



UvA-DARE (Digital Academic Repository)

Field-induced suppression of the phase transition in Bi₂Sr₂CaCu₂O₈

Kes, P.H.; Beek, C.J. van der; Maley, M.P.; McHenry, M.E.; Huse, D.A.; Menken, M.J.V.; Menovsky, A.A.

Published in:
Physical Review Letters

DOI:
[10.1103/PhysRevLett.67.2383](https://doi.org/10.1103/PhysRevLett.67.2383)

[Link to publication](#)

Citation for published version (APA):

Kes, P. H., Beek, C. J. V. D., Maley, M. P., McHenry, M. E., Huse, D. A., Menken, M. J. V., & Menovsky, A. A. (1991). Field-induced suppression of the phase transition in Bi₂Sr₂CaCu₂O₈. *Physical Review Letters*, 67(17), 2383-2386. DOI: 10.1103/PhysRevLett.67.2383

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <http://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

Field-Induced Suppression of the Phase Transition in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$

P. H. Kes,^(a) C. J. van der Beek,^(a) M. P. Maley, and M. E. McHenry^(b)

Exploratory Research and Development Center, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

D. A. Huse

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

M. J. V. Menken and A. A. Menovsky

Natuurkundig Laboratorium, University of Amsterdam, Amsterdam, The Netherlands

(Received 6 May 1991)

Magnetization measurements in field on a $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystal do not reveal any sharp phase transition between the normal and superconducting states. The $M(H)$ curves for temperatures about T_c in fields up to 5 T all display diamagnetic behavior. Above the mean-field transition temperature T_c^{MF} , quasi-two-dimensional diamagnetic fluctuations are responsible. Below T_c^{MF} strong deviations from the conventional mean-field (Abrikosov) behavior lead to an apparent $T_c(B)$ which increases with field. This effect clearly demonstrates the inadequacy of the mean-field theory to describe the vortex state below the crossover line $H_{c2}(T)$.

PACS numbers: 74.60.Ec, 74.40.+k

It has been a general belief that the in-field transition between the normal and mixed states in a type-II superconductor is given by a second-order phase transition defined as $H_{c2}(T)$. However, recent theoretical work [1] regarding the high- T_c cuprates rather characterized $H_{c2}(T)$ as a crossover line between the normal state and a vortex liquid. A similar prediction has been formulated based on the analogy with quasi-two-dimensional (2D) magnetic insulators [2]. In the high-temperature superconductors (HTS), the vortex-liquid regime in the (B, T) phase diagram is quite extended, especially when the material, because of its large anisotropy, is quasi-2D. For example, for $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (Bi 2:2:1:2) with an anisotropic effective-mass ratio $\Gamma \geq 3000$ [3], above a field $B_{2D} \approx \Phi_0/\Gamma s^2$ in the c direction the pancake vortices in adjacent CuO_2 double layers with spacing s are essentially decoupled [4]. Consequently, the vortex-lattice melting temperature in the limit of weak pinning is expected to be the same as for a 2D superconductor of thickness s ($s = 1.5$ nm); i.e., for $B > B_{2D} \approx 1$ T it melts at about 30 K. Below the melting line it is natural to consider the Abrikosov lattice as the ground state when investigating fluctuation effects [5]. For the liquid state it can no longer be expected that this is allowed [6]. The magnetic properties in the liquid state may therefore deviate from the well-known Abrikosov behavior. As we shall see below, considerable deviations are indeed observed due to fluctuations.

Note that the fluctuations suppress the melting line in a field by over 50 K from the mean-field transition $T_c \approx 90$ K. This can be contrasted with the fluctuation effects in zero field [7] where the Kosterlitz-Thouless (KT) transition at T_c is suppressed by only 2 K below the Ginzburg-Landau (GL) transition temperature T_c^0 [8].

