Comments on "Vortex phase diagram of HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ thin films from magnetoresistance measurements"

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We make comments on the paper presented by Kim et al. [Phys. Rev. B 61, 11317 (2000)]. The authors analyzed activation energies of HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ thin films with a scaling relation, and defined four vortex regions for thin films. We find that the definitions of four vortex regions and the scaling relation are questionable when studying their definition of the resistivity range for thermally activated flux flow. Using the empirical activation energy form suggested by Zhang et al. [Phys. Rev. B 71, 052502 (2005)] for lower resistivity data, we find that the form is not only in good agreement with the resistivity $\rho(T, H)$, but also with the apparent activation energy $-\partial \ln \rho(T, H)/\partial T^{-1}$.

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Previously, Kim et al. [1] reported an investigation of resistive behaviors of Hg$_2$Ba$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ (Hg-1223) thin films in the mixed state. A scaling relation was proposed for analyzing the resistive behavior and was found in good agreement with the apparent activation energy $-\partial \ln \rho(T, H)/\partial T^{-1}$ (the so-called effective activation energy in this paper) in a specialized resistivity range. With this scaling, they suggested that the vortex system could be divided into four different vortex regions corresponding to the flux flow (FF) region, the thermally activated flux flow (TAFF) region, the critical state region, and the vortex solid (VS) region. Three characteristic temperatures corresponding to $T_{ff}$, $T^*$, and $T_{irr}$ were defined for the boundaries of these regions. They claimed that the TAFF behavior was limited in the region of $T^* < T < T_{ff}$ and the corresponding activation energy was expressed as $U_0(T, H) \sim H^{-1.1}(1 - T/T_c)^{1.5}$ for the magnetic field range from 1 to 9 T. In this comment, we point out that the scaling relation and the definitions of the four different vortex regions are questionable. We propose that the activation energies of Hg-1223 thin films relate to lower resistivity where $T < T^*$. Using lower resistivity data, we find that the activation energy is expressed as the form suggested by Zhang et al. [2].

After the discovery of high temperature superconductors (HTSCs), activation energies of different HTSCs have been widely studied in theories and experiments. According to Palstra et al. [2], activation energies of HTSCs should be determined in the temperature interval over which the resistivity changes from $10^{-4}$ to 1 $\mu\Omega$ cm or for the resistivity ratio $\rho(T, H)/\rho_n$ approximately below 1%, where $\rho_n$ is normal-state resistivity. The temperature interval is widely accepted for studying activation energies of HTSCs; besides, it is widely accepted that TAFF resistivity shall be ohmic (linear I-V relation), and the activation energy is independent of the applied current density $j$ for $j \rightarrow 0$ [3, 4, 5, 6, 7, 8]. This means that non-ohmic behavior ought to be observed for decreasing temperature out of the TAFF region.

Using the data of Fig. 1 and Fig. 4 in Ref. [1], we roughly redraw the $\rho(T^*, H)$ data in Arrhenius plot with gray circles as shown in Figure 1(a), for which the data in the range of $\mu_0 H(T^*) < 7.0$ T were presented due to $\mu_0 H(T^*)$ data being only presented for $\mu_0 H(T^*) < 7.0$ T in Fig. 4 of Ref. [1]. One will easily find that $T^*(H)$ results in that TAFF behavior is related to the resistivity value $\rho > 1.4 \mu\Omega$ cm with resistivity ratio $\rho/\rho_n > 1.5\%$, where $\rho_n = \rho(140 \text{ K, } H = 0) \approx 93 \mu\Omega$ cm. In this case, Kim et al. gave the TAFF temperature interval over which the resistivity approximately changes from 1.4 to 10 $\mu\Omega$ cm, or $\rho(T, H)/\rho_n$ approximately above 1.5%. This interval is apparently mismatched with the interval suggested by Palstra et al. Below temperature $T^*$, Kim et al. defined the critical state region, but they did not further present physical meaning for the region. In comparing with other HTSCs, it is very dubious that non-ohmic resistivity can be found around the so-called $T^*$. As a result, we argue that definitions of the TAFF and the critical state regions in the article are questionable and the TAFF region ought to relate to the temperature interval as suggested by Palstra et al.; besides, we argue that the definition of $T_{ff}$ is incorrect in the paper [2].

Normally, the TAFF resistivity is expressed as $\rho = \rho_0 \exp(-U_0/T)$ with the activation energy $U_0(T, H) = U_0(0, H)(1 - t)^{\beta}$, where $t = T/T_c$, $\beta$ is constant, and $T_c$ is the critical temperature. Considering the interlayer decoupling in high fields, Zhang et al. [2] suggested an empirical relation

