PHYSICAL REVIEW B **74**, 064504 (2006)

Correlation between oxygen isotope effects on transition temperature and magnetic penetration depth in high-temperature superconductors close to optimal doping

R. Khasanov,[1,2] A. Shengelaya,[3] K. Conder,[4] E. Morenzoni,[2] I. M. Savić,[5] J. Karpinski,[6] and H. Keller[1]
[1]*Physik-Institut der Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*
[2]*Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[3]*Physics Institute of Tbilisi State University, Chavchavadze 3, GE-0128 Tbilisi, Georgia*
[4]*Laboratory for Developments and Methods, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[5]*Faculty of Physics, University of Belgrade, 11001 Belgrade, Serbia and Montenegro*
[6]*Solid State Physics Laboratory, ETH 8093 Zürich, Switzerland*
(Received 12 April 2006; revised manuscript received 6 July 2006; published 9 August 2006)

The oxygen-isotope (^{16}O-^{18}O) effect (OIE) on the in-plane magnetic penetration depth $\lambda_{ab}(0)$ in optimally doped $YBa_2Cu_3O_{7-\delta}$ and $La_{1.85}Sr_{0.15}CuO_4$, and in slightly underdoped $YBa_2Cu_4O_8$ and $Y_{0.8}Pr_{0.2}Ba_2Cu_3O_{7-\delta}$ was studied by means of muon-spin rotation. A substantial OIE on $\lambda_{ab}(0)$ with an OIE exponent $\beta_O = -d \ln \lambda_{ab}(0)/d \ln M_O \approx -0.2$ (M_O is the mass of the oxygen isotope), and a small OIE on the transition temperature T_c with an OIE exponent $\alpha_O = -d \ln T_c / d \ln M_O \simeq 0.02-0.1$ were observed. The observation of a substantial isotope effect on $\lambda_{ab}(0)$, even in cuprates where the OIE on T_c is small, indicates that lattice effects play an important role in cuprate high-temperature superconductors.

DOI: 10.1103/PhysRevB.74.064504 PACS number(s): 74.72.−h, 76.75.+i, 82.20.Tr, 74.25.Kc

I. INTRODUCTION

The observation of unusual isotope effects in cuprate high-temperature superconductors (HTSs) on the transition temperature T_c,[1–4] and on the zero-temperature in-plane magnetic penetration depth $\lambda_{ab}(0)$,[5–15] poses a challenge to the understanding of high-temperature superconductivity. To date, most isotope effect studies on T_c and $\lambda_{ab}(0)$ in HTSs were performed by substituting oxygen ^{16}O with ^{18}O. It was observed that the oxygen isotope (^{16}O-^{18}O) effect (OIE) on both T_c and $\lambda_{ab}(0)$ have a tendency to increase with decreasing doping.[5–15] Later on it was shown that for different families of HTS cuprates there is a universal correlation between the isotope shifts of these two quantities;[9,12–15] namely, in the underdoped region $\Delta T_c/T_c$ and $\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ scale linearly with respect to each other with $|\Delta T_c/T_c| \simeq |\Delta\lambda_{ab}(0)/\lambda_{ab}(0)|$. However, close to optimal doping the situation is not so clear. Khasanov and co-workers[11,12] observed that in optimally doped $YBa_2Cu_3O_{7-\delta}$ the small OIE on T_c is associated with a rather big isotope shift of λ_{ab} that is even compatible with the OIE on λ_{ab} in underdoped cuprates. In contrast, Tallon *et al.*[15] showed that in slightly overdoped $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ the OIE on $\lambda_{ab}(0)$ is zero while the OIE on T_c still remains substantial.

In this paper we concentrate on studies of the OIE on T_c and $\lambda_{ab}(0)$ in optimally doped $La_{1.85}Sr_{0.15}CuO_4$ and $YBa_2CuO_{7-\delta}$, as well as in slightly underdoped $YBa_2Cu_4O_8$ and $Y_{0.8}Pr_{0.2}Ba_2CuO_{7-\delta}$. All the samples show a rather small OIE on T_c associated with a relatively large OIE on $\lambda_{ab}(0)$. The oxygen isotope exponents on T_c ($\alpha_O = -d \ln T_c / d \ln M_O$, where M_O is the mass of the oxygen isotope) and the in-plane magnetic penetration depth $\lambda_{ab}(0)$ ($\beta_O = -d \ln \lambda_{ab}(0)/d \ln M_O$) were found to be $\alpha_O = 0.024(8)$ and $\beta_O = -0.21(4)$ for $YBa_2CuO_{7-\delta}$, $\alpha_O = 0.10(1)$ and $\beta_O = -0.19(6)$ for $Y_{0.8}Pr_{0.2}Ba_2CuO_{7-\delta}$, $\alpha_O = 0.048(8)$ and $\beta_O = -0.18(6)$ for $YBa_2Cu_4Cu_4O_8$, and $\alpha_O = 0.08(1)$ and $\beta_O = -0.18(5)$ for $La_{1.85}Sr_{0.15}CuO_4$. The fact that a substantial OIE on $\lambda_{ab}(0)$ is observed even in cuprates having a relatively small OIE on T_c suggests that lattice effects have to be considered in any realistic model of high-temperature superconductivity.