In this paper we report on magnetization measurements on a high-quality Bi 2:2:1:2 single crystal in a com-

mercial SQUID system with the field along the c direction. The data are all taken in the vortex-liquid and normal regimes, i.e., in the fully reversible field-temperature regime above the irreversibility or melting line. The crystal weight and dimensions are 11.4 mg and $4 \times 4 \times 0.11$ mm³ and its lattice parameters are $a = 0.5333$ nm, $b = 0.5485$ nm, and $c = 3.076$ nm. The composition as determined by microprobe analysis is $\text{Bi}_{2.2}\text{Sr}_{1.9}\text{CaCu}_2\text{O}_x$. Details of the preparation will be published in Ref. [9]. High-resolution electron microscopy confirmed the high purity of the crystal, for only minor traces of the 2:2:0:1 phase could be detected in a concentration of 2 out of 1000 CuO_2 double layers [10]. T_c has been determined from the ac susceptibility transition in a 2.8- μT ac field applied parallel to the a - b planes in a shielded dc environment of less than 0.3 μT . A linear extrapolation of the $\chi'(T)$ data to zero defined $T_c(0) = 88.1$ K, and that to $\chi' = -1$, the transition width of 1.5 K, demonstrating the uniformity of our sample.

In Fig. 1 our $M(T)$ data are shown for various fields ($\mathbf{H} \parallel c$) between 0.1 and 5 T. The gradual decrease above 90 K indicates the effect of diamagnetic fluctuations [11]. Since this effect is negligibly small above 120 K, we corrected for a background signal by subtracting M at 120 K. The data sets between 70 and 87 K display an essentially linear behavior. Assuming linear $M(T, H)$ behavior to be valid near $H_{c2}(T)$, as is the case in Abrikosov's solution, extrapolation to $M = 0$ would determine $T_c(B)$. These intercepts are shown in the inset of Fig. 1. It is seen that the resulting " $T_c(B)$ " increases with increasing B , opposite to the usual behavior. We stress here that we do not believe these data represent the mean-field $H_{c2}(T)$, but rather that they demonstrate that the simple linear construction fails, for reasons to be discussed below.

It has been recently pointed out [12] that the linear

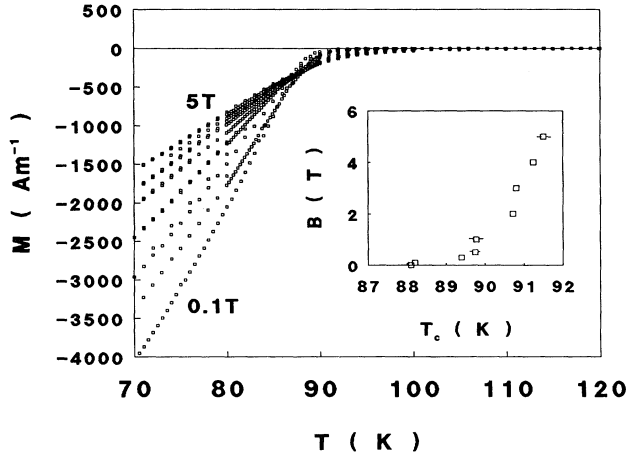


FIG. 1. Compilation of M -vs- T data of a Bi 2:2:1:2 single crystal in fields of 0.1, 0.3, 0.5, 1, 2, 3, 4, and 5 T (bottom to top) measured in both increasing and decreasing T runs. Inset: " $T_c(B)$ " as determined by linearly extrapolating $M(T)$ back to $M=0$.

Abrikosov regime near H_{c2} is very narrow in T because of the large dH_{c2}/dT values of the HTS. Our measurements might therefore display the subsequent logarithmic regime in which $-M \propto (\Phi_0/\lambda^2) \ln(\beta H_{c2}/H)$, where β is a constant of order unity, $\lambda(t) = 0.7\lambda_L(0)(1-t)^{-1/2}$ is the Ginzburg-Landau penetration depth, and $\lambda_L(0)$ is the London penetration depth at $T=0$. From the slope of dM/dT vs $\ln(H)$ the value of $\lambda_L(0)$ can be determined; see the inset of Fig. 2, where $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) data [13] are also shown. The YBCO data give $\lambda_L(0) = 140 \pm 9$ nm, in good agreement with the literature [14]. Our data, however, show a kink at about 1 T which would lead to two values, namely, $\lambda_L(0) = 170$ and 260 nm. In fact, a detailed comparison of our Bi 2:2:1:2 results with the computations of Ref. [12], taking $S \equiv -\mu_0 dH_{c2}/dT|_{T_c} = 1$ or 2 T/K, shows that neither the upturn of " $T_c(B)$ " nor the field dependence of dM/dT can be satisfactorily explained.

