Temperature dependence of the magnetization of a $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal close to T_c

R. Jin, A. Schilling, and H. R. Ott
Laboratorium für Festkörperphysik, Eidgenössische Technische Hochschule Zürich-Hönggerberg, 8093 Zürich, Switzerland
(Received 29 November 1993)

The magnetization $M(T,H)$ of a $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal has been measured above and below the superconducting transition temperature in externally applied magnetic fields H up to 50 kOe for $H \| c$. We find that $M(T,H)$ is independent of H at a particular temperature T^* for external fields exceeding 10 Oe, and exhibits a two-dimensional (2D) scaling behavior as a function of $[T-T_c(H)]/(HT)^{1/2}$. The parameters $\xi_{ab}(0)\approx 21.4$ Å and $\xi_c(0)\approx 0.4$ Å are estimated from fitting the experimental data to a full Lawrence-Doniach model calculation of the fluctuation-induced magnetic susceptibility. From the same analysis, we obtain $dH_{c2}/dT \approx -14$ kOe/K in the range 5 kOe$<H<$50 kOe.

The magnetic properties of conventional type-II superconductors near the transition temperature T_c are well described by Abrikosov's solution[1] of the mixed state in high fields H close to H_{c2}, where H is an externally applied magnetic field and H_{c2} is the upper critical field. In this description, $M(T,H)$ varies linearly with $[H_{c2}(T)-H]$. The upper critical field H_{c2} can therefore be evaluated by extrapolating $M(T,H)$ from the superconducting state to the crossing point with the normal-state $M(T,H)$ curve. This procedure to evaluate $H_{c2}(T)$ has been shown to be inadequate for high-T_c cuprate superconductors.[2] The failure must mainly be traced back to strong fluctuations of the superconducting order parameter, which, for cuprate superconductors, occur within a sizable temperature range around the superconducting transition temperature T_c, and it may at least be questioned whether a distinct phase transition fixes $H_{c2}(T)$. These fluctuations have been claimed to be responsible for the particular temperature dependence of the electrical resistivity $\rho(T)$ above T_c of these superconductors,[3] but more recently they are also believed to cause a crossing behavior of the reversible magnetization[4-6] at a particular temperature T^*, a few degrees below the zero-field superconducting transition temperature $T_c(0)$. In rather high fields, i.e., of magnitude comparable to H_{c2}, $M(T,H)$ has been found to obey certain scaling features[5-9] in the reversible regime of superconducting $YBa_2Cu_3O_7$, $(La_{1-x}Sr_x)_2CuO_4$,and $Bi_2Sr_2Ca_2Cu_3O_{10}$.

In this paper, we report on measurements of $M(T,H)$ of a $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal in external fields between 1.5 Oe and 50 kOe and $H\|c$. We find that all $M(T,H)$ curves for $H\geq 10$ Oe cross at one point in the $[H,T]$ plane. This implies that a field independence of the magnetization M^* at T^* is observed down to very low fields. We confirm the previously reported scaling behavior for some cuprate superconductors in high fields also for $Bi_2Sr_2CaCu_2O_{8+\delta}$. In addition, the analysis of our experimental data allows one to evaluate the characteristic parameters $\xi_{ab}(0)$ and $\xi_c(0)$, the zero-temperature coherence lengths parallel and perpendicular to the basal plane, respectively.

For our experiments, we used a $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal of mass $m=2.65$ mg; the dimensions in the a and b directions were $\sim 3\times 3.5$ mm^2. The crystal was grown from the melt in a temperature gradient. The zero-field cooling magnetization $M(T,H)$ was measured with a commercial superconducting quantum interference device (SQUID) magnetometer. The temperature T was varied between 60 and 110 K, and external fields H parallel to the crystallographic c axis between 0 and 50 kOe were available. All $M(T,H)$ data have been corrected for background and demagnetization effects as described below. After these corrections, a critical temperature $T_{c0}=90.7$ K was deduced from monitoring the magnetization in an externally applied dc field of $H=1.5$ Oe. Cooling the sample in a field of 1.5 Oe gave 87% of perfect flux expulsion, confirming the high quality of the sample.