II. EXPERIMENTAL DETAILS

Powder samples of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, $YBa_2Cu_4O_8$, and $La_{1.85}Sr_{0.15}CuO_4$ were synthesized by solid state reactions.[16,17] Oxygen isotope exchange was performed while heating the samples in $^{18}O_2$ gas. In order to ensure that the ^{16}O- and ^{18}O-substituted samples are subjects of the same thermal history, the annealing of the two samples is performed simultaneously in $^{16}O_2$ and $^{18}O_2$ (95% enriched) gas, respectively. The ^{18}O content of the samples, as determined from a change of the sample weight after the isotope exchange, was found to be 90% for $YBa_2Cu_3O_{7-\delta}$, 82% for $Y_{0.8}Pr_{0.2}Ba_2Cu_3O_{7-\delta}$ and $YBa_2Cu_4O_8$, and 85% for $La_{1.85}Sr_{0.15}CuO_4$. The total oxygen content for the $YBa_2Cu_3O_{7-\delta}$ and $La_{1.85}Sr_{0.15}CuO_4$ samples was determined by means of very accurate volumetric analysis.[16] The oxygen contents are 6.951(2) [6.953(2)] and 3.9981(3) [3.9976(3)] for the ^{16}O- (^{18}O) substituted $YBa_2Cu_3O_{7-\delta}$ and $La_{1.85}Sr_{0.15}CuO_4$ samples, respectively.

In order to determine the OIE on T_c, field-cooled magnetization (M_{FC}) measurements were performed with a superconducing quantum interference design magnetometer in a field of 1 mT at temperatures between 1.75 and 100 K. For the investigation of the OIE on $\lambda_{ab}(0)$, transverse-field muon-spin resonance (μSR) experiments were performed at the Paul Scherrer Institute (PSI), Switzerland, using the πM3 μSR facility. The samples were field cooled from far above T_c in a field of 0.2 T. In a powder sample the magnetic penetration depth λ can be extracted from the muon-spin depolarization rate $\sigma(T) \propto 1/\lambda^2(T)$, which probes the second moment $\langle \Delta B^2 \rangle^{1/2}$ of the probability distribution of the local

1098-0121/2006/74(6)/064504(6)

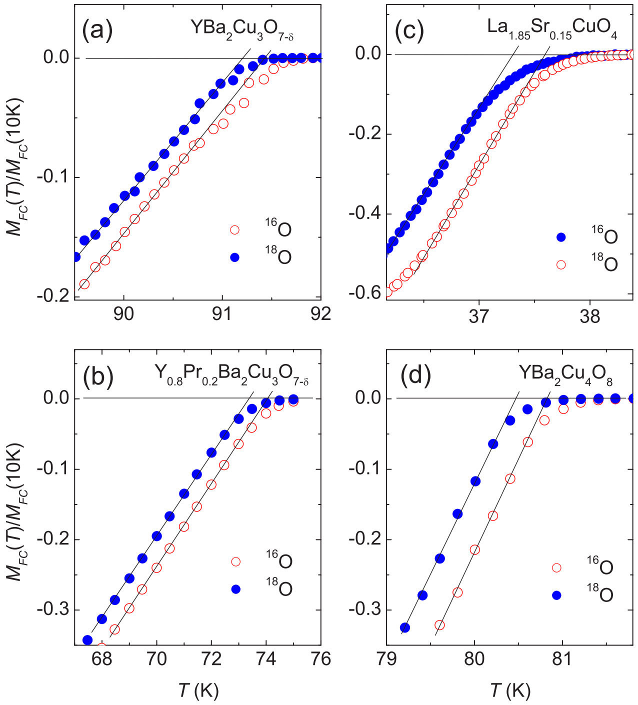

FIG. 1. (Color online) Section near T_c of the low-field (1 mT, field cooled) magnetization curves (normalized to the value at 10 K) for ^{16}O and ^{18}O-substituted $YBa_2Cu_3O_{7-\delta}$ (a), $Y_{0.8}Pr_{0.2}Ba_2Cu_3O_{7-\delta}$ (b), $La_{1.85}Sr_{0.15}CuO_4$ (c), and $YBa_2Cu_4O_8$ (d).

magnetic field function $p(B)$ in the mixed state.[18] For highly anisotropic layered superconductors (like cuprate superconductors) λ is mainly determined by the in-plane penetration depth λ_{ab}:[18] $\sigma(T) \propto 1/\lambda_{ab}^2(T)$. The depolarization rate σ was extracted from the μSR time spectra using a Gaussian relaxation function $R(t)=\exp(-\sigma^2 t^2/2)$. The superconducting contribution σ_{sc} was obtained by subtracting the dipolar contribution σ_{nm} measured above T_c as $\sigma_{sc}^2=\sigma^2-\sigma_{nm}^2$.

III. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependences of the field-cooled magnetization for the ^{16}O- (^{18}O) substituted samples investigated in this work. It is seen that the magnetization curves for the ^{18}O-substituted samples are shifted almost parallel to lower temperatures, implying that the T_c's of the ^{18}O samples are lower than those of the ^{16}O samples.

The results of the OIE on T_c are summarized in Table I. The transition temperature T_c was determined as the temperature where the linearly extrapolated transition slope intersects the zero line. The OIE exponent α_O is defined by $\alpha_O=-d\ln T_c/d\ln M_O$. Taking into account an incomplete oxygen isotope exchange (90% for $YBa_2Cu_3O_{7-\delta}$, 82% for $Y_{0.8}Pr_{0.2}Ba_2Cu_3O_{7-\delta}$ and $YBa_2Cu_4O_8$, and 85% for $La_{1.85}Sr_{0.15}CuO_4$), we found $\alpha_O=0.024(8)$, 0.10(1), 0.048(8), and 0.08(1) for $YBa_2Cu_3O_{7-\delta}$, $Y_{0.8}Pr_{0.8}Ba_2Cu_3O_{7-\delta}$, $YBa_2Cu_4O_8$, and $La_{1.85}Sr_{0.15}CuO_4$, respectively. Note that these values are in fair agreement with the previously published results.[2–15]

TABLE I. Summary of the OIE results on T_c for $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ($x=0.0, 0.2$), $YBa_2C_4O_8$, and $La_{1.85}Sr_{0.15}CuO_4$. The values of $\Delta T_c/T_c$ and α_O are corrected for the incomplete ^{18}O exchange (see text for an explanation).

Sample	^{16}O T_c (K)	^{18}O T_c (K)	$\Delta T_c/T_c$ (%)	α_O
$YBa_2Cu_3O_{7-\delta}$	91.45(5)	91.20(5)	−0.3(1)	0.024(8)
$Y_{0.8}Pr_{0.2}Ba_2Cu_3O_{7-\delta}$	74.0(1)	73.2(1)	−1.3(3)	0.104(12)
$YBa_2Cu_4O_8$	80.86(5)	80.46(5)	−0.6(1)	0.048(8)
$La_{1.85}Sr_{0.15}CuO_4$	37.63.(2)	37.31(2)	−1.0(1)	0.08(1)

Figure 2 shows the temperature dependences of the superconducting part of the μSR depolarization rate $\sigma_{sc} \propto \lambda_{ab}^{-2}$ of the samples studied. It is seen that the data points for the ^{16}O-substituted samples are systematically higher than those for the ^{18}O ones, implying that an oxygen isotope shift on σ_{sc} is present. As in Ref. 18, the data in Fig. 2 were fitted to the power law $\sigma_{sc}(T)/\sigma_{sc}(0)=1-(T/T_c)^n$ with $\sigma_{sc}(0)$ and n as free parameters, and T_c taken from the magnetization measurements (see Table I). The values of $\sigma_{sc}(0)$ obtained from the fits are listed in Table II and are in agreement with previous results.[18–20] The exponents n were found to be the same within error for each set of ^{16}O-^{18}O samples, implying that σ_{sc} has nearly the same temperature dependence for the two isotopes (see Fig. 2). The values of the relative shift of $\lambda_{ab}(0)$ and the oxygen isotope exponent β_O obtained from the measured values of $\sigma_{sc}(0)$ and corrected for the incomplete ^{18}O exchange are summarized in Table II.

Note that, the observed OIE's on T_c and $\lambda_{ab}(0)$ are not caused by a possible difference in the carrier concentrations

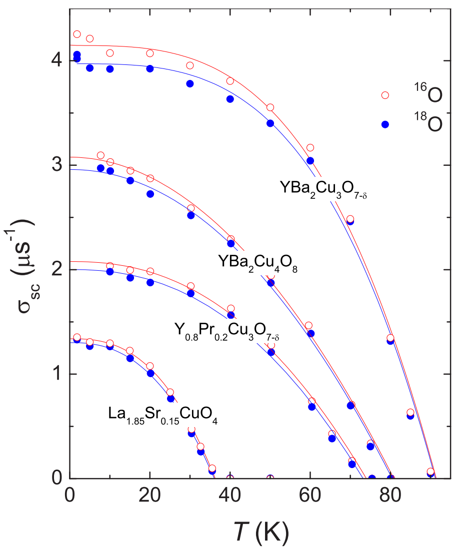

FIG. 2. (Color online) Temperature dependences of depolarization rate σ_{sc} for ^{16}O- and ^{18}O-substituted (from the top to the bottom) $YBa_2Cu_3O_{7-\delta}$, $YBa_2Cu_4O_8$, $Y_{0.8}Pr_{0.2}Ba_2Cu_3O_{7-\delta}$, and $La_{1.85}Sr_{0.15}CuO_4$ samples (200 mT, field cooled). The solid lines correspond to fits to the power law $\sigma_{sc}(T)/\sigma_{sc}(0)=1-(T/T_c)^n$. The error bars are smaller than the size of the points.

