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Anisotropy scaling close to the *ab* plane in $La_{1.9}Sr_{0.1}CuO_4$ by torque magnetometry

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The effective mass anisotropy ratio γ is generally determined relative to the main axes of a superconductor. Torque measurements with arbitrary field orientations, especially near the *ab* plane, are presented. The scaling of the apparent anisotropy ratio $\gamma_{\rm app}$ is verified also very close to the *ab* plane in the highly anisotropic $La_{1.9}Sr_{0.1}CuO_4$. This method allows a very precise determination of γ_{ac} and shows the importance of the field orientation for *ab*-plane measurements. [S0163-1829(99)50502-X]

Torque magnetometry is a powerful tool to probe high-T_c superconductors. Superconducting parameters such as the effective mass anisotropy ratio $\gamma=\sqrt{m_c^*/m_{ab}^*}$, the penetration depth λ_{ab}, and the coherence length ξ_{ab} are usually extracted from angular-dependent torque measurements and analyzed in terms of a three-dimensional anisotropic London model, derived by Kogan *et al.*[1,2] Deviations from this model, which is based on a mean-field theory, can be observed in high-T_c superconductors near their critical temperature T_c.[3,4] Nevertheless a torque analysis is still possible in the presence of thermal fluctuations. Recently, a specific investigation of the magnetic torque in the critical-fluctuation regime has been proposed by Schneider *et al.*[5] Obviously an analysis of the critical-fluctuation regime requires high-quality samples with a sharp and narrow superconducting transition compared to the width of the critical-fluctuation range. Data at temperatures well below the critical regime are less sensitive to the width of the transition and can successfully be discussed in terms of the anisotropic London model,[2,6,7] assuming a thermodynamic equilibrium of the vortex lattice. Unfortunately, the temperature range where reversible torque curves can be obtained is usually quite narrow, depending on the type and quality of the material. In some samples this range is simply absent due to the overlap between a regime driven by fluctuations and one dominated by pinning. Recently, a method was proposed to enhance the vortex-lattice relaxation by applying a weak transverse ac magnetic field[8] and hence to extend the reversible region in the (H,T) phase diagram requested for torque investigations. With this ''vortex-shaking'' method the data acquisition takes much longer than conventional measurements and thus requires a high-stability torque sensor.

Angular-dependent torque measurements are usually obtained by turning the magnetic field **B** within the *ac* or the *bc* plane of the sample. Only a few measurements have been performed with the field within the *ab* plane.[9–12] The specific study of the *ab* anisotropy is quite delicate, because the in-plane magnetic-field orientation is crucial. We show in this work that a small misalignment of the magnetic field **B** can lead immediately to misleading results from the *c*-axis component of the magnetization, particularly in highly anisotropic materials ($\gamma\gg1$). For thin-film studies, the criterion for the *ab*-plane rotation is better defined than for single crystals. Indeed, as soon as **B** crosses the *ab* plane of the film, a large torque irreversibility appears,[12] whereas for a single crystal of finite thickness it is more difficult to define precisely when the rotation of **B** occurs within the *ab* plane.

In this experiment we describe and control very precisely the effects produced by a misorientation of the magnetic field **B** on in-plane, angular-dependent torque measurements $\tau(\theta)$ in a high-T_c superconductor. The measurements were performed on a slightly underdoped $La_{1.9}Sr_{0.1}CuO_4$ (La214) single crystal with a critical temperature of $T_c\approx25.8$ K. The La214 material has a tetragonal structure. The anisotropy ratios γ_{ac} and γ_{bc} are thus the same and the in-plane anisotropy ratio is $\gamma_{ab}=\gamma_{bc}/\gamma_{ac}=1$. To confirm the validity of data obtained by turning the magnetic field **B** close to the *ab* plane, we first perform a direct and precise measurement of the anisotropy ratio γ_{ac}. An extraction of γ_{ac} through the doping level is not accurate enough.[13,14] Figure 1 displays angular-dependent measurements achieved by rotating the magnetic field **B** in the *ac* plane of the sample. This crystal is a typical case where complete reversibility of $\tau(\theta)$ cannot be achieved below the temperature range where fluctuations dominate. At $T=22.8$ K and $B=0.5$ T the irreversibility due to pinning can be removed by applying a weak transverse ac magnetic field [see Fig. 1(a) and inset].[8] A least-squares fit with Kogan's expression[2] yields an anisotropy ratio of $\gamma_{ac}=43.0(4)$, see also Eq. (1). This value of anisotropy for underdoped La214 is compatible with those determined by

