Giant Superconducting Anisotropy in $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$

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(Received 8 May 1989)

Using torque magnetometry, the superconducting anisotropy of a single crystal of $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ has been measured in the temperature range $77.5 < T < 83$ K ($T_c = 85$ K). The data provide direct experimental evidence for a giant anisotropy. A London analysis provides an excellent description of the results and establishes a temperature-independent value of 3×10^3 for the superconducting effective-mass anisotropy.

PACS numbers: 74.70.Vy, 74.60.Ec, 75.30.Gw

It is generally recognized that anisotropy plays an important role in the properties of high-T_c superconductors. A member of the bismuth family, $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ (Bi-Sr-Ca-Cu-O hereafter), is thought to be one of the most anisotropic, but experiments have given widely varying estimates for the magnitude of its anisotropy in the superconducting state. Quasi-two-dimensional behavior is a *sine qua non* for the existence of two proposed new phenomena in Bi-Sr-Ca-Cu-O, a Kosterlitz-Thouless phase transition[1] and flux-lattice melting.[2] The importance of these proposals motivated the work reported here.

Obtaining a reliable number for the superconducting anisotropy in any high-T_c material has proved to be an experimental challenge. A number of different techniques have been used to estimate the parameter $\gamma = (m_c/m_a)^{1/2}$, where m_c and m_a are the Ginzburg-Landau superconducting effective masses[3] for pair motion along the c direction, and in the a-b plane, respectively. Initial reports of values for $Y_1Ba_2Cu_3O_{7-\delta}$, obtained from resistive H_{c2} measurements, ranged up to about 10. More recent results, obtained using a variety of other methods (torque magnetometry,[4] dc magnetization,[5] and decoration experiments[6]) suggest a value for γ of around 5, close to that found for the conventional three-dimensional superconductor $NbSe_2$ ($\gamma \sim 3$).[7] In the case of Bi-Sr-Ca-Cu-O, the separation of the Cu-O planes is ~ 12 Å, significantly larger than in $Y_1Ba_2Cu_3O_{7-\delta}$, and some resistive H_{c2} experiments[8-10] have suggested γ values an order of magnitude larger. Unfortunately, as has been emphasized by Malozemoff,[11] such measurements are subject to large uncertainties because of the weak flux pinning in these materials. Even in the case[5] of $Y_1Ba_2Cu_3O_{7-\delta}$, this difficulty results in an overestimate of the anisotropy by about 50%. The problem is likely to be more severe in the case of Bi-Sr-Ca-Cu-O where flux pinning in single crystals essentially vanishes[12] above a temperature of ~ 50 K. Weak pinning leads to a resistive transition whose anisotropy can be interpreted in terms of differences in the flux-flow viscosity.[12] Perhaps as a consequence of these difficulties, estimates of γ have wandered widely, ranging from ~ 15 (Ref. 13) to ~ 140.[12]

Fortunately, in contrast to the resistive H_{c2} technique, it turns out that the recently introduced[4] method of torque magnetometry is well suited to the low-pinning regime. This approach is based on the peculiar magnetic structure of anisotropic superconductors: When the external magnetic field does not point in a principal crystal direction, the magnetization has a nonzero component normal to the field, resulting in a mechanical torque.[14] In fields $H \gg H_{c1}$, the torques due to demagnetization effects are very small.[4,14] The existing theoretical treatment[14] is based on the London equations. In the intermediate field domain, $H_{c1} \ll H \ll H_{c2}$, the vortex cores are widely separated and the London approach is appropriate, notwithstanding its simplicity. The only other criterion that must be satisfied for the experimentally observed torque to have the fundamental origin discussed is that the pinning be weak so that vortices can readily move and assume their equilibrium configuration. We have confirmed that this is the case for Bi-Sr-Ca-Cu-O in these studies.

In the case of $Y_1Ba_2Cu_3O_{7-\delta}$, it has been shown experimentally[4] that the angular dependence of the torque, $\tau(\theta)$, in a field, H, is quite well described by the expression[14]

$$\tau(\theta) = \frac{\phi_0 HV}{64\pi^2\lambda^2}\frac{\gamma^2-1}{\gamma^{2/3}}\frac{\sin 2\theta}{\epsilon(\theta)}\ln\left(\frac{\gamma\eta H_{c2\parallel}}{H\epsilon(\theta)}\right), \qquad (1)$$

$$\epsilon(\theta) = (\sin^2\theta + \gamma^2\cos^2\theta)^{1/2}.$$

Here, ϕ_0 is the flux quantum, V the sample volume, and λ the average penetration depth. $H_{c2\parallel}$ is the upper critical field measured along the c axis, η is a constant of order unity,[14] and θ is the angle between the field and the c axis. For $Y_1Ba_2Cu_3O_{7-\delta}$ the maximum torque, τ_{max}, is observed for $\theta \sim 70°$ [see Fig. 1(a)] but Eq. (1) implies that the maximum should move to higher angles if the material is more anisotropic.

