Comparative study of the pressure effects on the magnetic penetration depth in electron- and hole-doped cuprate superconductors

D Di Castro¹, R Khasanov³, A Shengelaya⁴, K Conder⁵, D-J Jang⁶, M-S Park⁶, S-I Lee⁷ and H Keller²

¹ CNR-INFM-Coherentia and Dipartimento di Ingegneria Meccanica, Università’ di Roma ‘Tor Vergata’, Via del Politecnico 1, I-00133 Roma, Italy
² Physik-Institut der Universität Zürich, Winterthurerstrasse 190, CH-8057, Zürich, Switzerland
³ Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
⁴ Physics Institute of Tbilisi State University, Chavchavadze 3, GE-0128 Tbilisi, Georgia
⁵ Laboratory for Developments and Methods, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
⁶ National Creative Research Initiative Center for Superconductivity and Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea
⁷ National Creative Research Initiative Center for Superconductivity, Department of Physics, Sogang University, Seoul, Korea

E-mail: daniele.di.castro@uniroma2.it

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Abstract

The effect of pressure on the magnetic penetration depth $\lambda$ was tested for the hole-doped superconductor YBa$_2$Cu$_3$O$_{7-\delta}$ and in the electron-doped one Sr$_{0.9}$La$_{0.1}$CuO$_2$ by means of magnetization measurements. Whereas a large change of $\lambda$ was found in YBa$_2$Cu$_3$O$_{7-\delta}$, confirming the non-adiabatic character of the electron–phonon coupling in hole-doped superconductors, the same quantity is not affected by pressure in electron-doped Sr$_{0.9}$La$_{0.1}$CuO$_2$, suggesting a close similarity of the latter to conventional adiabatic Bardeen–Cooper–Schrieffer superconductors. The present results imply a remarkable difference between the electronic properties of hole-doped cuprates and electron-doped Sr$_{0.9}$La$_{0.1}$CuO$_2$, giving a strong contribution to the long debated asymmetric consequences of hole and electron doping in cuprate superconductors.

(Some figures in this article are in colour only in the electronic version)
are also strong experimental evidences which indicate for \( n \)-HTSs the existence of conventional s-wave symmetry \( [6-8] \). This is in apparent contrast with \( p \)-HTSs, where d-wave pairing symmetry is well accepted (see for example \( [9, 10] \), although a multi-component (d + s-wave) order parameter is now acquiring overwhelming evidences \( [11, 12] \). These asymmetric behaviors raised the fundamental question whether or not the mechanism of superconductivity in \( n \)-HTSs is common to that one in \( p \)-HTSs.

An important characteristic feature of the \( p \)-HTSs is the presence of a strong electron–phonon interaction, which leads to non-adiabatic effects and polaron formation. Indeed, in \( p \)-HTSs, induced lattice modification, by, e.g., oxygen isotope substitution \( [13-16] \) or application of external pressure \( [17] \), led to substantial changes in the superconducting critical temperature \( T_C \) and the magnetic penetration depth \( \lambda(0) \). Since \( \lambda(0) \) is related to the effective mass \( m^* \), these results were interpreted in the framework of non-adiabatic theory of the electron–phonon interaction \( [18, 19] \) and of polaron superconductivity \( [20, 21] \). The conventional phonon-mediated theory of superconductivity is based on the Migdal adiabatic approximation, in which \( m^* \) is independent of the lattice vibrations. However, if the coupling between the carriers and the lattice is strong enough, and the typical phonon frequency \( \omega_{ph} \) is comparable to the Fermi energy \( E_F \), the Migdal adiabatic approximation breaks down and \( m^* \) depends on the lattice degrees of freedom, with the opening of new interaction channels which give rise to, e.g., anomalous pressure and isotope effects \( [18, 19] \).

Whereas non-adiabatic interaction appears to be a characteristic feature of \( p \)-HTSs, on the contrary in low temperature BCS superconductors the adiabatic approximation usually holds. For example, the BCS low temperature superconductors \( \text{RbOs}_2\text{O}_6 \) \( [22] \) and \( \text{YBa}_2 \) \( [23] \), whereas showing a \( T_C \) shift with pressure, do not present any pressure effect on \( \lambda(0) \), indicating the adiabatic character of the electron–lattice interaction in these systems. A limit case is \( \text{MgB}_2 \). Studies of the pressure \( [24] \) and boron isotope \( [25] \) effects evidenced shifts of \( \lambda(0) \) compatible with the adiabatic limit.

