Muon-Spin-Rotation Measurements of the Penetration Depth of the Infinite-Layer Electron-Doped $Sr_{0.9}La_{0.1}CuO_2$ Cuprate Superconductor

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Muon-spin-rotation (μSR) measurements of the in-plane penetration depth λ_{ab} have been performed in the infinite-layer electron-doped $Sr_{0.9}La_{0.1}CuO_2$ high-T_c superconductor (HTS). Absence of the magnetic rare-earth ions in this compound allowed us to measure for the first time the absolute value of $\lambda_{ab}(0)$ in electron-doped HTSs using μSR. We found $\lambda_{ab}(0) = 116(2)$ nm. The zero-temperature depolarization rate $\sigma(0) \propto 1/\lambda_{ab}^2(0) = 4.6(1)\ \mu s^{-1}$ is more than 4 times higher than expected from the Uemura line. Therefore, this electron-doped HTS does not follow the Uemura relation found for hole-doped HTSs.

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The high-T_c cuprate superconductors are obtained by doping holes or electrons into the antiferromagnetic (AFM) insulating state. Both electron- and hole-doped cuprates share a common building block, namely, the copper-oxygen plane, and one would expect that the same pairing mechanism is applicable. There are a number of important differences, however, between the generic phase diagrams of the electron-doped and hole-doped materials. In order to elucidate the mechanism of high-T_c superconductivity, it is very important to clarify the origin of similarities and differences between hole-doped (p-type) and electron-doped (n-type) cuprates.

The magnetic field penetration depth λ is one of the fundamental lengths of a superconductor, related to the superfluid phase stiffness $\rho_s \propto 1/\lambda^2$, or what is often referred to as superfluid density $n_s/m^* \propto 1/\lambda^2$ (superconducting carrier concentration n_s divided by the effective mass m^*). Accurate and precise measurements of the absolute value of $\lambda(T \rightarrow 0)$ are very important for understanding superconductivity in cuprates. The muon-spin-rotation (μSR) technique provides a powerful tool to measure λ in type II superconductors. Detailed μSR investigations of polycrystalline high-T_c superconductors (HTSs) have demonstrated that λ can be obtained from the muon-spin depolarization rate $\sigma(T) \propto 1/\lambda^2(T)$, which probes the second moment of the magnetic field distribution in the mixed state [1]. One of the most interesting result of μSR investigations in HTSs is a remarkable proportionality between T_c and the zero-temperature depolarization rate $\sigma(0) \propto 1/\lambda^2(0)$ for a wide range of p-type underdoped HTSs (so-called Uemura line) [2,3]. This observation indicates that the superfluid density is an important quantity which determines T_c in HTSs. This is not expected in conventional BCS theory and therefore the Uemura relation has an important implication for the physics of HTSs [4].

Unfortunately, it was not known up to now whether the n-type cuprates also obey the Uemura relation. The large dynamic relaxation due to rare-earth magnetic moments in n-type cuprates $R_{2-x}Ce_xCuO_{4-\delta}$ ($R =$ Nd, Sm, Pr) with the so-called T' structure prevented the determination of $\sigma(0)$ in μSR experiments [5]. Because of this problem, other techniques such as microwave surface impedance and magnetization were used to determine the penetration depth in n-type cuprates. However, it is difficult to determine the absolute value of λ with these experiments and the reported values vary in a very wide range from 100 to 300 nm even for optimally doped samples. Therefore, there is no consensus about the penetration depth value for n-type cuprates. Another difficulty concerns the quality of the samples. A long-standing mystery for the T'-structure n-type cuprates is the effect of an oxygen reducing procedure. Superconductivity shows up only when a minute amount ($\Delta y \approx 0.02$) of interstitial oxygens are removed by the reducing procedure [6]. The role of the tiny amount of interstitial oxygen was not clear up to now. The control of the oxygen content requires rather extreme conditions, such as temperatures as high as 850 °C–950 °C in Ar, which is not far below the sintering temperature. Therefore, the control of the sample quality and reproducibility becomes a serious problem.

