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Pressure effect on the in-plane magnetic penetration depth in $YBa_2Cu_4O_8$

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Abstract

We report a study of the pressure effect (PE) on the in-plane magnetic field penetration depth λ_{ab} in $YBa_2Cu_4O_8$ by means of Meissner fraction measurements. A pronounced PE on $\lambda_{ab}^{-2}(0)$ was observed with a maximum relative shift of $\Delta\lambda_{ab}^{-2}/\lambda_{ab}^{-2} = 44(3)\%$ at a pressure of 10.2 kbar. It arises from the pressure dependence of the effective in-plane charge carrier mass and pressure-induced charge carrier transfer from the CuO chains to the superconducting CuO_2 planes. The present results imply that the charge carriers in $YBa_2Cu_4O_8$ are coupled to the lattice.

One of the fundamental questions concerning the physics of the cuprate high-temperature superconductors (HTSs) is whether the electron–phonon interaction plays an essential role in these systems or not. The conventional phonon-mediated theory of superconductivity is based on the Migdal adiabatic approximation in which the effective supercarrier mass m^* is independent of the lattice vibrations. However, if the interaction between the carriers and the lattice is strong enough, the Migdal adiabatic approximation breaks down and m^* depends on the lattice degrees on freedom (see e.g. [1]). One way to explore a possible coupling of the supercarriers to the lattice is a study how the magnetic field penetration depth λ is affected by the crystal lattice modifications. In the mean-field approximation the zero-temperature London penetration depth of anisotropic superconductor is given by [2, 3]

$$\frac{1}{\lambda^2(0)} = \frac{e^2}{\pi^2\hbar c^2}\oint_{S_F} \mathrm{d}s|\mathbf{v}_F(s)|, \tag{1}$$

where the integral runs over the Fermi surface S_F and v_F is the Fermi velocity. For a spherical or elliptical Fermi surface, one recovers for the zero-temperature penetration depth the standard result,

$$\lambda^{-2}(0) \propto n_s/m^*, \tag{2}$$

where n_s is the superconducting charge carrier density and m^* is the effective mass of the superconducting charge carriers. In a real superconductor, however, the ionic potential modifies the spherical Fermi surface of free electrons drastically. Thus, this relation shows that the superfluid density n_s/m^* is just a way of parameterizing experimental results, with no strict connection of the m^* to the band mass. However, such an interpretation still can be used to indicate the *relative* changes of the n_s and/or m^* caused by doping (see e.g. [4, 5]), isotope substitution (see e.g. [6, 7]), etc. Under the assumption that one can separate the two quantities n_s and m^*, equation (2) implies that a change of the so-called in-plane magnetic penetration depth λ_{ab} is due to a shift in n_s and/or in-plane charge carrier mass m^*_{ab}:

$$\Delta\lambda^{-2}_{ab}(0)/\lambda^{-2}_{ab}(0) = \Delta n_s/n_s - \Delta m^*_{ab}/m^*_{ab}. \tag{3}$$

Therefore, if the contribution of n_s is known, λ measurements open an unique possibility to investigate an unusual (non-adiabatic) coupling of the charge carriers to the crystal lattice in HTSs.

One way to explore the role of lattice vibrations in HTSs is to perform the isotope effect experiments. Previous studies [6–11] showed a substantial oxygen-isotope ($^{16}O/^{18}O$) effect on the in-plane penetration depth λ_{ab}, which indicates a non-adiabatic coupling of the electrons to phonon modes involving the movement of the isotope substituted atoms. An alternative way to explore lattice effects in HTSs is pressure experiments. The squeezing of the crystal lattice by external hydrostatic or uniaxial pressure affects the lattice parameters, the phonon spectrum and consequently the electron–lattice coupling. Surprisingly, the pressure effect (PE) on the magnetic field penetration depth has not attracted much attention. To our knowledge only one experiment related to this topic for the two-dimensional organic superconductor κ − (BEDT-TTF)$_2$Cu(NCS)$_2$ has been reported so far [12]. It was shown that both $\lambda^{-2}(0)$ and the transition temperature T_c linearly decrease with pressure p. Furthermore, T_c versus $\lambda^{-2}(0)$ measured for different p follows the universal 'Uemura' line [13, 4].

