Electronic Correlations, Superconductivity, and Quantum Fluctuations Combined: Theory and Quantitative Interpretation of Experiment

Electrons in multi-atomic systems such as solids lead to their either metallic, semiconducting or insulating properties. This standard division broke down with the discovery of the Mott insulators and in particular strongly correlated (Mott) metals, in which a discontinuous phase transition between those states is observed. The fact inducing such a transition can be the external pressure or change of stoichiometry of the parent compound. The latter case takes place, e.g., for high-temperature superconductors. For the case of heavy electron systems, the subsystem of localized electrons delocalizes and turns itinerant under influence of other (conduction) electrons. This situation composes the first puzzle to solve.

The basic question is: What causes those transitions microscopically? Interesting for us here is the mutual proportion between interparticle interaction (Coulomb repulsion) and their kinetic energy. Namely, if the repulsive interaction is predominant over their average (or maximal) kinetic (band) energy, then the particles get localized back on the parent atoms creating that many-atom system. This process is the essence of *Mott transition*.

It turned out experimentally that when such Mott-insulator state has some unoccupied states by electrons (parent atoms are ions), then electrons can move by hopping between those empty (hole) states and the insulating state becomes *Mott metallic state*, in which electrons avoid each other, i.e., move in mutually *correlated* fashion. The most formidable feature of state is that manner electrons is that they can then form a superconducting state, i.e., carry electric current without any resistance. This state emerges under doping from the magnetic insulating state!

The fundamental question is how to describe this insulator to superconductor evolution, the last turning out at "high" ($\sim$ 100 K) temperature. The project author originally devised theoretical t-J model and, under influence of qualitative ideas of P. W. Anderson (1986) formulated a precise mathematical language of pairing in that case. A crucial problem still remains to formulate and test *quantitatively* description of concrete physical properties. We concentrated our research during the last 5 years on that task. In this project we would like to concentrate on influence of quantum collective excitations onto specific properties of high-temperature superconducting and related systems (e.g., heavy fermions). Those specific properties encompass calculations of charge carrier lifetime at nonzero temperature, appearance of the so-called *pseudogap* (second gap) or evolution of their Fermi surface with the doping. This is the second puzzle. All of these properties are absent in metallic state with no sizable correlations present.

Our new method formulated in 2020 and its successes in describing the collective excitations (paramagnons and plasmons) may carry out prospect that a quantitative answer can be provided to at least some of those profound questions. In Fig. 1 we present single copper oxygen plane with electrons (left) and with marked repulsive interaction (U), which induces correlated motion of them. Right: phase diagram containing main states of high temperature superconductor.

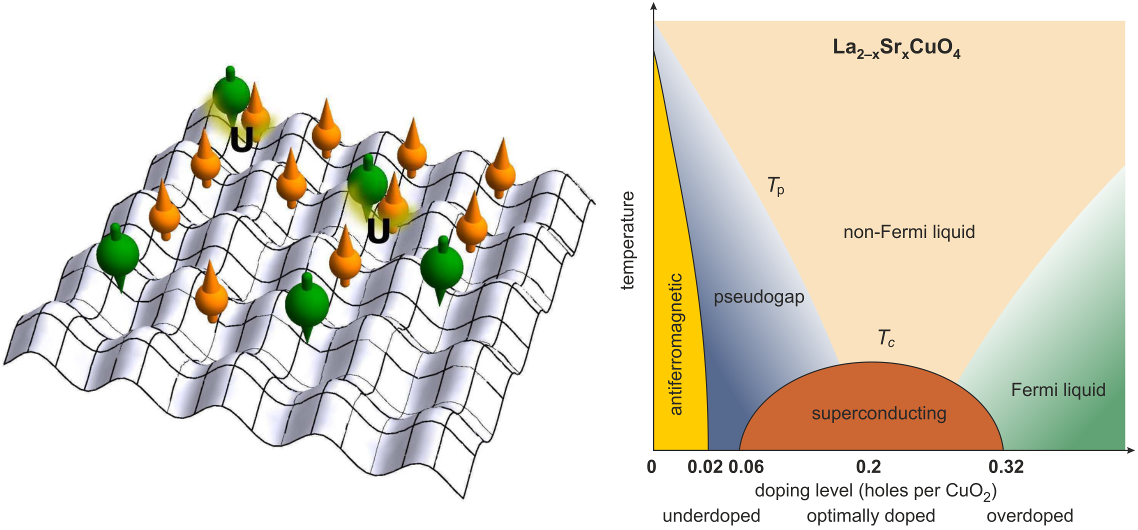

Fig. 1. Left: Lattice of strongly-correlated electrons in two dimensions. **Right:** Generic hole-density vs. temperature phase diagram of a high-temperature superconductor. Supercoductivity appears in between metallic and Mott-insulating phases.