High critical temperature ($T_C$) superconductor is widely studied since the discovery of La$_{2-x}$Ba$_x$CuO$_4$ in 1986. However, the properties of these materials are hardly to be explained by BCS theory which is successful in explaining the properties of conventional superconductor. It’s still an open question for the mechanism of high temperature superconductivity in cuprates. Among numerous theoretical models, stripe phase has attracted considerable attention that the spin and charge in high $T_C$ superconductors distributes inhomogeneous and forms “stripe”[1,2,3]. It was experimentally observed by neutron scattering or other method in La$_2$CuO$_4$-based system [4,5,6,7,8,9,10,11,12] and YBa$_2$Cu$_3$O$_{y}$[13,14,15]. It generally appears that the fluctuating stripe promote to superconductivity, but static stripe may suppress superconductivity[10]. However, there is evidence that it is local magnetic order rather than charge-stripe order which is responsible for the anomalous suppression of superconductivity[17].

In La$_2$CuO$_4$ system, several structural phase transitions occur with doping of alkaline-earth and rare-earth metals[17,18,19,20,21,22]. With decreasing temperature a transition from high-temperature-tetragonal (HTT) phase to low-temperature-orthorhombic (LTO) phase, then low-temperature-tetragonal (LTT) phase (or Pccn phase, depends on the hole concentration) was observed. The LTO and LTT phases involve distortion of CuO$_2$ planes due to the tilting of CuO$_6$ octahedras producing stripe pinning potential. Here we call the temperature $T_{LT}$ at which the structure transition from LTO to LTT occurs. In La$_{2-x-y}$Nd$_y$Sr$_x$CuO$_4$, the substitution of La by Nd enhances the pinning potential, which pins the stripe from fluctuating (Nd free sample) to static[2,8]. When $x=1/8$ there is an anomalous suppression of superconductivity due to the stripe phase. In La$_{1.6-x}$Nd$_{0.4}$Sr$_x$CuO$_4$, neutron diffraction experiment shows that the charge ordering and structural transition are essentially coincident for $x=0.10$ and 0.12[8,17]; however, the charge ordering occurs significantly below the structural transition temperature $T_{LT}$[17]. Several groups have investigated the relationship among structural distortion, stripe phase and superconductivity, using high-pressure to control the structure transition and superconductivity[22,23]. It was found that the hydrostatic pressure lower than 5 GPa compresses the CuO$_2$ planes, which weakens the pinning potential, suppresses the LTT distortion and enhances the superconductivity.

It is well known that the isotope effect study is very important in the conventional superconductors in which $\alpha_C\sim\ln T_C/\ln M_O=0.5$, and is the illation of BCS theory. Although many believe that antiferromagnetism is important for superconductivity, there has been renewed interest in possible role of electron-lattice coupling[24,25]. Therefore, the research of isotope substitution is necessary to study mechanism of high-$T_c$ superconductivity. Several oxygen isotope substitution experiments have been done in La$_{2-x}$Sr$_x$CuO$_4$ and La$_{2-x}$Ba$_x$CuO$_4$ with fluctuating stripe phase, and a large isotope exponent ($\alpha_O\sim1$) on $T_C$ was found near 1/8 doping[26,27,28,29]. To check possible change in the isotope effect induced by Nd doping and investigate the relationship among structural distortion, stripe phase and superconductivity, we systematically study the oxygen isotope effect in La$_{1.6-x}$Nd$_{0.4}$Sr$_x$CuO$_4$ with $x=0.10,0.125,0.15$ and 0.175. It is found that $T_C$ is suppressed, while $T_{LT}$ is enhanced with the substitution of $^{16}$O by $^{18}$O, indicating that the distortion of CuO$_2$ plane suppresses superconductivity. Because the charge ordering and structural transition are essentially coincident for $x=0.10$ and 0.12, therefore, in this sense the results of isotope effect definitely provide an evidence for the competing between stripe phase and superconduc-
tivity. Compared to the Nd free sample with fluctuating stripe phase, a larger isotope exponent $\alpha_C$ is observed in La$_{1.6-x}$Nd$_{0.4}$Sr$_2$CuO$_4$ with static stripe phase, suggesting a strong electron-lattice coupling in cuprates.

Polycrystalline samples La$_{1.6-x}$Nd$_{0.4}$Sr$_2$CuO$_4$ for $x = 0.10, 0.125, 0.15$ and $0.175$ were prepared by conventional solid-state reaction. All samples were characterized by X-ray diffraction (XRD) and no observable impurity phase is found. One pellet for each sample with different $x$ was cut into two pieces for oxygen-isotope diffusion. The two pieces for each composition were put into an alumina boat which were sealed in a quartz tube filled with oxygen pressure of 1 bar (one for $^{18}$O$_2$ and another for $^{16}$O$_2$) mounted in a furnace, respectively. The quartz tubes formed parts of two identical closed loops. They were first heated at 980 $^\circ$C for 90 h, then slowly cooled to 500 $^\circ$C, kept for 10 h and finally cooled to room temperature with furnace. The obtained samples were re-examined by X-ray diffraction to confirm them single phase. The oxygen-isotope enrichment is determined by the weight changes of both $^{16}$O and $^{18}$O samples. The $^{18}$O samples have about 80%(±5%) $^{18}$O and 20%(±5%) $^{16}$O. To ensure the isotope exchange effect, back-exchange of $^{18}$O sample by $^{16}$O was carried out in the same way and the weight change showed a complete back-exchange. Resistance measurements were performed using the ac four-probe method with an ac resistance bridge system (Linear Research Inc. LR-700P). To reduce the experimental deviation, each couple of $^{16}$O and $^{18}$O samples are measured synchronously in a cooling process.