To check whether the electron–hole asymmetry in HTS does concern also the nature of the electron–phonon coupling, in this work we measured the pressure effect on \( \lambda \) in the \( n \)-HTS \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \), by means of magnetization measurements under pressure. This system belongs to the family of electron-doped infinite-layer superconductors (ILSs). This class of materials has the simplest crystal structure among all cuprates superconductors, and the charge reservoir block, commonly present in cuprates, does not exist in the infinite-layer structure. Moreover, the buckling of \( \text{CuO}_2 \) plane is absent \( [26] \), and the oxygen content is stoichiometric without vacancies or interstitial oxygen \( [26] \), which, instead, is a common problem of other \( n \)-HTSs and \( p \)-HTSs families. These properties allow to study the effect of pressure on this system avoiding modification of \( n_s \) (superconducting carrier density) and \( T_C \) via secondary route, as, for example, charge transfer processes. Finally, ILSs have much higher \( T_C \) (\( \sim 43 \) K) compared to the other \( n \)-HTSs. For comparison, we also report the same measurement on the \( p \)-HTS \( \text{YBa}_2\text{Cu}_3\text{O}_{7-\delta} \).

The temperature dependence of the inverse squared magnetic penetration depth \( \lambda^{-2} \) was extracted from Meissner fraction measurements at low magnetic field. Small and negligible pressure effects on \( T_C \) were found in \( \text{YBa}_2\text{Cu}_3\text{O}_7 \) and \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \), respectively. Whereas a pronounced pressure effect on \( \lambda^{-2} \) was revealed in the \( p \)-HTS \( \text{YBa}_2\text{Cu}_3\text{O}_7 \) at low temperature, zero pressure effect was detected in the \( n \)-HTS \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \), suggesting that this superconductor is in the adiabatic limit.

A high quality polycrystalline sample of \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \) with a sharp superconducting transition \( T_C \) \( \sim 43 \) K was synthesized using by a cubic multianvil press \( [27] \). The \( p \)-HTS polycrystalline sample of \( \text{YBa}_2\text{Cu}_3\text{O}_7 \) (\( T_C \) \( \sim 90.5 \) K) was prepared by standard solid state reaction \( [28] \). The samples were mixed with Fluorinert FC77 (pressure transmitting medium) with a sample to liquid volume ratio of approximately 1/6. The pressure was generated in a copper–beryllium piston cylinder clamp, which allows to reach hydrostatic pressures up to 1.2 GPa. The pressure was measured in situ by monitoring the \( T_C \) shift of a small piece of Pb included in the pressure cell. The value of the Meissner fraction was calculated from 0.5 mT field-cooled (FC) SQUID magnetization measurements assuming spherical grains. The temperature dependence of the effective (powder average) penetration depth was calculated from the measured Meissner fraction by using the Shoenberg model \( [29] \). For anisotropic polycrystalline superconductors, the effective penetration depth is dominated by the in plane contribution \( (\lambda = 1.3\lambda_{ab} \ [30]) \). Therefore, the effective penetration depth evaluated in this study is mainly a measure of the in plane penetration depth \( \lambda_{ab} \). The error bars on \( \lambda^{-2} \) were determined by the reproducibility in repeated measurements.

