Pressure effects on the superconducting properties of $YBa_2Cu_4O_8$

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Measurements of the magnetization under high hydrostatic pressure (up to 10.2 kbar) in $YBa_2Cu_4O_8$ were carried out. From the scaling analysis of the magnetization data the pressure induced shifts of the transition temperature T_c, the volume V, and the anisotropy γ have been obtained. It was shown that the pressure-induced relative shift of T_c mirrors essentially that of the anisotropy. This observation uncovers a generic property of cuprate high-temperature superconductors.

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In the cuprate high-temperature superconductors (HTS), the canonical change in T_c with pressure is that it first increases, passes through a maximum value at some critical pressure, and then decreases.[1,2] It has been argued that there are at least two effects determining the total pressure dependence of T_c, an intrinsic effect and the one that arises from the pressure-induced changes in the charge carrier concentration.[1,2] However, there are effects that make the discrimination between these contributions difficult. In most HTS the application of pressure does not simply compress the lattice, but also prompts mobile oxygen defects to assume a greater degree of local order.[3] This leads to relaxation effects that are both temperature and pressure dependent. An exception is the double-chain compound $YBa_2Cu_4O_8$ with a fixed oxygen stoichiometry. Bucher *et al.*[4] found that in this compound T_c increases under hydrostatic pressure with the rate $dT_c/dp \simeq 5.5$ K/GPa. Subsequent studies revealed that with increasing pressure T_c passes through a maximum around 9 GPa and then decreases.[1–3] Furthermore, measurements of the in-plane penetration depth λ_{ab} of $YBa_2Cu_4O_8$ revealed pressure-induced changes that cannot be simply attributed to the pressure changes of T_c.[5,6] Since in cuprate high-temperature superconductors, including $YBa_2Cu_4O_8$, the critical regime where thermal critical fluctuations dominate is experimentally accessible, various critical properties are not independent but related by universal relations.[7–14] Accordingly, the isotope or pressure effects on these quantities are related as well.[11,14] Here we explore the universal relationship between the pressure effects on the transition temperature T_c, volume V, and anisotropy γ emerging from the pressure-induced changes of the magnetization near T_c. It is shown that in the underdoped $YBa_2Cu_4O_8$ the pressure effect on T_c mirrors essentially that on the anisotropy. This uncovers a generic property of anisotropic type II superconductors, unexistent in the isotropic case.

The polycrystalline $YBa_2Cu_4O_8$ samples were synthesized by solid-state reactions using high-purity Y_2O_3, $BaCO_3$, and CuO.[5] The hydrostatic pressure was generated in a copper-beryllium piston cylinder clamp that was especially designed for magnetization measurements under pressure.[15] The sample was thoroughly mixed with Fluorient FC77 (pressure transmitting medium) with a sample-to-liquid volume ratio of approximately 1/6. The pressure was measured *in situ* by monitoring the T_c shift of the small piece of In $[T_c(p=0) \simeq 3.4$ K$]$ included in the pressure cell. The field-cooled magnetization measurements were performed with a Quantum Design superconducting quantum interference device (SQUID) magnetometer at temperatures ranging from 2 to 100 K. In Fig. 1(a) we displayed the field-cooled (0.5 mT) magnetization M of a $YBa_2Cu_4O_8$ powder sample vs T near T_c for various applied hydrostatic pressures (0.0,