TABLE II. Summary of the OIE results on $\lambda_{ab}(0)$ for $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ $(x=0.0,0.2)$, $YBa_2Cu_4O_8$, and $La_{1.85}Sr_{0.15}CuO_4$. The values of $\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ and β_O are corrected for the incomplete ^{18}O exchange (see text for an explanation).

Sample	^{16}O $\sigma(0)$ (μs^{-1})	^{18}O $\sigma(0)$ (μs^{-1})	$\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ (%)	β_O
$YBa_2Cu_3O_{7-\delta}$	4.15(4)	3.96(4)	2.6(5)	−0.21(4)
$Y_{0.8}Pr_{0.2}Ba_2Cu_3O_{7-\delta}$	2.08(1)	2.00(1)	2.4(7)	−0.19(6)
$YBa_2Cu_4O_8$	3.07(3)	2.96(3)	2.2(7)	−0.18(6)
$La_{1.85}Sr_{0.15}CuO_4$	1.34(1)	1.29(1)	2.2(6)	−0.18(5)

of the ^{16}O and ^{18}O samples. This is because the oxygen contents in the ^{16}O- and ^{18}O-substituted $YBa_2Cu_3O_{7-\delta}$ and $La_{1.85}Sr_{0.5}CuO_4$ are the same within error (see Sec. II) and $YBa_2Cu_4O_8$ is a stoichiometric compound with a fixed oxygen content.[17,21] Additional arguments are given in Refs. 5–14.

In order to demonstrate that the change of the oxygen content within the precision of our volumetric analysis cannot account for the observed OIE on T_c and $\lambda_{ab}(0)$ we used the following procedure. Tallon *et al.*[22] observed that in a wide range of doping $(0.05 \lesssim p \lesssim 0.19)$ the following empirical relation holds: $T_c\lambda_{ab}^{-2}(0) \propto p-0.05$ (p is the number of holes per planar Cu). This implies that

$$\frac{\Delta p}{p-0.05} = \frac{\Delta T_c}{T_c} - 2\frac{\Delta\lambda_{ab}(0)}{\lambda_{ab}(0)}. \qquad (1)$$

Taking into account that oxygen is divalent and that the unit cell of $YBa_2Cu_3O_{7-\delta}$ contains two plane and one chain Cu atoms, the change in the hole concentration Δp caused by the change of the oxygen content can be estimated as $\Delta p = -2\Delta y$ for $La_{2-x}Sr_xCuO_{4-y}$ and $\Delta p = -(2/3)\Delta\delta$ for $YBa_2Cu_3O_{7-\delta}$. For the above mentioned errors in the determination of the oxygen content (±0.002 for $YBa_2Cu_3O_{7-\delta}$ and ±0.0003 for $La_{1.85}Sr_{0.15}CuO_4$, see Sec. II) and with $p \simeq 0.15$ for the optimally doped samples, one gets $|\Delta T_c/T_c - 2\Delta\lambda_{ab}(0)/\lambda_{ab}(0)| < 1.3\%$ and $< 0.6\%$ $YBa_2Cu_3O_{7-\delta}$ and $La_{1.85}Sr_{0.15}CuO_4$, respectively. These values are more than five times smaller than one would obtain by substituting $\Delta T_c/T_c$ and $\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ in Eq. (1) by the values listed in Tables I and II.

In Fig. 3 the transition temperature T_c is plotted versus the μSR depolarization rate $\sigma_{sc}(0) \propto \lambda_{ab}^{-2}(0)$ for the samples studied. Recent OIE results for $Y_xPr_{1-x}Ba_2Cu_3O_{7-\delta}$ (Refs. 9–11) and $La_{2-x}Sr_xCuO_4$ (Refs. 6 and 8) are also included in the graph. Since the absolute values of $\lambda_{ab}(0)$ for the $La_{2-x}Sr_xCuO_4$ samples studied in Refs. 6 and 8 are not known, the values of $\sigma_{sc}(0)$ for the ^{16}O-substituted samples were estimated from comparison with previous data.[23,24]

