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Two-dimensional fluctuations in the magnetization of $Bi_2Sr_2Ca_2Cu_3O_{10}$

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Magnetization measurements on c-axis-oriented bulk $Bi_2Sr_2Ca_2Cu_3O_{10}$ with the magnetic field parallel to the c axis are reported. The results show large fluctuation effects, which can be explained by Ginzburg-Landau fluctuation theory for a two-dimensional (2D) system. The magnetization in high fields displays good scaling behavior as a function of $[T-T_c(H)]/(TH)^{1/2}$. The weak-field fluctuation diamagnetic susceptibility $\chi(T)$ above T_c can be fitted well in terms of the 2D Lawrence-Doniach model. Values of $\xi_{ab}(0)$ and dH_{c2}/dT derived from our fluctuation analysis are consistent with those obtained by fitting the Hao-Clem variational model to the reversible magnetization data below T_c.

In addition to high superconducting transition temperatures, the most prominent characteristics of the cuprate superconductors are their short ($\sim$nm) superconducting coherence lengths (ξ) and strong anisotropic superconducting, as well as normal-state, properties. These characteristics result in very pronounced fluctuation effects in their thermodynamic and transport properties.[1-6] Particularly, in the Bi-based oxides, which are considered to be the most anisotropic of the superconductors, it was shown that the fluctuation diamagnetism persists to temperatures well above T_c ($T\sim 2T_c$).[5,6] Furthermore, it was also shown that the temperature dependence of weak-field fluctuation diamagnetism in these high-T_c superconductors could be described well by a Josephson-coupled two-dimensional (2D) superconductor model proposed by Lawrence and Doniach,[7] and modified by Klemm.[8] However, the successful application of the model has been limited so far to temperatures above T_c and in the weak-field limit.[6]

As pointed out by a number of groups,[9-11] in high fields the spatial correlation that is transverse to the applied field direction is limited to the magnetic length given by $(\phi_0/2\pi H)^{1/2}$, where ϕ_0 is the flux quantum, due to confinement of the quasiparticles to low Landau levels. This limitation effectively reduces the dimensionality of the system and further enhances the effect of the fluctuation. This implies that the $|\Psi(\mathbf{r})|^4$ term in the Ginzburg-Landau (GL) expression for free energy in the region of mixed-state and normal-state transition has to be included in calculations of the thermodynamic and transport properties, where $\Psi(\mathbf{r})$ is the order parameter. This was done by a number of groups with an approximation where only the lowest Landau level is considered.[10,11] In particular, a recent theoretical calculation by Ullah and Dorsey,[11] who applied the Hartree approximation to treat the quadratic term in the GL Hamiltonian based on the Lawrence-Doniach (LD) model of layer superconductors, results in a scaling form of various thermodynamic and transport properties in high fields in terms of the variable $t_g=A[T-T_c(H)]/(TH)^n$, where A is a field- and temperature-independent coefficient, and n is $\frac{2}{3}$ for a 3D system, and $\frac{1}{2}$ for a 2D system.[2,11] The 3D scaling function is shown by Welp *et al.*[2] to work very well for the magnetization,[2] electrical conductivity,[2] Ettinghausen effect,[3] and specific heat[4] of single crystals of $YBa_2Cu_3O_7$. However, they found that the magnetization of the Bi(2:2:1:2) single crystal did not scale well for the temperature range below T_c in terms of either 2D or 3D scaling variables.[12] Recently, Kim, Gray, and Trochet[13] reported that fluctuation conductivity of $Tl_2Ba_2Ca_1Cu_2O_x$ films shows good agreement with a 2D scaling behavior for temperatures higher than a few degrees above $T_c(H)$, but a deviation occurs very near and below $T_c(H)$.

In this paper, we present high-precision magnetization measurements of c-axis-oriented bulk $Bi_2Sr_2Ca_2Cu_3O_{10}$ in magnetic fields applied perpendicular to the CuO planes. The magnetization data for high fields show excellent 2D scaling behavior in the variable $[T-T_c(H)]/(TH)^{1/2}$ near T_c, in good agreement with the prediction by Ullah and Dorsey.[11] Weak-field fluctuation-diamagnetic susceptibility $\chi(T)$ above T_c is found to be proportional to $T/(T-T_c)$, as expected from earlier work based on the 2D LD model.[6-8] The values of $\xi(0)_{ab}$, dH_{c2}/dT, as determined from our 2D fluctuation analysis, are consistent with those values we reported earlier[5] obtained by fitting the Hao-Clem variational model[14] to the reversible magnetization data below 90 K, where fluctuations become much less pronounced. This consistency indicates that the unconventional behavior[1,5] of Bi-based superconductors in the region of the mean-field transition is due to 2D fluctuation effects and also demonstrates that 3D anisotropic GL theory, on which the Hao-Clem model is based, is still applicable in studying reversible magnetization of quasi-2D superconductors in temperature and field regions where fluctuation effects are sufficiently small.