In figure 1, the temperature dependence of \( \lambda^{-2} \) for \( \text{YBa}_2\text{Cu}_3\text{O}_{7-\delta} \) and \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \) at different pressures is shown. We note here that in the present work we are not focusing on the temperature dependence of \( \lambda^{-2} \), which, in non-aligned polycrystalline powder, can be affected, especially at low temperature, by impurity scattering \( [31] \), chemical and/or structural defects \( [32] \), and by the c-axis contribution, although the latter is small in an anisotropic superconductor \( [30] \). Here we are interested only in the relative shift of \( \lambda^{-2}(0) \) with pressure, which instead is not affected by all the above contributions. Due to the unknown average grain size, and thus the unknown absolute value of \( \lambda \), the data in figure 1 are normalized to the value of \( \lambda^{-2} \) at the lowest temperature, \( T_m = 7 \) K, and pressure, \( p_0 \) \( (p_0 = 0.05 \) GPa for \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \) and 0.08 GPa for \( \text{YBa}_2\text{Cu}_3\text{O}_{7-\delta} \)\). Data at temperatures lower than \( T_m \) are affected by the superconducting transition of Pb, used to measure the pressure. A pronounced pressure effect on \( \lambda^{-2} \) is present in \( \text{YBa}_2\text{Cu}_3\text{O}_{7-\delta} \) at low temperature, whereas no pressure effect is observed for \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \) within errors. Insets of figure 1 show in details the region close to \( T_C \) for the two compounds. The \( \text{YBa}_2\text{Cu}_3\text{O}_{7-\delta} \) sample shows a small shift of the \( \lambda^{-2}(T) \) curves with pressure, related to a corresponding small decrease of the critical temperature. The variation of \( T_C \) with pressure was estimated by a linear extrapolation to \( \lambda^{-2} = 0 \) (see inset of figure 1). The results are shown in the inset of figure 3. A linear fit gives \( dT_C/dp = -0.69(5) \) K GPa\(^{-1} \). Different types of \( p \)-HTSs...
show various pressure induced effects on $T_c$, attributed to charge transfer, constant shift in $T_c^\text{max}$ (where $T_c^\text{max}$ corresponds to the optimally doped value), and to thermal activated oxygen ordering (see, i.e., [33]). However, usually $dT_c/dp$ peaks in the underdoped region of the phase diagram and tends to zero near optimal doping. In the case of optimal- and over-doped YBa$_2$Cu$_3$O$_{7-\delta}$, the main contribution arises from the Cu–O chain to the CuO$_2$ plane charge transfer [33]. Given the value of $T_c$ and the negative pressure effect we found in this work, and looking at the $T_c$ dependence on $\delta$ and hole concentration in YBa$_2$Cu$_3$O$_{7-\delta}$, reported, for example, in [34], it is possible to deduce that our sample is indeed slightly over-doped with $\delta \approx 0.03$.

In the case of the $n$-HTS Sr$_{0.9}$La$_{0.1}$CuO$_2$, there is an almost complete overlap of the curves at different pressures close to $T_c$ (inset to the lower panel of figure 1), indicating absence of a pressure effect on $T_c$ in this system. This result is in agreement with previous reports. Indeed, the onset of superconductivity was found to be almost pressure independent in some $n$-HTSs [35–37] and, in particular, zero pressure effect on $T_c$ was already previously found in Sr$_{0.9}$La$_{0.1}$CuO$_2$ [38]. These findings have been attributed for example to the absence of the apical oxygen in $n$-HTS [35], or to the fact that in Sr$_{0.9}$La$_{0.1}$CuO$_2$ c-axis coherence length $\xi_c$ is larger than the inter-CuO$_2$ layer distance and therefore a further enhancement of the inter-layer coupling by lattice compression should not enhance superconductivity [38]. Moreover, the absence of the charge reservoir block makes pressure induced charge transfer to the Cu–O planes unlikely [38].

Let us now consider the effect of the pressure on $\lambda^{-2}$ in the low temperature region. Looking at the left panel of figure 2, a clear increase of $\lambda^{-2}$ with increasing pressure at low temperature is visible for YBa$_2$Cu$_3$O$_{7-\delta}$. By using the values of $\lambda^{-2}$ measured at 7 K, we calculated the relative shift $\Delta \lambda^{-2}/\lambda^{-2} = [\lambda^{-2}(p) - \lambda^{-2}(p_0)]/\lambda^{-2}(p_0)$ and plotted it in figure 3 as a function of pressure. The relative shift increases linearly and monotonously with pressure with a slope $8(1)\%$/GPa. The relative shift between the lowest (0.08 GPa) and the highest pressure (1.05 GPa) is $\Delta \lambda^{-2}/\lambda^{-2} = 8.8(8)\%$.