In Fig. 1 we show the temperature dependence of the magnetization for different values of external magnetic

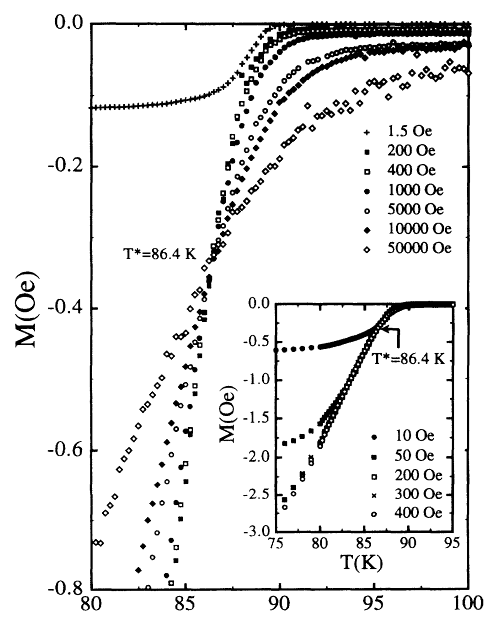

FIG. 1. Temperature and magnetic-field dependence of the magnetization of single-crystalline $Bi_2Sr_2CaCu_2O_{8+\delta}$. The crossing point $T^*=86.4$ K is indicated. The inset emphasizes the temperature dependence of the magnetization in low fields.

0163-1829/94/49(13)/9218(4)/$06.00

fields. Quite prominent is the increasing rounding of the transition with increasing H. The inset presents the dependence of M versus T in fields of less than 400 Oe. This figure reveals the most interesting experimental result of this paper, namely, that all magnetization curves $M(T,H)$ pass through one point (M^*,T^*) for $H>10$ Oe. The crossing temperature T^* is 86.4 K, corresponding to a magnetization $M^*\approx-0.33$ Oe. In comparison with previous publications,[4–6] we emphasize that the crossing behavior of $M(T,H)$ not only occurs in high fields close to $H_{c2}(T)$, but also in rather low fields, except for fields of less than 10 Oe, as will be mentioned below. Depending on the value of the external field, $M(T,H)$ follows the same trace in a restricted temperature range. This implies that the field independence of the magnetization is first valid over a varying temperature range which depends on H. The minimum external field for M to reach $M^*(T^*,H)$ is found to be 10 Oe. As the applied magnetic field exceeds 400 Oe, the crossing of the $M(T,H)$ curves at only one point $M^*(T^*,H)$ sets in; i.e., above T^*, $|M(T,H)|$ increases with increasing H, and the opposite is observed below T^*. The latter behavior is observed in conventional type-II superconductors in the mixed state.

As pointed out above, many of the physical properties of high-T_c cuprate superconductors are considerably influenced by strong fluctuation effects. Welp *et al.*[6] claimed a fluctuation-related high-field scaling behavior of thermodynamic and transport quantities of superconducting $YBa_2Cu_3O_7$ single crystals near T_c if plotted versus the variable $[T-T_c(H)]/(TH)^{2/3}$, where $T_c(H)$ is the mean-field transition temperature in the magnetic field H. Theoretically, such a scaling behavior is predicted by considering a fluctuation region around T_c growing with H according to a field-dependent Ginzburg criterion.[5] If the considered field values exceed the limit $H'(T)$, where

$$H'(T)=H_{c2}(T)/3+(\sqrt{\theta}/3)\sqrt{H'(T)H_{c2}(0)T/T_{c0}}\ , \qquad (1)$$

with θ as the Ginzburg fluctuation parameter,[5] it may be assumed that only the lowest Landau level (LLL) is occupied by the quasiparticles, which greatly simplifies the analysis. In this LLL approximation, the exponent of the scaling variable $[T-T_c(H)]/(TH)^n$ varies with the dimension D of the system in zero field. Values of $n=\frac{1}{2}$ or $\frac{2}{3}$ for two-dimensional (2D) or three-dimensional (3D) systems, respectively, have been established.[5,6]

