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Layer-specific hole concentrations in Bi$_2$Sr$_2$(Y$_{1-x}$Ca$_x$)Cu$_2$O$_{8+\delta}$ as probed by XANES spectroscopy and coulometric redox analysis

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The high-$T_c$ superconductive copper oxide, $M_mA_2Q_{n-1}Cu_2O_{m+2+2n\pm\delta}$ or $M - m (n-1)n$, is believed to possess an antiferromagnetic insulating ground state related to its “undoped parent phase.” By increasing the CuO$_2$-plane hole concentration the phase undergoes an insulator-metal transition and starts to show superconductivity with a transition temperature, $T_c$, that strongly depends on the concentration of induced holes. In the multi-layered structure of an $M - m (n-1)n$ phase the superconductive $Q_{n-1}Cu_2O_{2n}$ block containing the CuO$_2$ plane(s) is sandwiched with two AO layers and an $M_mO_{m\pm\delta}$ “charge reservoir” block with a layer sequence of $AO-CuO_2-(Q-CuO_2)_{n-1}-AO-(MO_{1, \pm \delta/m})_m$. Among the variety of known $M - m (n-1)n$ phases ($M = $, e.g., Cu, Bi, Pb, Tl, Hg, Al, Ga, and B; $m = 0 \pm 3$; $A = $, e.g., Ba, Sr, and La; $Q = $, e.g., Ca, a rare-earth element $R$; $n = n - 1$), only a limited number of phases, e.g., (La,Sr)$_2$CuO$_{4+\delta}$ (0201), CuBa$_2$RCu$_2O_{4+\delta}$ (Cu-1212), Bi$_2$Sr$_2$(R,Ca)Cu$_2$O$_{4+\delta}$ (Bi-2212) and (Tl$_2$,Pb)$_2$Sr$_2$(R,Ca)Cu$_2$O$_{4+\delta}$ ([Tl,Pb]-1212), allow us to experimentally observe the actual appearance of superconductivity adjacent to the insulator-metal boundary. This is because many of these phases are structurally rather weak to sustain doping within a sufficiently wide range. Another difficulty arises from the fact that no universal experimental tool to accurately probe the local CuO$_2$-plane hole concentration in the multilayered copper-oxide superconductor has been realized yet. Thus, for instance, the threshold CuO$_2$-plane hole concentration for the appearance of superconductivity has been established only for the simplest case, i.e., for an $m = 0$, $n = 1$ system, (La,Sr)$_2$CuO$_{4+\delta}$, at $0.050 \pm 0.06$. Here we report the layer-specific hole concentrations in an $m = 2$, $n = 2$ system, Bi$_2$Sr$_2$(Y$_{1-x}$Ca$_x$)Cu$_2$O$_{8+\delta}$, within the whole Cu$^{II}$-for-Y$^{III}$ substitution range, i.e., from an undoped insulating state ($x = 0$) to a slightly overdoped state ($x = 1$), as probed by two independent experimental techniques: x-ray absorption near-edge structure (XANES) spectroscopy and coulometric redox titration. The two techniques - a direct physical technique and an indirect but highly precise wet-chemical technique - are found to reveal highly consistent values for the actual CuO$_2$-plane hole concentration.

Since for an $M - m (n-1)n$ phase with $n = 2$ all the CuO$_2$ planes are equivalent, the CuO$_2$-plane hole concentration, $p(CuO_2)$, that is related to the nominal valence of copper, $V(Cu)$, according to $p(CuO_2) = V(Cu) - 2$, can be calculated for these phases from the stoichiometry of the phase when both the exact oxygen content and the valences of the other metals than copper are accurately established. In the case of the Bi-2212 phase, the analytical difficulties arise...
from the fact that, besides copper, bismuth may also exhibit mixed valence states. Distinguishing the individual valences of Cu and Bi is possible by means of a wet-chemical redox analysis method based on the selective reduction of Bi$^{V}$ (i.e., pentavalent Bi in the solid structure) by Fe$^{2+}$ ions in an acidic solution and a subsequent electrochemical determination of the remaining amount of Fe$^{2+}$ ions by anodic oxidation$^{1,7}$ [Note that we use Roman numerals to denote the oxidation state/valence of a species in matrix and Arabic numerals for the charges of ions in solution.] The analysis can yield valence values with a high precision of ±0.01, but a critical question has remained to be addressed to the solution-based redox methods in general: how well are the solid-state characteristics, i.e., the fine-distribution of the remaining amount of Fe$^{2+}$ ions by anodic oxidation$^{1,7}$ can yield valence values with a reproducibility of less than 0.01. The coulometric titration, i.e., anodic oxidation, as follows:

$$\text{Cu}^{+} \text{ (excess)} \rightarrow \text{Cu}^{2+} + e^- \text{ (coulometry)}.$$

