its resistivity in magnetic fields of $\mu_0 H = 0.0, 0.5, 1.0, 3.0, 5.0, 7.0$ and $9.0$ T with different symbols. The solid lines plot linear regressions in the low resistivity range. According to the conventional
analysis method, these linear fits are based on the assumption \( U(T, H) = U_0(H)(1-t) \), where each \( U_0(H) \) was determined by using each slope. Note that there is a crossing point where all the linear fitting lines approximately focus together, except for the line for zero field, and this point leads to \( T_{c*} \approx 53.8 \) K. The inset shows \( \ln \rho_0f \) data and the corresponding solid line with the linear fitting \( \ln \rho_0 = \ln \rho_0f + U_0/T_c \). From the fitting, we determined \( \rho_0f = 6.668 \) m\( \Omega \) cm and \( T_c \approx 53.8 \) K which coincides with the value of \( T_{c*} \). Using the \( \rho_0f, T_c \) and \( U_0(H) \) data, we regressed the \( \rho(T, H) \) data as shown in figure 1(a) by solid lines. Since the assumption of \( U(T, H) = U_0(H)(1-t) \) leads to \( -\partial \ln \rho(T, H)/\partial T^{-1} = U_0 \), we present \( U_0(H) \) data in figure 1(b) with horizontal solid lines where each of them has a limited length. Each length covers the temperature interval which corresponds to the interval of the reciprocal temperature for determining \( U_0(H) \) in the Arrhenius plot. For decreasing temperature, note that each \( -\partial \ln \rho(T, H)/\partial T^{-1} \) dataset approximately intersects its horizontal \( U_0(H) \) line center with a divergent trend in the temperature interval. This means that each \( U_0(H) \) approximates to the average value of its \( -\partial \ln \rho(T, H)/\partial T^{-1} \) in the temperature interval. The similar divergent trends were also observed in YBCO [22, 23]. The analysis indicates that the TAE determined from the conventional method may have problems in characteristics and the method suggested by Zhang et al [23] ought to be taken into consideration.

In figure 1(b), one may have noticed that each \( -\partial \ln \rho(T, H)/\partial T^{-1} \) set can be divided into five regimes: (i) the normal state regime at high temperature, where \( -\partial \ln \rho(T, H)/\partial T^{-1} \) is almost temperature-and magnetic-field-independent; (ii) the primary superconducting transition regime, where \( -\partial \ln \rho(T, H)/\partial T^{-1} \) quickly increases and the resistivity begins sharply decreasing (see figure 1(a)); (iii) the platform regime, where \( -\partial \ln \rho(T, H)/\partial T^{-1} \) for each field measurement show a step structure (see figure 1(b)); (iv) the second sharply increasing regime, where \( -\partial \ln \rho(T, H)/\partial T^{-1} \) quickly increases to a high value range and \( \partial T/\partial \ln \rho \) data show a linear type (see figure 1(c)) and (v) the strong fluctuation regime, where the \( -\partial \ln \rho(T, H)/\partial T^{-1} \) curve shows an irregular shape due to the resistivity reaching the low measurable range.

For analyzing TAFF behavior with the second analytic method, the first thing is to validate one or two regimes which relate to the TAFF behavior. Apparently, the data in regimes (i) and (ii) do not relate to TAFF behavior, as the data are in the normal state in regime (i) and in the flux flow regime in regime (ii). The data show a platform structure and possibly relate to TAFF behavior in regime (iii). Note that resistivity data in the regime are only about one order of magnitude less than that in regime (i) (where the resistivity is in the normal state) (see figures 1(a) and (b)). Therefore, we conclude that the data in regime (iii) are not in the TAFF regime [22]. In regime (iv), the resistivity is about two to three orders of magnitude less than that in regime (i). The resistivity in this range, as suggested by Palstra et al [22], relates to TAFF behavior. According to the vortex glass transition theory, the linear (ohmic) resistivity ought to linearly vanish in a form \( \rho \propto (T - T_g) \), where \( T_g \) is the vortex glass transition temperature [32, 33]. Accordingly, \( \partial T/\partial \ln \rho \propto (T - T_g) \) [34, 35]. In figure 1(b), one will easily find that \( \partial T/\partial \ln \rho \) curves show approximately linear curvatures in regime (iv). The data in regime (v) show an irregular trend, as the resistivity is going to a deeply superconducting state where the resistivity may be dominated by non-ohmic characteristics; besides, the measuring voltmeter reached its low measuring limitation in experiments. The analysis concludes that the TAE resistivity is in regime (iv).

Figure 3 shows \( U_0(H) \) determined by the first analytic method with circles and by the second with triangles. The stars show corresponding \( \rho(H) \) for the second method. All the dashed lines in figures 1(a) and (b) and figure 2 are regression curves with the regression parameters of \( U_0(H) \) and \( \rho_e(H) \) in figure 3. In the analysis of these data with the second method, we first derived \( U_0 \) with equation (2) as \( U_0 \) is the only free parameter in the equation except for \( q \). We found that the energy relation, \( U(T, H) = U_0(1-t)^q \) with \( q = 2 \), leads to good consistency with the experimental data, where \( t = T/T_c \) and \( T_c = 53.8 \) K. After determination of each \( U_0(H) \), each \( \rho_e(H) \) can be easily determined by fitting equation (1). One will find that all the regressions (dashed lines) in figures 1(a) and (b) and figure 2 are in good agreement with experimental data and confirm the correctness of the analytic method. Note that, although each temperature interval in regime (iv), which we used to determine \( U_0(H) \) with the second analytic method, is somewhat less than that we used to determine \( U_0(H) \) with the first analytic method (see figures 1(b) and (c)), the regressions of the second method are still giving better fitting results.

