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## High- $T_c$ superconductivity in strongly overdoped cuprates

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It is widely accepted that, in the overdoped region,  $p > 0.27$  hole/Cu, where superconductivity disappears, the properties of cuprates are conventional, i.e. Fermi-liquid like. In fact, until recently, such conventional scenario for overdoped cuprates has never been verified experimentally owing to the difficulty of overdoping the CuO<sub>2</sub> plane.

Here we report on the successful synthesis of high-purity polycrystalline samples of strongly overdoped YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7+x</sub> and Cu<sub>0.75</sub>Mo<sub>0.25</sub>Sr<sub>2</sub>YCu<sub>2</sub>O<sub>7+x</sub> [1] with oxygen content,  $x$ , up to 0.4 (i.e.  $p > 0.5$  hole/Cu, well beyond the superconducting dome) using a high-pressure oxygenation method at 4-6 GPa. Surprisingly, all samples exhibit bulk superconductivity in the 80-90 K range with little variations of  $T_c$  as a function of  $x$ . This result is confirmed by the observation of a nearly  $x$ -independent superfluid density by muon-spin-relaxation spectroscopy. Remarkably, a common feature of both systems is a record short apical distance between the apical oxygen and the planar Cu atom, which points at a partial occupancy of both Cu  $d_{x^2-y^2}$  and  $d_{z^2}$  orbitals [2,3]. Low-temperature specific heat measurements suggest the existence of a significant fraction of unpaired electrons, consistent with a picture of electronic phase separation. Finally, a study of the local structure by means of Extended X-ray Absorption Fine Structure (EXAFS) spectroscopy unveils huge ( $\sim 1$  Å) dynamical distortions of the lattice at  $T_c$  that involve the apical oxygen [4,5], which reflects a lattice-driven change of the electronic structure in the superconducting state. The above unexpected results put into question the validity of the current phenomenological description of cuprates. Specifically, we discuss the possibility of multi-orbital superconductivity and the implications of the nonadiabatic scenario suggested by our experiments on the electron-lattice dynamics.

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