The normalized torque, $\tau(\theta)/\tau_{max}$, depends on just two parameters, γ and $\eta H_{c2\parallel}/H$. However, when the anisotropy is large, the dependence on the latter is negligible[15] for θ close to 90°. It is useful to introduce an "angular half-width," θ_h, as a measure of the breadth of the region of interest and the definition of this quantity is indicated in Fig. 1(a). The dependence of θ_h on γ calculated with the help of Eq. (1) is shown in Fig. 1(b). Provided that γ is itself temperature independent, *the angular variation of the torque for $\theta \sim 90°$ should be temperature independent, with a half-width that provides a direct measure of the anisotropy.*

The measurements reported here were performed using a torque magnetometer designed and built specifically for this investigation by one of us.[16] It is a null-deflection instrument with a temperature stability of 0.01 K and angular displacements of the field relative to the crystal can be measured with an uncertainty of $\pm 0.03°$. All these features were crucial to the success of the measurements reported. The field was maintained at a constant value of 1 T, and the torque was examined in the temperature range $77.5 < T < 83$ K: A crystal was grown for this investigation from a melt mixture of Bi_2O_3, $SrCO_3$, $CaCO_3$, and CuO oxides in high-purity Al_2O_3 crucibles. The nominal cation ratio of the liquid mixture was 2:2:1:2, as indicated in the title of our Letter, but the actual ratio in the final crystal, as determined by the ICP spectrochemical technique, was 2:1.48:0.6:1.56. The crystal was annealed for seven days in air at 845 °C and was single phase as judged by x-ray diffraction. Both conventional SQUID and torque magnetometry indicated a sharp transition at ~85 K, with the former indicating a Meissner fraction of unity within the ~20% uncertainty in estimating the demagnetization factor. Bi-Sr-Ca-Cu-O cleaves very readily along the *a-b* plane and the sample actually used in our measurements was obtained in this manner from the characterized parent crystal. It was in the form of a thin flat plate with edge dimensions 1.5×0.8 mm^2 and had a thickness of about 10 μm. Despite the flat-plate geometry of the sample, shape effect torques may readily be shown to be negligible[4,14] in our experimental regime.

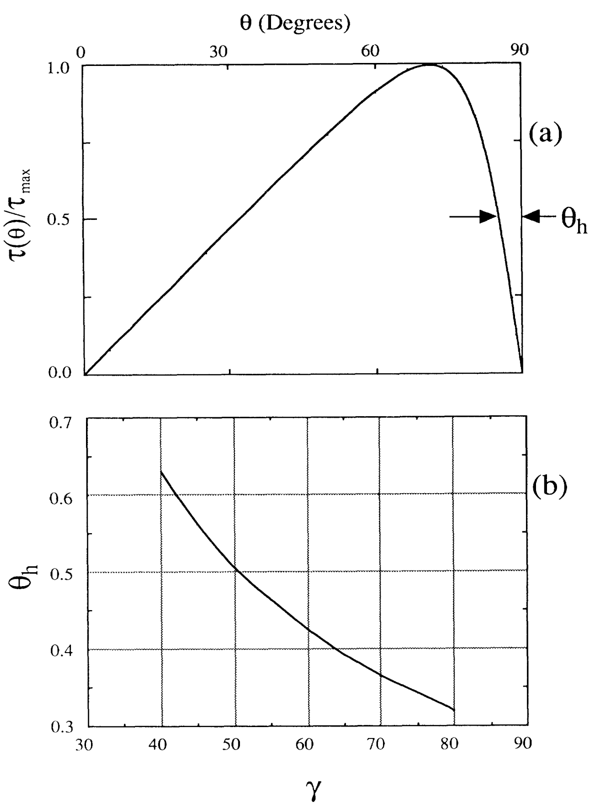

FIG. 1. (a) Angular variation of the normalized torque obtained from Eq. (1) using $\gamma = 5$ and $\eta H_{c2\parallel}/H = 15$, representing (Ref. 2) the case of $Y_1Ba_2Cu_3O_{7-\delta}$ in a field of 1 T and at a temperature 5 K below T_c. τ_{max} is the maximum magnitude of the torque and the quantity θ_h (discussed in the text) is also defined in this figure. (b) The dependence of θ_h on γ calculated from Eq. (1), using $\eta H_{c2\parallel}/H = 35$ (Ref. 14).