There exists another class of n-type cuprates $(Sr, L)CuO_2$ ($L =$ La, Sm, Nd, Gd) with a so-called infinite-layer structure [7,8]. The n-type infinite-layer superconductors (ILSs) have several merits. First, the simplest crystal structure among all HTSs consisting of an infinite stacking of CuO_2 planes and (Sr, L) layers. The charge reservoir block commonly present in cuprates does not exist in the infinite-layer structure. Second, the stoichiometric oxygen content without vacancies or interstitial oxygen [9]. Third, n-type ILSs have much higher $T_c \simeq$ 43 K compared to the n-type cuprates with T' structure $T_c \simeq 25$ K. Although n-type ILSs have existed for quite a while, not many studies of their physical properties were performed because of the lack of high-quality samples with a complete superconducting volume. Recently, high-quality n-type ILS samples of $Sr_{0.9}La_{0.1}CuO_2$ with a sharp superconducting transition $T_c \simeq 43$ K were synthesized by using a cubic multianvil press [10].

In this Letter, we report studies of the penetration depth λ in $Sr_{0.9}La_{0.1}CuO_2$ ILSs using the transverse-field (TF) μSR technique. We confirmed microscopically that this compound is a bulk superconductor. Because of the absence of magnetic rare-earth ions, it was possible to measure the penetration depth in n-type HTSs for the first time using μSR, yielding $\lambda_{ab}(0) = 116(2)$ nm. The zero-temperature depolarization rate $\sigma(0) = 4.6(1)\ \mu s^{-1}$ is more than 4 times larger than expected from the Uemura plot. This shows that the n-type ILS does not follow the Uemura relation established in p-type HTSs.

The polycrystalline samples $Sr_{0.9}La_{0.1}CuO_2$ (SLCO) for this study were prepared with the high-pressure technique using a cubic multianvil press [10]. Magnetization measurements showed a single sharp superconducting transition at $T_c \simeq 43$ K and the saturation of the susceptibility at low temperatures, indicating good sample quality. The μSR measurements were performed at the Paul Scherrer Institute (PSI, Switzerland) using low-momentum muons (29 MeV/c). A detailed discussion of the TF-μSR technique is given in [11], where details of the application of the technique to the determination of λ can be found.

Figure 1(a) shows TF-μSR muon-spin precession signals in an applied field of 600 mT above and below T_c. For visualization purposes the apparent precession frequencies are modified from the actual precession frequencies by the use of a rotating reference frame. In the normal state above T_c, the oscillation shows a small relaxation due to random local fields from nuclear magnetic moments. Below T_c, the relaxation rate strongly increases due to the inhomogeneous field distribution of the flux-line lattice. It is well known that in n-type cuprates there is a competition between the antiferromagnetically ordered state and superconductivity [5]. The static magnetism, if present, could enhance the muon depolarization rate and falsify the interpretation of the TF-μSR results. We have therefore carried out zero-field (ZF) μSR experiments to determine whether such static magnetism exists in SLCO. Typical ZF-μSR spectra are shown in Fig. 1(b) for temperatures above and below T_c. The ZF relaxation is exponential with a small relaxation rate of 0.149(4) and 0.184(5) μs^{-1} at 50 and 2.5 K, respectively. Thus, there is no evidence for the static magnetism in SLCO down to 2.5 K. Moreover, the ZF relaxation rate is small and changes very little between 50 and 2.5 K. Therefore, the increase in TF relaxation rate below T_c is attributed entirely to the vortex lattice.

