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Angular dependence of the upper critical field of $YBa_2Cu_3O_{7-\delta}$ single crystals

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The angular dependence of the upper critical field of a $YBa_2Cu_3O_{7-\delta}$ single crystal has been measured with dc magnetization. The results are describable with a three-dimensional anisotropic Ginzburg-Landau theory with an anisotropy of five in the upper critical field.

INTRODUCTION

The new CuO-based superconductors are characterized by a very anisotropic, layered structure and very short superconducting coherence lengths. Recent measurements[1] of H_{c2} in single crystals of $YBa_2Cu_3O_{7-\delta}$ by dc magnetization revealed a coherence length of 3.0 Å, compared with a lattice parameter of 11.87 Å, in the **c** direction. This leads naturally to the suggestion that this material may show two-dimensional effects at sufficiently low temperature. Although the quantitative properties of an array of two-dimensional superconducting layers are not well understood, such dimensional crossover behavior is expected to strongly affect the temperature dependence of the critical fields, the strength of the vortex line pinning, and the nature of fluctuations.

The observation of fluctuation effects in the specific heat[2] and in the magnetic susceptibility[3] at the superconducting transition of $YBa_2Cu_3O_{7-\delta}$ single crystals points to three-dimensional (3D) character. Recent measurements of the magnetic torque of grain-aligned $YBa_2Cu_3O_{7-\delta}$ samples[4] in the reversible regime indicate anisotropic 3D behavior with a mass anisotropy of 25. Another probe of the dimensionality of the superconductivity is the angular dependence of the upper critical field. For $YBa_2Cu_3O_{7-\delta}$ single crystals this quantity has been measured in several studies using resistive transition curves[5] or ac susceptibility.[6] However, since then it has become evident that ac susceptibility and resistivity may be strongly influenced by flux-flow and flux-creep phenomena.[7] In this paper we present measurements of the angular dependence of the upper critical field as determined from the onset of diamagnetism in a dc magnetization experiment which is not affected by flux motion. This work extends our earlier measurements along the symmetry directions to intermediate angles. The results are consistent with 3D anisotropic Ginzburg-Landau (GL) theory and an upper-critical-field anisotropy of five.

EXPERIMENT

dc magnetization was measured with a commercial superconducting quantum interference device (SQUID) magnetometer using a rotating sample holder specially constructed for this experiment. The sample holder, shown in Fig. 1, consists of a rotating sample platform and pulley made from a single piece of epoxy mounted on a phosphor bronze axle. The rotating assembly is suspended in the central section of a quartz tube whose top and bottom sections have been slit vertically to provide access. The pulley is turned by a wire which extends to the top of the magnetometer. The orientation of the sample with respect to the magnetic field was monitored by the Hall voltage generated in a semiconducting film which was mounted on the opposite side from the sample on the sample platform. In a separate experiment it was verified that the Hall voltage follows a $\cos\theta$ law which was used to determine the angle.

Magnetization data were taken in a fixed field of 5 T as a function of temperature at various fixed field directions. After each temperature sweep it was checked that the orientation had not changed due to relaxation effects in the wire or thermal contractions. In this way the orientation of the sample could be controlled to within about 1°. The data were taken on the same crystal, No. 2 of Ref. 1, which was used to determine the temperature dependence of H_{c2}.

RESULTS AND DISCUSSION

Figure 2 shows zero-field-cooled magnetization curves in fields of 1 G and 5 T along the **c** direction. The high value of the transition temperature of 92.5 K and the narrow magnetic transition width (10%–90%) of less than 1 K in low fields underline the high quality of the crystal. In a field of 5 T the magnetization varies linearly with tem-

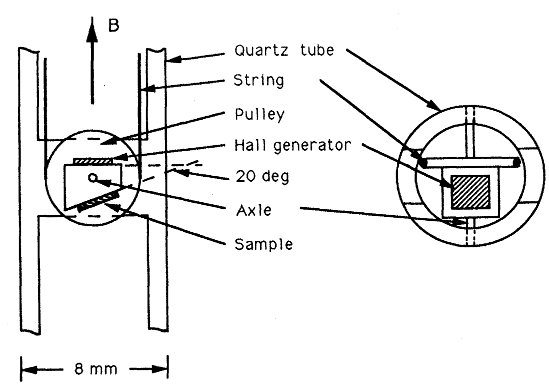

FIG. 1. Design of the sample rotator for dc-magnetization measurements in a SQUID magnetometer.