The angular dependence of the torque at $T = 77.5$ K and in the limited angular range from 80° to 90° is shown in Fig. 2(a). Any irreversibility, at this and higher temperatures, was below our instrumental resolution, demonstrating the absence of flux pinning as mentioned previously. As θ approaches 90° the variation in the torque becomes extraordinary rapid, so in Fig. 2(b) the angular scale has been expanded once again so as to show just the last two degrees of the characteristic. This figure contains data for the lowest and highest temperatures investigated (77.5 and 83 K) and they are experimentally indistinguishable. The solid curve was obtained from Eq. (1) using $\gamma = 55$ and it is in good agreement with both data sets. [The anisotropy can be estimated directly by noting that θ_h in Fig. 2(b) is about 0.45°, and then referring to Fig. 1(b).] The fitting uncertainty for γ is estimated to be ± 5.

To further test the theory, we have obtained torque data over the complete angular range, an example of which is shown in Fig. 3. The theoretical prediction for low angles is influenced by both $\eta H_{c2\parallel}/H$ and γ, but the latter is fixed by the data close to 90° and treating the former as a fitting parameter we obtain a very good fit for $\eta H_{c2\parallel}/H = 35$ T, as shown in Fig. 3. The value of the constant η is not well known theoretically but is thought[17] to be of order unity. Our torque data therefore imply a value for $-dH_{c2\parallel}/dT$ of a few tesla per degree kelvin, which is in order-of-magnitude agreement

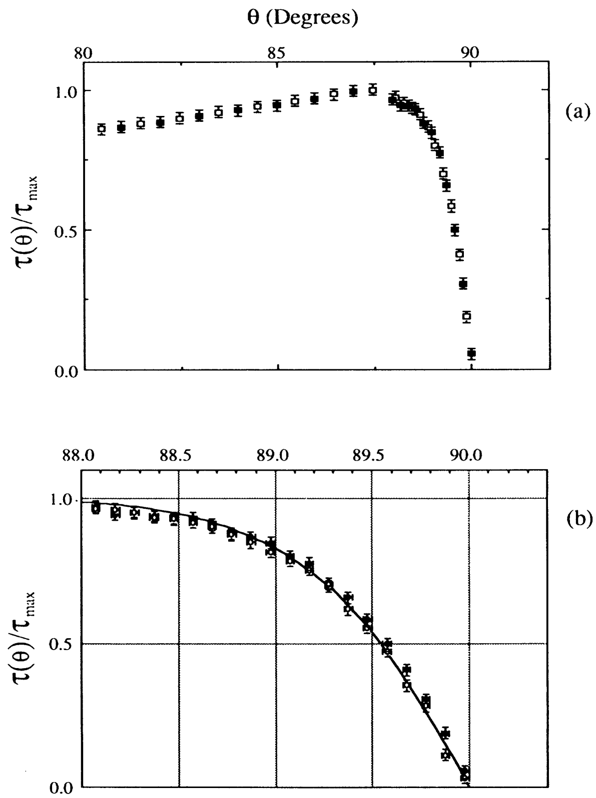

FIG. 2. (a) Experimental normalized angular dependence of the torque in a field of 1 T and at a temperature of 77.5 K for the single crystal of Bi-Sr-Ca-Cu-O discussed in the text. The open squares are data points recorded with the angle θ increasing; closed squares with the angle decreasing. For this data set, $\tau_{max} = 2.56\times10^{-2}$ dyn cm. (b) Normalized torque data for the magnetic field lying close to the a-b plane ($\theta = 90°$). Full circles are data for $T = 77.5$ K and consist of all the points in Fig. 2(a), while the closed circles are data for $T = 83.0$ K. The measured values of τ_{max} were 2.56×10^{-2} and 9.3×10^{-3} dyn cm, respectively. The full line was obtained from Eq. (1), using the parameters $\gamma = 55$ and $\eta H_{c2\parallel}/H = 35$.

