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Effect of doping on the linear temperature dependence of the magnetic penetration depth in cuprate superconductors

J. Le Cochec[a], G. Lamura[a], A. Gauzzi[b*], F. Licci[b], A. Revcolevschi[c], A. Erb[d], G. Deutscher[e] and J. Bok[a]

[a]Laboratoire de Physique du Solide, ESPCI, 10, rue Vauquelin, F-75231 Paris, France
[b]MASPEC-CNR Institute, Area delle Scienze, 43010 Parma-Fontanini, Italy
[c]Laboratoire de Physico-chimie des Solides, UMR 8648, Univ. Paris Sud, 91405 Orsay, France
[d]DPMC, Université de Genève, 1200 Genève, Switzerland
[e]School of Physics and Astronomy, Tel Aviv University, Ramat Aviv, Tel Aviv 69978, Israel

We report on measurements of the low temperature dependence of the magnetic penetration depth λ_{ab} in several single crystals of $La_{2-x}Sr_xCuO_4$, $Bi_2Sr_2CaCu_2O_8$ and $YBa_2Cu_3O_{6+x}$ at various doping levels ranging from the under- to the overdoped regimes by using a novel single-coil technique achieving 10 pm resolution. We have found a linear dependence of λ_{ab} in all samples with a rapidly increasing slope $d\lambda_{ab}/dT$ as doping decreases. Our analysis of the data indicates that a superconducting gap with *d*-wave symmetry is sufficient to quantitatively account for the above slope values in the optimally or over- doped samples. In the underdoped samples, the *d*-wave model predicts much smaller values than those measured by assuming realistic values for the zero-temperature λ_{ab} and gap Δ. The experimental data are compatible with a model of thermodynamic phase fluctuations of the order parameter. Therefore, we put forward the hypothesis that the gapless properties observed in cuprates may have qualitatively different physical origins depending on the doping level.

1. INTRODUCTION

It has been established that most cuprate superconductors display gapless properties at low temperature. To account for these properties, the existence of lines of nodes in the gap function, as in the case of a *d*-wave gap, is currently invoked [1,2]. Alternative explanations exist, such as those based on thermally activated phase fluctuations of the gap [3]. This picture was already proposed back in the 70's for granular superconductors [4] and is suited for metals with low density of carriers and reduced dimensionality, which is indeed the case of cuprates. In order to establish whether such fluctuations are relevant or not in cuprates, we report here on measurements of the variations of the magnetic penetration depth λ_{ab} at different doping levels, since these variations are directly related to the low energy excitation spectrum.

2. EXPERIMENTAL

We have performed our measurements on four single crystals: one underdoped $La_{1.86}Sr_{0.14}CuO_4$ (LSCO) [5] with T_c=24 K, one optimally doped $YBa_2Cu_3O_{6.9}$ (YBCO) [6] (T_c = 91 K) and one underdoped $Bi_2Sr_2CaCu_2O_8$ (BSCCO) [7] (T_c=83 K). The BSCCO sample was subsequently overdoped by annealing it at 750 °C in flowing oxygen for 84 hours. The resulting T_c after this treatment was 61 K. The λ_{ab} measurements at low temperature have been performed with a novel single coil mutual inductance technique with very high resolution in the 10 pm range, as described elsewhere [8].

3. RESULTS AND DISCUSSION

In figs. 1 and 2, we report the low temperature dependence of λ measured in the above samples. In Tab. 1 we report the experimental values of

* To whom correspondence should be addressed:
E-mail : gauzzi@maspec.bo.cnr.it

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$d\lambda_{ab}/dT$ and those predicted by the above two models: 1) simple *d*-wave; 2) phase fluctuations. We recall that the prediction of the first model requires the knowledge of $\lambda_{ab}(0)$ and of the zero-temperature superconducting gap Δ_0 (not the pseudogap). As to the prediction of 2), we have extended the validity of the formula proposed by Roddick and Stroud [3] to the more general case of anisotropic continuous medium, which is suited to describe cuprates. Within the Gaussian approximation, we obtain:

$$\frac{d\lambda_{ab}(T)}{dT} \approx \frac{\mu_0 k_B}{\Phi_0^2}\lambda_{ab}^3(0)\left(\frac{m_c^*}{m_{ab}^*\xi_{ab}^2\xi_c}\right)^{\frac{1}{3}} \qquad (1)$$

where Φ_0 is the flux quantum, the indices *ab* and *c* refer to the *ab*-plane and *c*-axis respectively, m^* is the effective mass and ξ is the BCS coherence length. Eq. (1) requires the knowledge of a second additional parameter, which is the quantity in parentheses. Neither $\lambda_{ab}(0)$ nor such second quantity are directly measured in our case, so we have taken realistic parameters from the literature and obtained the values reported in Tab. 1.

We estimate the uncertainty on both parameters to be less than 100%, hence the large difference found in Tab. 1 between experimental and predicted values lead us to conclude that: 1) the *d*-wave model quantitatively accounts for the experimental values observed in the optimally doped YBCO and overdoped BSCCO; 2) both underdoped samples exhibit much larger values than those predicted by the *d*-wave model for any realistic values of $\lambda_{ab}(0)$ and Δ_0. Such large slopes are compatible with the phase fluctuation model leading to eq. (1).

This result suggests that the gapless properties observed in cuprates may have different origins depending on the doping level. Measurements on more samples in both under- and overdoped regimes are in progress. These measurements should confirm our preliminary conclusion and indicate beyond which doping level phase fluctuations become negligible. In any case, the high uniformity of the BSCCO samples rules out the possibility that extrinsic factors may be responsible for the large slope value observed in the underdoped regime.

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Table 1. Experimental and theoretically expected values for $d\lambda_{ab}/dT$. Values of Δ_0 calculated from $2\Delta_0 = 5\ k_B T_c$. Units are Å and K. λ_{ab} values used for the d-wave prediction are also shown.

Samples	Exp.	$\lambda_{ab}(0)$	d-wave	Phase fluct.
YBCO	4.5±0.1	1500	4.5	0.5
LSCO	167.5±0.9	6500	98	160
BSCCO-under	42.4±0.2	2500	10	40
BSCCO-over.	10.3±0.1	1800	10	4

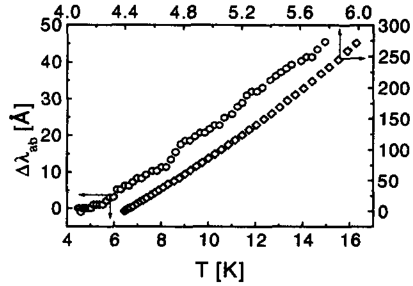

Fig. 1. Low temperature dependence of λ in the underdoped LSCO (diamonds) and optimally doped YBCO (circles). Note the two different scales.

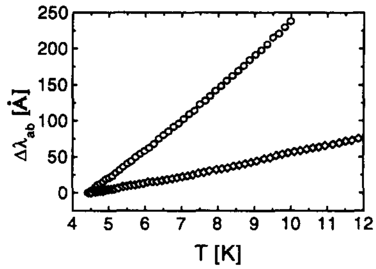

Fig. 2. The same as in fig. 1 for the underdoped (circles) and overdoped (diamonds) BSCCO samples.

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