$$\rho = \rho_{0f} \exp[-U(T, H)/T],$$

with

$$U(T, H) = g(H)f(t),$$

and

$$f = (1 - t)^{\beta},$$

where $\rho_{0f}$ is constant, and $g$ and $\beta$ are magnetic field dependent. Using the progression $(1 - t)^{\beta} = 1 - \beta t + \beta(\beta - 1)t^2/2! - \beta(\beta - 1)(\beta - 2)t^3/3! + \ldots$, we have $\ln \rho \approx -$
(\ln \rho_0 + g \beta / T_c) - (g / T)[1 + \beta(\beta - 1)/2! - \beta(\beta - 1)(\beta - 2)/3! + \ldots]$, where the term $(\ln \rho_0 + g \beta / T_c) \approx \ln \rho_0$ is temperature independent. With $\beta = 1$, we have $\ln \rho_0 \approx \ln \rho_0 + g / T_c$. However, we find if $\beta$ largely deviates from $\beta = 1$, the relation of $\ln \rho_0 \approx \ln \rho_0 + g / T_c$ will bring in large uncertainty and errors for determining $\rho_{0f}$ and $T_c$ in the relation of $\ln \rho_0 = \ln \rho_{0f} + g \beta / T_c$ plot (see Ref. 2), as the value of the local slope $-\partial \ln \rho(T, H) / \partial T^{-1}$ largely changes from one local temperature to the other as shown in Fig. 1(b). This means that we shall determine the $\rho_{0f}$ value in the other way when $\beta$ largely deviates from $\beta = 1$.

Accordingly, we must determine four free parameters $T_c$, $\rho_{0f}$, $g(H)$, and $\beta(H)$ using Eqs. 1, 2, and 3 with the experimental data. Generally, $T_c$ and $\rho_{0f}$ are magnetic field independent and therefore can be eliminated from the free parameter list in each magnetic field. In simplicity, we follow the selection of Kim et al. to take $T_c = 131$ K (this will not lead to large errors as the transition width is less than 2 K in zero magnetic field and $T_c$ shall be determined around the transition interval). We consider the resistivity value for $\rho_{0f}$ (by trial and error) which is not only getting better regression for each $\rho(T, H)$ curve in TAFF region, but also is in good agreement with each $-\partial \ln \rho(T, H) / \partial T^{-1}$. Hence, this will leave only two free parameters $g$ and $\beta$ for each magnetic field. At first, we use the formula

$$U(T, H) \approx T \ln[\rho_{0f} / \rho(T, H)]$$

(4) with $\rho(T, H)$ data to determine the parameters, and then check the parameters with corresponding regressions for the curves in Figs. 1(a) and (b). The gray solid lines in Figs. 1(a) and (b) show the results which we take $\rho_{0f} = 8 \, \mu \Omega$ cm for regressions. One will find that the regressions are in good agreement with the data in the temperature interval where the resistivity roughly changing from $10^{-2}$ to $1 \, \mu \Omega$ cm. Note that the interval matches the temperature interval suggested by Palstra et al. 3.

In fact, a $\rho_{0f}$ value can be selected in a broad range without changing the consistent matches of all the fits for $U(T, H)$ and $\rho(T, H)$ curves in TAFF region. However, changing $\rho_{0f}$ value will lead to changes of fitting parameters and still results in uncertainty in analysis. This means that we can not decide the $\rho_{0f}$ value which is only good for the fits of $U$ or $\rho$ curves, and we have to check the results with $-\partial \ln \rho(T, H) / \partial T^{-1}$ relation. We find that the value of $\rho_{0f}$ will change the consistent matches of the fits for $-\partial \ln \rho(T, H) / \partial T^{-1}$ curves in TAFF region.

Figures 2(a) and (b) show the fitting results of $-\partial \ln \rho(T, H) / \partial T^{-1}$ with $\rho_{0f} = 6 \, \mu \Omega$ cm and $10 \, \mu \Omega$ cm, respectively. The fits are not good in Fig. 2(a) for low...
fields and in Fig. 2(b) for high fields, respectively, while they are in good agreement with experimental data in other field ranges. The analysis suggests that we have $\rho_{0f} = 8.0 \pm 1.5 \, \mu\Omega \, cm$ for getting better fits for all $-\partial \ln \rho(T, H)/\partial T^{-1}$ curves. The deviations between the regressions and experimental data in low temperature range are possibly due to competing relations between coupling and decoupling and between pinning and depinning.

Figures 3(a) and (b) represent $g(H)$ and $\beta(H)$ data for $\rho_{0f} = 6, 7, 8, 9, 10 \, \mu\Omega \, cm$, respectively. With $\rho_{0f} = 8 \, \mu\Omega \, cm$, we find that $g \sim H^{-1.94}$ and $\beta \approx 3$ for $1 \leq \mu_0 H \leq 3 \, T$, while $g \sim H^{-0.73}$ and $\beta$ approximately linear increases with $H$ for $5 \leq \mu_0 H \leq 9 \, T$. The characteristic changes of $g$ and $\beta$ around $\mu_0 H = 4 \, T$ are probably due to the crossover from 3D to 2D as discussed in Ref. [2].

In summary, we suggest that the analysis of activation energies and definitions of the four different vortex regions are incorrect in Ref. [1], as the TAFF temperature interval presented in it does not match the interval suggested by Palstra et al. [3]. Using the temperature interval suggested by Palstra et al., we find that the empirical activation energy form suggested by Zhang et al. [2] is in good agreement with the lower resistivity data.

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