Nonequilibrium superconductivity emerging from synergistic effects of light and phonons in strongly correlated systems

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Recently, laser-controlled superconductivity (SC) has been studied extensively to go beyond the limit of superconducting critical temperature T_C in equilibrium. One of the approaches is selective excitations of phonon modes of correlated electron materials by strong laser irradiation. Surprisingly, in the case of a bi-layered cuprate, indication of superconductivity above T_c has been reported [1,2]. This fascinating experiment has motivated theoretical studies for understanding its mechanism.

On the other hand, proposals for an alternative strategy ascribed to a more generic mechanism are also desirable. This is because the strategy based on coherent phonon excitations does not seem to be general in correlated electron materials at present due to strong restriction on the details of phonon modes in materials. Recently, we have proposed an alternative way to enhance SC in a correlated electron system without lattice degrees of freedoms [3]. In this study, we have shown that strong and non-resonant laser irradiation to a charge uniform state dynamically enhances SC without deteriorating into inhomogeneities that suppress SC in equilibrium. However, this approach can be applied only to uniform states in cuprates. Since inhomogeneous states were observed in a number of cuprates below optimal doping [4], it is important to verify whether strong and non-resonant laser irradiation dynamically melts static inhomogeneity and enhances SC.

Our purpose in this project is to clarify microscopic origin of the light-enhanced SC observed in the experiments. In addition, we also aim to clarify what happens when strong lasers are irradiated to equilibrium systems with inhomogeneity. Here, we summarize our main achievements for each topic.

(i) *Development of time-dependent variational Monte Carlo method for electron-phonon coupled systems:* In order to analyze an effective model for cuprates with light-driven phonon excitations, we need to treat not only strong electron correlations but also many phonons excited by laser irradiation. For this purpose, we extended a many-variable variational Monte Carlo (mVMC) method to nonequilibrium electron-phonon coupled systems. As a trial state, we adopt a tensor product state of an electron wave function and a phonon wave function with an electron-phonon correlation factor [5]. By introducing a large number of variational parameters to the phonon part, we can treat multi-phonon excitations by light.

As benchmarks of the mVMC method, we calculated relaxation dynamics after an electron-phonon interaction quench protocol of the one-dimensional Holstein model. We found that our trial wave function well reproduces the exact results for the time evolution of double occupancy and charge correlations. This result shows that the mVMC method offers an efficient and accurate way to study challenging problems of nonequilibrium electron-phonon coupled systems. The analysis of an effective model for the cuprates with phonons under laser irradiation will be reported elsewhere.

(ii) *Laser-enhanced superconductivity caused by dynamically melting charge inhomogeneity:* By using the mVMC method [6,7], we numerically study dynamics of *d*-wave SC and charge inhomogeneity when laser pulses are irradiated to an inhomogeneous ground state in a two-dimensional correlated electron system. We found that strong and non-resonant laser irradiation can melt charge inhomogeneity, and enhance *d*-wave SC. We observed that the lifetime of such enhanced SC is prolonged by keeping the laser intensity constant in the middle of the laser irradiation. Our findings will shed light on a new way to realize SC that is not attainable in equilibrium in strongly correlated electron systems.

References

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