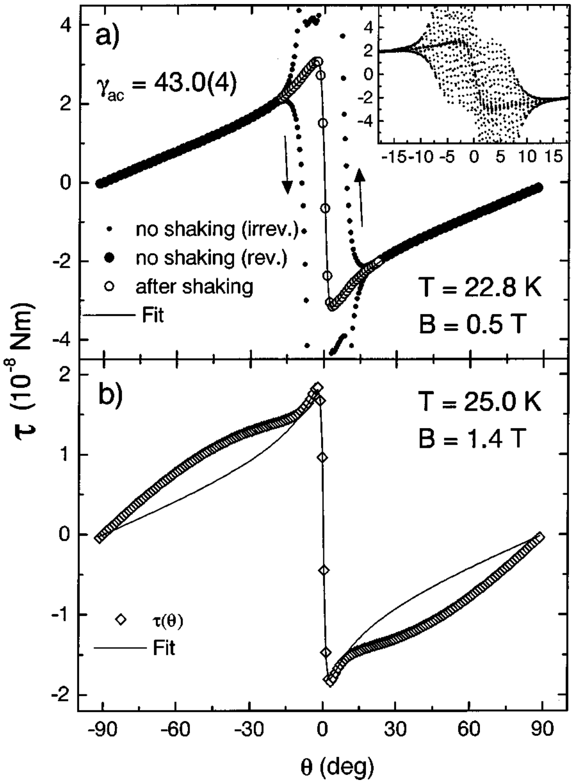

FIG. 1. Angular-dependent torque $\tau(\theta)$ obtained by rotating the magnetic field **B** clockwise and counterclockwise in the *ac* plane of the $La_{1.9}Sr_{0.1}CuO_4$ single crystal. (a) Measurement performed at $T = 22.8$ K and $B = 0.5$ T. Irreversibility is removed by shaking the vortices (Ref. 8). The fit with Kogan's expression leads to $\gamma_{ac} = 43.0(4)$. Inset: details of the relaxation obtained by vortex shaking. (b) Similar measurement taken at $T = 25.0$ K and $B = 1.4$ T. The effects of fluctuations are clearly visible by comparing these data with the curves expected for the three-dimensional anisotropic model.

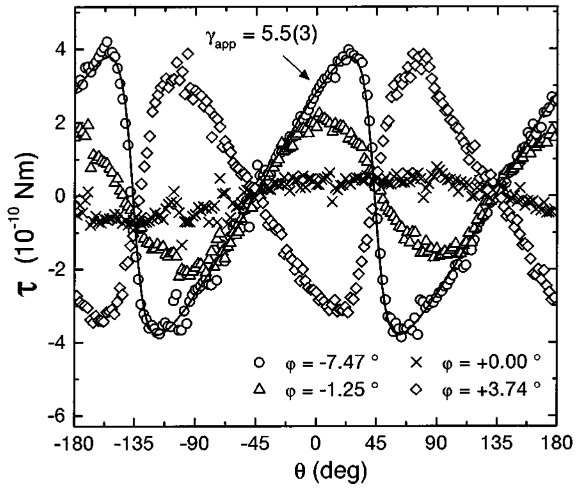

FIG. 2. Angular-dependent torque $\tau(\theta)$ obtained for different precession angles φ at $T = 25.2$ K and $B = 0.5$ T. The curves can be fitted by the Kogan expression, which leads to an apparent anisotropy ratio γ_{app}. At $\varphi = 0.00°$ the magnetic field lies precisely in the *ab* plane during its rotation.

