Lattice Coupling Conspires in the Correlated Cuprate High-T_c Superconductivity

For the cuprate high temperature superconductivity (high-T_c) research over the past three decades, the biggest challenge is to identify the relevant low energy degrees of freedom that are critical to formulating the correct theoretical model for high-T_c superconductivity. The main difficulty lies in the closeness between various relevant energy scales. For low energy processes that are comparable to the superconducting gap energy Δ_{sc}, there are the spin exchange energy J, the lattice vibration (phonon) energy Ω_{ph}, and the van Hove singularity energy $E_{(\pi,0)}$. However, anomalous isotope effects on T_c and superfluid density in the cuprates cannot be captured by traditional phonon-mediated superconductivity theories. Historically, a purely electronic Hamiltonian – the Hubbard model – was widely regarded to encapsulate all the core physics of the high-T_c phenomena.

In a recent paper published in *Science*, scientists from Stanford University and from Stanford Institute for Materials and Energy Sciences (SIMES), in collaboration with material scientists from Japan and theoreticians from Japan, the Netherlands, and Berkeley, reinstated the substantial role of the lattice vibration in the cuprate high-T_c superconductivity – however, in a subtle way that is highly intertwined with the electronic correlations. They finely straddled 18 differently hole-doped high-T_c compound $Bi_2Sr_2CaCu_2O_{8+\delta}$ within 8% change of hole carrier concentration, a doping range where T_c evolves from 47 K to 95 K through a putative quantum critical point, around which the electronic correlation effect experiences a sudden change. Then systematic experiments were carried out using the angle-resolved photoemission spectroscopy (ARPES) facility at SSRL Beam Line 5-4. Here, the high-resolution ARPES end station provided critical information of both the superconducting gap and the electron-lattice coupling.

As shown in Fig. 1, the electron-lattice coupling at (π, 0) – the momentum where the superconducting gap is maximum – suddenly increases in strength when the doping is sensitively reduced from 22% to 19%, indicated by the rapid growth of the spectral "dip" shaded in grey. In the meantime, the superconducting gap quadruples, superconducting T_c doubles, and various electronic correlation effects become prominent. The phonon energy extracted from the ARPES spectra is around 37 meV, which agrees with a particular type of out-of-plane copper-oxygen bond buckling phonon. What is peculiar is the positive feedback between the development of superconductivity and the lattice coupling when the temperature is lowered, which cannot be simply explained under conventional single-particle framework. This phonon was predicted to be capable of enhancing the superconducting T_c by as much as 50% at moderate coupling, and is now experimentally demonstrated to show lock-step evolution with the growth of the superconductivity.

Fig. 2 also unifies the layer-dependence of T_c with the doping dependent perspective. For single-layer cuprate (e.g. Bi-2201) where the CuO_2 plane sits on the crystal mirror plane, this phonon is practically decoupled from the superconducting electrons as forbidden by symmetry. Indeed, single-layer cuprate spectra lack the coupling feature, and its T_c is much lower than its multi-layer counterparts, whose lattice symmetry allows the aforementioned coupling. Intriguingly, the correlation effects are also accordingly stronger in the multi-layer systems, which supports the self-consistent conjecture – the electronic correlation and the lattice coupling cooperatively feedback to each other, where the latter, with correct properties, enhances the superconductivity.