According to Refs. 23 and 24 in the underdoped regime T_c is proportional to $\sigma_{sc}(0) \propto \lambda_{ab}^{-2}(0)$ with a universal slope for most HTS families and saturates close to optimal doping to a value characteristic for each HTS family (Uemura relation). Furthermore, recent experiments on an ultrathin $La_{2-x}Sr_xCuO_4$ film clearly show that the Uemura relation $T_c \propto n_s/m^*$ holds when the superfluid density is modulated by an electric field.[25] Superconductors that belong to the Y124 family (including $YBa_2Cu_4O_8$) contain CuO chains free of disorder and thus exhibit enhanced values of $\lambda_{ab}^{-2}(0)$ compared to the Uemura line.[26,27] The "universal" T_c vs $\sigma_{sc}(0)$ curves for the HTS families $Y_xPr_{1-x}Ba_2Cu_3O_{7-\delta}$ (YPr123), $La_{2-x}Sr_xCuO_4$ (La214), and $YBa_2Cu_4O_8$ (Y124) are shown in Fig. 3. Figure 3 suggests that the relation between isotope shifts of T_c and $\lambda_{ab}(0)$ can be explained qualitatively by the empirical Uemura line. Indeed T_c and $\sigma_{sc}(0)$ for the ^{18}O-substituted samples are always smaller than those for the ^{16}O samples. It is also seen that for samples close to optimal doping a small OIE on T_c is associated with a rather large OIE on $\lambda_{ab}(0)$. In order to investigate these results in more detail, we plot in Fig. 4 the OIE shift of $\lambda_{ab}(0)$ $[\Delta\lambda_{ab}(0)/\lambda_{ab}(0)]$ versus the OIE shift of T_c $(\Delta T_c/T_c)$. It is remarkable that different experimental techniques [SQUID magnetization,[6] magnetic torque,[8] bulk μSR,[9,10] low-energy (LE) μSR (Ref. 11)] and different types of samples (single crystals,[8] powders,[6,9,10] thin films[11]) yield consistnt results within experimental error. However, one can easily see that the Uemura relation can explain the observed correlation between $\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ and $\Delta T_c/T_c$ only qualitatively but not quantitatively. Following Uemura *et al.*[23,24] for different families of underdoped cuprates, T_c scales linearly with the μSR depolarization rate $\sigma_{sc}(0) \propto \lambda_{ab}^{-2}(0)$, yielding $\Delta\lambda_{ab}(0)/\lambda_{ab}(0) \simeq 0.5|\Delta T_c/T_c|$ (line A in Fig. 4). It is seen, however, that all the experimental points are systematically higher. At low doping level $\Delta\lambda_{ab}(0)/\lambda_{ab}(0) \simeq |\Delta T_c/T_c|$ (line

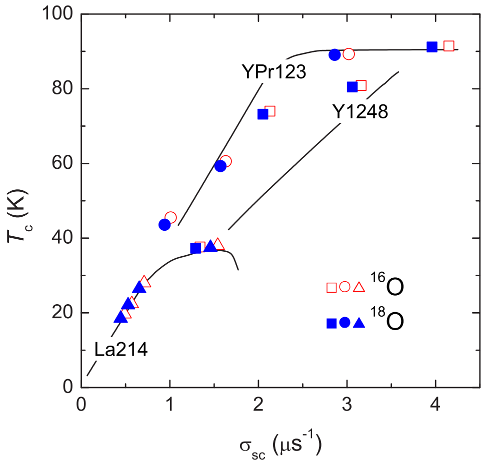

FIG. 3. (Color online) Plot of T_c versus $\sigma_{sc}(0)$ for ^{16}O- (open symbols) and ^{18}O- (closed symbols) substituted $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, $YBa_2Cu_4O_8$, and $La_{2-x}Sr_xCuO_4$. Squares are the μSR data obtained in the present study. Circles are bulk μSR data for $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ (Refs. 9 and 10) and LE μSR data for optimally doped $YBa_2Cu_3O_{7-\delta}$ (Ref. 11). Triangles are torque magnetization and Meissner fraction data for $La_{2-x}Sr_xCuO_4$ (Refs. 6 and 8). The solid lines correspond to the universal T_c vs $\sigma_{sc}(0)$ relations for the YPr123, La214, and Y124 families of HTSs (Refs. 23, 24, 26, and 27).

B in Fig. 4), whereas close to the optimal doping $\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ is almost constant and considerably larger than $\Delta T_c/T_c$ [$\Delta\lambda_{ab}(0)/\lambda_{ab}(0) \approx 10|\Delta T_c/T_c|$].[12–14]

According to the London theory λ_{ab}^{-2} is proportional to the so-called superfluid density $\lambda_{ab}^{-2} \propto n_s/m_{ab}^*$ (n_s is the density of supercarriers and m_{ab}^* is the in-plane charge carrier mass). Concerning the relation between $\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ and $\Delta T_c/T_c$, one should distinguish two cases: (i) change of the carrier density n by doping (note that n is not necessarily equal to n_s as discussed in Ref. 25), and (ii) change of the oxygen mass by isotope substitution. In the recent electrostatic modulation experiments,[25] it was shown that the change of the carrier density within the *same* sample leads to $T_c \propto n_s$, and $\Delta\lambda_{ab}(0)/\lambda_{ab}(0) = 0.5|\Delta T_c/T_c|$, in accordance with the Uemura relation in the underdoped regime.[23,24] Note that in Ref. 25 carriers were implanted in or removed from the sample by changing the electric field, so the crystal lattice is not affected. This implies that in this case changes of both T_c and $\lambda_{ab}(0)$ are due to a change of the carrier concentration n_s, while the in-plane charge carrier mass m_{ab}^* stays constant.[28] The isotope substitution, in contrast, modifies the lattice, but leaves the doping (oxygen content) unchanged (see discussion above). In addition, it is found that $\Delta\lambda_{ab}(0)/\lambda_{ab}(0) = |\Delta T_c/T_c|$, so there is a factor of 2 difference in the slope of lines *A* and *B* in Fig. 4. This factor of 2 can be explained by a simple model, assuming that $T_c \propto n_s$ and $\lambda_{ab}^{-2}(0) \propto n_s/m_{ab}^*$ (London model). This implies that in case (i) described above, $\Delta\lambda_{ab}(0)/\lambda_{ab}(0) = 0.5|\Delta T_c/T_c| = 0.5|\Delta n_s/n_s|$ (Uemura relation). However, in case (ii) the isotope substitution would lead to a change in n_s as well as in m_{ab}^* (${}^{16}m_{ab}^* < {}^{18}m_{ab}^*$) in order to account for the factor of 2.