Additional evidence for deviations from the mean-field theory is seen in Fig. 2 where the $M(H)$ data above 0.1 T are plotted for a series of temperatures about T_c . Results below 0.1 T and below 86 K (e.g., at 80 K) show an initial sharp decrease to $M = -7200$ A/m followed by a steep rise to -2700 A/m at 20 mT (without correcting for the demagnetization effect). This result seems in accord with the conventional magnetization about H_{c1} . The high-field behavior at 80 K also agrees with the Abrikosov prediction. Evidently, the results increasingly deviate from the canonical behavior when T is increased. A clearly detectable diamagnetic signal remains above $T_c(0)$. It shows a fast increase which levels off at about 1 T and remains almost constant up to 5 T.

The data depicted in Figs. 1 and 2 are the major results of this paper. They suggest that strong fluctuation effects

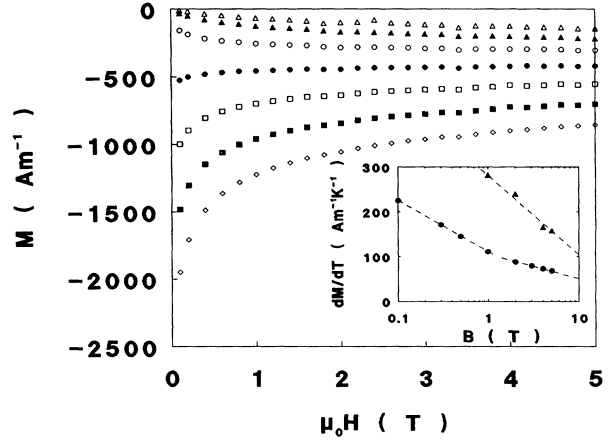


FIG. 2. Compilation of M -vs- H data above 0.1 T at 80 K (\diamond), 82 K (\blacksquare), 84 K (\square), 86 K (\bullet), 88 K (\circ), 90 K (\blacktriangle), and 92 K (\triangle). Inset: A semilogarithmic plot of the slopes of the linear parts of the $M(T)$ data vs field (circles). Note the kink at about $B_{2D} \approx 1.0$ T. For comparison the data of YBCO [13] are shown as well (triangles).

play an important part in the experimental $T_c(B)$. The fluctuation diamagnetization has been reviewed in Ref. [1]. The scaling of M and χ' follows from the singular part of the free energy per unit volume, or per unit area per coupled layer when it is used in 2D:

$$F_s \propto k_B T \xi_+^{-D} F(B/\bar{B}), \quad (1)$$

where $\bar{B} \equiv \Phi_0/\xi_+^2$ and D is the dimensionality. The scaling function F is different for each of the four regimes: 2D or 3D, weak or strong fluctuations (the latter being the critical regime). The coherence length ξ_+ diverges at T_c in the critical regime between T_c and T_c^0 ; for $D=2$ this divergence is exponential, while for $D=3$, $\xi_+ \propto (T - T_c)^{-\nu}$, with $\nu \approx \frac{2}{3}$. The coherence length behaves classically in the weak-fluctuation regime (WFR) above T_c^0 , namely, as $\xi_+ \approx \xi_{GL}(0)\tau_0^{-1/2}$, with $\tau_0 = (T - T_c^0)/T_c^0$. In 2D a convenient interpolation formula has been proposed [8]: $\xi_+ \approx b^{-1/2} \xi_c \sinh[(b\tau_c/\tau)^{1/2}]$, with b a dimensionless constant of order unity, $\tau \equiv (T - T_c)/T_c$, $\tau_c \equiv (T_c^0 - T_c)/T_c$, and $\xi_c \approx \xi_{GL}(0)\tau_c^{-1/2}$. The susceptibility in zero field in the 2D WFR is [8]

$$-\chi_s^{2D} = (\pi\mu_0 k_B T / 3\Phi_0^2) \xi_+^2. \quad (2)$$

The scaling of M is given by

$$-M_s = \partial F_s / \partial B \propto (k_B T \xi_+^{2-D} / \Phi_0) F'(B/\bar{B}). \quad (3)$$