(3)

From the amount of electrons produced in Eq. (3), the value of $\delta$ is calculated$^{1,7}$

The value of Bi valence was determined with another redox experiment, i.e., Fe$^{3+}$/Fe$^{2+}$ coulometric titration$^{1,7}$. This experiment allows us to detect selectively the amount of Bi$^{V}$ in the presence of Cu$^{II}$. The sample is dissolved in 1-M HCl containing a known amount of Fe$^{2+}$ ions. Pentavalent Bi reacts completely with Fe$^{2+}$ ions according to:

$$\text{Bi}^{V} + 2\text{Fe}^{2+} \rightarrow \text{Bi}^{3+} + 2\text{Fe}^{3+}.$$

(4)

The valence of Bi, V(Bi)$_{\text{tot}}$, is obtained by analyzing the amount of Fe$^{2+}$ ions that did not participate in reaction given by Eq. (4) through anodic oxidation:

$$\text{Fe}^{2+} \text{ (excess)} \rightarrow \text{Fe}^{3+} + e^- \text{ (coulometry)}.$$

(5)

Note that for Cu$^{III}$ reaction with water, i.e.,

$$4\text{Cu}^{III} + 2\text{H}_2\text{O} \rightarrow 4\text{Cu}^{2+} + \text{O}_2 + 4\text{H}^+,$$

(6)

is more preferable than that with Fe$^{2+}$ ions, which prevents Cu$^{III}$ from interfering the determination of the valence of bismuth. The value of the Cu valence, $V(\text{Cu})_{\text{tot}}$, can be calculated from the results of the oxygen content and Bi valence analyses, i.e., values of $\delta$ and $V(\text{Bi})_{\text{tot}}$, taking into account the cation stoichiometry of the phase.

The both redox experiments, i.e., those described by Eqs. (1)–(3) and (4) and (5), were carried out at room temperature under a flowing argon atmosphere. The 1-M HCl cell solution was freed from dissolved oxygen by bubbling argon gas through it and the initial redox power of the cell was standardized by performing each time a pretitration with a small amount of the corresponding reducing agent. As sources of the Cu$^{+}$ and Fe$^{2+}$ ions, Cu$_2$O and FeCl$_2$·4H$_2$O, respectively, were used. Before the actual analyses, blank titrations were carried out to check the Cu$^{+}$ and Fe$^{2+}$ contents of these reductants. Each redox experiment was repeated at the minimum of five times to reveal the oxygen content and valence values with a reproducibility of less than ±0.01. The coulometric titration of Cu$^{+}$ ions [cf. Eq. (3)] was performed at a constant current of 5 mA until the potential of the AgCl/Ag indicator electrode reached 980 mV. The corresponding values in the case of the anodic oxidation of Fe$^{2+}$ ions [cf. Eq. (5)] were 3 mA and 820 mV.

The x-ray absorption experiments were carried out on the 6-m High-Energy Spherical Grating Monochromator (HSGM) beam line at Synchrotron Radiation Research Center (SRRC) in Hsinchu, Taiwan. Both O K-edge and Cu L$_{2,3}$-edge XANES spectra were collected and the measurements were performed at room temperature. The powder samples were attached by conducting tape, and then put into an ultra high vacuum chamber ($\sim 10^{-9}$ torr) in order to...
avoid surface contamination. The x-ray-fluorescence-yield spectra were recorded from the samples using a microchannel-plate (MCP) detector system consisting of a dual set of MCPs with an electrically isolated grid mounted in front of them. The grid was set to a voltage of 100 V, the front of the MCPs to ~2000 V, and the rear to ~200 V. The grid bias ensured that positive ions did not enter the detector, while the MCP bias ensured that no electrons were detected. The detector was located parallel to the sample surface at a distance of ~2 cm. Photons were incident at an angle of 45° in respect to the sample normal. The incident photon flux ($I_0$) was monitored simultaneously by a Ni mesh located after the exit slit of the monochromator. All the absorption measurements were normalized to $I_0$. The photon energies were calibrated with an accuracy of 0.1 eV using the O K-edge absorption peak at 530.1 eV and the Cu L$_3$ white line at 931.2 eV of a CuO reference. The monochromator resolution was set to ~0.22 and ~0.45 eV at the O K (1s) and Cu L$_{2,3}$ (2p) absorption edges, respectively. The x-ray-fluorescence-yield spectroscopy method applied is bulk-sensitive, the probing depth being 1000–5000 Å.

