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2009 J. Phys.: Condens. Matter 21 275701

(http://iopscience.iop.org/0953-8984/21/27/275701)

IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **21** (2009) 275701 (5pp) doi:10.1088/0953-8984/21/27/275701

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

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Received 4 March 2009, in final form 4 May 2009
Published 10 June 2009
Online at stacks.iop.org/JPhysCM/21/275701

Abstract

The effect of pressure on the magnetic penetration depth λ was tested for the hole-doped superconductor $YBa_2Cu_3O_{7-\delta}$ and in the electron-doped one $Sr_{0.9}La_{0.1}CuO_2$ by means of magnetization measurements. Whereas a large change of λ was found in $YBa_2Cu_3O_{7-\delta}$, 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)

High transition temperature (T_c) superconductivity in cuprates is obtained by introducing holes or electrons into the antiferromagnetic parent compound. Both electron (n-HTSs) and hole (p-HTSs) doped cuprate superconductors share a common building block, i.e., the copper–oxygen plane. However, there are a number of important differences between the generic phase diagrams of the electron-doped and hole-doped materials, which are commonly known as the 'electron–hole asymmetry' problem. For example, the doping ranges where the antiferromagnetic state and the superconducting state emerge in n-HTSs are different from those in p-HTSs, and the existence of a pseudogap in n-HTSs, certainly present in p-HTSs, is still object of debates. Recently, Shengelaya *et al* [1] showed that n-HTSs do not follow the Uemura relation [2] between T_c and the superfluid density (λ^{-2}), found for p-HTSs, indicating a remarkable difference between these two families of superconductors. Moreover, although in n-HTSs a d-wave symmetry of the order parameter has been reported [3–5], there 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 ω_{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 $RbOs_2O_6$ [22] and YB_6 [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 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 λ in the *n*-HTS $Sr_{0.9}La_{0.1}CuO_2$, 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 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 ($\simeq$43 K) compared to the other *n*-HTSs. For comparison, we also report the same measurement on the *p*-HTS $YBa_2Cu_3O_{7-\delta}$.

The temperature dependence of the inverse squared magnetic penetration depth λ^{-2} was extracted from Meissner fraction measurements at low magnetic field. Small and negligible pressure effects on T_c were found in $YBa_2Cu_3O_7$ and $Sr_{0.9}La_{0.1}CuO_2$, respectively. Whereas a pronounced pressure effect on λ^{-2} was revealed in the *p*-HTS $YBa_2Cu_3O_7$ at low temperature, zero pressure effect was detected in the *n*-HTS $Sr_{0.9}La_{0.1}CuO_2$, suggesting that this superconductor is in the adiabatic limit.

A high quality polycrystalline sample of $Sr_{0.9}La_{0.1}CuO_2$ with a sharp superconducting transition $T_c \simeq 43$ K was synthesized by using a cubic multianvil press [27]. The *p*-HTS polycrystalline sample of $YBa_2Cu_3O_7$ ($T_c \simeq 90.5$ 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 ($\lambda = 1.31\lambda_{ab}$ [30]). Therefore, the effective penetration depth evaluated in this study is mainly a measure of the in plane penetration depth λ_{ab}. The error bars on λ^{-2} were determined by the reproducibility in repeated measurements.

In figure 1, the temperature dependence of λ^{-2} for $YBa_2Cu_3O_{7-\delta}$ and $Sr_{0.9}La_{0.1}CuO_2$ at different pressures is shown. We note here that in the present work we are not focusing on the temperature dependence of λ^{-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 λ, the data in figure 1 are normalized to the value of λ^{-2} at the lowest temperature, $T_m = 7$ K, and pressure, p_0 ($p_0 = 0.05$ GPa for $Sr_{0.9}La_{0.1}CuO_2$ and 0.08 GPa for $YBa_2Cu_3O_{7-\delta}$). 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 λ^{-2} is present in $YBa_2Cu_3O_{7-\delta}$ at low temperature, whereas no pressure effect is observed for $Sr_{0.9}La_{0.1}CuO_2$ within errors. Insets of figure 1 show in details the region close to T_c for the two compounds. The $YBa_2Cu_3O_{7-\delta}$ 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