The scaling function F' saturates at large arguments for $D=2$ and grows proportional to $(B/\bar{B})^{1/2}$ in 3D. For small B , F' is linear in the argument. Low-field contours of constant M would thus reveal the prevailing dimensionality, because they are equivalent to contours of constant $B\xi_+^{4-D}$. For $D=3$ this leads to $B \propto (T - T_c^0)^{1/2}$ in the WFR and $B \propto (T - T_c)^\nu$ in the critical regime. Both

would then have downward curvature of such contours for 3D. For $D=2$, on the other hand, the contours are straight in the WFR and curve upwards in the critical regime.

The inset of Fig. 3 shows contours of $-M=10, 30$, and 100 A/m at T above 86 K. The curvature shows that $D=2$. The dashed lines indicate that $T_c^0=88.4\pm 0.4$ K in agreement with our experimental definition of $T_c(0)$. For 2D, $M_s(B)$ should saturate to about $-\bar{M}=k_B T_c^0/\Phi_0 s$, so $M=-390$ A/m for Bi 2:2:1:2. This agrees reasonably well with the value $M=-310$ A/m at 88 K and 5 T (see Fig. 2). Note also that down to 0.3 T, M indeed is constant. In Fig. 1 this corresponds to the point at which all the lines coincide. The combination of $M(B)$ being a nonzero constant at T_c^0 and the essentially linear behavior of M vs T with increasing slope for smaller fields causes " $T_c(B)$ " as defined above to increase with B .

In the WFR the coupling strength between the superconducting layers was explicitly taken into account by Gerhardtts [15] and Klemm, Beasley, and Luther [16]. The dimensionality is represented by a parameter $r=(8/\pi^2)\Gamma^{-1}[\xi_{GL}(0)/s]^2$ which, with $\Gamma=3000$ and $\xi_{GL}(0)\approx 2$ nm, is estimated to be $r=4.6\times 10^{-4}$. We now compare our data with the theoretical $M(B)$ curve at T_c depicted in Fig. 5 of Ref. [15]. In the regime between $B=1$ and 5 T the magnetization is given by $-M=0.3k_B T_c/s\Phi_0$, which yields $M=-120$ A/m. This value corresponds to our experimental data slightly above $T=92$ K suggesting that this might be the mean-field (BCS) transition temperature T_c^{MF} . According to a re-

mark in Ref. [8], T_c^{MF} is shifted with respect to T_c^0 by an amount of order $\tau_c T_c^0 \ln[\xi_{GL}(0)/\xi_c]=0.5\tau_c T_c^0 \ln \tau_c$. With $\tau_c=2.5\times 10^{-2}$ [7] this amounts to $T_c^{MF}-T_c^0=4.0$ K, so that $T_c^{MF}=92$ K is in accord with the above analysis.

In addition, we compare with the temperature dependence of M at $B=0.3B_s$ and $B=5B_s$, shown in Fig. 7(b) of Ref. [15]. For $r<10^{-2}$, the scaling field B_s is given by $B_s=3.7\Phi_0/\Gamma s^2=3.7B_{2D}$, yielding for Bi 2:2:1:2, $B_s=1.07$ T. In Fig. 3 the theory for $r=10^{-4}$ is represented by the solid lines. The symbols depict our data at $0.3, 2$, and 5 T. For comparison a theoretical anisotropic 3D result is depicted by the dashed line. As was concluded in Refs. [15] and [16] the shape of the curves is not unique, but the scaling with B_s is. This horizontal scaling is very sensitive to the choice of T_c^{MF} , and not so much to the value of S . Given the value of $B_s=1.07$ T, the best fit to the 0.3 - and 5 -T data was obtained with $S=1.1$ T/K and $T_c^{MF}=92.2$ K (solid lines in Fig. 3). The deviation from the 0.3 -T data occurs within a 1 -K interval above T_c^{MF} . For 5 T this interval is 15 times smaller. The 2 -T data show behavior similar to the 5 -T results in accord with the 2D nature of the fluctuations.