The specimen used for this study came from a $40\times3\times0.1$ mm^3 highly c-axis-oriented Bi(2:2:2:3) thin tape (with grain misorientations typically around 6° or less) sandwiched in a silver sheath, made by a method reported previously.[15] The composition of the superconducting material as determined by various means of chemical analysis is $Bi_{1.8}Pb_{0.4}Sr_2Ca_{2.2}Cu_3O_y$ (at least 95% phase pure). The transport critical current density of this tape exceeds 30 000 A/cm^2 at 77 K and zero field. T_c has been determined from shielding measurements at 2 Oe to be 107.5 K, with a transition width of 2.6 K, as reported earlier.[5] The high critical current density and sharp transition demonstrate the excellent quality of this specimen. The tape was cut into ten pieces and stacked along the c axis for the magnetization measurement in a Quantum Design superconducting quantum interference device (SQUID) magnetometer in fields applied parallel to the c axis. The data are taken by measuring the magnetization versus temperature at various fixed magnetic fields in the temperature range from the irreversible temperature to 300 K. Background signals and normal-state magnetization were carefully subtracted using the extrapolation of a curve fitted to the measured magnetic-moment-versus-temperature data between 200 and 300 K, as described in our earlier report.[5] The measurements were performed with different sample holders, and both 2- and 3-cm scan lengths were used. The results were all consistent. All data sets of $4\pi M(T)$ versus T after the substraction show very similar behavior.

Shown in Fig. 1, is a plot of $4\pi M$ versus T measured at fields between 500 and 50 000 Oe. The strong fluctuation effect is clearly demonstrated by the large excessive diamagnetization above 110 K and the crossover of various $4\pi M$-versus-T curves. We first studied the temperature dependence of the weak-field fluctuation diamagnetic susceptibility $\chi(T)$ above T_c based on the static models by Lawrence and Doniach,[7] Klemm,[8] and Prober and Beasley.[16] Within these models, it has been shown that $\chi(T)/T \propto T_c/(T-T_c)^n$ near T_c, where n is 1 for a 2D system, and $\frac{1}{2}$ for a 3D system. The weak-field regime defined by Klemm[8] corresponds to $B<S_0=\phi_0/(sL)$, where ϕ_0 is the flux quantum $hc/2e$, s [18.6 Å for Bi(2:2:2:3)] is the CuO layer repeat distance along the c axis, and L is in effective length[8] in the ab plane, which has the same order of magnitude as the average grain size of our specimen ($\sim$ 10 μm). Thus, the weak-field regime we studied here is equivalent to applied magnetic fields of less than a few KOe. A plot of $T/\chi(T)$ versus T of Bi(2:2:2:3) for fields at 500, 1000, and 2000 Oe is shown in Fig. 2(a). The data taken at all three fields display rather good linearity, at least between 114 and 130 K, which clearly indicates the 2D characteristics of the weak-field fluctuation diamagnetism. The mean-field transition temperature $T_c^{\rm MF}$ was obtained as the intercept of the straight line, shown in Fig. 2(a), from a least-squares fit to the data of $T/\chi(T)$ versus T at temperatures between 114 and 130 K. The corresponding values of T_c are found to be (111.13 ± 0.02) K at 500 Oe, (111.09 ± 0.02) K at 1000 Oe, and (111.06 ± 0.04) K at 2000 Oe. Thus, $T_c^{\rm MF}$ is taken to be (111.08 ± 0.07) K for Bi(2:2:2:3). The value of $T_c^{\rm MF}$, determined in this way, is about 3.6 K higher than that from a 2-Oe shielding measurement. This result is similar to that reported by Kes *et al.*,[1] where $T_c^{\rm MF}$ was found

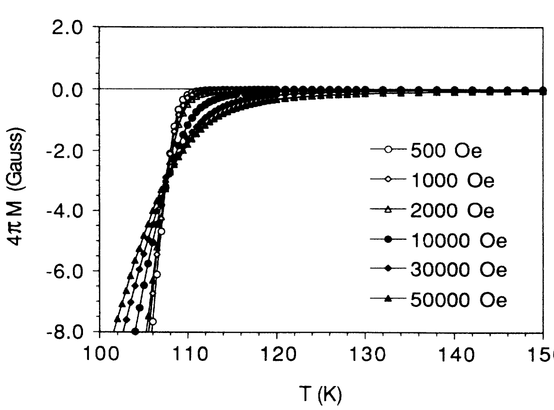

FIG. 1. Temperature dependence of magnetization of Bi(2:2:2:3) in various magnetic fields parallel to the c axis.