In this paper we report the first investigation of the in-plane magnetic penetration depth λ_{ab} under high hydrostatic pressure (up to 10.2 kbar) in $YBa_2Cu_4O_8$ (Y124). The temperature dependence of λ^{-2}_{ab} was extracted from Meissner fraction measurements at low magnetic field. A pronounced pressure effect on λ_{ab} with a maximum relative shift $\Delta\lambda^{-2}_{ab}(0)/\lambda^{-2}_{ab}(0) = 44(3)\%$ at a hydrostatic pressure $p = 10.2$ kbar was observed. We demonstrate that this effect mainly ($\simeq 2/3$) arises from the pressure dependence of the in-plane charge carrier mass m^*_{ab}.

The polycrystalline $YBa_2Cu_4O_8$ samples were synthesized by solid-state reactions using high-purity Y_2O_3, $BaCO_3$ and CuO. The powder samples were ground for about 60 min and then passed through a 10 μm sieve in order to obtain the very small grains that are needed for the determination of λ from Meissner fraction measurements. The grain size distribution of the powder was then determined by analysing scanning electron microscope (SEM) photographs. The measured particle radius distribution $N(R)$ is shown in the inset of figure 1(a). The hydrostatic pressure was generated in a copper–beryllium piston cylinder clamp that was especially designed for magnetization measurements under pressure [14]. The sample was mixed with Fluorient FC77 (pressure transmitting medium) with a sample to liquid volume ratio of approximately 1/6. With this cell hydrostatic pressures up to 12 kbar can be achieved [14]. 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 value of the Meissner fraction was calculated from 0.5 mT field-cooled (FC) SQUID magnetization measurements. The absence

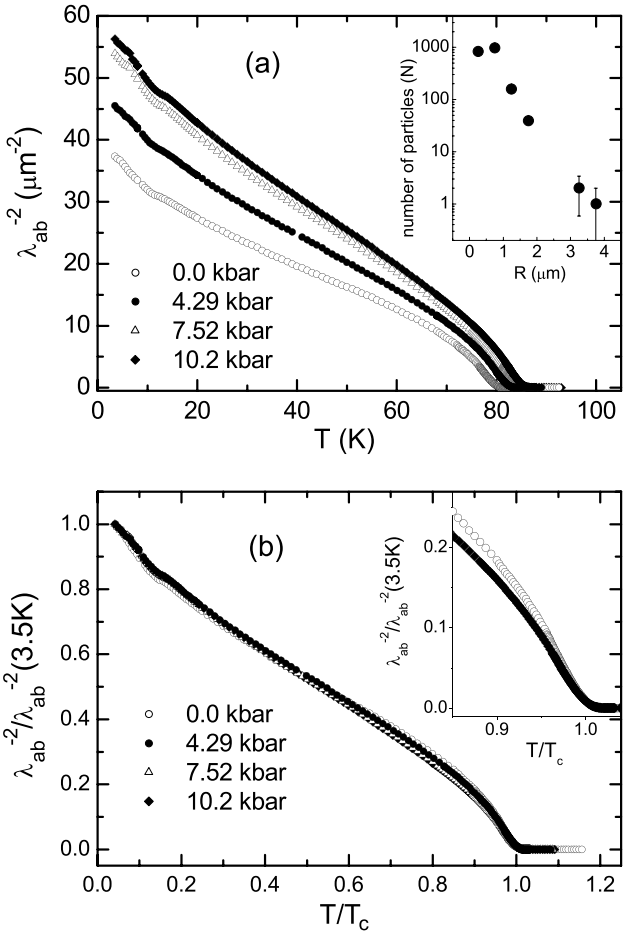

Figure 1. (a) λ_{ab}^{-2} as a function of T for a $YBa_2Cu_4O_8$ fine powder sample at hydrostatic pressures $p = 0.0, 4.29, 7.52$ and 10.2 kbar as obtained from low-field SQUID magnetization measurements. The inset shows the grain size distribution in a semilogarithmic scale. Errors are statistical. (b) Normalized superfluid density $\lambda_{ab}^{-2}(T)/\lambda_{ab}^{-2}$ (3.5 K) as a function of reduced temperature T/T_c for the same pressures. The inset shows the data for $p = 0.0$ and 10.2 kbar close to $T/T_c = 1$.

of weak links between the grains was confirmed by the linear magnetic field dependence of the FC magnetization in low fields (0.25, 0.5, 0.75, and 10 mT) measured at 8 K for each pressure (0.0, 4.29, 7.52, and 10.2 kbar).