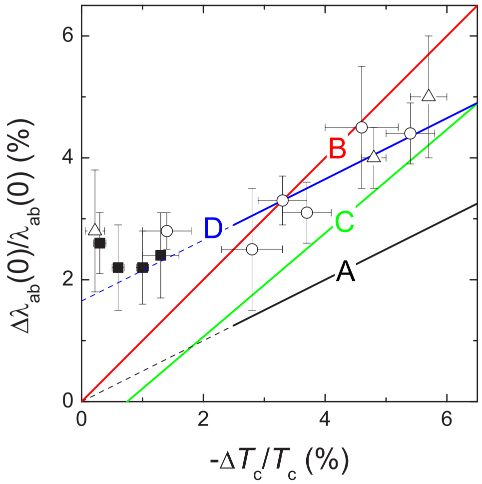

FIG. 4. (Color online) Plot of the OIE shift $\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ versus the OIE shift $-\Delta T_c/T_c$ for $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, $YBa_2Cu_4O_8$, and $La_{2-x}Sr_xCuO_4$. Squares are the μSR data obtained in the present study. Circles are bulk μSR data for $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ (Refs. 9 and 10) and LE μSR data for optimally doped $YBa_2Cu_3O_{7-\delta}$ (Ref. 11). Triangles are torque magnetization and Meissner fraction data for $La_{2-x}Sr_xCuO_4$ (Refs. 6 and 8). The lines correspond to the differential Uemura relation with $\Delta\lambda_{ab}(0)/\lambda_{ab}(0) = 0.5|\Delta T_c/T_c|$ (*A*), $\Delta\lambda_{ab}(0)/\lambda_{ab}(0) = |\Delta T_c/T_c|$ (*B*), the pseudogap line from Ref. 15 (*C*), and the 2D QSI relation given by Eq. (2) (*D*). The dashed lines indicates that the differential Uemura (line *A*) and 2D-QSI (line *D*) relations are strictly valid only in the underdoped regime (see text for details).

Now we discuss the observed $\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ vs $\Delta T_c/T_c$ dependence presented in Fig. 4 in more detail. Tallon *et al.*[15] showed that the relation between the oxygen isotope shifts of $\lambda_{ab}(0)$ and T_c may be understand in terms of a normal-state pseudogap which competes with superconductivity. Both $\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ and $|\Delta T_c/T_c|$ were found to increase with increasing pseudogap energy E_g. At the critical doping (when the pseudogap is closed) $\Delta\lambda_{ab}(0)/\lambda_{ab}(0)$ is equal to zero, while $|\Delta T_c/T_c| \simeq 0.8\%$ (line *C* in Fig. 4). This is, however, inconsistent with the experimental data presented in Fig. 4, especially close to optimal doping (see Fig. 4). Schneider and Keller[29–32] showed that the relation between the isotope shifts of $\lambda_{ab}(0)$ and T_c arises naturally from the doping-driven three-dimensional to two-dimensional (3D-2D) crossover and 2D quantum superconductor to insulator (2D QSI) transition in the highly underdoped limit. Close to the 2D QSI transition the following relation holds:[31,32]

$$\Delta\lambda_{ab}(0)/\lambda_{ab}(0) = (\Delta d_s/d_s - \Delta T_c/T_c)/2, \tag{2}$$

where $\Delta d_s/d_s$ is the oxygen isotope shift of the thickness of the superconducting sheets d_s of the sample. The best fit of Eq. (2) to the experimental data gives $\Delta d_s/d_s = 3.3(4)\%$ (line *D* in Fig. 4). Note that Eq. (2) is strictly valid only in the underdoped region. The fit, however, describes the behavior at all doping levels reasonably well. Since the lattice parameters are not modified by oxygen substitution[33,34] the observation of an isotope effect on d_s implies local lattice distortions involving oxygen that are coupled to the superfluid. It was shown that in anisotropic superconductors falling into the 2D XY QSI universality class at zero temperature, the isotope effects on the transition temperature, specific heat, and magnetic field penetration depth are related by a universal relation. This implies a dominant role of fluctuations so that pair formation and pair condensation do not occur simultaneously. From these results Schneider and Keller conclude that the observed isotope effects do not provide direct information on the underlying pairing mechanism and must be attributed to the shift of the phase diagram upon isotope substitution caused by electron-lattice interaction.[29–32] Bussmann-Holder *et al.*[35–37] investigated the origin of the isotope effects on the superconducting transition temperature and the magnetic penetration depth within a polaronic model. For this purpose the well-known *t*-*J* Hamiltonian was extended to incorporate the hole induced charge channel and the important effects from the lattice. This results in a two-component Hamiltonian, where interactions between the charge channel (local hole plus induced lattice distortion) and the spin channel (antiferromagnetic fluctuations modified by lattice distortions) are explicitly included.[35–37] This polaronic model predicts for the OIE on T_c and $\lambda_{ab}(0)$ the relation $\Delta\lambda_{ab}(0)/\lambda_{ab}(0) = |\Delta T_c/T_c|$ (line *D* in Fig. 4), in agreement with experiments in the underdoped regime.