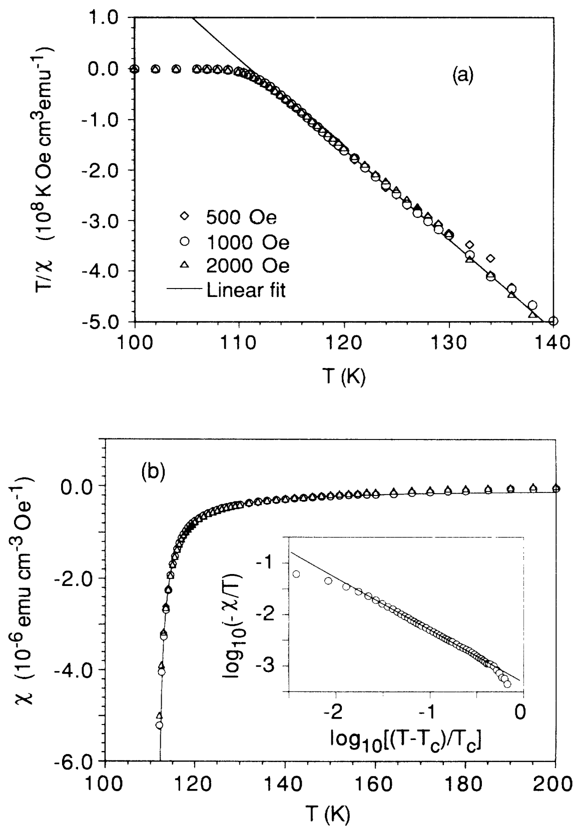

FIG. 2. (a) T/χ data plotted as a function of T, measured at 500, 1000, and 2000 Oe. The solid line is a linear fit to the data of 1000 Oe between 114 and 130 K. (b) Temperature dependence of χ, measured at 500, 1000, and 2000 Oe. The solid curve is a theoretical fit to the data of 1000 Oe using Eq. (1). The inset shows a log-log plot of $-\chi/T$ vs $(T-T_c)/T_c$ for the data of 1000 Oe. The solid line is a theoretical fit.

to be about 4° higher than that from ac susceptibility measurement of a Bi(2:2:1:2) single crystal. Figure 2(b) shows a fit of the 2D LD model to the data for $\chi(T)$, taken at 1000 Oe with $T_c = 111.08$ K via Eq. (1).

$$\chi = -\frac{1}{3} g_{\text{eff}} \frac{\pi k_B \xi_{ab}^2(0) T}{\phi_0^2 s} \frac{T_c}{T - T_c} , \tag{1}$$

where g_{eff} is the effective number of complex s-wave order parameters in the CuO plane, which is taken as 3 for three effective CuO planes in Bi(2:2:2:3) within the 2D fluctuation regime.[6,8] The fit is in good agreement with the data at temperatures from 113 to 170 K. This can be seen more clearly from the inset of Fig. 2(b), showing a log-log plot of $-\chi/T$ versus $(T-T_c)/T_c$ for the data taken at 1000 Oe, where the solid line is the theoretical fit by using Eq. (1) with $T_c = 111.08$ K. At temperatures higher than 170 K, the absolute values of $\chi(T)$ obtained from fitting are slightly higher than the experimental data. This is because the LD model is a mean-field theory in its approach and overestimates the contribution to the fluctuational diamagnetic susceptibility χ from the high-energy, short-wavelength fluctuations.[16] The best fit to the data for all three fields (500, 1000, and 2000 Oe) yields $\xi_{ab}(0) = (9.7 \pm 0.4)$ Å. This value is quite close to what we derived by fitting the Hao-Clem variational model to the reversible magnetization data below T_c, which gives $\xi_{ab}(0) = (10.5 \pm 0.6)$ Å.[5]

Because of large fluctuations, as discussed above, the thermodynamic and transport properties in the transition region in high magnetic fields scales with the variable $A[T - T_c(H)]/(TH)^n$. In the particular case of magnetization, the scaling behavior is given by [2,11]

