Correlated Decrease between the Superconducting Volume Fraction and \( T_c \) and Possible Phase Separation in the Overdoped Regime of La\(_{2-x}\)Sr\(_x\)CuO\(_4\)

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Correlated Decrease between the Superconducting Volume Fraction and $T_c$ and Possible Phase Separation in the Overdoped Regime of La$_{2-x}$Sr$_x$CuO$_4$


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Abstract. In order to prove the possible phase separation in the overdoped high-$T_c$ superconductors, suggested from the muon-spin-relaxation measurements, the superconducting (SC) volume fraction has been investigated in detail in the overdoped regime of La$_{2-x}$Sr$_x$CuO$_4$. From measurements of the magnetic susceptibility, $\chi$, using a single crystal in which the Sr concentration, $x$, continuously changes in the overdoped regime, both the absolute value of $\chi$ at 2 K, $|\chi_{2K}|$, on field cooling reflecting the SC volume fraction and $T_c$ have been found to decrease with increasing $x$. Moreover, it appears that $|\chi_{2K}|$ has a roughly linear relation to $T_c$. It has been concluded that phase separation into SC and normal-state regions takes place in the overdoped regime of La$_{2-x}$Sr$_x$CuO$_4$.

Keywords: magnetic susceptibility, phase separation, La$_{2-x}$Sr$_x$CuO$_4$, overdoped regime, PACS: 74.25.Ha, 74.62.Dh, 74.72.Dn

The inhomogeneity of the superconductivity in the CuO$_2$ planes is one of the recent central issues in the study of high-$T_c$ superconductivity. Scanning-tunneling-microscopy (STM) experiments in the optimally doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ have revealed that both the local density of states and the superconducting (SC) gap are spatially inhomogeneous [1]. However, STM is very sensitive to the surface electronic state. Therefore, the inhomogeneity in the CuO$_2$ plane is still controversial and it is necessary to confirm it from measurements reflecting the bulk nature of a sample.

In the overdoped regime of Tl$_2$Ba$_2$CuO$_{6+\delta}$, it has been found from the muon-spin-relaxation ($\mu$SR) measurements that the SC carrier density over the effective mass decreases with an increase in the hole concentration, suggesting possible microscopic phase separation into SC and normal-state regions [2]. From measurements of the magnetic susceptibility, $\chi$, in La$_{2-x}$Sr$_x$CuO$_4$ (LSCO), on the other hand, it has been pointed out that the shielding volume fraction estimated from $\chi$ at 4.2 K on zero-field cooling using bulk samples is almost 100% in the range 0.07 $\leq x \leq$ 0.27 [3]. In general, however, the shielding volume fraction is larger than the real SC volume fraction in the presence of inhomogeneity such as the microscopic phase separation.

In this paper, we have investigated the hole-concentration dependence of the SC volume fraction from the $\chi$ measurements on field cooling in the overdoped regime of LSCO [4].

A single-crystal rod with the Sr concentration, $x$, changing continuously in the overdoped regime was grown by the traveling-solvent floating-zone method. Several pieces of single crystal obtained by slicing the single-crystal rod were used for the $\chi$ measurements. The $x$ value of each single-crystal piece was estimated by ICP. The details have been described elsewhere [4]. The $\chi$ measurements were carried out at low temperatures down to 2 K, using a superconducting quantum interference device magnetometer.

Figure 1 shows the temperature dependence of $\chi$ in a magnetic field of 10 Oe on field cooling for powdered or non-powdered samples of single-crystal LSCO pieces with $x = 0.198 - 0.273$, together with the data of polycrystalline powder samples of LSCO with $x = 0.18$, 0.20 and 0.22 [5]. The SC transition looks broad for the powdered samples, which is ascribed to the temperature dependence of the penetration depth. With increasing $x$, the absolute value of $\chi$ at 2 K, $|\chi_{2K}|$, as well as $T_c$ decreases and becomes almost zero for $x > 0.273$. As for the data of non-powdered samples of
There are two possible origins of the phase separation in the overdoped regime. One is related to the decrease of the SC condensation energy with increasing $x$ [7]. In this case, phase separation into the hole-poor SC region with $x \sim 0.19$ and the hole-rich normal Fermi-liquid state region with $x \sim 0.30$ will probably take place. The other is due to doping of holes into the Cu$3d$ orbital, producing free Cu spins around the holes [8] and/or disturbing the antiferromagnetic correlation between Cu spins [9]. Both of them will bring about the local destruction of superconductivity around holes, generating normal-state regions in the SC sea.

In summary, it has been found from the $\chi$ measurements in the overdoped regime of LSCO that both $T_c$ and $|\chi_{2K}|$ decrease with increasing $x$, strongly suggesting the phase separation into SC and normal-state regions.

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REFERENCES

6. In order to avoid the difference in the effect of the demagnetizing field between samples, we formed each single-crystal piece into the same rectangular shape within the error of $\pm 4\%$.