resistivity.[14] The proper extraction of high γ values from the torque data requires a correction that takes the mechanical deformation of the sensor itself into account. It is indeed essential to consider the exact orientation of the sample slightly tilted on the flexed cantilever with respect to the applied field.[15,16] The precise knowledge of the elastic properties of the torque sensor is thus required for making this correction. In our case, this important correction does increase γ_{ac} from 35 to 43.0 and also explains the small uncertainty associated with γ_{ac}. For comparison, a torque measurement $\tau(\theta)$ taken at $B = 1.4$ T and $T = 25.2$ K, i.e., 0.6 K below T_c, is shown in Fig. 1(b). The characteristic shape of the torque curve $\tau(\theta)$ with strong curvature can be attributed to thermal fluctuations[5,17] or to the broadening of the superconducting transition ΔT_c by inhomogeneities,[3] or both. The distinction between these two different origins is usually not trivial because of material quality. For the sample examined here, probably both the fluctuations and the ΔT_c distribution contribute to this characteristic torque signal. Therefore, without the vortex-shaking technique it would have been impossible to obtain the anisotropy ratio γ_{ac} directly by torque magnetometry in this sample upon rotating the field in the *ac* plane.

As mentioned above, the study of the torque signals obtained by turning the magnetic field **B** near and within the *ab* plane of the sample is an interesting and promising method for further investigation of high-T_c superconductors. An underdoped crystal with large γ was intentionally used to show how critical the field alignment for in-plane measurements is. As the precise orientation of a microscopic single crystal on a torque sensor is rather delicate, an adjustment procedure of the magnetic field to eliminate misalignment effects has been proposed in Refs. 11 and 12. The orientation of **B** with respect to the sample was controlled very accurately by an additional magnetic field, $\mathbf{b} = \mathbf{b}_0 \sin(\theta - \theta_0)$. The amplitude $\mathbf{b}_0$ was modulated in phase with the orientation of the main magnetic field θ. The angle θ_0 corresponds to the position of the node line, where **B** is parallel to the *ab* plane. The addition of the compensation field **b** leads to a small precession of the total magnetic field with respect to the sample. The La214 single crystal was mounted perpendicular and rigidly to the silicon lever of a high-sensitive capacitive torquemeter with an accuracy of about $\pm 5°$.[12] The angular-dependent torque $\tau(\theta)$ was then measured with different precessions of the total magnetic field **B**. The position of the angular node line θ_0 can easily be found from a torque curve without precession by noting the angle value of the crossing points, $\tau(\theta_0) = 0$, with the *ab* plane. Four different angular-dependent torque curves $\tau(\theta)$ with different amplitudes of precession b_0, taken at $T = 25.2$ K in a magnetic field $B = 0.5$ T, are displayed in Fig. 2. For convenience the precession amplitude b_0 is related to the precession angle $\varphi = \arctan(b_0/B) + \varphi_0$, where φ_0 is the misorientation without precession. The angle $\varphi = 0°$ corresponds to the situation where the total magnetic field rotates exactly in the *ab* plane. Owing to the high anisotropy of the sample, its magnetization almost always points along the principal direction of uniaxial anisotropy (*c* axis) given by the effective mass tensor M_{ij}, which can be diagonalized.[2,18,19] Indeed Hao and Clem[19] demonstrated that the procedure for obtaining the free-energy density F of the vortex lattice from its corresponding expression in the isotropic case by renormalization of the Ginsburg-Landau parameter κ depends on the orientation of the applied magnetic field **B**. This procedure is in principle valid only if **B** is parallel to one of the principal axes. However this procedure still remains a good approximation in the case of $B_{c1} \ll B < B_{c2}$.[19] Therefore the simplified expression derived by Kogan *et al.*[2] compared to the more general one established by Hao and Clem[19] can be used to analyze the measurements presented here. By adapting the usual expression, we obtain

$$\tau(\theta)=\frac{\Phi_0 VB}{16\pi\mu_0\lambda_a\lambda_\beta}(1-\gamma_{\mathrm{app}}^{-2})\frac{\sin 2\theta}{\epsilon(\theta)}\ln\frac{\eta B_{c2}^{\delta}}{B\epsilon(\theta)}, \qquad (1)$$