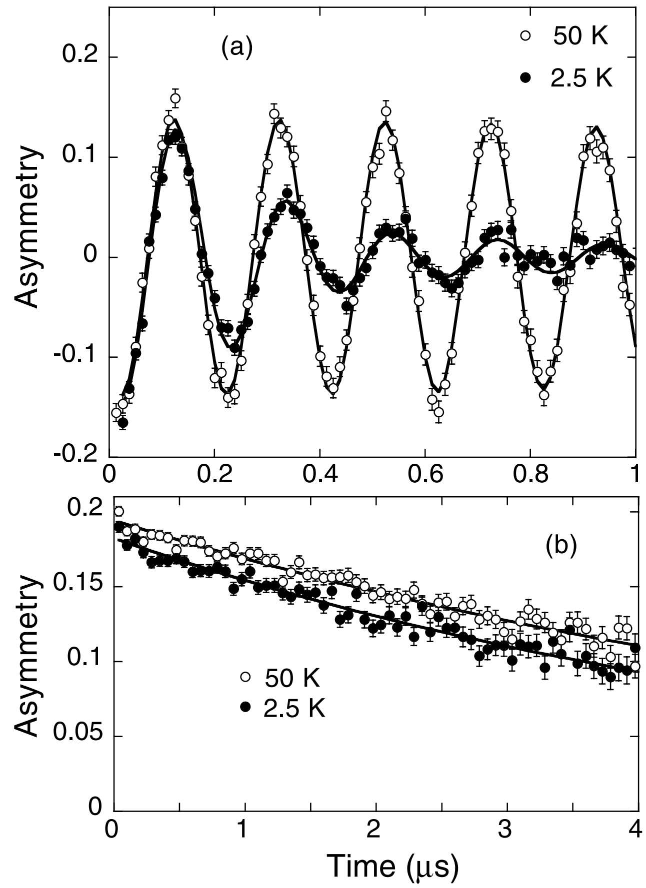

FIG. 1. (a) TF-μSR spectra in $Sr_{0.9}La_{0.1}CuO_2$ in a magnetic field of 0.6 T at temperatures $T = 50$ K (above T_c) and $T =$ 2.5 K (below T_c). Solid lines represent fits using Eq. (1). (b) ZF-μSR spectra in $Sr_{0.9}La_{0.1}CuO_2$ at 50 and 2.5 K. Solid lines show fits using an exponential function.

Detailed μSR experiments in polycrystalline HTSs have shown that the internal field distribution in the mixed state can be well approximated by a Gaussian distribution [11]. We used a two-Gaussian model for analyzing our asymmetry time spectra:

$$A(t) = \sum_{i=1}^{2} A_i \exp(-\sigma_i^2 t^2/2) \cos(2\pi\gamma B_i t + \varphi), \quad (1)$$

where A_i represent the asymmetries of the two components, σ_i the muon depolarization rates, B_i the local magnetic fields at the muon sites, $\gamma = 135.5$ MHz/T is the muon gyromagnetic ratio, and φ the initial phase. The solid lines in Fig. 1(a) show the best fits to Eq. (1). The fit is statistically satisfactory (χ^2 criterion), as can be seen qualitatively in Fig. 1(a).

Analysis of the asymmetry time spectra showed that below T_c in the present SLCO sample more than 80% of the muons stop in the superconducting regions (first component). In these regions the internal magnetic field is smaller than the external one because of the diamagnetic screening and the depolarization rate is much higher than in the normal state because of the flux-line lattice formation. The rest, 20%, of the muons (second component) oscillate with a frequency nearly equal to that corresponding to the applied magnetic field with a much smaller depolarization rate. This signal is most probably coming from the muons stopping in the nonsuperconducting grain boundaries and other defects in the structure and is often observed in polycrystalline HTSs [12]. As already mentioned samples of ILS prepared so far suffer from the small volume fraction of the superconducting phase. As a real space microscopic probe, μSR can distinguish between the superconducting and nonsuperconducting phases and determine their relative volume fractions. The present μSR measurements provide *microscopic* evidence for the excellent quality of the SLCO ILSs prepared with the cubic multianvil press technique [10].

In polycrystalline samples the effective penetration depth λ_{eff} (powder average) can be extracted from the μSR depolarization rate $\sigma \sim \lambda_{\mathrm{eff}}^{-2}$. It was shown [13,14] that, in polycrystalline samples of highly anisotropic systems such as the HTSs ($\gamma = \lambda_c/\lambda_{ab} > 5$), λ_{eff} is dominated by the shorter penetration depth λ_{ab} and $\lambda_{\mathrm{eff}} = 1.31\lambda_{ab}$. Recent magnetization measurements in grain-aligned SLCO showed a rather high anisotropy value $\gamma = 9$ [15,16]. Therefore, the measured λ_{eff} is solely determined by the in-plane penetration depth λ_{ab}.