Pressure experiments performed in identical experimental conditions on other cuprate superconductors [17, 39], and, in particular on YBa$_2$Cu$_4$O$_8$ [17], showed the absence of weak links between grains by measuring the low temperature magnetization as a function of weak magnetic field, both at zero pressure and at high pressure. Therefore we can deduce that the variation induced by the pressure on the measured magnetization comes from the change in the magnetic field penetration depth. The value of the change measured in the present experiment on YBa$_2$Cu$_3$O$_{7-\delta}$, although smaller than that one found in YBa$_2$Cu$_4$O$_8$ [17], is substantially larger than that expected for an adiabatic electron–lattice interaction in conventional superconductors, such as MgB$_2$ [24], RhO$_2$O$_4$ [22], and Yb$_6$ [23]. The presence of a substantial oxygen isotope effect on the zero-temperature magnetic penetration depth in YBa$_2$Cu$_3$O$_{7-\delta}$ measured by muon spin rotation [16] gives a strong indication that in this system a remarkable electron–lattice interaction is present, and non-adiabatic effects are thus expected. The large variation of $\lambda^{-2}$ with applied pressure, which induces a lattice modification as the isotope exchange, provides a further confirmation of the relevant role played by the lattice in hole-doped high temperature cuprate superconductors.

As to the electron-doped compound Sr$_{0.9}$La$_{0.1}$CuO$_2$, in the right panel of figure 2, $\lambda^{-2}$ in the low temperature region is shown. No clear trend of $\lambda^{-2}(T)$ with increasing pressure is seen, the curves coinciding within the error bar. In figure 3, the relative shift $\Delta \lambda^{-2}/\lambda^{-2}$ measured at 7 K is plotted as a function of pressure. In contrast to YBa$_2$Cu$_3$O$_{7-\delta}$, there is no variation of $\Delta \lambda^{-2}/\lambda^{-2}$ with pressure within the error bar. This is an important result if compared to the strong variation of $\lambda^{-2}$ found in YBa$_2$Cu$_3$O$_{7-\delta}$ (this work) and YBa$_2$Cu$_4$O$_8$ [17]). To give a more quantitative estimation, let us try to estimate the variation of $\lambda^{-2}$ with pressure, starting from the zeroth approximation of a free electron gas. Since $\lambda^{-2}(0) \propto \omega_p^2$, where $\omega_p$ is the plasma frequency, then a free electron gas estimate would give $d \ln \lambda^{-2}(0)/dp = 1/B \simeq 0.85\%$ GPa$^{-1}$, where $B = -d \ln B / d \ln \Omega \simeq 117$ GPa is the bulk modulus [40] and $\Omega$ the volume of the unit cell. Therefore, for a variation of pressure of about 0.8 GPa, $\Delta \lambda^{-2}/\lambda^{-2} \simeq 0.68\%$, that is of the order of the error bar in figure 3, and compatible with the experimental results. The same calculation applied to YBa$_2$Cu$_3$O$_{7-\delta}$ by using $B = 156$ GPa [41] for a variation of $0.8$ GPa, $\Delta \lambda^{-2}/\lambda^{-2} \simeq 8.8\%$. Therefore, we can deduce that the pressure effect on $\lambda^{-2}$ is substantial.

Figure 1. Temperature dependence of $\lambda^{-2}$ for YBa$_2$Cu$_3$O$_{7-\delta}$ (upper panel) and Sr$_{0.9}$La$_{0.1}$CuO$_2$ (lower panel) at different pressures. The insets show the data for enlarged temperature scale in the region close to $T_c$. 

![Temperature dependence of $\lambda^{-2}$ for YBa$_2$Cu$_3$O$_{7-\delta}$ (upper panel) and Sr$_{0.9}$La$_{0.1}$CuO$_2$ (lower panel) at different pressures. The insets show the data for enlarged temperature scale in the region close to $T_c$.](image-url)
temperature region, shown on the same vertical axis scale.

and linear fit for $\text{YBa}_2\text{Cu}_3\text{O}_7$. Inset: pressure dependence of the $T_c$ in particular for $\text{YBa}_2\text{Cu}_3\text{O}_7$. Are not unambiguously determined in the case of HTSs and density of state and of the electron–phonon coupling, which parameters, as the pressure dependence of the Fermi energy into account. However, this would imply the knowledge of the electron–phonon interaction should in this case be taken result. It is clear that the effects of the band structure and of the pressure effects in the electron-doped ILS Sr $0.9\text{La}_{0.1}\text{CuO}_2$ samples. The full line is a linear fit to the data. Inset: pressure dependence of the $T_c$, variation, $\Delta T_c$, and linear fit for $\text{YBa}_2\text{Cu}_3\text{O}_7$ sample.