where $\epsilon(\theta)=\sqrt{\sin^2\theta+\gamma_{\mathrm{app}}^{-2}\cos^2\theta}$, θ is the angle between the applied field **B** and the node line in the *ab* plane, Φ_0 is the flux quantum, γ_{app} is the apparent anisotropy ratio, B_{c2}^{δ} is the upper critical field in the δ direction, and λ_a and λ_β are the effective penetration depths along the a and β directions, respectively. The numerical parameter η is of the order of unity. For a direct measurement of the *ac* anisotropy ($\gamma_{\mathrm{app}}=\gamma_{ac}$), we have $\beta=b$ and $\delta=c$. Note that the above mean-field expression for $\tau(\theta)$, Eq. (1), is similar to the one proposed by Schneider *et al.* in the presence of critical fluctuations.[5] From a mathematical point of view they are identical, but the physical interpretation of the related fit parameters is different. In our case only the anisotropy ratio γ_{app} is studied and in both expressions its definition is the same. Although it is difficult to confirm or refute the presence of critical fluctuations, the interpretation of γ_{app} remains correct. The apparent anisotropy ratio γ_{app} can be extracted from the fit of $\tau(\theta)$ measured at different precession amplitudes b_0 or angles φ (Fig. 2). The data points $\tau(\theta)$ displayed in this figure have been taken by increasing and decreasing θ and show no evidence of hysteresis. At larger positive and negative precession angles the respective curves are mirror images of each other, corresponding to a sign change of their amplitude. In this particular case, the angle $\varphi=0°$ is related to a precession amplitude of $b_0=-32.5$ mT with a main magnetic field of $B=0.5$ T. Thus, it can be deduced that the sample is not mounted exactly perpendicular to the lever but has a misorientation of $\varphi_0=3.72°$. The angle φ measures the precession of the total magnetic field with respect to the *ab* plane within an accuracy of about $\sim 0.01°$. A systematic analysis of the apparent anisotropy ratio γ_{app} as a function of the precession angle φ is presented in Fig. 3. The dependence $\gamma_{\mathrm{app}}(\varphi)$ is in excellent agreement with the scaling function[10,20]

$$\gamma_{\mathrm{app}}(\varphi)=\sqrt{\gamma_{ac}^2\sin^2\varphi+\cos^2\varphi}. \qquad (2)$$

The inset of Fig. 3 shows the entire range of magnetic-field orientations with respect to the *ab* plane. Two additional points, which have not been taken into account for the fit, confirm the validity of the scaling of γ_{app} in the entire range of magnetic-field orientations. The anisotropy ratio γ_{ac}, which corresponds to $\varphi=-90°$, has been extracted from the measurement presented in Fig. 1(a). The manual mounting of the sample at $\varphi\approx-45°$ explains the horizontal error bar at this point. With the precession field **b** it would be impossible to achieve such an angle. Furthermore, the magnitude of the total field would have an elliptical angular dependence if the condition $b_0 \ll B$ is not fulfilled, which would lead immediately to erroneous results. The prefactor in Eq. (1), proportional to $(\lambda_a\lambda_\beta)^{-1}$, has also been analyzed for each measurement near the *ab* plane. By setting all fit parameters free, the value $(\lambda_a\lambda_\beta)$ is, within the error bars, almost φ independent. Only for the fit at $\varphi=0°$, corresponding to a torque signal $\tau(\theta)\simeq 0$, has the prefactor been fixed to avoid a divergence of the fit. This measurement corresponds to a magnetic-field rotation within the *ab* plane.

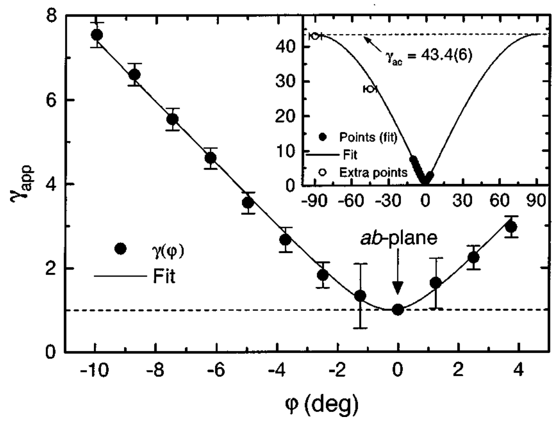

FIG. 3. Apparent anisotropy ratio γ_{app} as a function of precession angle φ. These data result from the analysis of torque curves presented in Fig. 2. The fit with the scaling function $\gamma_{\mathrm{app}}(\varphi)=\sqrt{\gamma_{ac}^2\sin^2\varphi+\cos^2\varphi}$ for precessions very close to the *ab* plane leads to an anisotropy of $\gamma_{ac}=43.4(6)$, which is in excellent agreement with the direct measurement displayed in Fig. 1(a). The entire range of magnetic-field orientations is shown in the inset.