The temperature dependence of $\lambda_{\rm eff}$ (powder average) was calculated from the measured Meissner fraction by using the Shoenberg model [15] modified for the known grain size distribution [16]. The in-plane penetration depth $\lambda_{ab}(T)$ (figure 1(a)) was determined from $\lambda_{\rm eff}(T)$ using the relation $\lambda_{\rm eff} = 1.31\lambda_{ab}$, which holds for highly anisotropic superconductors ($\lambda_c/\lambda_{ab} > 5$) [17]. The values of T_c and $\lambda_{ab}^{-2}(0)$ at each particular pressure were defined as: T_c—from the intersect of the linearly extrapolated $\lambda_{ab}^{-2}(T)$ in the vicinity of the superconducting transition with the $\lambda_{ab}^{-2} = 0$ line; $\lambda_{ab}^{-2}(0)$—from the intersect of the linear fit of $\lambda_{ab}^{-2}(T)$ at $T < 10$ K with the $T = 0$ line. Note that the value of $\lambda_{ab}(0)$ at ambient pressure was found to be $\lambda_{ab}(0) = 156$ nm, in a good agreement with the literature data [18, 5]. The values of $\lambda_{ab}^{-2}(0)$ and T_c obtained from the experimental data presented in figure 1 are summarized in table 1.

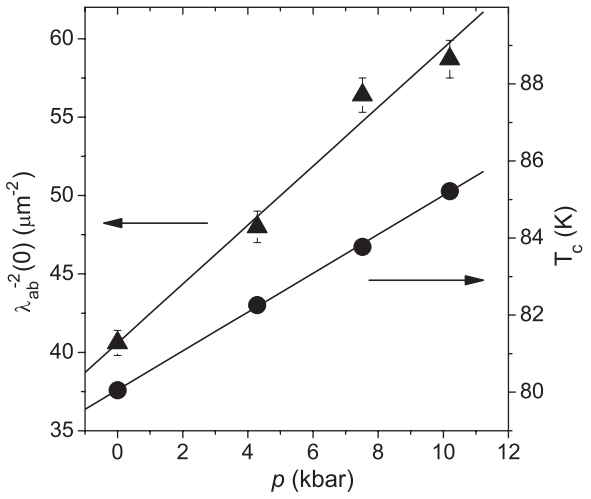

Figure 2. Pressure dependence of the transition temperature T_c (circles) and the zero-temperature in-plane magnetic penetration depth $\lambda_{ab}^{-2}(0)$ (triangles). The linear fits yield $dT_c/dp = 0.50(1)$ K kbar^{-1} and $d\lambda_{ab}^{-2}(0)/dp = 1.88(13)$ μm^{-2} kbar^{-1}. The errors in $\lambda_{ab}^{-2}(0)$ come from misalignments of the experimental setup (see text for an explanation).

Table 1. Summary of the PE results for $YBa_2Cu_4O_8$ extracted from the experimental data (see text for an explanation).

p (kbar)	T_c (K)	$\frac{\Delta T_c}{T_c}$ (%)	$\lambda_{ab}^{-2}(0)$ (μm^{-2})	$\frac{\Delta\lambda_{ab}^{-2}(0)}{\lambda_{ab}^{-2}(0)}$ (%)	$\frac{\Delta m_{ab}^*}{m_{ab}^*}$ (%)
0.0	80.05(2)	—	40.6(8)	—	—
4.29	82.26(2)	2.8(4)	48.0(1.0)	18(3)	−13(2)
7.52	83.77(3)	4.1(5)	56.4(1.1)	39(3)	−29(3)
10.2	85.22(3)	6.5(5)	58.7(1.2)	44(3)	−32(3)

The errors in $\lambda_{ab}^{-2}(0)$ come from misalignments of the experimental setup after the cell was removed from the SQUID magnetometer and put back again. We checked this procedure with a set of measurements at constant pressure. The systematic scattering of the magnetization data is about 0.5%, giving a relative error in $\lambda^{-2}(T)$ of about 2%.

Figure 1(b) shows a plot of the normalized superfluid density $\lambda_{ab}^{-2}(T)/\lambda_{ab}^{-2}(3.5\text{ K})$ versus the reduced temperature T/T_c. For all pressures the temperature dependences of λ_{ab}^{-2} are nearly the same. At low temperatures ($T/T_c < 0.5$) all curves appear to converge, while on approaching T_c ($0.6 < T/T_c < 1.0$) they begin to separate. As is shown in the inset of figure 1(b), $\lambda_{ab}^{-2}(T)/\lambda_{ab}^{-2}$ (3.5 K) decreases with increasing pressure. Note that the $\lambda_{ab}^{-2}(T)$ curves of the present work are very similar to those reported in [19] obtained for $YBa_2Cu_4O_8$ using the same experimental technique. The fast increase of λ_{ab}^{-2} close to T_c (see figure 1) in [19] was attributed to the contribution of the double chains to λ_{ab}^{-2}. Thus the decreasing of $\lambda_{ab}^{-2}(T)/\lambda_{ab}^{-2}(3.5\text{ K})$ close to $T/T_c = 1$ (see the inset in figure 1(b)) would imply that the contribution of the chains to λ_{ab}^{-2} decreases with increasing pressure, which is in good agreement with the NQR experiments [20].

