Optically driven superconductivity

J. Okamoto, A. Cavalleri, and L. Mathey, Theory of enhanced interlayer tunneling in optically driven high-T_c superconductors, Phys. Rev. Lett. **117**, 227001 (2016).

Recommended with a Commentary by Atsushi Fujimori, University of Tokyo

Optical control of superconductivity began decades ago with the observation of the instantaneous (on the time scale of picosecond) weakening of superconductivity using laser pulses with energies above the superconducting gap [1,2]. The phenomena were attributed to the excitation of quasi-particles across the superconducting gap. Before the state with excited quasi-particles is relaxed to the superconducting ground state (in microsecond), the amplitude of the superconducting order parameter oscillates, giving rise to the Higgs mode or amplitude mode, as detected by Raman scattering and THz spectroscopy of *s*-wave superconductors [3]. The Higgs mode can be driven not only by a monocycle THz pulse but also by multicycle THz light with energies below the superconducting gap through coherent forced oscillation [4].

Another recent striking result of optical control was the observation of transient (a few picosecond) superconducting signals, that is, Josephson plasma in the time-dependent optical conductivity, after THz pulse excitation (on the femtosecond scale) well above the T_c of the cuprate superconductor $YBa_2Cu_3O_{6+\delta}$ (YBCO) [5]. The transient "T_c" closely followed the so-called pseudogap temperature T^*, and reached room temperature in underdoped compounds. In that experiment, both the pump and probe light was polarized along the *c* axis and the energy of pump light was tuned to the energy of apical oxygen vibration. The vibration induces various effects that may lead to the transient enhancement of T_c:

(i) Non-linear electron-phonon coupling leading to unusual lattice distortion [6],

(ii) Suppression of charge order through modulating interlayer single-particle tunneling [7] or though coupling of the charge order to the vibration [8],

(iii) Parametric modulation of Josephson plasma resulting in the reduction of the phase fluctuations of superconducting order parameter [9,10].

In the recommended article, Okamoto, Cavalleri, and Mathey have demonstrated the enhancement of Josephson coupling using a realistic model of the bilayer system YBCO, basically along the third scenario that the periodic modulation of the system by coherent THz light modulates the (intra-bilayer and inter-bilayer) Josephson coupling strengths and thereby enhances the phase coherence. Although the calculation has been done for the superconducting state with thermal phase fluctuations of the order parameter and the enhancement of Josephson coupling strength is small, if incoherent or preformed Cooper pairs are formed in the pseudogap phase above T_c, the enhancement might become as gigantic as experimentally observed, and the system might be driven into a phase-coherent superconducting state up to T^*. The validity of this T_c enhancement scenario, therefore, relies on the preformed Cooper-pair origin of the pseudogap phase. The second scenario, where competition between charge (bond) order and superconductivity plays a major role, would explain the enhancement of T_c if the pseudogap is due to charge (bond) order. It should be noted, however, with decreasing hole concentration, T^* continue to increase (up to 300-400 K) while the charge ordering temperature T_{CO} reaches ~100 K

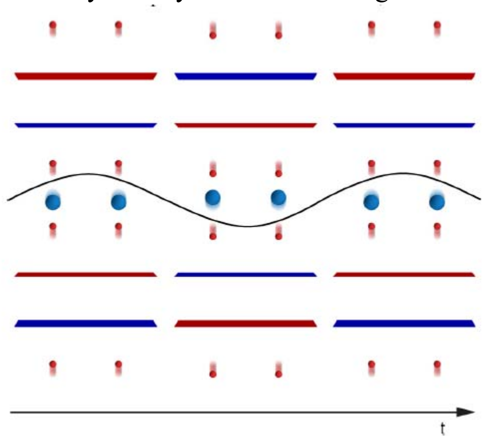

Fig. 1: Schematic crystal structure of YBCO as a function of time under THz irradiation polarized along the *c* axis. The CuO_2 bilayers and some atoms in the insulating layers including the displaced apical oxygen (small red spheres) are shown. (Reproduced from Ref. [10])

at ~1/8 doping and then drops [11].

Thus the elucidation of the transient enhancement of T_c up to ~T^* would give crucial information about the long-standing mystery of the origin of the pseudogap. Because the above scenarios (i)-(iii) do not exhaust all the possibilities, THz responses of other possible origins of the pseudogap such as short-range antiferromagnetic order, localized Cooper pairs, or other symmetry breaking and exotic orders so far proposed [12] will have to be examined theoretically.

Another fundamental question one may ask is how the THz light-driven enhancement of T_c in the 3D system K_3C_{60} (from T_c = 20 K in equilibrium to ~100 K) [13] is related or unrelated to the Josephson-coupled 2D system of the cuprates. If the weak three-dimensionality (finite single-particle hopping between the bilayers) in the cuprates helps to destroy the charge order and to enhance the superconductivity when optically driven, as discussed by Raines *et al.* [7], it could be possible that common processes are responsible for the enhancement of transient T_c in the cuprates and the truly 3D system K_3C_{60}.

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