DESCRIPTION FOR THE GENERAL PUBLIC

The intriguing properties of condensed-matter systems have inspired many fundamental concepts in quantum many-body physics. Of the utmost importance are strong correlations that lie at the heart of exciting and often unresolved phenomena such as high temperature superconductivity, colossal magnetoresistance, etc. However, theoretical analysis of the effects of strong interactions is usually significantly obscured by the complexity of the structures of solids, complicating the separation of various phenomena and also the presence of imperfections that blur the image.

Advances in methods of controlling and cooling of atomic gases led to obtaining Bose-Einstein condensation and Fermi degeneracy. However, recent developments have considerably extended the range of phenomena that can be observed using ultracold gases. Precise trapping of atoms in optical lattices, which are arbitrarily created periodical optical potentials, can be created with various dimensionality and geometry and also lead to strong localization of particles, allowed to investigate the properties of ultracold gases in a regime, when interactions even in extremely dilute gases are considered strong. The experimental possibilities of ultracold gases in optical lattices go way beyond observation of quantum phase transition in system of highly tunable interparticle interactions. Although the particles that are loaded in optical lattices are electrically neutral, it is possible to impose an additional external potential, which forces them to behave exactly like charged particles interacting with an external magnetic field. In the simplest case the potential can result from rotation, following from the formal equivalence between the Lorentz and the Coriolis forces. However, more control is obtained using additional photon-assisted tunneling or periodical shaking of the lattice to coherently transfer atoms from one internal state to another allowing application of wide range of external potentials.

In the solid-state physics phase transitions between different quantum states are classified by the principle of spontaneous symmetry breaking leading to the concept of order parameter. For every transition, an effective field theory can be formulated, generally called Landau-Ginzburg theory, which is determined by general properties such as dimensionality and symmetry of the order parameter giving a universal description of quantum states of matter. However, in 1980, a new quantum state was discovered which did not fit into this simple paradigm: in the quantum Hall (QH) state, the bulk of the two-dimensional (2D) sample is insulating, and the electric current is carried only along the edge of the sample. Furthermore, the flow of the unidirectional current avoids dissipation and gives rise to a quantized Hall effect. The QH state provided the first example of a quantum state, which is topologically distinct from all states of matter known before. In recent years, a new topological class of materials has been discovered, namely: topological insulators. These materials exhibit a nontrivial state with a full insulating gap in the bulk and gapless edge or surface states consisting of an odd number of Dirac fermions.

From theoretical point of view, strongly correlated ultra-cold atoms are quite demanding environment for analysis. A theory that describes them has to consider the wide versatility of optical lattices: from ease of modification of interparticle interactions, through varying geometry and dimensionality of lattices, presence of additional modifications from arbitrarily imposed potentials to the topology of the naturally arising phase degrees of freedom governing the quantum phase transitions in presence of strong correlations. Furthermore, a successful theory has to enable to predict the characteristic properties of the ultracold gases that can be directly verified experimentally.

The present project is motivated by the growing interest in topological phases of matter and the role of topology in quantum phase transitions. The universal nature of these phases and their remarkable properties call for extensive studies in model systems like ultracold atoms in optical lattice, which for high level of tunability and directness of observation of the underlying phenomena. The most important aspects is a possibility of simulating general classes of synthetic magnetic field potentials, which in connection to specially chosen geometry of the system is crucial in inducing topological phases, with a potentially high control of the physical parameters governing their ground state properties. Calculation of properties of these systems could allow for prediction of the presence of topologically non-trivial states and better understand of their nature.