The relation between σ and λ_{ab} is only valid for high magnetic fields ($B_{\mathrm{ext}} > 2\mu_0 H_{c1}$), when the separation between vortices is smaller than λ. In this case, according to the London model, σ is field independent [17]. To check for this, we measured σ as a function of the applied field at $T = 10$ K. Each point was obtained by field cooling the sample from above T_c to 10 K. The inset of Fig. 2 shows that σ strongly increases with increasing magnetic field up to $B_{\mathrm{ext}} \simeq 50$ mT and above 50 mT changes very little with magnetic field. Such a behavior is expected within the London model and is typical for polycrystalline HTSs [11]. It can be seen that, above 50 mT, $\sigma(B)$ shows a tendency of gradual decrease with increasing field. This can be due to the increase of λ with magnetic field due to the anisotropic order parameter and the associated nonlinear effect due to the Doppler shift of the quasiparticles in the nodal region [18,19]. However, the field range in our experiment is too narrow to discuss this in more detail. Based on the $\sigma(B)$ measurements, we studied the temperature dependence of σ in a magnetic field of 600 mT (the largest available field of the GPS spectrometer at PSI). We choose the highest magnetic field because at higher fields the enhanced vortex-vortex interaction helps to maintain the long-range order of the vortex lattice, which is important for the determination of λ.

Figure 2 shows the temperature dependence of the muon-spin depolarization rate $\sigma(T)$ at $B_{\mathrm{ext}} = 0.6$ T. The values of $\sigma(T)$ were derived after subtraction of the small normal-state temperature-independent depolarization rate originating from the copper nuclear moments [$\sigma(T)^2 = \sigma_1^2 - \sigma_{\mathrm{norm}}^2$]. From the data in Fig. 2 extrapolated to 0 K, we obtain the value $\sigma(0) = 4.6(1)\ \mu\mathrm{s}^{-1}$, which corresponds to $\lambda_{ab}(0) = 116(2)$ nm. The value $\sigma(0) = 4.6(1)\ \mu\mathrm{s}^{-1}$ is one of the highest among all HTSs. Figure 3 shows T_c plotted vs $\sigma(0)$ (Uemura plot [2,3]) for p-type cuprates, including the present result for n-type SLCO. One can see that SLCO strongly deviates from the Uemura line. It is interesting to consider the situation in n-type HTSs with the T' structure. As we have already mentioned, it was not possible to extract the value of λ in this type of compound with μSR, and most of the experiments were performed by means of the microwave surface impedance technique which yielded very controversial results due to the difficulty in extracting the absolute values of λ. There are, however, two studies of $\lambda(0)$ in $Nd_{1.85}Ce_{0.15}CuO_4$ (NCCO) single crystals by means of magnetization [20] and infrared optics [21]. We included in Fig. 3 these $\lambda(0)$ values converted to $\sigma(0)$. It is seen that, similar to ILS SLCO, n-type NCCO with the T' structure strongly deviates from the Uemura line. This was also pointed out by Homes *et al.* from the optical measurements [21]. Based on the presented results, one can conclude that n-type HTSs do not follow the Uemura relation established in p-type HTSs.

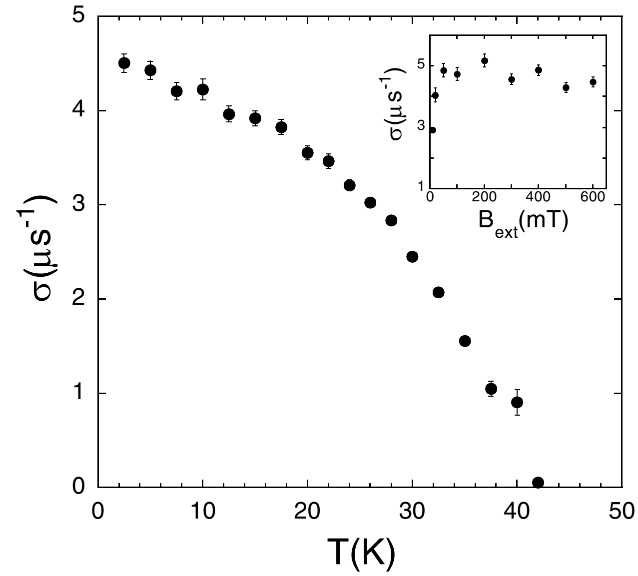

FIG. 2. Temperature dependence of the μSR depolarization rate $\sigma(T)$ of $Sr_{0.9}La_{0.1}CuO_2$. Inset: depolarization rate as a function of the external magnetic field B_{ext} at 10 K.