IV. CONCLUSION

In conclusion, the oxygen isotope ^{16}O-^{18}O effects on the in-plane magnetic penetration depth $\lambda_{ab}(0)$ and transition temperature T_c were studied in optimally doped $YBa_2Cu_3O_{7-\delta}$ and $La_{1.85}Sr_{0.15}CuO_4$, and in the slightly underdoped $YBa_2Cu_4O_8$ and $Y_{0.8}Pr_{0.2}Ba_2Cu_3O_{7-\delta}$ by means of muon-spin rotation and magnetization techniques. A small OIE on the transition temperature T_c was observed that is associated with a substantial OIE on the in-plane penetration depth $\lambda_{ab}(0)$, as shown in Fig. 4 and Tables I and II. This finding suggests that lattice effects are directly or indirectly involved in determining the superconducting state. It is worth to note that in colossal magnetoresistance (CMR) manganites similar peculiar OIE on various quantities (e.g., ferromagnetic transition temperature, charge-ordering temperature) were observed,[38] indicating that in both classes of perovskites, HTSs and CMR manganites, lattice vibrations play an essential role.

ACKNOWLEDGMENTS

This work was partly performed at the Swiss Muon Source (SμS), Paul Scherrer Institute (PSI, Switzerland). The authors are grateful to D. Di Castro, D. G. Eshchenko, A. Amato, and D. Herlach for assistance during the μSR measurements. This work was supported by the Swiss National Science Foundation, in part by the NCCR program MaNEP, and by the K. Alex Müller Foundation.

---

[1] B. Batlogg, G. Kourouklis, W. Weber, R. J. Cava, A. Jayaraman, A. E. White, K. T. Short, L. W. Rupp, and E. A. Rietman, Phys. Rev. Lett. **59**, 912 (1987).

[2] J. P. Franck, J. Jung, M. A-K. Mohamed, S. Gygax, and G. I. Sproule, Phys. Rev. B **44**, 5318 (1991).

[3] J. P. Franck, in *Physical Properties of High Temperature Superconductors IV*, edited by D. M. Ginsberg (World Scientific, Singapore, 1994), pp. 189–293.

[4] D. Zech, H. Keller, K. Conder, E. Kaldis, E. Liarokapis, N. Poulakis, and K. A. Müller, Nature (London) **371**, 681 (1994).

[5] G. M. Zhao and D. E. Morris, Phys. Rev. B **51**, 16487 (1995).

[6] G. M. Zhao, M. B. Hunt, H. Keller, and K. A. Müller, Nature (London) **385**, 236 (1997).

[7] G. M. Zhao, K. Conder, H. Keller, and K. A. Müller, J. Phys.: Condens. Matter **10**, 9055 (1998).

[8] J. Hofer, K. Conder, T. Sasagawa, G. M. Zhao, M. Willemin, H. Keller, and K. Kishio, Phys. Rev. Lett. **84**, 4192 (2000).

[9] R. Khasanov, A. Shengelaya, K. Conder, E. Morenzoni, I. M. Savić, and H. Keller, J. Phys.: Condens. Matter **15**, L17 (2003).

[10] R. Khasanov, A. Shengelaya, E. Morenzoni, M. Angst, K. Conder, I. M. Savić, D. Lampakis, E. Liarokapis, A. Tatsi, and H. Keller, Phys. Rev. B **68**, 220506(R) (2003).

[11] R. Khasanov, D. G. Eshchenko, H. Luetkens, E. Morenzoni, T. Prokscha, A. Suter, N. Garifianov, M. Mali, J. Roos, K. Conder, and H. Keller, Phys. Rev. Lett. **92**, 057602 (2004).

[12] R. Khasanov, A. Shengelaya, E. Morenzoni, K. Conder, I. M. Savic, and H. Keller, J. Phys.: Condens. Matter **16**, S4439 (2004).

[13] H. Keller, Physica B **326**, 283 (2003).

[14] H. Keller, in *Superconductivity in Complex Systems*, edited by K. A. Müller and A. Bussmann-Holder (Springer, Berlin, 2005), p. 143.

[15] J. L. Tallon, R. S. Islam, J. Storey, G. V. M. Williams, and J. R. Cooper, Phys. Rev. Lett. **94**, 237002 (2005).

[16] K. Conder, Mater. Sci. Eng., R. **32**, 41 (2001).