Temperature dependence of resistivity for the samples La$_{1.6-x}$Nd$_{0.4}$Sr$_2$CuO$_4$ with $x = 0.10, 0.125, 0.15$ and $0.175$ treated in $^{16}$O are shown in Fig.1. $T_C$ (defined as the midpoint of superconducting transition in resistivity) is 11K, 7.9K, 17.8K and 25K for $x = 0.10, 0.125, 0.15$ and 0.175, respectively, being consistent with that reported in other literatures[3,17,20,22]. The suppression of $T_C$ compared with La$_{2-x}$Sr$_x$CuO$_4$ is attributed to the static stripe phase induced by the substitution of Nd for La atoms[7]. The abnormal suppression on $T_C$ near 1/8 doping can be clearly seen in our samples, that is, the $T_C$ is the least for the sample with $x = 0.125$. A small resistivity jump appears at about 70K, which is indicated by an arrow and regarded as the signal of structural transition from LTO to LTT[17,18]. To show this jump clearly, the temperature dependence of derivative of resistivity is shown in the inset of Fig.1. A dip can be seen clearly in the derivative curve. Here we define $T_LT$ as the dip temperature: 66.7K, 71K, 73.1K and 80K for $x = 0.10, 0.125, 0.15$ and 0.175, respectively. $T_LT$ increases with increasing Sr doping, consistent with that reported in Ref.[17].

Figure 2 shows the temperature dependence of resistivity near the superconducting transition for the sample with $x = 0.125$. It should be pointed out that the superconducting transition is a little broadening, which may be caused by the fluctuation of Sr, Nd and/or O contents. $T_C$ is 7.9K and 6.6K for $^{16}$O and $^{18}$O samples, respectively. To ensure the change of $T_C$ from isotope substitution, back-exchange of $^{18}$O sample by $^{16}$O was performed. Fig.3 shows the Raman spectra at room temperature for the sample with $x = 0.125$. The apical O stretch mode is softened from 433(±1) cm$^{-1}$ to 413(±1) cm$^{-1}$ by the substitution of $^{18}$O for $^{16}$O. This frequency shift of 4.6%±0.3% suggests about 79% $^{18}$O substitution because Raman shift is in proportion to $1 - \sqrt{16/M^*}$[30,51]. The $^{18}$O substitution estimated by Raman shift is consistent with the result obtained from weight change. For comparison, $\rho(T)$ of back-exchanged samples are also shown in Fig.2. Two $^{16}$O/$^{18}$O samples show the same $T_C$, which definitely indicates the change of $T_C$ arises from the oxygen isotope exchange. The isotope exponent on $T_C$ in this sample $\alpha_C = -d\ln T_C/d\ln M_O$ is 1.89.
much larger than 0.5 deduced from BCS theory.

The phonon-mediated BCS theory shows that in condition of weak electron-phonon coupling the increase in lattice mass enhances the effective mass of charge carriers m∗, and lowers the superconducting gap Δ, and finally suppresses T C. This used to be successful in explaining the isotope effect in most of conventional superconductors, but failed in explaining the isotope effect in high T C superconductor[32]. Especially in La2−xSrxCuO4 [26, 27, 28, 29] the isotope exponent around 1/8 doping is about 1. Zhao et al. [28, 29] explain this with small polaron theory that the effective mass of supercarriers depends strongly on the oxygen-isotope mass in deeply underdoped regime, indicating strong electron-phonon coupling in it. The isotope exponent αC ∼ 1.89 in La1.6−xNd0.4SrxCuO4 with x=0.125 is much larger than that (∼ 1.0) in the Nd free sample La2−xSrxCuO4. It indicates a stronger electron-lattice coupling in La1.6−xNd0.4SrxCuO4. Nd doping induces a structural transition from LTO to LTT, which pins the stripe phase from fluctuating (Nd free sample) to static[7, 8] and enhances the distortion of CuO2 plane[20]. It has been reported in manganites that lattice distortion tends to introduce stronger electron-phonon coupling[33]. Therefore, the electron coupled to the more distorted CuO2 plane induced by Nd doping is responsible for the larger isotope exponent relative to the Nd free sample.