$$\frac{4\pi M}{(TH)^n} = F\left[A \frac{T - T_c(H)}{(TH)^n} \right] , \tag{2}$$

where F is the scaling function, A is a temperature- and field-independent coefficient, and n is $\frac{2}{3}$ for a 3D system and $\frac{1}{2}$ for a 2D system. Figure 3(a) shows a plot of the scaled fluctuation magnetization of Bi(2:2:2:3) assuming 2D behavior, where only the data at 10 000, 30 000, and 50 000 Oe are plotted for clarity. The free parameters involved in this scaling fit are values of $T_c(H)$. In this special case, where high magnetic fields are parallel to the c axis, $H_{c2}(T)$ depends linearly on T near T_c in both 2D and 3D mean-field theory,[2,6,17] so that we can write $T_c(H)$ as $T_c^{\text{MF}} - H/(dH_{c2}/dT)$. Thus, by using the mean-field transition temperature T_c^{MF} (111.08 K) for zero field, which is derived from the analyzed results for the weak-field fluctuation susceptibility as shown above, the only adjustable parameter we used in the fitting is dH_{c2}/dT near T_c. The best fit for 2D behavior was obtained with $-dH_{c2}/dT$ equal to 3.9 T/K. However, it is noted that this good scaling fit with different values of $-dH_{c2}/dT$ ranging from 3.3 to 4.2 T/K can be hardly distinguished from any other, and holds down to 101.5 K for $H = 50\,000$ Oe. Shown in Fig. 3(b) is the best possible scaling fit to our data using the 3D expression [or Eq. (2) with $n = \frac{2}{3}$], where the corresponding fitting parameters are $T_c^{\text{MF}} = 111.02$ and $-dH_{c2}/dT = 3.2$ T/K. The splitting near the transition region for different fields inevitably exists. This clearly shows that the nature of the superconducting transition of Bi(2:2:2:3) is two dimensional and also that no 2D-to-3D crossover was observed in Bi(2:2:2:3). This result is quite opposite to what Fastampa *et al.*[18] found in experiments using Bi(2:2:1:2) thin films, where the angular-dependent magnetic field H^* at the onset of the resistivity exhibits a crossover from 2D to anisotropic 3D behavior. Let us estimate the possible temperature range of 3D behavior (or critical region) by calculating the dimensional crossover temperature T^* given by Klemm.[8] T^* is defined through $\xi_c(T^*) = \xi_c(0)/(1 - T^*/T_c)^{1/2} = s/\sqrt{2}$, where ξ_c is the GL coherence length perpendicular to the layers. By using the anisotropy ratio for Bi-based superconductors (~ 50),[19] the value of $\xi_c(0)$ for Bi(2:2:2:3) is of the order of 0.2 Å, where $\xi_{ab}(0)$ is taken as 9.6 Å. Thus, the value of $T^* - T_c$ is less than 0.03 K for $s = 18.6$ Å. Such an extremely narrow width of the critical region is virtually impossible to observe by magnetization measurements.

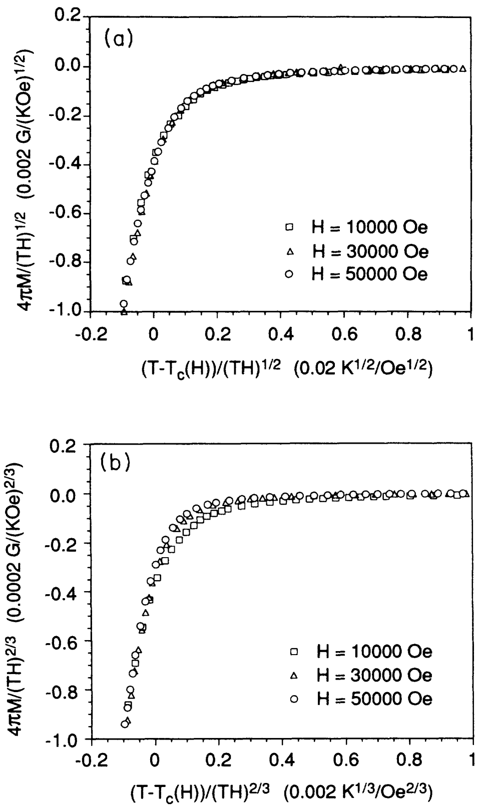

FIG. 3. (a) 2D scaling of the magnetization data for Bi(2:2:2:3), measured at 10 000, 30 000, and 50 000 Oe. (b) 3D scaling of the same magnetization data as shown in (a).

Once again, the value of $-dH_{c2}/dT$ derived from the best fit of our data to the 2D scaling theory is 3.9 T/K, which is rather close to the value 3.6 T/K derived by fitting the 3D anisotropic Hao-Clem model to the reversible magnetization data below T_c. Our self-consistently-determined results for $-dH_{c2}/dT$ and $\xi_{ab}(0)$ from 2D fluctuation analysis demonstrate that the 3D anisotropic

GL theory can still be used for qualitively studying the mixed-state magnetic properties of Bi-based superconductors, at least in large magnetic fields applied perpendicular to CuO layers and in the region where fluctuation effects are sufficiently small.

In conclusion, the results presented here show that the magnetization properties near $T_c(H)$ in high fields and above T_c^{MF} in weak fields can be described well by GL fluctuational theory for a 2D superconductor. No critical region (2D-to-3D crossover) is observed, based on the scaling behavior of high-field magnetization data, due to its extremely narrow extent. These results also explain that the development of the characteristic fan-shaped magnetization near $T_c(H)$,[1,5] and the divergence of the GL parameter κ near T_c,[5] obtained as the result of applying the Hao-Clem variational model to layered superconductors, are simply due to the large, extended thermodynamic fluctuations of the superconducting order parameter.

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