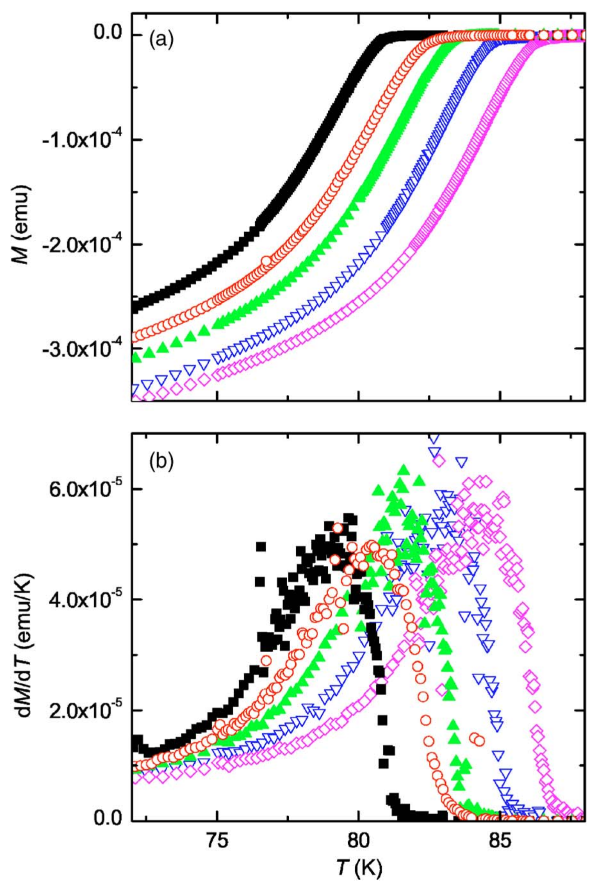

FIG. 1. (Color online) (a) Field-cooled (0.5 mT) magnetization of a $YBa_2Cu_4O_8$ powder sample vs T near T_c for various applied hydrostatic pressures (from the left to the right) 0.0, 2.67, 4.29, 7.52, and 10.2 kbar. (b) dM/dT vs T for the data shown in Fig. 1(a).

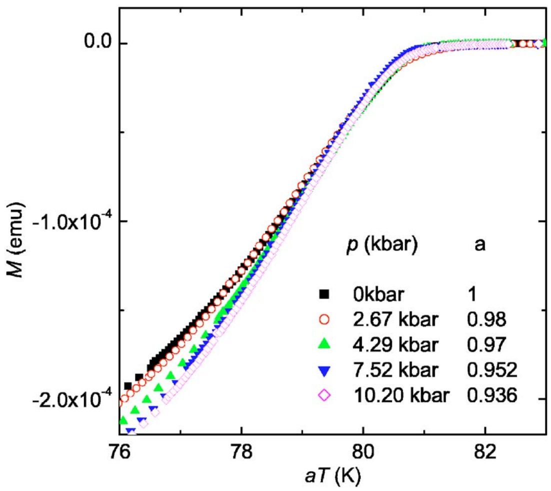

FIG. 2. (Color online) Magnetization data rescaled according to ${}^{p=0}M(T)={}^{p}M(aT)$ [Eq. (5)].

2.67, 4.29, 7.52, and 10.2 kbar). To identify the temperature regime where critical fluctuations play an essential role it is instructive to consider the behavior of dM/dT vs T displayed in Fig. 1(b). With decreasing temperature dM/dT is seen to raise below the transition temperature and after passing a maximum value it decreases. This behavior contradicts the mean-field behavior where dM/dT below T_c adopts a constant value.[16] It implies that the fluctuation-dominated regime is accessible and attained. This calls for an analysis beyond the mean-field approximation as outlined below.

The detailed description of the scaling analysis adopted for magnetization changes caused by isotope substitution or applying pressure can be found in Refs. 17 and 18. Briefly, the basic principles of the analysis can be summarized as follows. When three-dimensional (3D) Gaussian or 3D-XY thermal fluctuations dominate, the combination $m(T,\delta,H)/(\gamma\epsilon^{3/2}(\delta)T\sqrt{H})$ adopts at T_c a fixed value[8–10,12]

$$\frac{m(T_c)}{T_c[\gamma\epsilon^{3/2}(\gamma,\delta)]_{T_c}\sqrt{H}} = -\frac{k_B C}{\Phi_0^{3/2}}, \tag{1}$$

where $m=M/V$ is the magnetization per unit volume, C a constant adopting for Gaussian, and 3D-XY fluctuations distinct universal values. Furthermore, $\epsilon(\delta)=(\cos^2(\delta)+\sin^2(\delta)/\gamma^2)^{1/2}$, where δ is the angle between the applied magnetic field H and the c axis, Φ_0 the flux quantum, and k_B Boltzmann's constant. In powder samples this relation reduces to

$$\frac{m(T_c)}{T_c\sqrt{H}f(\gamma(T_c))} = -\frac{k_B C}{\Phi_0^{3/2}}, \quad f(\gamma(T_c)) = [\gamma\langle\epsilon^{3/2}(\gamma,\delta)\rangle]_{T_c}. \tag{2}$$

As the pressure effect on the magnetization at fixed magnetic field is concerned it implies that the relative shifts of the magnetization M, volume V, magnetization per unit volume m, anisotropy γ, and T_c are not independent but close to T_c related by

$$\frac{\Delta M}{M} = \frac{\Delta V}{V} + \frac{\Delta T_c}{T_c} + \frac{\Delta f}{f}. \tag{3}$$