For a magnetic field above 1.0 T, we find that \( U \propto H^{-0.57}(1-t) \) for the data derived from the Arrhenius plot with the first method and \( U \propto H^{-0.99}(1-t)^2 \) with the second method. Note that the TAE determined by the second method is about one order larger than that determined from the first, as shown in the figure. The reason for the large difference between the two analytic methods is due to the first method not taking into account the temperature-dependent relation of the

Figure 3. (a) The circles show \( U_0(H) \) extracted from the slopes in the Arrhenius plot in figure 2. The downward triangles show \( U_0(H) \) data determined by using the relation \( -\partial \ln \rho/\partial T^{-1} = [U_0(1-t)^q - T]/[1 + q t/(1 - t)] \), where \( q = 2 \). The stars represent corresponding \( \rho_e \) data.

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It leads to a conclusion that the vortex melting field is very high at low temperature. One may notice that the transition widths of the upper critical magnetic field of the superconductor is very high compared to YBCO. The circles show the ac susceptibility measurement is somewhat higher than that of the normal state resistivity measurement. Besides, we found that the onset temperature of the superconducting transition $T_{\text{onset}}(H)$ of the ac susceptibility measurement is now ongoing.

**Figure 4.** Critical magnetic fields. The circles show the $H(T_c)$ data, the downward triangles the $H(T_{c0})$, the squares the $H(T_{10\%})$, the diamonds the $H(T_{50\%})$ and the upward triangles the $H(T_{90\%})$.

prefactor in equation (1), while the second method takes this into consideration. Apparently, the second method is closer to the theoretical description.

Figure 4 shows the vortex glass transition boundary $H(T_g)$, $H(T_{c0})$, $H(T_{10\%})$, $H(T_{50\%})$ and $H(T_{90\%})$, where $T_g$ is the glass transition temperature, $T_{c0}$ the zero resistance temperature, $T_{10\%}$ 10% of the normal state resistivity temperature, $T_{50\%}$ 50% and $T_{90\%}$ 90%. Here, $H(T_g)$ was determined by using the $\partial T/\partial \ln \rho \propto (T - T_g)$ relation (dashed lines in figure 2(c)). We find that the data can be fitted by a relation $H_g = H_{\text{g0}}(1 - T_g/52.05)^2$, where $H_{\text{g0}} \approx 201 \text{T}$. The $H_{\text{g0}}$ value may not be true at zero temperature, but it leads to a conclusion that the vortex melting field is very large for the SFAOF superconductor when the temperature approaches zero. A similar characteristic can also be observed for $H(T_{c0})$ data, since each $T_{c0}(H)$ is slightly higher than that of $T_g(H)$. The normalized transition widths (defined as $(1 - T_{10\%}/T_{90\%})$) are comparable to YBCO and thus suggest that the anisotropy of the SFAOF is similar to YBCO. The $H(T_{90\%})$ curve shows a steep increase, indicating that the upper critical magnetic field of the superconductor is very high at low temperature. One may notice that the transition widths between $T_{c0}(H)$ and $T_{10\%}(H)$ are comparable to that between $T_{50\%}(H)$ and $T_{90\%}(H)$, suggesting that the superconductor may have better analysis results on further improving the quality of the superconductor.

In comparison, a sample that was prepared in the same sample batch was used in ac susceptibility measurements with magnetic fields up to 7.0 T and frequencies up to 1.11 kHz. We found that $T_g(H)$ is somewhat larger than the corresponding temperature of the peak in the imaginary component in ac susceptibility measurement. However, the similar $H$ increasing trends were also found in the ac measurement. Besides, we found that the onset temperature of the superconducting transition $T_{\text{onset}}(H)$ of the ac susceptibility measurement is somewhat higher than that of $T_{c0}(H)$. Detailed analysis of the ac measurement is now ongoing.

**4. Conclusion**

In summary, we analyze the resistive TAFF behavior of SFAOF with two theoretical analysis. For the first method, $\rho_{0j} = \text{const}$ and $U = U_0(1 - t)$ were assumed, and thus the Arrhenius plot was employed in the analysis. This method is simple and easy in analysis, but the analysis results remain inconsistent with experimental data. The second method assumes that the prefactor $2\rho_0 U/T$ is temperature-dependent, while $\rho_0$ is not temperature-dependent. By using the second method, equation (2) is obtained. The second method results in the regressions in good agreement with experimental data. The TAE analysis shows $U \sim H^{-1}(1 - t)^2$ for a magnetic field above 1.0 T. The second method is also simple and easy, since only two free parameters are in the analysis. We suggest that the second method shall be used instead of the first for the analysis of TAFF behavior of other superconductors. The study shows that critical magnetic fields of SFAOF may have large values at low temperature, comparable to CBS.

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