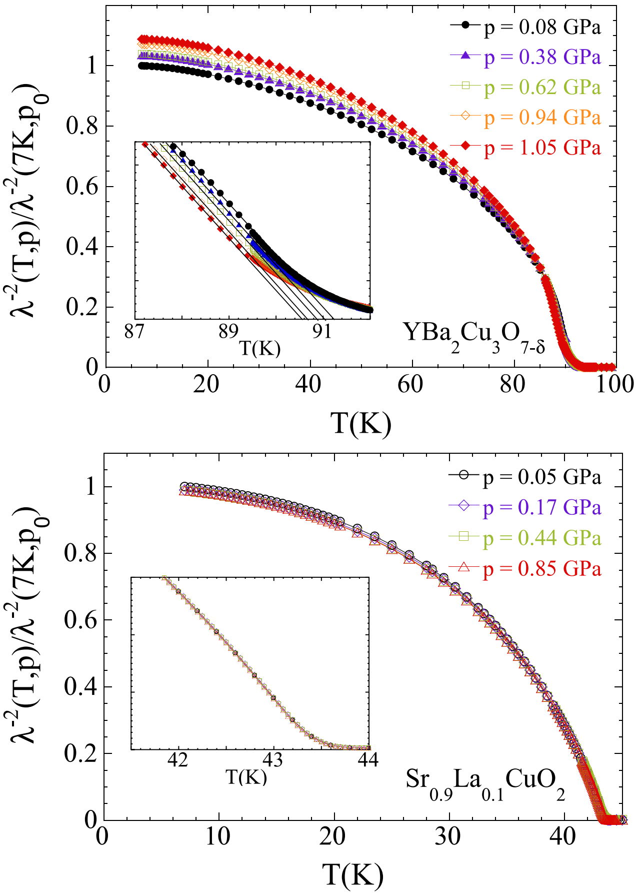

Figure 1. Temperature dependence of λ^{-2} for $YBa_2Cu_3O_{7-\delta}$ (upper panel) and $Sr_{0.9}La_{0.1}CuO_2$ (lower panel) at different pressures. The insets show the same data for enlarged temperature scale in the region close to T_c.

show various pressure induced effects on T_c, attributed to charge transfer, constant shift in T_c^{max} (where T_c^{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 $YBa_2Cu_3O_{7-\delta}$, 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 δ and hole concentration in $YBa_2Cu_3O_{7-\delta}$, reported, for example, in [34], it is possible to deduce that our sample is indeed slightly over-doped with $\delta \simeq 0.03$.

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 ξ_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 λ^{-2} in the low temperature region. Looking at the left panel of figure 2, a clear increase of λ^{-2} with increasing pressure at low temperature is visible for $YBa_2Cu_3O_{7-\delta}$. By using the values of λ^{-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 $YBa_2Cu_4O_8$ [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 $YBa_2Cu_3O_{7-\delta}$, although smaller than that one found in $YBa_2Cu_4O_8$ [17], is substantially larger than that expected for an adiabatic electron–lattice interaction in conventional superconductors, such as MgB_2 [24], $RbOs_2O_6$ [22], and YB_6 [23]. The presence of a substantial oxygen isotope effect on the zero-temperature magnetic penetration depth in $YBa_2Cu_3O_{7-\delta}$ 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 λ^{-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, λ^{-2} in the low temperature region is shown. No clear trend of $\lambda^{-2}(7\ K)$ 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 $YBa_2Cu_3O_{7-\delta}$, 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 λ^{-2} found in $YBa_2Cu_3O_{7-\delta}$ (this work) and $YBa_2Cu_4O_8$ ([17]). To give a more quantitative estimation, let us try to estimate the variation of λ^{-2} with pressure, starting from the zeroth approximation of a free electron gas. Since $\lambda^{-2}(0) \propto \omega_p^2$, where ω_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 $B = -dp/d\ln\Omega \simeq 117$ GPa is the bulk modulus [40] and Ω 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 $YBa_2Cu_3O_{7-\delta}$ by using $B = 156$ GPa [41] for a variation of