Judging from the x-ray-diffraction data, the synthesized Bi$_2$Sr$_2$(Y$_{1-x}$Ca$_x$)Cu$_2$O$_{8+\delta}$ samples are of single phase in the whole compositional range of 0 $\leq x \leq$ 1. From the wet-chemical redox analysis continuous decrease from 0.52 to 0.25 in the amount of excess oxygen, $\delta$, is revealed upon increasing Ca content, $x$, from 0 to 1, as shown in Fig. 1. The obtained values for $\delta$ are essentially identical to those (ranging from 0.51 to 0.23) previously reported for air-synthesized Bi$_2$Sr$_2$(Y$_{1-x}$Ca$_x$)Cu$_2$O$_{8+\delta}$ samples based on iodometric titration. As expected, with increasing $x$ the c-axis parameter of the unit cell increases, while both $a$- and $b$-axis parameters decrease (not shown). The expansion of the unit cell along the $c$ axis as $x$ increases is related to the fact that the ionic radius of Ca$^{II}$ is larger than that of Y$^{III}$. The contraction of the unit cell in the $a, b$-plane direction with increasing $x$ is due to an increase in the overall hole concentration, $p_{\text{tot}}$.

We calculate $p_{\text{tot}}$ for each sample from the known cation stoichiometry and the analyzed oxygen content as the amount of holes per half formula unit, i.e., the sum of the CuO$_2$-plane and BiO$_{1+\delta}$-layer hole concentrations. In Fig. 1, $p_{\text{tot}}$ is given against $x$. As the Ca$^{II}$ for Y$^{III}$ substitution proceeds, $p_{\text{tot}}$ increases monotonically even though $\delta$ decreases. From Fig. 1, with increasing $p_{\text{tot}}$ the hole concentration of the CuO$_2$ plane, $p(CuO_2)_{\text{tot}}$, calculated from $V(Cu)_{\text{tot}}$ as $p(CuO_2)_{\text{tot}} = V(Cu)_{\text{tot}} - 2$, increases from 0.02 to 0.12 when $x$ ranges from 0 to 0.1 in Bi$_2$Sr$_2$(Y$_{1-x}$Ca$_x$)$_2$O$_{8+\delta}$. Within the whole substitution range, the value of $p(CuO_2)_{\text{tot}}$ is essentially lower than that of $p_{\text{tot}}$, owing to the fact that upon oxidizing the phase some part of holes goes into the Bi$_2$O$_2+\delta$ charge-reservoir block. The value of the concentration of holes in one BiO$_{1+\delta}$ layer given by $p(BiO_{1+\delta})_{\text{tot}} = V(Bi)_{\text{tot}} - 3$ increases with increasing $x$ from 0.00 to 0.13, despite the fact that the amount of excess oxygen, $\delta$, in the Bi$_2$O$_2+\delta$ block decreases (Fig. 1).

The increase in the CuO$_2$-plane hole concentration with Ca substitution is clearly revealed from the O K-edge XANES data. Figure 2 displays the O K-edge XANES spectra obtained for the samples in the energy range of 525–555 eV. With increasing $x$, a pre-edge peak develops around 528.3 eV. This peak was previously ascribed to holes in the $p_{xy}$ orbital. A similar feature has been observed...
established for many other $p$-type doped superconductive copper oxides. The peak at $530.5$ eV is due to the wide antibonding $Bi6p_{x,y,z}O$ and $O2p_{x,y,z}$ band, while the shoulder at $529.5$ eV, that is most clearly seen for the $x=0$ sample, arises from a transition into $O2p$ states hybridized with the upper Hubbard band (UHB). The O K-edge spectral features are analyzed by fitting Gaussian functions to the three pre-edge peaks. Before the fitting of the spectra, the energy of the pre-edge peaks is first normalized to have the same spectral weight, with the redox titration data given in Fig. 1 for the Cu and Bi valences of Cu and Bi increase with quite similar rates with increasing Ca substitution level. This is highly consistent with the redox titration data given in Fig. 1 for the Cu and Bi valence values.