Figure 4 shows the temperature dependence of resistivity near T LT for the samples of x = 0.125. T LT is enhanced from 71K to 72.3K with the substitution of 16O by 18O the isotope exponent αLT is about -0.19. As shown in Fig.4, the resistivities are almost the same for the back-exchanged samples. It ensures that the change in T LT arises from the isotope effect. The increase of T LT indicates the enhancement of stabilization for LTT phase, suggesting the enhancement of distortion in CuO2 plane by substitution of 16O by 18O. As shown in Fig.2 and Fig.4, the substitution of 16O by 18O leads to a decrease in Tc and an increase in TLT. The oxygen isotope effect provides an evidence that the distortion of CuO2 plane suppresses the superconductivity, being consistent with the increase of Tc by lowering the impact of the disorder in Bi2212[34]. It has been reported that the charge ordering and structural transition are essentially coincident for x=0.10 and 0.12[8, 17]. Therefore, the increase of TLT indicates the enhancement of charge stripe, suggesting the competing between the stripe phase and superconductivity.

For the samples La1.6−xNd0.4SrxCuO4 with x=0.10, 0.15 and 0.175, the oxygen isotope exponents for superconducting transition αC are 1.24, 0.98, 0.33, while for structural transition αLT are -0.32, -0.20, -0.17, respectively. All samples show that the substitution of 16O by 18O leads to a decrease in Tc and an increase in TLT. Sr content dependence of oxygen isotope exponent for superconducting transition αC and structural transition αLT is shown in Fig.5. The largest αC is observed in the sample with x=0.125, such 1/8 anomaly for αC has been reported in La2CuO4-based superconductors[20, 27, 28, 29]. However, the αLT decreases with increasing Sr content. For comparison, αC reported in La2−xSrxCuO4 [27, 29, 30, 31, 32] is also shown in Fig.5. It clearly shows a trend that αC decreases with increasing Sr content except for an anomaly around x=0.125 in La2−xSrxCuO4. Our observation in La1.6−xNd0.4SrxCuO4 shows similar trend except that αC for all Nd doped samples is larger than that in La2−xSrxCuO4. It further indicates that the stronger distortion of CuO2 plane induced by Nd doping leads to a stronger electron-lattice coupling. The sample with x = 0.10 shows the largest αLT value, which may be due to the approach to the phase boundary from LTO to LTT/Fccn for this Sr content[17]. The large isotope effect caused by the instability of lattice around phase boundary has also been found in cobalt[57].
In the phase diagram of La$_{2-x-y}$Nd$_x$Sr$_y$CuO$_4$ system, $T_{LT}$ and the temperature of occurrence of stripe phase increases simultaneously with keeping Sr content constant and increasing Nd content. Therefore, it can be believed that substitution of $^{16}$O by $^{18}$O leads to an increase of $T_{LT}$, consequently to enhancement of stripe phase. With keeping Nd content unchanged and increasing Sr doping level, the temperature where stripe phase occurs shows a hump as a function of Sr doping level, while $T_{LT}$ increases with increasing Sr doping level. The suppression of stripe phase for $x > 1/8$ is just caused by the deviation of hole concentration from $1/8$. In our case, the oxygen isotope substitution doesn’t change the hole concentration. Therefore, the increasing of $T_{LT}$ caused by substitution of $^{18}$O by $^{16}$O for each composition indicates the enhancement of stripe phase. These results show us a direct evidence for the competing between static stripe phase and superconductivity. Recently, Reznik et al. found that a strong anomaly in Cu-O bond-stretching phonon in La$_{1.6-x}$Sr$_x$CuO$_4$ appears in superconducting doping level, while disppears in non-superconducting doping level. It suggests the importance of electron-phonon coupling to the mechanism of superconductivity. The anomaly is the strongest in the samples with static stripe phase: La$_{1.48}$Nd$_{0.4}$Sr$_{0.12}$CuO$_4$ and La$_{2.6}$Ba$_2$CuO$_4$. Our isotope substitution confirms the strong electron-phonon coupling in La$_{1.6-x}$Nd$_x$Sr$_x$CuO$_4$ system, and supports the importance of electron-phonon coupling to the mechanism of superconductivity for high $T_C$ superconductors.

In conclusion, oxygen isotope effect is systematically studied in La$_{1.6-x}$Nd$_x$Sr$_x$CuO$_4$ with static stripe phase. $T_C$ is suppressed and $T_{LT}$ is enhanced with the substitution of $^{18}$O by $^{16}$O. These results provide an evidence that the distortion of CuO$_2$ plane suppresses the superconductivity, and there exists a competing between static stripe phase and superconductivity. $\alpha_C$ shows $1/8$ anomaly, similar to that the observation in Nd free sample. Larger oxygen isotope effect on $T_C$ is observed compared to the Nd free samples. It indicates that stronger distortion of CuO$_2$ plane leads to a stronger electron-phonon coupling. In addition, our results confirm the strong electron-phonon coupling in the La$_{1.6-x}$Nd$_x$Sr$_x$CuO$_4$. It is well known that distortion of CuO$_2$ plane is common feature shared by high-$T_c$ cuprates. Therefore, electron-phonon coupling should play important role in the mechanism of high-$T_c$ superconductivity.

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