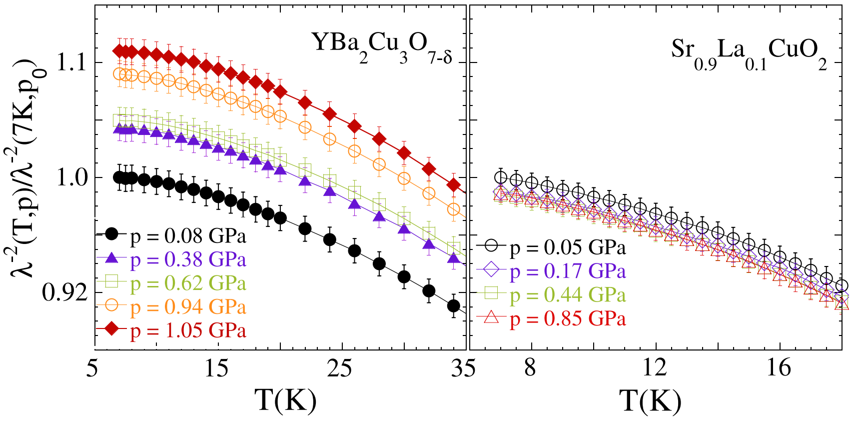

Figure 2. Temperature dependence of λ^{-2} for $YBa_2Cu_3O_{7-\delta}$ (left panel) and $Sr_{0.9}La_{0.1}CuO_2$ (right panel) at different pressures in the low temperature region, shown on the same vertical axis scale.

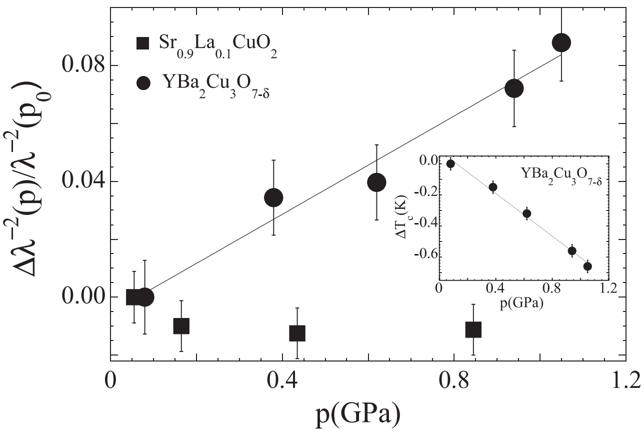

Figure 3. Pressure dependence of $\Delta\lambda^{-2}/\lambda^{-2}$ (see text) for the $YBa_2Cu_3O_{7-\delta}$ and $Sr_{0.9}La_{0.1}CuO_2$ samples. The full line is a linear fit to the data. Inset: pressure dependence of the T_c variation, ΔT_c, and linear fit for $YBa_2Cu_3O_{7-\delta}$ sample.

pressure of about 1 GPa would give $\Delta\lambda^{-2}/\lambda^{-2} \simeq 0.64\%$, 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 $YBa_2Cu_3O_{7-\delta}$. Beside these considerations, it is worth to recall that most of the strong effect of pressure on λ^{-2} found in $YBa_2Cu_4O_8$ [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 $YBa_2Cu_3O_{7-\delta}$ results.