[17] J. Karpinski, S. Rusiecki, E. Kaldis, B. Bucher, and E. Jilek, Physica C **160**, 449 (1989).

[18] P. Zimmermann, H. Keller, S. L. Lee, I. M. Savic, M. Warden, D. Zech, R. Cubitt, E. M. Forgan, E. Kaldis, J. Karpinski, and C. Krüger, Phys. Rev. B **52**, 541 (1995).

[19] C. L. Seaman, J. J. Neumeier, M. B. Maple, L. P. Le, G. M. Luke, B. J. Sternlieb, Y. J. Uemura, J. H. Brewer, R. Kadono, R. F. Kiefl, S. R. Krietzman, and T. M. Riseman, Phys. Rev. B **42**, 6801 (1990).

[20] G. Aeppli, E. J. Ansaldo, J. H. Brewer, R. J. Cava, R. F. Kiefl, S. R. Kreitzman, G. M. Luke, and D. R. Noakes, Phys. Rev. B **35**, 7129 (1987).

[21] B. Bucher, J. Karpinski, E. Kaldis, and P. Wachter, Physica C **157**, 478 (1989).

[22] J. L. Tallon, J. W. Loram, J. R. Cooper, C. Panagopoulos, and C. Bernhard, Phys. Rev. B **68**, 180501(R) (2003).

[23] Y. J. Uemura, G. M. Luke, B. J. Sternlieb, J. H. Brewer, J. F. Carolan, W. N. Hardy, R. Kadono, J. R. Kempton, R. F. Kiefl, S. R. Kreitzman, P. Mulhern, T. M. Riseman, D. Ll. Williams, B. X. Yang, S. Uchida, H. Takagi, J. Gopalakrishnan, A. W. Sleight, M. A. Subramanian, C. L. Chien, M. Z. Cieplak, Gang Xiao, V. Y. Lee, B. W. Statt, C. E. Stronach, W. J. Kossler, and X. H. Yu, Phys. Rev. Lett. **62**, 2317 (1989).

[24] Y. J. Uemura, L. P. Le, G. M. Luke, B. J. Sternlieb, W. D. Wu, J. H. Brewer, T. M. Riseman, C. L. Seaman, M. B. Maple, M. Ishikawa, D. G. Hinks, J. D. Jorgensen, G. Saito, and H. Yamochi, Phys. Rev. Lett. **66**, 2665 (1991).

[25] A. Rüfenacht, J.-P. Locquet, J. Fompeyrine, D. Caimi, and P. Martinoli, Phys. Rev. Lett. **96**, 227002 (2006).

[26] J. L. Tallon, C. Bernhard, U. Binninger, A. Hofer, G. V. M. Williams, E. J. Ansaldo, J. I. Budnick, and Ch. Niedermayer, Phys. Rev. Lett. **74**, 1008 (1995).

[27] C. Bernhard, Ch. Niedermayer, U. Binninger, A. Hofer, Ch. Wenger, J. L. Tallon, G. V. M. Williams, E. J. Ansaldo, J. I. Budnick, J. I. Stronach, D. R. Noakes, and M. A. Blankson-Mills, Phys. Rev. B **52**, 10488 (1995).

[28] Ch. Niedermayer, C. Bernhard, U. Binninger, H. Glückler, J. L. Tallon, E. J. Ansaldo, and J. I. Budnick, Phys. Rev. Lett. **71**, 1764 (1993).

[29] T. Schneider and H. Keller, Phys. Rev. Lett. **86**, 4899 (2001).

[30] T. Schneider, Phys. Rev. B **67**, 134514 (2003).

[31] H. Keller and T. Schneider, cond-mat/0401505 (unpublished).

[32] T. Schneider and H. Keller, New J. Phys. **4**, 144 (2004).

[33] K. Conder, D. Zech, Ch. Krüger, E. Kaldis, H. Keller, A. W. Hewat, and E. Jilek, in *Phase Separation in Cuprate Superconductors*, edited by E. Sigmund and K. A. Müller (Springer, Berlin, 1994), p. 210.

[34] F. Raffa, T. Ohno, M. Mali, J. Roos, D. Brinkmann, K. Conder, and M. Eremin, Phys. Rev. Lett. **81**, 5912 (1998).

[35] A. Bussmann-Holder and H. Keller, Eur. Phys. J. B **44**, 487 (2005).

[36] A. Bussmann-Holder, H. Keller, and K. A. Müller, in *Superconductivity in Complex Systems*, edited by K. A. Müller and A. Bussmann-Holder (Springer, Berlin, 2005), p. 365.

[37] A. Bussmann-Holder, H. Keller, A. R. Bishop, A. Simon, R. Micnas, and K. A. Müller, Europhys. Lett. **72**, 423 (2005).

[38] G. M. Zhao, H. Keller, R. L. Greene, and K. A. Müller, in *Physics of Manganites*, edited by T. A. Kaplan and S. D. Mahanti (Kluwer Academic/Plenum Publishers, New York, 1999), p. 221.