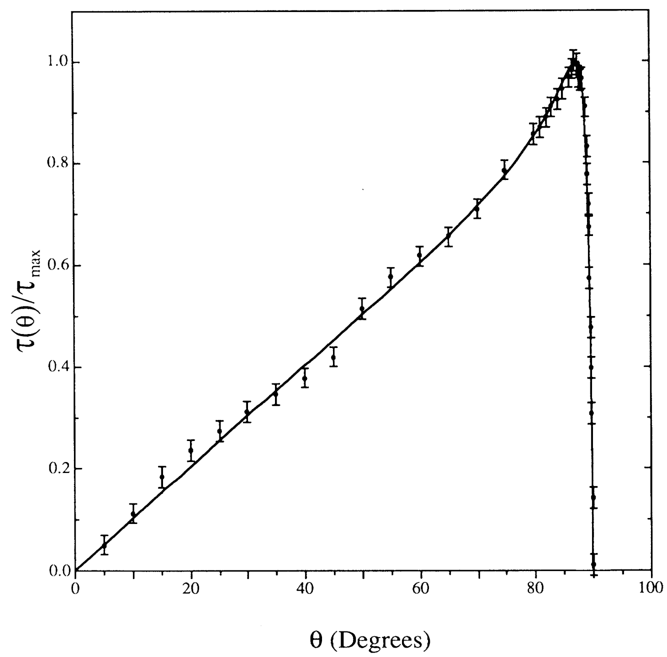

FIG. 3. Normalized torque data for Bi-Sr-Ca-Cu-O at a temperature of 77.5 K and in field of 1 T. The curve is the theoretical result from Eq. (1) using $\gamma = 55$ and $\eta H_{c2\parallel}/H = 35$.

with published estimates for this and other high-T_c materials. Hence, not only is the lower-angle fit good, but it has been obtained with a physically reasonable choice of the only remaining free parameter in the theory.

On first sight it might seem that any torque measurement of the sort described can only establish a lower bound on the anisotropy, because any regions within the crystal that happen to be misaligned at the tenth of a degree level could measurably increase θ_h and reduce the apparent value of γ. Small misaligned regions can certainly occur. In addition to the data reported here, we have made torque measurements on a total of nine other crystals. While the overall characteristics were very similar to those reported, all displayed clear structure in the region $88 < \theta < 90°$ which we associated with slightly misaligned regions. In the absence of regions whose presence can be directly detected in this way, a small sample curvature might still increase θ_h above the true value. However, this possibility is also strongly constrained by the good theoretical fit to the torque characteristic in the range $80 < \theta < 88°$, since the shape of the characteristic in this region is insensitive to a slight sample curvature but is still a strong function of the anisotropy.

For both $Y_1Ba_2Cu_3O_{7-\delta}$ and Bi-Sr-Ca-Cu-O, with, respectively, moderate and giant anisotropies, the success of Eq. (1) in describing torque data is remarkable. We would therefore like to spell out here some further theoretical consequences of the Bi-Sr-Ca-Cu-O result. In the first place, with the field lying in the Cu-O plane, the equilibrium flux-line lattice (FLL) consists of isosceles triangles with their long dimensions (the median to the base) lying parallel to the Cu-O plane, and base parallel to **c**. The side-to-base ratio is $(1+3\gamma^2)^{1/2}/2 \sim 47$ and the small angle of the triangle is $\tan^{-1}(3\gamma)^{1/2} \sim 0.6°$.[18] For $H = 1$ T the base dimension is 63 Å while that of the side is about 3000 Å. The elastic properties of such FLL should be extremely anisotropic. In fact, the modulus for a "hard" shear (vortices displaced in the c direction across Cu-O layers) should exceed that for "sliding shear" (displacements parallel to the a-b plane) by a factor of $\gamma^4 \sim 10^7$ (Ref. 19). Even for $Y_1Ba_2Cu_3O_{7-\delta}$, where this factor is only ~ 600, some observations interpretable as evidence for a soft sliding shear have been reported[6] and the question of FLL stability must now be of serious concern in Bi-Sr-Ca-Cu-O. It would not be surprising, for example, if a FLL instability turns out to be one of the factors causing the precipitous drop[12] in critical current as the temperature is increased. Lastly, the torque discussed in this paper is associated with the appearance of a transverse component of magnetization, M_T, in addition to the usual longitudinal component, M_L, in the direction of the field. In agreement with theory, Tuominen and Goldman have found by direct SQUID measurement[20] that the maximum value for M_T/M_L in $Y_1Ba_2Cu_3O_{7-\delta}$ is about 2.7. The same theory that leads to Eq. (1) predicts a maximum value of ~ 27 for this ratio in Bi-Sr-Ca-Cu-O.

In conclusion, our results establish that the superconducting effective mass anisotropy in $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ has the giant value of 3×10^3, providing strong support for recent proposals[1,2] which depend on the existence of an extreme anisotropy in this material. In the temperature range studied, our results are well described by a theory which is essentially three dimensional in character, presumably reflecting the applicability of the mean-field approximation in the vicinity of the transition temperature.

We would like to acknowledge useful discussions with L. P. Gor'kov and G. W. Crabtree. We are also indebted to K. E. Gray and A. M. Goldman for searching criticism of some preliminary data and to C. Farrell for invaluable help with computing. This work was supported by NASA Grants No. NAG-3-814 and No. NCC-123 and by the U.S. Department of Energy, Basic Energy Sciences, Materials Science, under Contract No. W-31-109-ENG-3.

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