From these considerations, one can argue that the absence of a pressure effect in the electron-doped ILS $Sr_{0.9}La_{0.1}CuO_2$ 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 $Sr_{0.9}La_{0.1}CuO_2$ 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 $Sr_{0.9}La_{0.1}CuO_2$ indicate the presence of a preponderant s-wave component in the symmetry of the superconducting order parameter [45, 8, 46, 44]. This suggests for $Sr_{0.9}La_{0.1}CuO_2$ 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 $Sr_{0.9}La_{0.1}CuO_2$ and conventional superconductors. For example, it was found [47] that T_c in $Sr_{0.9}La_{0.1}CuO_2$ 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 ($YBa_2Cu_3O_{7-\delta}$) and a *n*-HTS ($Sr_{0.9}La_{0.1}CuO_2$), by means of magnetization measurements. The results for $YBa_2Cu_3O_{7-\delta}$ confirm the non-adiabatic character of the electron–lattice interaction in the *p*-HTSs. On the contrary, the *n*-HTS $Sr_{0.9}La_{0.1}CuO_2$ shows absence of non-adiabatic effects, as found in conventional BCS superconductors like $RbOs_2O_6$, 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 $Sr_{0.9}La_{0.1}CuO_2$. The present work open to future pressure experiments on other electron-doped HTSs, in order to check if the adiabatic behavior is a universal property of *n*-HTSs, looking for further evidences for the asymmetric consequences of hole and electron doping in cuprate superconductors.

Acknowledgments

The authors gratefully acknowledge C Grimaldi and P Postorino for helpful discussions on the subject. This work was partly supported by the EU Project CoMePhS, the Swiss National Science Foundation SCOPES grant No. IB7420-110784, and the K Alex Müller Foundation.