There are several important differences between the normal-state properties of the p- and n-type cuprates. The p-type materials show T-linear in-plane electrical resistivity [22] and incommensurate magnetic fluctuations [23], whereas the T' n-type materials show a T^2 dependence of the in-plane resistivity [24] and commensurate magnetic fluctuations [25]. Recent NMR experiments in n-type cuprates found no evidence of the pseudogap in contrast to p-type materials [26,27]. Present results show

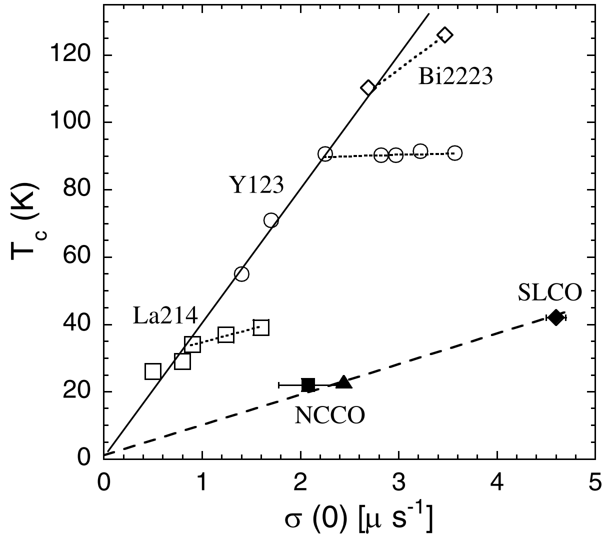

FIG. 3. T_c vs $\sigma(0)$ for p- and n-type cuprate superconductors. Open symbols represent data taken from Uemura *et al.* for various p-type HTSs [3]. The solid line is the universal Uemura line for different underdoped p-type HTSs. Dotted lines represent deviation from the Uemura relation near optimal doping. Solid diamond shows the $Sr_{0.9}La_{0.1}CuO_2$ (SLCO) data obtained in the present work. Solid square and triangle show the data for $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ (NCCO) single crystals obtained from magnetization [20] and optical [21] measurements, respectively. Dashed line represents a tentative T_c vs $\sigma(0)$ relation for n-type cuprates.

that the differences between the p- and n-type cuprates extend also to the superconducting state. Namely, we observed that in n-type cuprates the superfluid density n_s/m^* is more than 4 times larger compared to p-type cuprates with the same T_c.

Finally, let us comment on the temperature dependence $\sigma(T)$ presented in Fig. 2. One can see that at low temperatures (below $\sim$15 K) $\sigma(T)$ is not constant and instead follows the linear temperature dependence. Usually a linear low-temperature behavior of $\sigma(T)$ is taken as an indication for a d-wave gap function with line nodes [28]. However, experience with p-type cuprates showed that single crystals are required for a conclusive determination of the intrinsic temperature dependence of σ and hence of λ using the μSR technique [19]. Unfortunately, single crystals of SLCO are not available at present. Concerning the pairing symmetry in SLCO based on other experiments, we note that the recent tunneling experiments suggest strong-coupling s-wave pairing in SLCO [29]. On the other hand, NMR spin-lattice relaxation and Knight shift measurements were found to be more consistent with the line-node gap [26]. It remains to be understood why different experimental techniques provide controversial results concerning the pairing symmetry in SLCO.

In summary, we performed TF-μSR measurements of the in-plane penetration depth λ_{ab} in the n-type ILS $Sr_{0.9}La_{0.1}CuO_2$. Absence of the magnetic rare-earth elements in this compound allowed us to measure for the first time the absolute value of $\lambda_{ab}(0)$ in n-type HTSs using μSR. We found $\lambda_{ab}(0) = 116(2)$ nm. The zero-temperature depolarization rate $\sigma(0) \propto 1/\lambda^2(0) = 4.6(1)\ \mu\mathrm{s}^{-1}$ is more than 4 times higher than expected from the Uemura line. Therefore, this n-type HTS does not follow the Uemura relation in contrast to the p-type HTS. We also performed ZF-μSR experiments and found no evidence of magnetic order in SLCO. This indicates the competitive character of AFM order and superconductivity in n-type cuprates, in agreement with the recent neutron scattering experiments [30].

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