Both comparisons with the weak-fluctuation theory point to $T_c^{MF}=92.2\pm 0.5$ K. Combining this with the trend in the $T_c(B)$ plot in Fig. 1 we estimate $S_{MF}=3$ to 7 T/K. Such a large value seems to disagree with the best fit in Fig. 3. However, it would be in line with Palstra's result $S=7$ T/K for YBCO [17]. The corresponding coherence length would point to local pairing, since $\xi(0)\leq 1$ nm.

The temperature dependence of the Ettinghausen effect in YBCO [17] about T_c could be well described by Ullah and Dorsey [18]. Starting from the Lawrence-Doniach model [19] and incorporating the interaction between fluctuations, good agreement with the data was achieved for $S=7$ T/K. However, a breakdown of scaling below T_c could not be explained by the mean-field approach. We think this breakdown is similar to the deviating behavior of our in-field $M(T)$ data in Fig. 1. Recently, Ikeda and Tsuneto [20] computed the effect of fluctuations on $M(T)$ and found reasonable agreement with the YBCO results [13] using $S=3.7$ T/K. However, a similar computation for Bi 2:2:1:2 by only changing Γ yields $M(T)$ curves which clearly disagree with our data, especially because " $T_c(B)$ " decreases with B . On the other hand, Ikeda, Ohmi, and Tsuneto [21] were able to fit their theory nicely to the in-field $R(T)$ data on Bi 2:2:1:2 single crystals [22]. Because the interpretation of $R(T)$ curves may also involve thermally activated flux motion, this agreement may be fortuitous. We therefore argue that the magnetization data provide a stricter test for theoretical models [23].

In summary, the apparent increase of " $T_c(B)$ " with B actually reflects the 2D nature of the fluctuations. As the system is cooled in a field, a gradual transition occurs

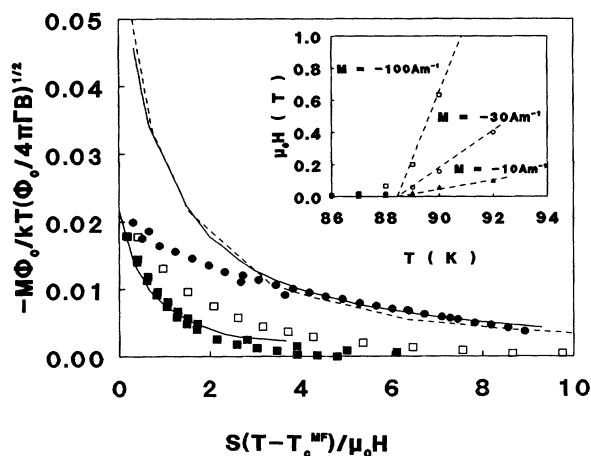


FIG. 3. Comparison of $-M\Phi_0/k_B T(\Phi_0/4\pi\Gamma B)^{1/2}$ vs $S(T-T_c^{MF})/\mu_0 H$ plots for experimental data at 0.3 T (\bullet), 2 T (\square), and 5 T (\blacksquare) with the WFR theory [15] for layered compounds with $r=10^{-4}$ and $B/B_s=0.3$ and 5 (solid lines) and anisotropic 3D behavior (dashed line). The experimental data fit is obtained with $S=1.1$ T/K, $T_c^{MF}=92.2$ K, and $B_s=1$ T. Inset: Contours of constant M above 86 K for $-M=10, 30$, and 100 A/m. The dashed lines display the expected 2D WFR behavior and define T_c^0 .

from the normal state to a kind of mixed-state behavior (the vortex liquid) that clearly deviates from the mean-field behavior. These deviations are greatly enhanced over what is seen in YBCO because of the extreme anisotropy of Bi 2:2:1:2. We leave it for further theoretical research to clarify these intriguing features.