In more recent work,[5,8,9] it was claimed that the reversible magnetization of both $(La_{1-x}Sr_x)_2CuO_4$ and $Bi_2Sr_2Ca_2Cu_3O_{10}$ reveal crossing $M(T,H)$ curves and, in addition, a scaling behavior as a function of $[T-T_c(H)]/(TH)^{1/2}$. Particularly, the latter compound is known to be considerably anisotropic, and thus it may be anticipated that $n=\frac{1}{2}$. An alternative attempt to consider the influence of fluctuations in calculations of physical properties of particularly anisotropic cuprate superconductors is due to Bulaevskii, Ledvij, and Kogan.[4] In their approach, the quasi-2D character of these superconductors was taken into account by regarding them as a stack of Josephson-coupled layers according to the model of Lawrence and Doniach[10] (LD) and by considering the entropy contribution of spatially fluctuating vortices. For high fields $H>H_{cr}$, where

$$H_{cr}(T)=\frac{\phi_0}{\pi\lambda_J^2}\ln\frac{\lambda_J/\xi_{ab}(T)}{4\sqrt{\ln[\lambda_J/\xi_{ab}(T)]}}\ , \qquad (2)$$

a crossing point of $M(H)$ at $M^*(T^*,H)$ is predicted. The parameter $\lambda_J=\gamma s$ is the Josephson length, γ is the anisotropy parameter, ϕ_0 is the superconducting flux quantum, and s is the layer separation. The resulting equation for $M(T,H)$ fits the experimental data quite well for $T<T^*$, but the agreement between calculation and experiment is much less satisfactory for $T>T^*$.[4] In view of these experiments and the claimed difference in scaling behavior between $YBa_2Cu_3O_7$ and $Bi_2Sr_2Ca_2Cu_3O_{10}$, it seemed of interest to check these ideas on $Bi_2Sr_2CaCu_2O_{8+\delta}$, a superconductor of known extreme anisotropy.

In attempts to verify by experiment the above-mentioned concepts to explain a crossing point or a particular scaling behavior, various difficulties have to be kept in mind. First of all, the geometrical configuration of the experiment requires that the raw data for $M(T,H)$ be carefully corrected for demagnetization effects. Tests for the scaling conjectures in particular require a reliable evaluation of $T_c(H)$ from experiment, which in turn also necessitates a reliable subtraction of background contributions to M in the normal state. Below we discuss the analysis procedure used in this work.

It has previously been found that fluctuation-induced diamagnetism appears at temperatures below $\sim 2T_c$.[11] In our experiments, the magnetization above 150 K is temperature independent. Therefore we evaluated the normal-state background from data between 150 and 180 K and subtracted a corresponding constant value for each field H. For the demagnetization corrections, we used the demagnetization factor N of the crystal, determined independently by measuring, after zero-field cooling, the susceptibility χ_m at $T=6$ K in external fields H between 0 and 60 Oe. The magnetization M varies perfectly linearly with H, implying that $\chi_m=M/H$ is constant and the sample is completely magnetically screened. The deviation of χ_m from $-1/4\pi$ is thus ascribed to demagnetization effects, and the demagnetization factor N is calculated from $N=(1/4\pi\chi_m)-1$. We obtained $N=0.965$, and this value is used for correcting all the measured χ_m data according to $1/\chi_{\rm eff}=(1/\chi_m)-4\pi N$.

