Plasmon resonance mechanism for light-enhanced superconductivity in high-Tc superconductors

Recent pump-probe experiments on high Tc superconductors, conducted in the group of A. Cavalleri, have demonstrated that phonon motion stimulated by mid-infrared lasers transiently enhances superconductivity. In this paper, we propose a new scenario to explain this observation. We point out a resonance phenomenon between the pump pulse, the probe pulse, and the plasma mode of the superconducting state, in analogy to a Fano-Feshbach resonance.

Reaching room temperature superconductivity has been a major challenge since the discovery of superconductivity. Most of attempted methods are static modifications of system parameters, for example, by chemical doping or by pressure application. In a series of experiments, A. Cavalleri's group introduced a completely novel approach. Using laser pulses in the mid-infrared regime, phonon motion was excited (Fig. 1), and light-enhanced superconductivity in the following transient state was observed. This observation, reflected by the superconducting fluctuations above the transition temperature, suggests a new method of material design by dynamical control via laser pulses. However, these phenomena are not well understood so far, despite the fact that many theoretical groups have engaged in its study.

In this work [1], we report on a new description of optically driven high T_c superconductors. We model the layered structure of high T_c cuprates as a Josephson junction chain, as a framework to explain the observed non-equilibrium superconducting state. Our approach allows us to calculate the optical conductivity, which is the central experimental observable, both in a driven-steady state and in a transient state. We find that a pump frequency just above the plasma frequencies of the Josephson junctions, indeed very close to the frequency used in the experiments, is sufficient to enhance the interlayer Josephson coupling, i.e., the superconducting tunneling energy (Fig. 2). We point out that this mechanism can be considered as a Fano-Feshbach resonance between the pump pulse, the probe, and the plasma mode of the Josephson junction. In a follow-up paper [2], we have expanded this scenario to the transient response and have shown that the qualitative features of the experimental results of $YB_2C_3O_{6.5}$ can be well explained within this model.

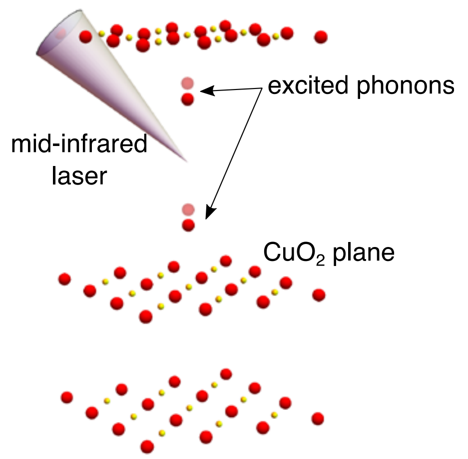

Fig.1: Schematic of optically driven YBCO. Mid-infrared laser excites apical oxygen atoms between CuO2 planes.

The non-equilibrium state that we find is a genuine non-thermal state. As a key result, we find that the driven state showing enhanced Josephson coupling actually has a smaller DC threshold current than the equilibrium state, which indicates larger noise or fluctuations. We demonstrate that such an apparent contradiction can be resolved by considering the non-thermal distribution of current spectral weights. In this non-equilibrium superconducting state, the fluctuation-dissipation theorem indeed no longer holds, and the system response crucially depends on how the state has been probed.

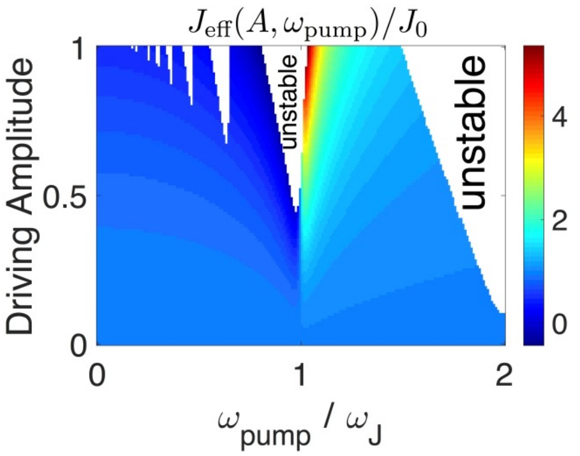

Fig.2: The effective Josephson coupling as a function of the driving amplitude and frequency ωpump. We see significant enhancement near the blue-detuned side of the plasma frequency ωJ.

In summary, we have developed a new theory of enhanced superconductivity based on a Fano-Feshbach resonance mechanism of the plasma mode. Our study provides new insights into the important problem of transient superconductivity in pump-probe experiments, and presents a new scenario for the understanding of fluctuating superconductivity above the critical temperature.

Junichi Okamoto, Hamburg University, Project B7

Original publications:

"Theory of enhanced interlayer tunneling in optically driven high Tc superconductors"
Physical Review Letters 117, 127201 (2016)
DOI: 10.1103/PhysRevLett.117.227001
J. Okamoto, A. Cavalleri, L. Mathey

"Transiently enhanced interlayer tunneling in optically driven high-Tc superconductors"
Physical Review B 96, 144505 (2017)
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J. Okamoto, W. Hu, A. Cavalleri, L. Mathey