pressure of about 1 GPa would give $\Delta \lambda^2/\lambda^2 \approx 0.64\%$, a value one order of magnitude smaller than the experimental result. It is clear that the effects of the band structure and of the electron–phonon interaction should in this case be taken into account. However, this would imply the knowledge of parameters, as the pressure dependence of the Fermi energy density of state and of the electron–phonon coupling, which are not unambiguously determined in the case of HTSs and in particular for $\text{YBa}_2\text{Cu}_3\text{O}_7$. Beside these considerations, it is worth to recall that most of the strong effect of pressure on $\lambda^2$ found in $\text{YBa}_2\text{Cu}_3\text{O}_8$ [17] was ascribed to the change of the effective mass, or, in other words, to the pressure dependence of the non-adiabatic electron–phonon coupling, thus supporting our conclusions about the $\text{YBa}_2\text{Cu}_3\text{O}_7$ results.

From these considerations, one can argue that the absence of a pressure effect in the electron-doped ILS Sr $0.9\text{La}_{0.1}\text{CuO}_2$ can be ascribed to the negligible role played by non-adiabatic effects in this system. To reinforce this guess, we recall that, in a superconductor close to the clean limit, the zero-temperature superfluid density is essentially determined by $\lambda^2(0) \propto n_s/m^*$ [42, 43, 13], where $n_s$ is the superconducting charge carrier density and $m^*$ is the effective mass of the superconducting carriers. Therefore, a variation of $\lambda^2(0)$ can be ascribed either to a change of $n_s$ or to a change of $m^*$ or both [42, 43, 13]. In this respect, the results obtained on the Sr $0.9\text{La}_{0.1}\text{CuO}_2$ indicate that either both $n_s$ and $m^*$ do not vary with pressure, or both vary of an identical relative amount. We think that the second hypothesis is highly unlikely. Indeed, an important hint is given by the zero pressure effect on $T_c$, which indicates that the change in $n_s$, due to possible pressure induced charge transfer, cannot be substantial, as mentioned above. On the other hand, recent studies of the temperature dependence of the penetration depth in Sr $0.9\text{La}_{0.1}\text{CuO}_2$ indicate the presence of a preponderant s-wave component in the symmetry of the superconducting order parameter [45, 8, 46, 44]. This suggests for Sr $0.9\text{La}_{0.1}\text{CuO}_2$ a behavior more similar to conventional BCS superconductors, where pressure has been shown to have no effect on the penetration depth [22–24].

This consideration supports other experimental findings which suggest similarities between Sr $0.9\text{La}_{0.1}\text{CuO}_2$ and conventional superconductors. For example, it was found [47] that $T_c$ in Sr $0.9\text{La}_{0.1}\text{CuO}_2$ is much more affected by magnetic impurities (Ni) than by non-magnetic ones (Zn), as observed in conventional superconductors. Moreover, bulk and surface sensitive techniques show absence of pseudogap [44, 8] in this n-HTS.

In conclusion, we performed a comparative study of the pressure effects on the magnetic penetration depth in a p-HTS ($\text{YBa}_2\text{Cu}_3\text{O}_7$–HTS) and a n-HTS (Sr $0.9\text{La}_{0.1}\text{CuO}_2$), by means of magnetization measurements. The results for $\text{YBa}_2\text{Cu}_3\text{O}_7$–HTS confirm the non-adiabatic character of the electron–lattice interaction in the p-HTSs. On the contrary, the n-HTS Sr $0.9\text{La}_{0.1}\text{CuO}_2$ shows absence of non-adiabatic effects, as found in conventional BCS superconductors like RbOs$_2$O$_6$, YB$_6$, and MgB$_2$. Our results, together with the previously obtained indications of the presence of an s-wave symmetry order parameter in this system, strongly suggest that there are fundamental differences in the electronic properties of p-HTSs and the n-HTS ILS superconductor Sr $0.9\text{La}_{0.1}\text{CuO}_2$. The present work open to future pressure experiments on
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