For the evaluation of $T_c(H)$, we compare our data $\chi_{\rm eff}$ for the fluctuation-induced contribution to the magnetic susceptibility $\chi_{\rm fl}$ in the normal state, with theoretical predictions available in the literature. The problem was first investigated theoretically by Schmid[12] and subsequently was treated for a lower-dimensional system by Lawrence and Doniach.[10] The latter model has been used in previous work,[8,13,14] where the 2D limit for $\chi_{\rm fl}$ due to superconducting-fluctuation diamagnetism in low fields parallel to c,

$$\chi_{\rm fl}(T)=-\frac{n\pi k_B\xi_{ab}^2(0)T}{3\phi_0^2 s}\frac{T_c(H)}{T-T_c(H)}\ , \qquad (3)$$

was employed for this type of analysis. Here n is the effective number of independently fluctuating CuO_2 layers per unit cell and k_B is Boltzmann's constant. It is, however, not clear whether this approximation is valid close to T_c, and therefore we have chosen to use the more complete solution of the Lawrence-Doniach model for H perpendicular to the layer planes ($H\|c$), given in Ref. 15,

$$\chi_{fl}(T)=-\frac{\pi k_B \xi_{ab}^2(0)T}{6\phi_0^2} \times \frac{T_c(H)/[T-T_c(H)]}{\sqrt{\xi_c^2(0)T_c(H)/[T-T_c(H)]+(s/2n)^2}}, \tag{4}$$

where, in comparison with the original solution, s now denotes the distance between pairs of CuO layers in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Refs. 11 and 16) and $n=2$. The temperature dependence of the coherence length in the c direction, $\xi_c(T)$, is assumed as $\xi_c(T)=\xi_c(0)[T_c/(T-T_c)]^{1/2}$. In the case of $\xi_c(T)\ll s/2n$, $\chi_{fl}(T)$ in Eq. (4) approaches the two-dimensional limit as given in Eq. (3). If, however, $\xi_c(T)\gg s/2n$, Eq. (4) is a good approximation for a three-dimensional system,[12] as expected for T approaching T_c.[10] We take $s=15.4$ Å for $Bi_2Sr_2CaCu_2O_{8+\delta}$. The LD low-field regime requires $H\ll H_{c2}(0)$.[8] According to a previous estimate for our crystal, $H_{c2}(0)\approx 900$ kOe,[17] and therefore we selected the fit region as $T_c(0)<T<110$ K and $H\leq 50$ kOe. First, we fitted our data to $\chi_{fl}(T)$ for each field value using Eq. (4) and a starting value $\xi_{ab}(0)=19$ Å.[17] The resulting fitting parameters $\xi_c(0)$ and $T_c(H)$ are subsequently used to establish an improved value for $\xi_{ab}(0)$. Repeating this procedure iteratively results in a self-consistent set of parameters. Although $\xi_{ab}(0)$ and $\xi_c(0)$ vary slightly with H, we found that the fit quality is not significantly worse if we keep these parameters constant. The quoted values $\xi_{ab}(0)\approx(21.4\pm0.5)$ Å and $\xi_c(0)=(0.4\pm0.04)$ Å are obtained for $H=1000$ Oe. Figure 2 displays a $\chi_{fl}(T)$ fitting curve for $H=50$ Oe using Eq. (4). The variation of the fit parameter $T_c(H)$ is shown in Fig. 3. The inset in Fig. 3 gives the H dependence of $T_c(H)$ in external fields less than 1000 Oe. Here $H_{c2}(0)\approx 720$ kOe is given by $H_{c2}(0)=\phi_0/2\pi\xi_{ab}^2(0)$ and is consistent with $H_{c2}(0)\gg H_{expt}$.