Figure 2 shows the pressure dependence of T_c and $\lambda_{ab}^{-2}(0)$ extracted from the data presented in figure 1. As is seen, $\lambda_{ab}^{-2}(0)$ as well as T_c increase with increasing pressure almost linearly.

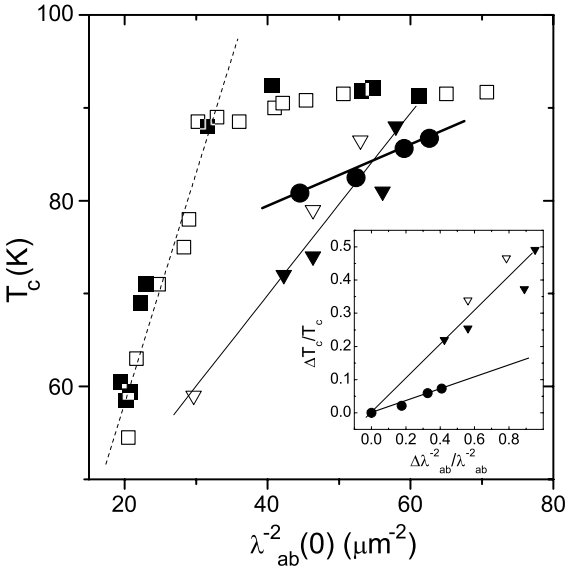

Figure 3. T_c versus $\lambda_{ab}^{-2}(0)$ for various Y123 and Y124 samples. The dashed line corresponds to the 'Uemura' line [13, 4]. The open and closed squares are Y123 data from Zimmermann *et al* [24] and Tallon *et al* [22]. Open and closed down triangles are data of $Y_{1-x}Ca_xBa_2Cu_4O_8$ and $YBa_{2-x}La_xCu_4O_8$ taken from Shengelaya *et al* [23] and Tallon *et al* [22]. Closed circles are the pressure data of $YBa_2Cu_4O_8$ from the present study. The inset shows the $\Delta T_c/T_c$ versus $\Delta\lambda_{ab}^{-2}(0)/\lambda_{ab}^{-2}(0)$ for various Y124 samples. The solid lines are linear fits of the data. While the slope of the linear fit to the doped samples is dominated by changes in n_s only, the slope of the $YBa_2Cu_4O_8$ pressure data is determined mostly (∼70%) by changes in m^*_{ab} (see text for an explanation).

The linear fit yield $dT_c/dp = 0.50(1)$ K kbar^{-1} and $d\lambda_{ab}^{-2}(0)/dp = 1.88(13)$ μm^{-2} kbar^{-1} for $T_c(p)$ and λ_{ab}^{-2}, respectively. The value of dT_c/dp is in good agreement with the literature data (see e.g. [21]). The values of the relative pressure shifts $\Delta T_c/T_c$ and $\Delta\lambda_{ab}^{-2}(0)/\lambda_{ab}^{-2}(0)$ are summarized in table 1. The pressure shift of a physical quantity X is defined as $\Delta X/X = [X_{p>0} - X_{p=0}]/X_{p=0}$.

Now we turn to discuss the zero-temperature values of $\lambda_{ab}^{-2}(0)$. Figure 3 shows T_c plotted versus $\lambda_{ab}^{-2}(0)$ for our $YBa_2Cu_4O_8$ sample at different pressures (see table 1), together with previous results of $Y_{1-x}Ca_xBa_2Cu_4O_8$ and $YBa_{2-x}La_xCu_4O_8$ [22, 23] and oxygen-deficient $YBa_2Cu_3O_{7-\delta}$ (Y123) [22, 24]. We used the relation $\lambda_{ab}^{-2}(0)$ (μm^{-2}) = $\sigma(0)$ (μs^{-1})/(0.266)^2 [25] to calculate $\lambda_{ab}^{-2}(0)$ from the values of the zero-temperature muon-spin depolarization rate $\sigma(0)$ reported in [22–24]. In the underdoped regime T_c scales linearly with $\lambda_{ab}^{-2}(0)$ on a single universal line for most HTS families (dashed line in figure 3). This is a generic behaviour expected for HTSs that contain CuO_2 planes only [13, 4]. It was found that several HTS systems containing CuO chains exhibit enhanced values of $\lambda_{ab}^{-2}(0)$ compared to the 'Uemura line' [22]. This deviation from Uemura scaling was explained by an additional contribution to $\lambda_{ab}^{-2}(0)$ from the disorder-free CuO chains [22]. It was also shown [5] that the changes in the superfluid density (n_s/m^*) are solely determined by the corresponding changes in the charge carrier concentration within the superconducting CuO_2 planes and the transition temperature T_c, while the concentrations of the dopant atoms are irrelevant.

