## Muon-Spin-Rotation Measurements of the Penetration Depth in the Infinite-Layer Electron-Doped Cuprate Superconductor Sr<sub>0.9</sub>La<sub>0.1</sub>CuO<sub>2</sub>

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Muon spin rotation ( $\mu$ SR) measurements of the in-plane penetration depth  $\lambda_{ab}$  have been performed in the electron-doped infinite layer high- $T_c$  superconductor (HTS) Sr<sub>0.9</sub>La<sub>0.1</sub>CuO<sub>2</sub>. Absence of the magnetic rare-earth ions in this compound allowed to measure for the first time the absolute value of  $\lambda_{ab}(0)$  in electron-doped HTS using  $\mu$ SR. 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<sup>-1</sup> is more than four times higher than expected from the Uemura line. Therefore this electron-doped HTS does not follow the Uemura relation found for hole-doped HTS.

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The high- $T_c$  cuprate superconductors are obtained by doping holes or electrons into the antiferromagnetic (AF) 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 (HTS), it is very important to clarify the origin of similarities and differences between hole-doped (p-type) and electron-doped (p-type) cuprates.

The magnetic field penetration depth  $\lambda$  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<sub>s</sub> divided by the effective mass m\*). Accurate and precise measurements of the absolute value of  $\lambda(T \to 0)$  are very important for understanding superconductivity in cuprates. The muonspin-rotation ( $\mu SR$ ) technique provides a powerful tool to measure  $\lambda$  in type II superconductors. Detailed  $\mu SR$ investigations of polycrystalline HTS have demonstrated that  $\lambda$  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  $\mu$ SR investigations in HTS 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 HTS (so-called Uemura line) [2, 3]. This observation indicates that the superfluid density is an important quantity which determines  $T_c$  in HTS. This is not expected in conventional BCS theory and therefore the Uemura relation has an

important implication for the physics of HTS [4].

Unfortunately, it is 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 so called T'-structure prevented the determination of  $\sigma(0)$  in  $\mu$ SR experiments [5]. Because of this problem, other techniques like 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  $\lambda$  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 is not clear up to now. The control of the oxygen content requires rather extreme conditions, such as temperatures as high as 850°-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,Ln)CuO<sub>2</sub> (Ln=La, Sm, Nd, Gd) with so-called infinite-layer structure [7, 8]. The *n*-type infinite-layer superconductors (ILS) have several merits. First, the simplest crystal structure among all HTS consisting of an infinite stacking of CuO<sub>2</sub> planes and (Sr, Ln) layers. The charge reservoir block commonly present in cuprates does not exist in the infinite-layer structure. Second, the stoi-

chiometric oxygen content without vacancies or interstitial oxygen [9]. Third, n-type ILS 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 ILS 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  $\mathrm{Sr_{0.9}La_{0.1}CuO_2}$  with a sharp superconducting transition  $T_c \simeq 43$  K were synthesized by using a cubic multi-anvil press [10].

In this letter we report studies of the penetration depth  $\lambda$  in  $\mathrm{Sr_{0.9}La_{0.1}CuO_2}$  ILS using the transverse-field (TF)  $\mu\mathrm{SR}$  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 HTS for the first time using  $\mu\mathrm{SR}$ , yielding  $\lambda_{ab}(0){=}116(2)$  nm. The zero-temperature depolarization rate  $\sigma(0){=}4.6(1)$   $\mu\mathrm{s}^{-1}$  is more than four 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 HTS.

The polycrystalline samples  $\rm Sr_{0.9}La_{0.1}CuO_2$  (SLCO) for this study were prepared with the high-pressure technique using a cubic multi-anvil 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 the good sample quality. The  $\mu \rm SR$  measurements were performed at the Paul Scherrer Institute (PSI, Switzerland) using low-momentum muons (29 MeV/c). A detailed discussion of the TF- $\mu \rm SR$  technique is given in [11] where details of the application of the technique to the determination of  $\lambda$  can be found.

Fig. 1(a) shows TF- $\mu$ SR 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- $\mu$ SR results. We have therefore carried out zero-field (ZF)  $\mu$ SR experiments to determine whether such static magnetism exists in SLCO. Typical ZF- $\mu$ SR spectra are shown in Fig. 1(b) for temperatures above and below  $T_c$ . The ZF relaxation is exponential with a small relaxation rate 0.149(4)  $\mu$ s<sup>-1</sup> and  $0.184(5) \mu s^{-1}$  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.

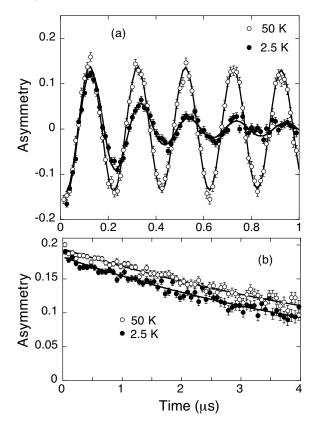


FIG. 1: (a) TF- $\mu$ SR spectra in Sr<sub>0.9</sub>La<sub>0.1</sub>CuO<sub>2</sub> in a magnetic field of 0.6 T at temperatures T=50 K (above T<sub>c</sub>) and T=2.5 K (below T<sub>c</sub>). Solid lines represent fits using Eq. (1). (b) ZF- $\mu$ SR spectra in Sr<sub>0.9</sub>La<sub>0.1</sub>CuO<sub>2</sub> at 50 K and 2.5 K. Solid lines show fits using an exponential function.