As may be seen in Fig. 3, fitting our experimental data with Eq. (4) results in a somewhat unexpected field dependence of T_c in low fields, where this approximation should be particularly valid. The slope $-dH_{c2}/dT$, which is constant for external fields exceeding 5 kOe (see Fig. 3), decreases progressively as T increases, and $T_c(H)$ extrapolates to the same value $T_c(0)=90.7$ K as is obtained from the onset of diamagnetism by measuring the magnetization in an external field of 1.5 Oe. This behavior is clearly revealed by the inset of Fig. 3. Similar phenomena have been observed in $YBa_2Cu_3O_7$ and $Ba_{1-x}K_xBiO_3$ superconductors,[18-20] where $T_c(H)$ has been evaluated from measurements of thermal conductivity, magnetization, or resistivity, respectively. If we attempt to fit our data M/M^* by using Eq. (13) of Ref. 5, where the slope $(dH_{c2}/dT)_{T_{c0}}$ is the only fitting parameter, this latter quantity again turns out to be temperature dependent for T close to T_{c0}. This, of course, is not consistent with Ginzburg-Landau theory where $H_{c2}(T)$ is expected to vanish linearly with $(T-T_{c0})$.

Our observations and their analysis demonstrate that it is difficult to unambiguously evaluate the mean-field transition temperatures $T_c(H)$ for cuprate superconductors, particularly in cases where the superconducting parameters are extremely anisotropic, as in our material. We are led to conclude that the $T_c(H)$ values extracted from fits

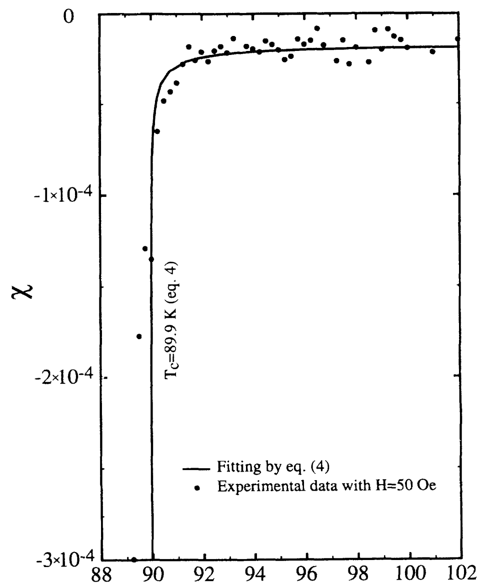

FIG. 2. Temperature dependence of χ_{eff} for $H=50$ Oe close to T_c (solid circles). The solid line is a fit to the experimental data using Eq. (4).

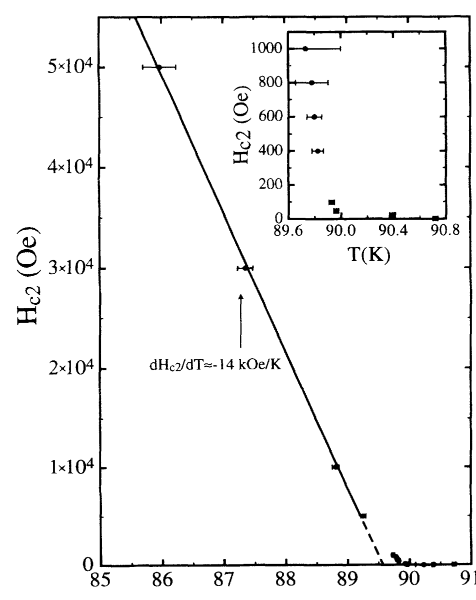

FIG. 3. Temperature dependence of the upper critical field for $H\|c$ deduced from $T_c(H)$ by fitting χ_{eff} to χ_{fl} as expressed in Eq. (4) (solid circles). The solid line is a linear approximation for $H\geq 5$ kOe. The inset emphasizes the apparent dependence of $H_{c2}(T)$ at temperatures very close to $T_c(0)$.

to our curves obtained in fields of less than 5 kOe can merely be regarded as fit parameters to describe the fluctuation-induced magnetic response by using Eq. (4). It is even doubtful whether the $T_c(H)$ curve for $H \geq 5$ kOe is more than representing some sort of a crossover field. Nevertheless, it may be noted that evaluating $H_{c2}(0)$ by using the conventional equation $H_{c2}(0) = -0.693 T_c (dH_{c2}/dT)_{T_c}$ (Ref. 21) and inserting the constant slope $dH_{c2}/dT \approx -14$ kOe/K from Fig. 3 results in a value $H_{c2}(0) = 860$ kOe, not significantly different from the estimate quoted above.