Under the assumption that equation (3) is valid, there are two contributions which may cause a change of $\lambda_{ab}(0)$ under pressure: (i) the charge carrier concentration n_s and (ii) the in-plane charge carrier mass m^*_{ab}. In order to separate them, we use the following procedure.

Doping of the parent compound $YBa_2Cu_4O_8$ with La or Ca [5, 22, 23] leads mainly to a change of the charge carrier concentration n_s within superconducting CuO_2 planes [26, 27]. The change of the m^*_{ab} can be caused by the changes of n_s if one take into account that bands in $YBa_2Cu_4O_8$ are not parabolic. This appears if one assumes that n_s is directly related to the doping and, therefore, to the volume of the occupied Fermi surface, and m^*_{ab} would be an appropriate average of $\hbar k/v_F$ over the Fermi surface (k is the wavevector). Combining these two arguments one can conclude that changes in λ_{ab} due to doping are determined as

$$\left.\frac{\Delta\lambda_{ab}^{-2}}{\lambda_{ab}^{-2}}\right|_d \simeq \left.\frac{\Delta n_s}{n_s}\right|_d - \left.\frac{\Delta m^*_{ab}}{m^*_{ab}}\right|_d. \tag{4}$$

Here the index d stands for doping.

The PE on T_c observed in HTSs is usually explained in terms of the so-called pressure-induced charge transfer (PICT) model [21, 28–30]. In underdoped $YBa_2Cu_4O_8$, pressure induces a charge carrier transfer from the chains to the planes. This finding is further supported by NQR measurements under pressure [20] and by our $\lambda_{ab}^{-2}(T)$ data, indicating that the contributions from the chains to λ_{ab}^{-2} decreases with increasing pressure (see the inset in figure 1(b)). Within the PICT model the pressure dependence of T_c is determined as

$$\frac{dT_c}{dp} = \left(\frac{dT_c}{dp}\right)^{intr} + \left(\frac{dT_c}{dn_s}\right)\left(\frac{dn_s}{dp}\right), \tag{5}$$

where the first term describes an intrinsic pressure dependence of T_c and the second term arises from the pressure-induced changes in the charge carrier concentration n_s within the superconducting CuO_2 planes. Taking into account that the maximum value of the transition temperature in Y124 was found to be 104–108 K at $p \simeq 100$ kbar in the pressure experiments [31] and can be estimated to be 94–97 K in a case of doping [32], the first term in equation (5) would be equal to $(dT_c/dp)^{intr} = 0.07$–0.14 K kbar^{-1}. Note that this value is in good agreement with $dT_c/dp = 0.1$–0.2 K kbar^{-1} observed in the optimally doped cuprates, where the intrinsic contribution in dT_c/dp dominates (see e.g. [33]). In the underdoped $YBa_2Cu_4O_8$ the reported values of dT_c/dp lie within the range 0.5–0.63 K kbar^{-1} [21]. Thus one can almost neglect the first term in equation (5) and assume that the shift of T_c due to doping and pressure is caused by almost the same change of n_s, so that $\Delta n_s/n_s|_d \simeq \Delta n_s/n_s|_p$. Here the index p means pressure. Then from equations (3) and (4) for the pressure shift of the in-plane charge carrier mass m^*_{ab} one readily obtains

$$\left.\frac{\Delta m^*_{ab}}{m^*_{ab}}\right|_p \simeq \left.\frac{\Delta\lambda_{ab}^{-2}}{\lambda_{ab}^{-2}}\right|_d - \left.\frac{\Delta\lambda_{ab}^{-2}}{\lambda_{ab}^{-2}}\right|_p. \tag{6}$$