Quantitative estimations for the CuO$_2$-plane hole concentration are obtained from the Cu L$_{2,3}$-edge XANES spectra. The Cu L$_{2,3}$-edge spectra measured for the samples in the energy range of 925–955 eV are shown in Fig. 4. For the $x=1.0$ sample, the spectrum exhibits two narrow peaks centered at $931.2$ and $951.2$ eV. These peaks are due to divalent copper states, i.e., transitions from the Cu$(2p_{3/2,1/2})3d^{9}O2p^{6}$ ground-state configuration into the Cu$(2p_{3/2,1/2})3d^{10}O2p^{5}$ excited state, where $(2p_{3/2,1/2})^{-1}$ denotes a $2p_{3/2}$ or $2p_{1/2}$ hole. Oxidation of copper beyond the divalent state is seen as shoulders on the high-energy side of these peaks. Such shoulders, first observed for fully-oxygenated CuBa$_2$YC$_2$O$_7$ and later for various Bi-2212 samples, are interpreted as transitions from the Cu$(2p_{3/2,1/2})3d^{9}L$ ground state into the Cu$(2p_{3/2,1/2})3d^{10}L$ excited state, where $L$ denotes a ligand hole in the $O2p$ orbital, i.e., being due to Cu$^{III}$. With increasing $x$, both the absorption peaks become more asymmetric, as the $2p$ hole concentration on the oxygen site increases leading to an increase in the intensity of the high-energy shoulders. For each sample, the spectrum is analyzed by fitting the $L_3$ peak (that is more intense than the $L_2$ peak) and its shoulder with Gaussian functions. The integrated intensity of the shoulder [$I(Cu^{III})$] is normalized against the total spectral weight in the $L_3$ area below $935$ eV, i.e., the sum of integrated intensity of the main peak [$I(Cu^{II})$] and that of the shoulder itself. The normalized intensity of the shoulder, i.e., $I(Cu^{III})/[I(Cu^{II})+I(Cu^{III})]$, gives the ratio of the amount of Cu$^{III}$ to the total amount of Cu$^{II}$ and Cu$^{III}$, thus being nothing but a direct estimation for the hole concentration of the CuO$_2$ plane, $p(CuO_2)_{XAS}$. In Fig. 5, the thus obtained $p(CuO_2)_{XAS}$ values are plotted against $x$, together with the CuO$_2$-plane hole concentration values estimated based on the
The CuO$_2$-plane hole concentration, $p$(CuO$_2$)$_{\text{XAS}}$, as calculated from the fitted Cu L$_3$-edge XANES data with respect to the Ca-substitution level $x$, for the Bi$_2$Sr$_2$(Y$_{1-x}$Ca$_x$)Cu$_2$O$_{8+\delta}$ samples. Note that $p$(CuO$_2$)$_{\text{XAS}}$ are in good agreement with $p$(CuO$_2$)$_{\text{tit}}$ (given in Fig. 1) within the experimental error limits. Also note that both $p$(CuO$_2$)$_{\text{XAS}}$ and $p$(CuO$_2$)$_{\text{tit}}$ are always lower than $p_{\text{tot}}$.