References

[1] Shengelaya A, Khasanov R, Eshchenko D G, Di Castro D, Savić I M, Park M S, Kim K H, Lee S-I, Müller K A and Keller H 2005 *Phys. Rev. Lett.* **94** 127001
[2] Uemura Y J *et al* 1989 *Phys. Rev. Lett.* **62** 2317
[3] Tsuei C C and Kirtley J R 2000 *Phys. Rev. Lett.* **85** 182
[4] Prozorov R, Giannetta R W, Fournier P and Greene R L 2000 *Phys. Rev. Lett.* **85** 3700
[5] Chesca B, Ehrhardt K, Möle M, Straub R, Koelle D, Kleiner R and Tsukada A 2003 *Phys. Rev. Lett.* **90** 057004
[6] Kim M-S, Skinta J A, Lemberger T R, Tsukada A and Naito M 2003 *Phys. Rev. Lett.* **91** 087001
[7] Alff L, Meyer S, Kleefisch S, Schoop U, Marx A, Sato H, Naito M and Gross R 1999 *Phys. Rev. Lett.* **83** 2644
[8] Chen C-T, Seneor P, Yeh N-C, Vasquez R P, Bell L D, Jung C U, Kim J Y, Park M-S, Kim H-J and Lee S-I 2002 *Phys. Rev. Lett.* **88** 227002
[9] Van Harlingen D J 1995 *Rev. Mod. Phys.* **67** 515
[10] Tsuei C C and Kirtley J R 2000 *Rev. Mod. Phys.* **72** 969
[11] Khasanov R, Shengelaya A, Maisuradze A, La Mattina F, Bussmann-Holder A, Keller H and Müller K A 2007 *Phys. Rev. Lett.* **98** 057007
[12] Khasanov R, Strässle S, Di Castro D, Masui T, Miyasaka S, Tajima S, Bussmann-Holder A and Keller H 2007 *Phys. Rev. Lett.* **99** 237601
[13] Zhao G M, Hunt M B, Keller H and Müller K A 1997 *Nature* **385** 236
[14] Hofer J, Conder K, Sasagawa T, Zhao G-M, Willemin M, Keller H and Kishio K 2000 *Phys. Rev. Lett.* **84** 4192
[15] Khasanov R, Shengelaya A, Conder K, Morenzoni E, Savić I M and Keller H 2003 *J. Phys.: Condens. Matter* **15** L17
[16] Khasanov R *et al* 2004 *Phys. Rev. Lett.* **92** 057602
[17] Khasanov R, Karpinski J and Keller H 2005 *J. Phys.: Condens. Matter* **17** 2453
[18] Sarkar S 1998 *Phys. Rev.* B **57** 11661
[19] Grimaldi C, Cappelluti E and Pietronero L 1998 *Europhys. Lett.* **42** 667
[20] Alexandrov A S and Mott N F 1994 *Int. J. Mod. Phys.* B **8** 2075
[21] Bussmann-Holder A and Keller H 2007 *Polarons in Advanced Materials* ed A S Alexandrov (Dordrecht: Springer) p 599 (Bristol: Canopus Publishing Ltd)
[22] Khasanov R *et al* 2004 *Phys. Rev. Lett.* **93** 157004
[23] Khasanov R, Häfliger P S, Shitsevalova N, Dukhnenko A, Brütsch R and Keller H 2006 *Phys. Rev. Lett.* **97** 157002
[24] Di Castro D, Khasanov R, Grimaldi C, Karpinski J, Kazakov S M, Brütsch R and Keller H 2005 *Phys. Rev.* B **72** 094504
[25] Di Castro D *et al* 2004 *Phys. Rev.* B **70** 014519
[26] Jorgensen J D, Radaelli P G, Hinks D G, Wagner J L, Kikkawa S, Er G and Kanamaru F 1993 *Phys. Rev.* B **47** 14654
[27] Jung C U, Kim J Y, Kim M-S, Park M-S, Kim H-J, Yao Y and Lee S Y 2002 *Physica* C **366** 299
[28] Conder K 2001 *Mater. Sci. Eng.* R **32** 41
[29] Shoenberg D 1940 *Proc. R. Soc.* A **175** 49
[30] Fesenko V I, Gorbunov V N and Smilga V P 1991 *Physica* C **176** 551
[31] Hirschfeld P J and Goldenfeld N 1993 *Phys. Rev.* B **48** 4219
[32] Panagopoulos C, Zhou W, Athanassopoulou N and Cooper J R 1996 *Physica* C **269** 157
[33] Fietz W H, Weiss K-P and Schlachter S I 2005 *Supercond. Sci. Technol.* **18** S332–7
[34] Liang R, Bonn D A and Hardy W N 2006 *Phys. Rev.* B **73** 180505
[35] Murayama C, Mori N, Yomo S, Takagi H, Uchida S and Tokura Y 1989 *Nature* **339** 293
[36] Crusellas M A, Fontcuberta J, Piñol S, Beille J and Grenet T 1993 *Phys. Rev.* B **48** 615
[37] Bobrovskii V, Kazantsev V, Mushnikov N, Mitberg E, Podlesnyak A, Khlybov E and Mirmelstein A 2004 *Physica* C **402** 317
[38] Kim H C, Kim M-H, Jung M H, Park M-S and Lee S-I 2006 *Physica* B **378–380** 886
[39] Khasanov R, Di Castro D, Belogolovskii M, Paderno Yu, Filippov V, Brtsch R and Keller H 2005 *Phys. Rev.* B **72** 224509
[40] Shaked H *et al* 1994 *Phys. Rev.* B **50** 12752
[41] Ye J, Zou Z, Matsushita A, Oka K, Nishihara Y and Matsumoto T 1998 *Phys. Rev.* B **58** R619
[42] Uemura Y J *et al* 1991 *Phys. Rev. Lett.* **66** 2665
[43] Bernhard C *et al* 1995 *Phys. Rev.* B **52** 10488
[44] Liu Z Y, Wen H H, Shan L, Yang H P, Lu X F, Gao H, Park M-S, Jung C U and Lee S-I 2005 *Europhys. Lett.* **69** 263
[45] Khasanov R, Shengelaya A, Maisuradze A, Di Castro D, Savic I M, Weyeneth S, Park M S, Jang D J, Lee S-I and Keller H 2008 *Phys. Rev.* B **77** 184512
[46] White J S, Forgan E M, Laver M, Häflige P Sr, Khasanov R, Cubitt R, Dewhurst C D, Park M S, Jang D-J and Lee S-I 2008 *J. Phys.: Condens. Matter* **20** 104237
[47] Jung C U, Kim J Y, Park M-S, Kim M-S, Kim H-J, Lee S Y and Lee S-I 2002 *Phys. Rev.* B **65** 172501