This work has been financially supported by the Dutch Foundation of Scientific Research (NWO). P. H. Kes and C. J. van der Beek want to thank the ERDC for its hospitality.

^(a)Permanent address: Kamerlingh Onnes Laboratorium, Leiden University, P.O. Box 9506, 2300 RA Leiden, The Netherlands.

^(b)Permanent address: Department of Metallurgical Engineering and Materials Science, Carnegie Mellon University, Pittsburgh, PA 15213.

- [1] D. S. Fisher, M. P. A. Fisher, and D. A. Huse, *Phys. Rev. B* **43**, 130 (1991).
- [2] L. J. de Jongh, *Solid State Commun.* **70**, 955 (1989).
- [3] D. E. Farrell *et al.*, *Phys. Rev. Lett.* **63**, 782 (1989).
- [4] V. M. Vinokur, P. H. Kes, and A. E. Koshelev, *Physica (Amsterdam)* **168C**, 29 (1990); M. V. Feigelman, V. B. Geshkenbein, and A. I. Larkin, *Physica (Amsterdam)* **167C**, 177 (1990).
- [5] G. Eilenberger, *Phys. Rev.* **164**, 628 (1967).
- [6] E. Brezin, A. Fujita, and S. Hikami, *Phys. Rev. Lett.* **65**, 1949 (1990).
- [7] S. Martin, A. T. Fiory, R. M. Fleming, G. P. Espinoza, and A. S. Cooper, *Phys. Rev. Lett.* **62**, 677 (1989).
- [8] B. I. Halperin and D. R. Nelson, *J. Low. Temp. Phys.* **36**, 599 (1979).
- [9] M. J. V. Menken, A. J. M. Winkelman, and A. A. Menovsky (to be published).
- [10] H. W. Zandbergen (private communication).
- [11] D. C. Johnston and J. H. Cho, *Phys. Rev. B* **42**, 8710 (1990).
- [12] Z. Hao, J. R. Clem, M. W. McElfresh, L. Civale, A. P. Malozemoff, and F. Holtzberg, *Phys. Rev. B* **43**, 2844 (1991); Z. Hao and J. R. Clem (unpublished).
- [13] U. Welp, W. K. Kwok, G. W. Crabtree, K. G. Vandervoort, and J. Z. Liu, *Phys. Rev. Lett.* **62**, 1908 (1989).
- [14] S. Sridhar, D-H. Wu, and W. Kennedy, *Phys. Rev. Lett.* **63**, 1873 (1989).
- [15] R. R. Gerhardts, *Phys. Rev. B* **9**, 2945 (1974).
- [16] R. A. Klemm, M. R. Beasley, and A. Luther, *Phys. Rev. B* **8**, 5072 (1973).
- [17] T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer, and J. V. Waszczak, *Phys. Rev. Lett.* **64**, 3090 (1990).
- [18] S. Ullah and A. T. Dorsey, *Phys. Rev. Lett.* **65**, 2066 (1990).
- [19] W. Lawrence and S. Doniach, in *Proceedings of the Twelfth International Conference of Low Temperature Physics*, edited by E. Kanda (Academic Press of Japan, Kyoto, 1971), p. 361.
- [20] R. Ikeda and T. Tsuneto, *J. Phys. Soc. Jpn.* **60**, 1337 (1991).
- [21] R. Ikeda, T. Ohmi, and T. Tsuneto, *J. Phys. Soc. Jpn.* **60**, 1051 (1991).
- [22] B. Batlogg *et al.*, *Physica (Amsterdam)* **153-155C**, 1062 (1988).
- [23] In a private communication R. Ikeda and T. Tsuneto pointed out to us that a technical difficulty in their calculations causes the magnetization results to be less reliable for $T < T_c$. This problem does not occur in their computation of the fluctuation conductivity; the results for the resistance below T_c are therefore believed to be much more accurate.