coulometric redox analysis. Also given are the values of $p_{\text{tot}}$ for reference. As $x$ increases from 0 to 1, $p$(CuO$_2$)$_{\text{XAS}}$ increases from 0.04 to 0.15. The value of 0.15 obtained for the $x=1$ sample (Bi$_2$Sr$_2$CaCu$_2$O$_{8.52}$) is exactly the same as previously reported for similar samples based on Cu L$_3$-edge XANES analysis. For the whole sample series, the $p$(CuO$_2$)$_{\text{XAS}}$ values ranging from 0.04 to 0.15 are also in good agreement with those of $p$(CuO$_2$)$_{\text{tit}}$ ranging from 0.02 to 0.12, within the error limits estimated for the two analysis techniques, i.e., ±0.01 for $p$(CuO$_2$)$_{\text{tit}}$ and ±0.02 for $p$(CuO$_2$)$_{\text{XAS}}$. Moreover, both the analyses clearly reveal that the actual $p$(CuO$_2$) values are essentially lower than the $p_{\text{tot}}$. In Fig. 6, the relationship between $T_c$ and the CuO$_2$-plane hole concentration, $p$(CuO$_2$)$_{\text{tit}}$, taken as an average of $p$(CuO$_2$)$_{\text{tit}}$ and $p$(CuO$_2$)$_{\text{XAS}}$, is shown. Superconductivity appears in the Bi$_2$Sr$_2$(Y$_{1-x}$Ca$_x$)Cu$_2$O$_{8+\delta}$ system at $x=0.4–0.5$ with increasing Ca content. From Fig. 6, the threshold CuO$_2$-plane hole concentration for the appearance of superconductivity can be established at 0.06 ±0.01. With increasing Ca$^{II}$-for-Y$^{III}$ substitution level, $T_c$ increases up to $x$=0.8 such that the maximum $T_c$ of ~90 K is observed at $p$(CuO$_2$)$=0.12$. The $x=1$ sample with $p$(CuO$_2$)$=0.14$ is considered to be already slightly overdoped. In terms of the appearance of superconductivity the present threshold $p$(CuO$_2$) value of ~0.06 coincides with that established for the (La,Sr)$_2$CuO$_{4+\delta}$ system. On the other hand, the $p$(CuO$_2$)$_{\text{opt}}$ value of ~0.12 revealed for the Bi$_2$Sr$_2$(Y$_{0.2}$Ca$_{0.8}$)Cu$_2$O$_{8.30}$ sample with the highest $T_c$ is somewhat low if one expects a value close to 0.16. Here we would like to note, however, that $p$(CuO$_2$)$_{\text{opt}}$ being at ~0.16 has been experimentally established only for (La,Sr)$_2$CuO$_{4+\delta}$. The Hg-based single-CuO$_2$-plane copper oxide, HgBa$_2$CuO$_{4+\delta}$, is another phase for which determination of the actual CuO$_2$-plane hole concentration should be straightforward. Nevertheless, no direct evidence pointing out at $p$(CuO$_2$)$_{\text{opt}}$ being at 0.16 has been presented. For an optimally doped HgBa$_2$CuO$_{4+\delta}$ sample, a value of 0.18 was revealed based on O K-edge XANES analysis. Estimations based on the amount of excess oxygen in HgBa$_2$CuO$_{4+\delta}$ typically result in even higher $p$(CuO$_2$)$_{\text{opt}}$ values if integer valence values of II and −II, respectively, are assumed for Hg and O atoms in the HgO$_x$ charge reservoir. For optimally doped CuBa$_2$YCu$_2$O$_{7-\delta}$ O K-edge XANES data revealed a CuO$_2$-plane hole concentration of 0.20, while quantitative analysis of reflection intensities of convergent-beam electron diffraction data ended up to a value of 0.25. For the three-CuO$_2$-plane phases the question on the optimum CuO$_2$-plane hole concentration is rather complicated and far from understood yet. Against this discussion the present result of the $p$(CuO$_2$)$_{\text{opt}}$ value being at ~0.12 in the Bi$_2$Sr$_2$(Y$_{1-x}$Ca$_x$)Cu$_2$O$_{8+\delta}$ system suggests that the precise mechanism behind the $T_c$ degradation in the so-called over-doped region may not be totally equivalent among the various high-$T_c$ superconductive systems.

In conclusion, utilizing two independent analytical techniques, i.e., XANES spectroscopy and wet-chemical redox analysis, we have here unambiguously revealed that for Bi$_2$Sr$_2$(Y$_{1-x}$Ca$_x$)Cu$_2$O$_{8+\delta}$ samples sintered in air not only the oxygen content and the valence of Cu (CuO$_2$-plane hole
concentration) but also the valence of Bi (charge-reservoir hole concentration) change gradually as the Ca$^{II}$-for-Y$^{III}$ substitution proceeds. Moreover, excellent quantitative agreements have been demonstrated in the magnitude of the valence values estimated through the two techniques.

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