For $YBa_2Cu_4O_8$, where $\gamma \gg 1$ (see, e.g., Ref. 19) it reduces to

$$\frac{\Delta M}{M} = \frac{\Delta V}{V} + \frac{\Delta T_c}{T_c} + \frac{\Delta\gamma}{\gamma}. \tag{4}$$

On that condition it is impossible to extract these changes from the temperature dependence of the magnetization. However, supposing that close to criticality the magnetization data scale within experimental error as

$${}^{p=0}M(T) = {}^{p}M(aT), \tag{5}$$

the universal relation (4) reduces to

$$\frac{\Delta T_c}{T_c} = -\frac{\Delta V}{V} - \frac{\Delta\gamma}{\gamma} = \frac{T_c(p)}{T_c(0)} - 1 = \frac{1}{a} - 1. \tag{6}$$

In Fig. 2 we displayed the magnetization data rescaled according to Eq. (5). Near T_c the pressure-induced changes

TABLE I. Estimates for the pressure-induced relative change of volume V, transition temperature T_c, and anisotropy γ derived from the data shown in Fig. 2 with the aid of Eqs. (5)–(7). T_c and λ_{ab0}^{-2} at $p=0$, 4.29, 7.52, and 10.2 kbar taken from Khasanov *et al.* (Ref. 5). T_c and λ_{ab0}^{-2} at $p=1.2$ and 2.67 kbar were obtained from the linear interpolation of $T_c(p)$ and $\lambda_{ab0}^{-2}(p)$ data from Ref. 5. $\Delta\xi_{c0}/\xi_{c0}$ follows from Eq. (9) and $\Delta\xi_{ab0}/\xi_{ab0}$ from relation (10). Hereafter the relative pressure shift of the physical quantity X is determined as $\Delta X(p)/X(0)=[X(p)-X(0)]/X(0)$.

p (kbar)	$\Delta V/V$	a	$\Delta T_c/T_c$	$\Delta\gamma/\gamma$	T_c (K)	λ_{ab0}^{-2} (μm^{-2})	$\Delta\xi_{c0}/\xi_{c0}$	$\Delta\xi_{ab0}/\xi_{ab0}$	$2\Delta\lambda_{ab0}/\lambda_{ab0}$
0		1			79.07	34.3			
1.2	−0.0010	0.991	0.008	−0.007	79.67	35.9	−0.04	−0.05	−0.05
2.67	−0.0023	0.98	0.017	−0.015	80.41	37.5	−0.07	−0.09	−0.09
4.29	−0.0037	0.97	0.031	−0.027	81.4	39.2	−0.10	−0.13	−0.14
7.52	−0.0064	0.952	0.050	−0.044	82.73	44.1	−0.19	−0.23	−0.28
10.2	−0.0087	0.936	0.068	−0.059	84.22	45.0	−0.19	−0.25	−0.32

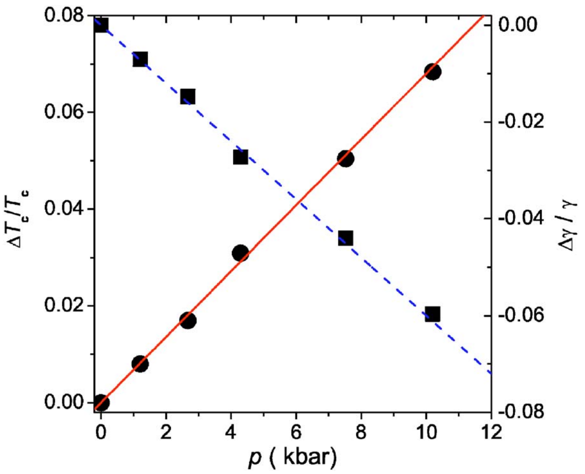

FIG. 3. (Color online) $\Delta T_c/T_c$ (●) and $\Delta\gamma/\gamma$ (■) vs p for the estimates listed in Table I. The solid line is $\Delta T_c/T_c=0.0068p$ and the dashed one is $\Delta\gamma/\gamma=-0.006p$ with p in kbar.

in $M(aT)$ is negligibly small so that Eqs. (5) and (6) can be applied within experimental error.