It seems surprising *a priori* that the torque curves taken near the *ab* plane at $T=25.2$ K and $B=0.5$ T can be fitted so well with Eq. (1) so close to T_c. In fact, at these given field and temperature values the effects of thermal fluctuations and ΔT_c broadening do not affect the torque signals significantly. One reason is that the upper critical field B_{c2}^{δ} in Eq. (1) is much larger than B_{c2}^{c} for **B** applied close to the *ab* plane. Thus, for constant B, the ratio B/B_{c2}^{δ} becomes much smaller along the *ab* plane, which reduces the effect of fluctuations. Now we can use Eq. (1) to check that the influence of a ΔT_c broadening is also negligible for smaller γ_{app}. Equation (1) can be rewritten

$$\tau(\theta)=A_1(T)A_2(\gamma_{\mathrm{app}},\theta)\ln A_3(T,\gamma_{\mathrm{app}},\theta), \qquad (3)$$

where $A_1(T)=(\Phi_0 VB)/[16\pi\mu_0\lambda_a(T)\lambda_\beta(T)]$, $A_2(\gamma_{\mathrm{app}},\theta)=(1-\gamma_{\mathrm{app}}^{-2})\sin 2\theta/\epsilon(\theta)$, and $A_3(T,\gamma_{\mathrm{app}},\theta)=[\eta B_{c2}^{\delta}(T)]/[B\epsilon(\theta)]$. The temperature dependence of A_1 and A_3 is driven by that of the $(\lambda_a\lambda_\beta)$ and B_{c2}^{δ} terms, respectively. Note that A_2 depends, in addition to θ, on the fit parameter γ_{app}, which is essentially temperature independent. The fit of the torque curves $\tau(\theta)$ with relatively small γ_{app} displayed in Fig. 2 leads to three fit parameters: $(\lambda_a\lambda_\beta)$, γ_{app}, and B_{c2}^{δ}. Unlike the first two parameters, the error bar at B_{c2}^{δ} is always relatively large compared to its value, which means that the global dependence on A_3 is rather weak. Moreover, as A_1 depends only on T and not on γ_{app}, and A_2 on γ_{app} but not on T, it follows that a broadening of the transition width ΔT_c has less influence on the determination of a smaller γ_{app}, i.e., for near *ab*-plane measurements.

The use of in-plane anisotropy to probe the symmetry of the order parameter still attracts considerable interest.[10–12,21] In the present case of the La214 single crystal, measurements close to and within the *ab* plane have been performed only at $T/T_c = 0.977$, which is too close to T_c to obtain reliable information on the pairing symmetry.[12] By reducing the temperature slightly, the pinning increases so dramatically that it precludes a reliable evaluation of the in-plane reversible torque signal, in contrast to what was observed in Tl2201 films.[11,12]

In conclusion we have shown that precise torque measurements with rotation of **B** close to and within the *ab* plane emphasize the crucial importance of the magnetic-field orientation in highly anisotropic high-T_c superconductors. One important advantage of keeping **B** close to the *ab* plane is to reduce dramatically the effects of thermal fluctuations close to T_c by reducing the corresponding apparent anisotropy ratio γ_{app}. With this procedure it is possible to derive precisely the effective mass anisotropy ratio γ_{ac} by taking advantage of the perfect angular scaling of the apparent anisotropy $\gamma_{\mathrm{app}}(\varphi)$. The verification of this scaling in $La_{1.9}Sr_{0.1}CuO_4$, which is relatively anisotropic ($\gamma_{ac} \sim 43$), demonstrates that the three-dimensional anisotropic London model remains valid even when **B** is applied as close as a few degrees from the *ab* plane. Finally we point out that the combination of a low-angle field configuration and vortex-lattice shaking by an additional weak ac field broadens the reversible range in the (H,T) phase diagram normally restricted by pinning effects on one side and fluctuations on the other.

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