Linear fits of $\lambda_{ab}^{-2}(0)$ versus T_c (see figure 3) give $\Delta\lambda_{ab}^{-2}(0)|_d = 1.0(1)\cdot\Delta T_c$ and $\Delta\lambda_{ab}^{-2}(0)|_p = 3.7(3)\cdot\Delta T_c$ for La and Ca doped Y124 and for $YBa_2Cu_4O_8$ under pressure, respectively. Thus the pressure dependence of the in-plane charge carrier mass may be written as

$$\left.\frac{\Delta m^*_{ab}}{m^*_{ab}}\right|_p \simeq -0.72(6) \times \left.\frac{\Delta\lambda_{ab}^{-2}(0)}{\lambda_{ab}^{-2}(0)}\right|_p. \tag{7}$$

The values of $\Delta m^*_{ab}/m^*_{ab}|_p$ obtained from equation (7) are summarized in table 1. A glance at table 1 shows that the relative change of the charge carrier mass upon pressure is significant. It decreases by 32% at $p = 10.2$ kbar[5]. A comparable mass change (24%) caused by substitution of the oxygen ($^{16}O/^{18}O$) isotope was recently observed in underdoped $La_{1.94}Sr_{0.06}CuO_4$ [9].

[5] In $YBa_2Cu_4O_8$ chains provide a substantial contribution to the condensate density n_s/m^*_{ab}. One would expect that the pressure reduces the mass of the charge carriers within superconducting chains as well. However, our measurements were performed on non-oriented powders, so the contributions from chains and planes cannot be separated in the measured $\lambda_{ab}(0)$ value. To do that one needs to perform similar measurements on a single crystal, which was not possible in the present study.

Note that in conventional BCS-type superconductors the pressure [34, 35] as well as the isotope [36] effects on the magnetic penetration depth were found to be almost negligible (at least one order of magnitude smaller) in comparison with the PE observed in the present study and the isotope effect data reported in [6–11]. The substantial isotope and/or pressure effects on the zero-temperature penetration depth requires a renormalization of the in-plane charge carrier mass $\tilde{m}^*_{ab} = m^*_{ab}(1+f)$, where f is the electron–phonon coupling constant[6]. f changes upon isotope exchange and applying pressure in the cuprates but remains nearly unaffected by boron isotope substitution and on applying pressure in MgB_2 [35, 36]. Within the Migdal treatment of the electron–phonon interaction [37] the coupling constant f is independent of the lattice vibration and assumed to be small [38, 39]. This is true if the parameter $\omega_0 f/E_F$ is small, where ω_0 is the relevant phonon frequency and E_F is the Fermi energy. Thus in conventional BCS-type superconductors effects on the penetration depth are expected to be of the order of the adiabatic parameter $\tilde{\gamma} = \omega_0 f/E_F \ll 1$. The Migdal theory retains terms only of order 0. Cuprates, however, have Fermi energies much smaller than those of conventional metals [40], so $\tilde{\gamma}$ is no longer negligible. This implies that observation of a substantial pressure effect on the in-plane charge carrier mass points to an unusual (non-adiabatic) coupling of the charge carriers to the crystal lattice and calls for a theory that goes beyond the Migdal adiabatic approximation [41, 42].

In summary, we report the first observation of the pressure effect on the zero-temperature in-plane magnetic field penetration depth $\lambda_{ab}(0)$ in a cuprate superconductor. A pronounced PE on both the transition temperature T_c and $\lambda^{-2}_{ab}(0)$ is observed which increases with increasing pressure. The pressure shift on $\lambda^{-2}_{ab}(0)$ is attributed to (i) the pressure-induced charge carrier transfer from chains to the planes and (ii) the decreasing of the in-plane charge carrier mass m^*_{ab}. At $p = 10.2$ kbar we observed $\Delta\lambda^{-2}_{ab}(0)/\lambda^{-2}_{ab}(0) = 44(3)\%$ and $\Delta m^*_{ab}/m^*_{ab} = -32(3)\%$. Such a large effect on m^*_{ab} implies that lattice effects play an essential role in cuprate superconductors.

Acknowledgments

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[6] Since pressure changes the electron density and hence the screening, f should consist of two terms $f = f_{el-ph} + f_{el-el}$ (the indices el–ph and el–el stand for electron–phonon and electron–electron interactions, respectively). We cannot separate these two terms from each other, but in analogy with PE measurements on λ in MgB_2 [35] and $RbOs_2O_6$ [34] we can assume that the pressure changes in f_{el-el} are of the order of a few percent only, and thus one can neglect the f_{el-el} term.

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