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

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

where  $A_i$  represent the asymmetries of the two components,  $\sigma_i$  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  $\varphi$  the initial phase. The solid lines in Fig.1 (a) show the best fits to Eq. (1). The fit is statistically satisfactory ( $\chi^2$  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 this 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 HTS [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  $\mu SR$  can distinguish between the superconducting and nonsuperconducting phases and determine their relative volume fractions. The present  $\mu SR$  measurements provide microscopic evidence for the excellent quality of the SLCO ILS prepared with the cubic multi-anvil press technique

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

The relation between  $\sigma$  and  $\lambda_{ab}$  is only valid for high magnetic fields  $(B_{ext} > 2\mu_0 H_{c1})$ , when the separation between vortices is smaller than  $\lambda$ . In this case, according to the London model  $\sigma$  is field independent [17]. To check for this, we measured  $\sigma$  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  $\sigma$  strongly increases with increasing magnetic field up to  $B_{ext} \simeq 50$  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 HTS [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  $\lambda$  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  $\sigma$  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  $\lambda$ .

Fig. 2 shows the temperature dependence of the muon spin depolarization rate  $\sigma(T)$  at  $B_{ext}$ =0.6 T. The values of  $\sigma(T)$  were derived after subtraction of the small normal state temperature-independent depolarization rate

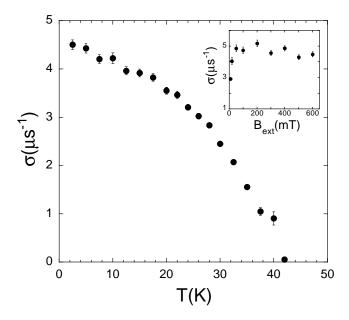


FIG. 2: Temperature dependence of the  $\mu$ SR depolarization rate  $\sigma(T)$  of Sr<sub>0.9</sub>La<sub>0.1</sub>CuO<sub>2</sub>. Inset: depolarization rate as a function of the external magnetic field B<sub>ext</sub> at 10 K.

originating from the copper nuclear moments  $(\sigma(T)^2 = \sigma_1^2$  $\sigma_{norm}^2$ ). From the data in Fig. 2 extrapolated to 0 K we obtain the value  $\sigma(0)=4.6(1) \ \mu s^{-1}$  which corresponds to  $\lambda_{ab}(0)=116(2)$  nm. The value  $\sigma(0)=4.6(1)$  $\mu s^{-1}$  is one of the highest among all HTS. Fig. 3 shows  $T_c$  plotted versus  $\sigma(0)$  (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 HTS with the T'-structure. As we already mentioned it was not possible to extract the value of  $\lambda$  in this type of compounds with  $\mu SR$ , and most of the experiments were performed by means of microwave surface impedance technique which vielded very controversial results due to the difficulty to extract the absolute values of  $\lambda$ . There are however two studies of  $\lambda(0)$  in Nd<sub>1.85</sub>Ce<sub>0.15</sub>CuO<sub>4</sub> (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 HTS do not follow the Uemura relation established in p-type HTS.

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

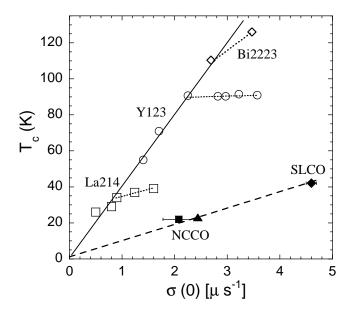


FIG. 3:  $T_c$  versus  $\sigma(0)$  for p- and n-type cuprate superconductors. Open symbols represent data taken from Uemura et~al. for various p-type HTS [3]. The solid line is the universal Uemura line for different underdoped p-type HTS. Dotted lines represent deviation from the Uemura relation near 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.

n-type cuprates found no evidence of the pseudogap in contrast to p-type materials [26, 27]. Present results show 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 four times larger compared to p-type cuprates with the same  $T_c$ .

Finally let us comment the temperature dependence  $\sigma(T)$  presented in Fig. 2. One can see that at low temperatures (below  $\sim 15 \text{ K}$ )  $\sigma(T)$  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 the single crystals are required for conclusive determination of the intrinsic temperature dependence of  $\sigma$  and hence of the  $\lambda$  using  $\mu SR$  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-nodes 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- $\mu$ SR measurements of the in-plane penetration depth  $\lambda_{ab}$  in n-type ILS  $\mathrm{Sr_{0.9}La_{0.1}CuO_2}$ . Absence of the magnetic rare-earth elements in this compound allowed to measure for the first time the absolute value of  $\lambda_{ab}(0)$  in n-type HTS using  $\mu$ SR. We found  $\lambda_{ab}(0)$ =116(2) nm. The zero-temperature depolarization rate  $\sigma(0) \propto 1/\lambda^2(0)$ = 4.6(1)  $\mu$ s<sup>-1</sup> is more than four times higher than expected from the Uemura line. Therefore this n-type HTS does not follow the Uemura relation in contrast to p-type HTS. We also performed ZF- $\mu$ SR experiments and found no evidence of magnetic order in SLCO. This indicates the competitive character of AF order and superconductivity in n-type cuprates in agreement with the recent neutron scattering experiments [30].

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