論 文 の 内 容 の 要 旨

論文題目　Superconductivity and spatial inhomogeneity induced by electron correlations in and out of equilibrium
（平衡および非平衡条件で電子相関により誘起される超伝導と空間不均一性）

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Realizing superconductivity at room temperature is Holy Grail in condensed matter physics. To date, the highest superconducting critical temperature T_c at ambient pressure has been recorded in copper oxide superconductors around 130 Kelvin, which has essentially remained unchanged for several decades. Most studies were performed along the line that the high-T_c superconducting phase emerges in a carrier-doped two-dimensional Mott insulator and its strong pairing is believed to be caused by emergent strong effective attraction between carriers which arises originally from the bare strong repulsion between electrons. However, strong quantum fluctuations in such a system also generate other complex orders which compete with superconductivity. Among competing states, strong candidates are charge inhomogeneous states such as phase segregation in a mesoscopic scale and static stripe states, which have been experimentally observed in cuprates. The reason why the inhomogeneities exist in the high T_c superconductors would be that strong effective attraction between electronic carriers required for high T_c unavoidably drives the tendency for electrons to gather spatially. Therefore, it is important to strengthen the effective attraction while circumventing the emergence of the spatial inhomogeneities for the purpose of realizing superconductivity at much higher temperature.

To go beyond the limit of T_c in equilibrium, laser-controlled superconductivity has been studied extensively in the world. Recently, superconductor-like properties above critical temperatures in equilibrium were observed in correlated electron materials whose phonon modes were selectively excited by strong laser irradiation. These observations have inspired studies on an alternative and general strategy to be pursued for higher-temperature superconductivity by utilizing a nonequilibrium process.

In this thesis, we propose a new approach to enhance superconductivity in two-dimensional correlated electron systems by laser irradiation, which is not restricted to the details of phonon modes. Especially, we focus on the competition among various inhomogeneous states and charge uniform superconducting state in the Hubbard model on a square lattice, one of the simplest models for cuprates, which is still under debate even about the nature of the ground states.

To achieve the goal, we numerically study the ground and nonequilibrium states in the correlated electron system by using the variational Monte Carlo method in and out of equilibrium. By introducing about ten thousand variational parameters to a variational wave function for the largest systems, we have succeeded in treating various competing states such as a charge-uniform superconducting state and inhomogeneous stripe states with different periodicities on an equal footing. To verify the accuracy of our trial wave function in nonequilibrium states, we present our benchmark results for relaxation dynamics during and after interaction quench protocols of fermionic Hubbard models. We find that our trial wave function well reproduces the exact results for the time evolution of physical quantities such as energy, momentum distribution, and superconducting correlations.

To understand the stability of inhomogeneous states and the competition with the charge uniform superconducting state in the ground states of the two-dimensional Hubbard model, we study their dependences on the hole doping concentration δ, band structure and the on-site Coulomb interaction. Our numerical results show that the stripe states emerge as the ground states above the weak coupling region. The periods of the stripe states sensitively and systematically decrease with the evolution of hole doping. For the realistic band structure of the cuprate superconductors, the stripe period of the ground state at $\delta=1/8$ agrees with the experiments. The charge-uniform superconducting states with *d*-wave symmetry compete as excited states in most regions, but with a tiny excitation energy of the order of 10 Kelvin in terms of the realistic energy scale of the cuprate superconductors. The uniform superconducting order increases with the increment of the interaction, which is essentially similar to the stripe order. These stripe and superconducting phases appear simultaneously in a similar region of the doping concentration and interaction. These same trends between the superconducting and stripe orders and their severe competitions are understood from the emergent strong effective attractions between carriers generated from the originally strongly repulsive Coulomb repulsion.

Our results in the strong coupling region show that the stripe phase is extended in a much wider range of δ compared with the experiments. On the other hand, by weakening the interaction, the energy difference between the stripe states and the uniform *d*-wave superconducting state becomes small, and these states are nearly degenerate in the intermediate coupling region. This implies that within the single-band effective Hamiltonians, an appropriate description would be given in the intermediate coupling region rather than in the strong coupling region at least in terms of the stability of the stripe and superconducting phases.

Our analysis of the ground states implies that enhancement of the superconductivity in the cuprates would be attained if the effective interaction can be increased without introducing charge inhomogeneity. To verify this expectation, we simulate nonequilibrium dynamics in a hole-doped Hubbard model with intermediate couplings under laser irradiation. First, we study whether the superconductivity can be enhanced by laser irradiated to a charge uniform ground state. Our results show that the strong laser irradiation can enhance the superconductivity, which is subject to the Higgs oscillations. This enhancement is caused owing to the following mechanisms. First, the effective interaction between carriers is enhanced by the dynamical localization mechanism, which drives the system into strong coupling regions. Second, the irradiation allows uniform strong superconductivity dynamically stabilized without deteriorating into equilibrium inhomogeneities that suppress superconductivity. We also show the results when lasers are irradiated to an inhomogeneous state. We find that the inhomogeneity dynamically melts by nonresonant laser irradiation, and thus it causes the resultant enhancement of the superconductivity.

Our findings shed light on a new way to realize superconductivity that is inaccessible in equilibrium in strongly correlated electron systems. This study will open up further ways of not only controlling physical properties of materials by laser irradiation but also its application to new devices by utilizing light.