Since a is less than one and decreases with increasing pressure the transition temperature increases in the pressure range considered here. Given then the bulk modulus $B=1178$ kbar (Ref. 20) for the pressure dependence of the relative volume change we obtain the expression

$$\frac{\Delta V}{V}=-\frac{p(\text{kbar})}{1178}, \tag{7}$$

and with Eq. (6) the estimates for the pressure-induced changes of the anisotropy listed in Table I. It is readily seen that the rise of T_c mirrors essentially the decrease of the anisotropy. Indeed the relative volume change is an order of magnitude smaller. Furthermore, from Fig. 3, showing $\Delta T_c/T_c$ and $\Delta\gamma/\gamma$ vs p for the estimates listed in Table I, it is seen that in the pressure range considered here, both $\Delta T_c/T_c$ and $\Delta\gamma/\gamma$ depend nearly linearly on pressure. Thus, under pressure not only T_c and the volume changes but the anisotropy is modified as well. A quick glance to Table I reveals that the pressure effect on T_c mirrors essentially that on the anisotropy.

In addition, recent in-plane penetration depth λ_{ab} measurements revealed that there is a pressure effect on this important property also.[5] It was shown that the in-plane penetration depth data of $YBa_2Cu_2O_8$ is consistent with 3D-*XY* critical behavior,[5] where the penetration depth and correlation length in direction i diverge near T_c as $\lambda_i^2(T)=\lambda_{i0}^2 t^{-\nu}$ and $\xi_i(T)=\xi_{i0}t^{-\nu}$, with $t=1-T/T_c$ and $\nu\simeq 2/3$. Moreover, as listed in Table I, the critical amplitude λ_{ab0}^{-2} was found to be pressure dependent. The consistency with 3D-*XY* critical behavior implies that the transition temperature T_c and the critical amplitudes of the in-plane penetration depths λ_{ab0} and the c-axis correlation lengths ξ_{c0} are not independent but related by[7–10,14,21]

$$k_B T_c=\frac{\Phi_0^2}{16\pi^3}\frac{g\xi_{c0}}{\lambda_{ab0}^2}, \quad g\simeq 0.453. \tag{8}$$

Universality implies that this relation holds irrespective of the applied pressure. Thus, in addition to Eq. (6) the pressure-induced relative changes are then related by

$$\frac{\Delta T_c}{T_c}=-2\frac{\Delta\lambda_{ab0}}{\lambda_{ab0}}+\frac{\Delta\xi_{c0}}{\xi_{c0}} \tag{9}$$

and, because of $\gamma=\xi_{ab0}/\xi_{c0}$,

$$\frac{\Delta\gamma}{\gamma}=\frac{\Delta\xi_{ab0}}{\xi_{ab0}}-\frac{\Delta\xi_{c0}}{\xi_{c0}}. \tag{10}$$

Using then the estimates for $\Delta T_c/T_c$ and $-2\Delta\lambda_{ab0}/\lambda_{ab0}$ the relative change $\Delta\xi_{c0}/\xi_{c0}$ is readily calculated with aid of Eq. (9), while the values for $\Delta\xi_{ab0}/\xi_{ab0}$ follow from relation (10). The values of $\Delta\xi_{c0}/\xi_{c0}$ and $\Delta\xi_{ab0}/\xi_{ab0}$ are listed in Table I.

From the scaling analysis of the pressure effect on magnetization and in-plane penetration depth it then emerges that the rise of the transition temperature of underdoped $YBa_2Cu_4O_8$ with increasing pressure is associated with a decreasing anisotropy and volume V. The relative change of the transition temperature $\Delta T_c/T_c$ is seen to mirror essentially that of the anisotropy $\Delta\gamma/\gamma$. This is consistent with the generic behavior for high-temperature superconductors, where for a given HTS family, T_c increases with reduced anisotropy.[10,13,14] Although these changes are small compared to those in the critical amplitudes of the in-plane penetration depth $\Delta\lambda_{ab0}/\lambda_{ab0}$ and the correlation lengths $\Delta\xi_{ab0}/\xi_{ab0}$, $\Delta\xi_{c0}/\xi_{c0}$ (see Table I) it becomes clear that the pressure-induced change of the anisotropy is the essential ingredient that remains to be understood microscopically. Empirically the anisotropy decreases rather steeply by approaching optimum doping and levels off in the overdoped regime.[10,13,14] Together with Eq. (6) this explains why the pressure effect on T_c becomes very small in optimally and overdoped cuprate superconductors.[1–3] Finally we note that the pressure range of the present study was limited to 10 kbar. It is well known that the T_c of $YBa_2Cu_4O_8$ passes through a maximum around 9 GPa before decreasing again for still higher pressures.[2] The pressure-dependent T_c closely follows the canonical bell-shaped $T_c(n)$ curve (n is the carrier concentration). It would be very interesting to extend studies to higher pressures.

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