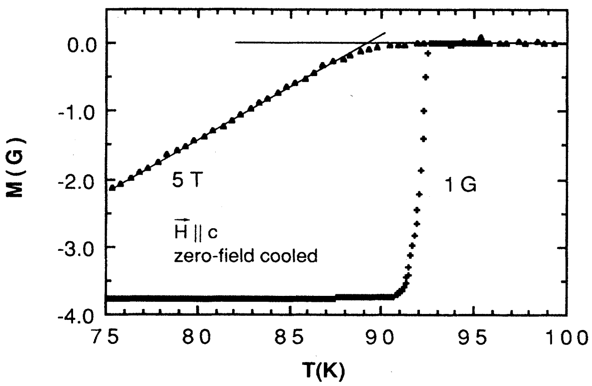

FIG. 2. Zero-field-cooled magnetization curves in fields of 1 G and 5 T perpendicular to the CuO planes. The straight lines indicate the construction of the nucleation temperature T_{c2}.

perature over a wide temperature range below the transition to diamagnetism. This behavior is expected from 3D GL theory and can be used for a precise determination of the mean-field nucleation temperature T_{c2} as shown by the construction in Fig. 2. In the range of the linear temperature dependence, field-cooled and zero-field-cooled experiments give identical results and magnetization curves show no hysteresis. The slope $\partial M/\partial T = 0.17$ G/K is found to be in good agreement with the prediction of GL theory.[1] Therefore, these measurements yield the equilibrium magnetization and are not affected by flux motion.

Figure 3 shows the temperature dependence of the magnetization in a field of 5 T for different orientations θ of the **c** axis with respect to the magnetic field. The normal-state base line of the magnetization has been determined from a least-squares fit to the data between 94 and 100 K. Between the different curves the base line is shifted up by 0.3 G for clarity. With increasing angle T_{c2} increases and the range of the linear temperature dependence of the magnetization decreases. From these data the angular dependence of T_{c2} can be constructed as shown in Fig. 4.

We consider two theoretical forms to fit the T_{c2} data of Fig. 4. The first is 3D anisotropic GL theory,[8] where the anisotropy is incorporated in different effective masses m_{ab} and m_c for in-plane and out-of-plane electron motion, respectively. The angular dependence of H_{c2} is given by

$$H_{c2}(\theta) = H_{c2}^{c}[\cos^2(\theta) + m_{ab}/m_c \sin^2(\theta)]^{-1/2},$$

where H_{c2}^{c} is the upper critical field along the **c** direction ($\theta = 0$). The anisotropy in the mass is related to the anisotropy in the critical field by $m_{ab}/m_c = (H_{c2}^{c}/H_{c2}^{ab})^2$. The same expression for the angular dependence of H_{c2} also applies to the Lawrence-Doniach model of weakly Josephson-coupled layers provided the anisotropy is not too large.[9] Within the GL theory H_{c2} is a linear function of T. Except for very low fields this behavior is observed experimentally.[1] Then the angular dependence of H_{c2} can be converted to that of T_{c2} by

$$T_{c2}(\theta) = T_{c0} + H_0/(\partial H_{c2}^{c}/\partial T) \times [\cos^2(\theta) + m_{ab}/m_c \sin^2(\theta)]^{1/2}.$$

T_{c0} is the zero-field transition temperature as determined from an extrapolation of the linear part of the phase diagram. $H_0 = 5$ T is the applied field. In a previous study[1] values of $T_{c0} = 91.5$ K and $\partial H_{c2}^{c}/\partial T = -1.9$ T/K were found. Therefore the above relation contains a single adjustable parameter, the mass anisotropy. The solid line in Fig. 4 is a fit with $m_c/m_{ab} = 25$ which corresponds to an anisotropy in the critical fields of five. This fit describes the data well over the entire angular range.

