Enhancing T c by oxygen isotope substitution in cuprates

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Abstract: The phase diagram of doped cuprates is generic. For low dopings a pseudogap is present at temperatures above the superconducting phase. The pseudogap phase is heterogeneous containing superconducting clusters which become phase coherent at T c (Müller in J. Phys. Cond. Matter 19:251002, 2007). Most recent propositions suggest to increase the cluster size and therefore to enhance T c . In the present note it is recalled that over a decade ago a giant oxygen isotope effect in low doped LSCO was reported. Thus, if indeed increasing the cluster sizes becomes possible, enhancing T c towards the onset of the pseudogap phase, then it may be even further enhanced by 16O to 18O substitution

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Abstract The phase diagram of doped cuprates is generic. For low dopings a pseudogap is present at temperatures above the superconducting phase. The pseudogap phase is heterogeneous containing superconducting clusters which become phase coherent at T_c (Müller in J. Phys. Cond. Matter 19:251002, 2007). Most recent propositions suggest to increase the cluster size and therefore to enhance T_c. In the present note it is recalled that over a decade ago a giant oxygen isotope effect in low doped LSCO was reported. Thus, if indeed increasing the cluster sizes becomes possible, enhancing T_c towards the onset of the pseudogap phase, then it may be even further enhanced by ^{16}O to ^{18}O substitution.

Keywords Superconductivity · Cuprates · T_c Enhancemenet · Isotope substitution

The generic phase diagram of hole-doped copper oxides is by now well known: when increasing the hole concentration n from zero, the antiferromagnetic (AFM) phase present is quickly suppressed, and via a glassy phase superconductivity sets in, at about 6 %. The transition temperature $T_c(n)$ increases as a function of n in a parabolic dome-like way, goes through a maximum and decreases to nothing at roughly 25 % hole doping. In a number of experiments it was discovered that upon cooling the system an electronic gap exists already at elevated temperatures, called $T^*(n)$, although no bulk superconductivity is observed. Various local probing experiments, including STM and EPR, revealed clusters of metallic character, and in part superconducting, that are embedded in a poorly-conducting AFM matrix [1].

The theoretical scenario is a percolative one: at sufficiently low temperature, phase coherence between the superconductive clusters or stripes occurs at $T_c(n)$. The larger n, the larger the clusters and the higher $T_c(n)$. This behavior has been successfully shown to occur by Monte Carlo simulations [2]. However, at very large n the above picture has to be replaced by the more conventional BCS one as the polaronic character is lost due to overlap of the carriers giving rise to a substantially larger Fermi energy.

Based on the above understanding for the occurrence of $T^*(n) \gg T_c(n)$ for small n, two propositions to enhance $T_c(n)$ towards $T^*(n)$ have been recently made. In both, the aim is to increase the size of the metallic clusters present such that the percolation towards 3D superconductivity occurs at higher temperature, hopefully near $T^*(n)$. In the first, Wolf and Kresin [3] propose to dope with oxygen the AFM CuO_2 planes in periodic stripes (called columns by them) with neighboring columns remaining undoped. The holes present in the doped columns would diffuse into the undoped ones, generating the pseudogap phase with large $T^*(n)$ in them, and $T_c(n)$ would approach it from below because it is expected that the clusters occurring there are larger than in the doped regions. This is assumed to be the case because the dopants are considered to be the cause for the depression of $T^*(n)$.

However, a number of experiments point towards cluster formation being an intrinsic phenomenon. Assuming this is the case, Müller and Shengelaya [4] have more recently proposed another way: to enhance the cluster size in the pseudogap phase, namely, to intercalate high-dielectric-constant layers such as ferro- or ferri-electrics, as well as quantum paralelctrics between the doped superconducting CuO_2 layers in cuprates, thereby reducing the Coulomb repulsion

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The stripe formation temperature T*

Isotope effect on

$$R = \frac{B_1 - A_1}{B_1 + A_1}$$
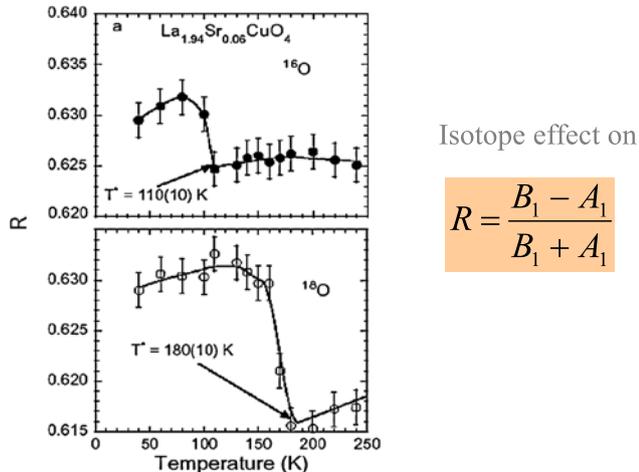
Lanzara et al., J. Phys.: Condens. Matter **11**, L541 (1999)

Fig. 1 Oxygen isotope effect on the stripe formation temperature T^*

between the intrinsically present clusters or stripes in the CuO_2 layers of the pseudogap phase. This should lead to smaller distances between these clusters and a coherence at higher temperature, i.e. higher T_c, with a smaller pseudogap $(T^* - T_c)$.

In addition to the two propositions above to enhance $T_c(n)$ towards the higher $T^*(n)$ for small n, there may be a third one, and experimental research will tell which is the valid one. In this context, it is of relevance that quite early on the isotope substitution ^{16}O by ^{18}O in $La_{1.84}Sr_{0.06}CuO_4$ resulted in a giant enhancement of $T^*(n)$ from 110 (10) to 180 (10) [5]; see Fig. 1, in which R is the ratio of certain near-edge X-ray absorption peaks.

In this experiment a shift of 70 (20) K was found by oxygen isotope substitution. Therefore, if an enhancement

of the percolation and thus of $T_c(n)$ can be achieved, then a further enhancement with oxygen isotope substitution on the order of 70 K can be expected for the superconducting transition temperature. We note that later in near optimally doped $La_{1.81}Sr_{0.16}Ho_{0.04}CuO_4$ an oxygen isotope effect at 60 to 70 K was reported [6], i.e. quite smaller than the only 6 % hole-doped LSCO in Fig. 1. However, in Ref. [7], work in $Bi_2Sr_2CaCu_2O_{8+\delta}$ is discussed [8] where a doping level of $n = 0.1$ with a T_c of 75 K had $T^*(0.1) = 180$ K. So with an ^{16}O to ^{18}O isotope substitution it might be possible to reach or exceed the room temperature in $T_c(n)$.

In summary, we note that once by suitable material arrangements the superconducting transition temperature $T_c(n)$ of copper oxide, a little doped, can be enhanced toward the much higher onset temperature of the pseudogap $T^*(n)$, then by ^{16}O to ^{18}O substitution,[1] $T_c(n)$ can be further substantially enhanced. This enhancement may well exceed the maximum transition temperature of a compound at the optimum doping.

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[1]Or using other isotopes of ions in HTS that exhibit a pseudogap like the cuprates.