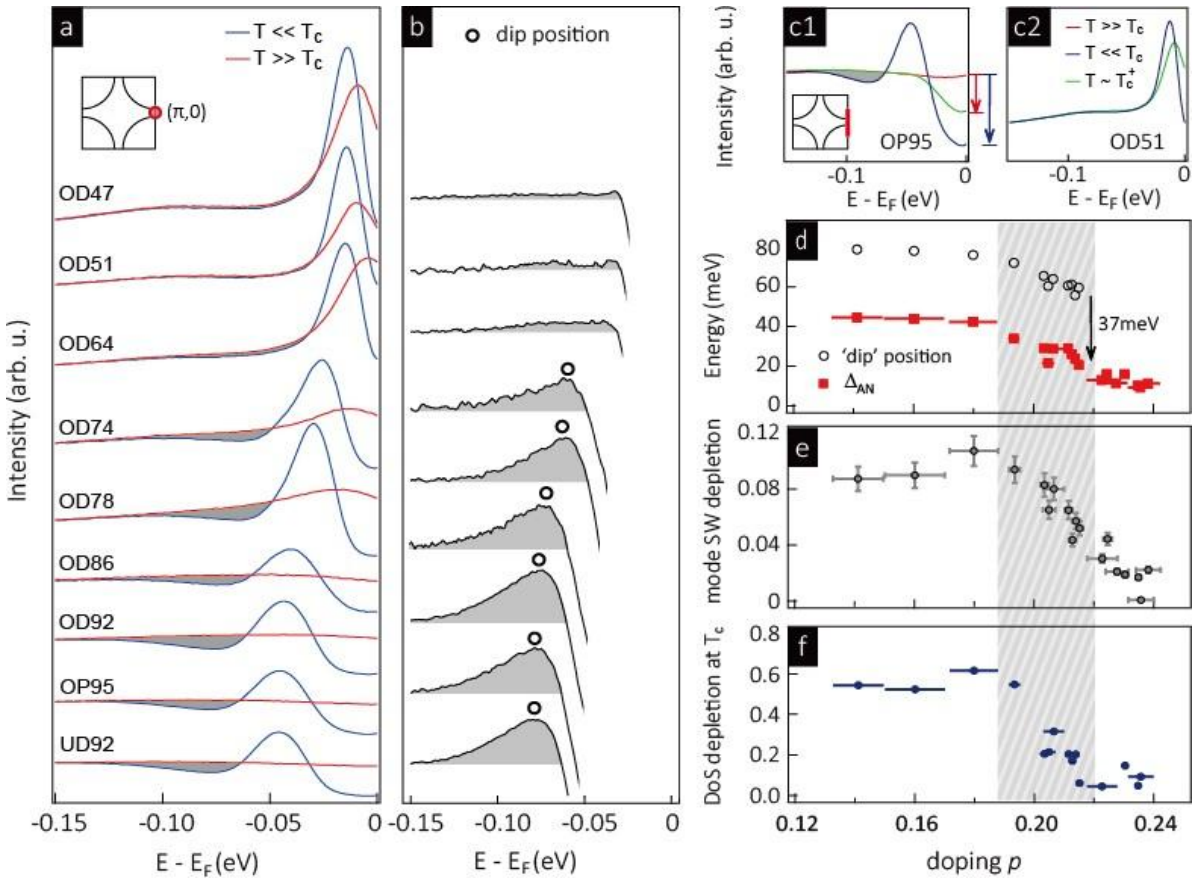

Figure 1: Abrupt growth of the electron-phonon coupling strength with underdoping. (a) The (π,0) FD-EDCs taken at low temperature (blue) and high temperature (red, $T \sim T^*$ for pseudogap regime, $T > T_c$ for sufficiently overdoped regime) from heavy overdoping (OD47) to slight underdoping (UD92). (b) The spectral intensity difference between the two temperatures for each doping. The black circles denote the dip maxima. (c) The integrated FD-EDC over the antinodal momenta at low temperatures ($T << T_c$, blue), just above T_c ($T \sim T_c^+$, green) and high temperatures ($T >> T_c$, red) for p = 16% sample (OP95, C1) and p = 23% sample (OD51, C2). The momentum integration range is noted by the red bar in the inset schematic BZ. (d) The doping dependent dip position and the co-evolving antinodal gap Δ_{AN} . (e) The doping dependent spectral weight of the dip (grey area in b) relative to the total spectral weight of the normal state. (f) The doping dependent antinodal spectral weight depletion at T_c^+ (red arrow in C1) relative to the full depletion at $T << T_c$ (blue arrow in C1), derived from the spectral intensity within ±2 meV of E_F. *Science,* doi: 10.1126/science.aar3394

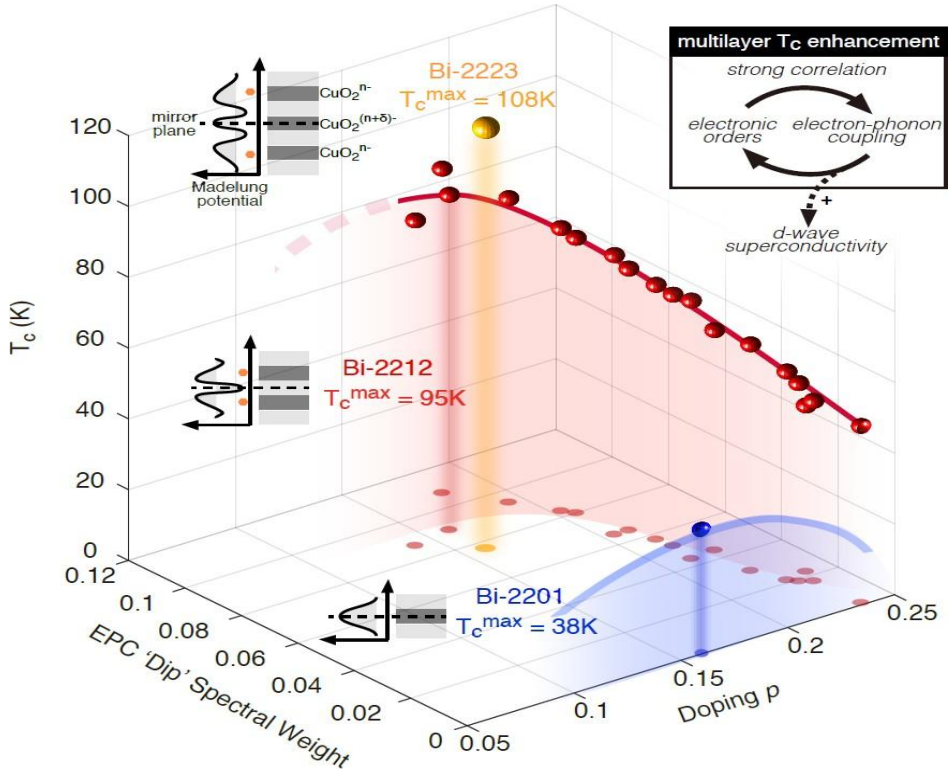

Figure 2: Intertwined growth of the superconductivity and the electron-phonon coupling tuned by the hole concentration. The red line is an illustration of the T_c in Bi-2212 (T_c^{max} = 95 K). The blue shade and line represent the single-layer Bi-2201 system, where the coupling to the B1g mode is weak and T max is only 38 K. The yellow ball represents the optimally doped tri-layer Bi-2223 where T_c^{max} is 108 K. The top-right inset shows the intertwined relation between the pseudogap and the EPC under strong electronic correlation. The Madelung potential and the lattice stacking along the c-axis are schematically depicted for the single- layer, bi-layer and tri-layer systems. The dark grey blocks represent the CuO_2^{n-} plane, and the light grey blocks represent the charge reservoir layers (Ca^{2+}, SrO, BiO^{+}). The orange dots mark the CuO_2^{n-} planes that experience to the first order a non-zero out-of-plane electric field. *Science,* doi: 10.1126/science.aar3394

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