Tinkham[10] has given the implicit expression

$$|H_{c2}(\theta)\cos(\theta)/H_{c2}^{c}| + [H_{c2}(\theta)\sin(\theta)/H_{c2}^{ab}]^2 = 1,$$

for the angular dependence of H_{c2} for a thin-film superconductor ($\xi_c > d$, where d is the film thickness). The characteristic feature is a cusplike variation of $H_{c2}(\theta)$ around 90°. In order to convert this expression to the angular dependence of T_{c2} we use the relations[10] $H_{c2}^{ab}(T) = \sqrt{3}\Phi_0/\pi d \xi_{ab}(T)$, $H_{c2}^{c}(T) = \Phi_0/2\pi\xi_{ab}^2(T)$, and $\xi_{ab}(T) = \xi_{ab0}(1 - T/T_{c0})^{-1/2}$, where $\Phi_0 = 2.07 \times 10^{-11}$ Tcm^2 is the flux quantum. Using these relations we obtain for the

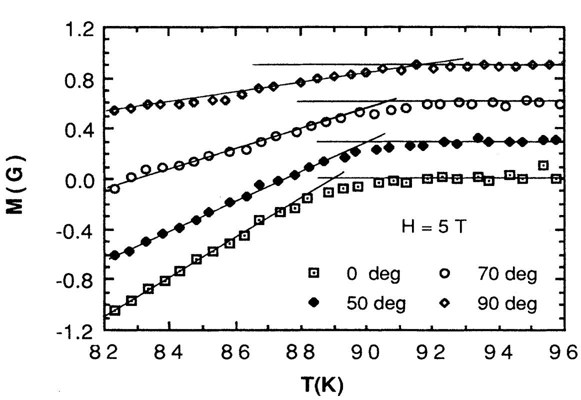

FIG. 3. Temperature dependence of the magnetization in a field of 5 T for different orientations of the **c** axis with respect to the field.

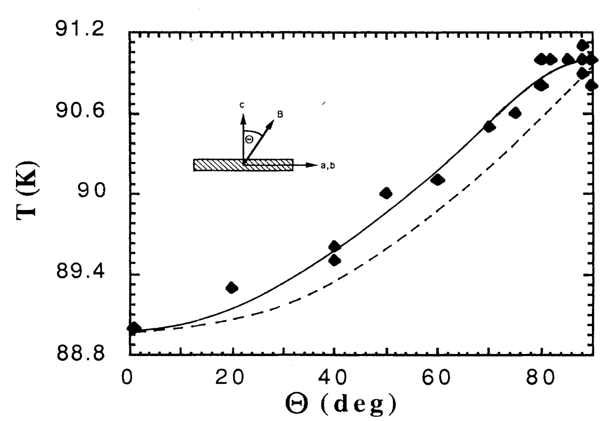

FIG. 4. Angular dependence of T_{c2}. The solid line is a fit to the anisotropic GL theory with a mass anisotropy of 25. The dashed line is a fit to Tinkham's 2D thin-film model.

angular dependence of T_{c2}

$$1-T_{c2}(\theta)/T_{c0}=(1-T_{c2}^{c}/T_{c0})\cos(\theta)+(1-T_{c2}^{ab}/T_{c0})\sin^2(\theta)\,.$$

T_{c2}^{c} and T_{c2}^{ab}, determined from the experimental data, are the nucleation temperatures for field orientations parallel to the **c** axis and the **a**,**b** axes, respectively.

A fit to the data with this thin-film expression is shown as a dashed line in Fig. 4. The pronounced cusplike angular dependence predicted by the above expression around $\theta=90°$ is not followed by the data. In addition, the value of d required by the fit is 123 Å, which does not correspond to any physically relevant dimension associated with the Cu-O layers. Furthermore, $H_{c2}^{ab}(T)$ is observed to be linear,[1] in contrast to the square-root variation predicted by $H_{c2}^{ab}(T)=\sqrt{3}\Phi_0/\pi d\xi_{ab}(T)$. Thus, the 2D thin-film expression provides a poor description of the data in several respects. In contrast, 3D GL theory correctly describes the angular and temperature dependence of H_{c2} and the linear temperature dependence of the magnetization below T_c. The 3D character of the superconductivity is expected near T_c since the coherence length diverges at the transition. If the value $\xi_{c0}=3$ Å (Ref. 1) is adopted for the out-of-plane coherence length and the film thickness is identified with the separation of the CuO double layers, then the crossover to two dimensionality should occur around 74 K, much lower than the temperatures where H_{c2} can be measured.

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