All this said, it is again not obvious that the $T_c(H)$ values obtained in this way are meaningful quantities to test the previously demonstrated scaling behavior of $M(T,H)$ now also for $Bi_2Sr_2CaCu_2O_{8+\delta}$. It is also not clear whether in our case, as has been claimed in previous work, a single scaling variable is sufficient to cover the whole temperature range of interest. In general, it may be expected that a 2D behavior for temperatures well within the normal state will turn into 3D behavior for temperatures close to $T_c(H)$. Since in our case $T_c(H)$ crosses T^* with increasing field, such behavior cannot *a priori* be ruled out. It seems therefore rather surprising that the attempt to scale our data for $H \geq H'(T)$ with a single variable is quite successful even for $T < T_c(H)$ if 2D behavior ($n = \frac{1}{2}$) is assumed, and it appears to work quite well also for small fields (see Fig. 4). A similar attempt assuming $n = \frac{2}{3}$ is obviously much less convincing (see inset of Fig. 4).

As mentioned above, the crossing of magnetization curves at a particular point $M^*(T^*,H)$ in arbitrary field exceeding a lower limit [see Eqs. (1) and (2)] may be justified with calculations based on the LLL approximation,[5] taking into account thermal motions of the vortices.[4] Our experiments clearly reveal the existence of this crossing point to extend to very low fields, where that type of calculations is obviously no longer valid. In other words, the onset of occupancy of higher Landau levels has no obvious consequences.

From the present investigation, we conclude that the magnetic response of superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ is characterized by a special feature, namely, a field-independent magnetization M^* at a particular temperature T^* for external fields exceeding 10 Oe. It seems remarkable that this field independence of M^*, which previously was found in high fields, persists to such low field values, at least in $Bi_2Sr_2CaCu_2O_{8+\delta}$.

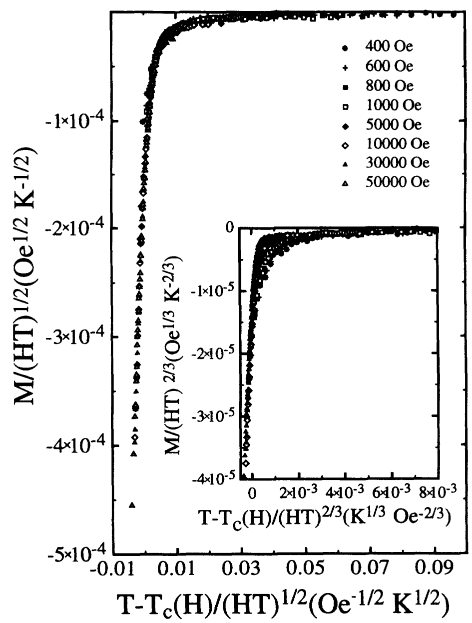

FIG. 4. $M/(HT)^{1/2}$ vs $[T - T_c(H)]/(HT)^{1/2}$ for $H(T) \geq H'(T) \sim H_{c2}(T)/3$ [see Eq. (1)]. The inset is a plot of $M/(HT)^{2/3}$ vs $[T - T_c(H)]/(HT)^{2/3}$ in the same field region.

The temperature dependence of the magnetic susceptibility, in varying external magnetic fields, corrected for background and demagnetization effects and hence representing the contribution due to superconducting fluctuations, is very well described by a full calculation based on the Lawrence-Doniach model.

Although not *a priori* expected to be applicable, a scaling ansatz involving a single scaling variable describes the experimental $M(T,H)$ remarkably well, again in a surprisingly wide range of external magnetic fields.

We thank J. D. Guo for his help in synthesizing the single crystals and gratefully acknowledge some stimulating discussions with B. Ivlev and G. Blatter. This work was financially supported by the Schweizerische Nationalfonds zur Förderung der wissenschaftlichen Forschung and by a grant from the SNF program NFP 30.

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