Phase transitions of ultracold bosons in the presence of gauge fields

PhD thesis abstract

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In this thesis the properties of strongly interacting bosons in the presence of gauge fields were studied. Such systems can be realized in optical lattices filled with ultracold atoms, which can be used as quantum simulators of condensed matter systems, where the atoms play the role of the charge carriers and the periodic interference pattern of laser light plays the role of the crystalline lattice potential. High controlability of these systems allows to tune the properties of the system in a wide range of parameters and to reach regimes unobtainable in conventional condensed matter systems. In particular, as the optical lattices are isolated systems the atoms can be cooled to temperature low enough, to study quantum phase transitions. Optical lattice systems are also considered to be pure compared to condensed matter systems due to relatively low number of defects. However, the charge-neutrality of the cold atoms makes it impossible to directly study the influence of the electrodynamical potentials. The effects of gauge field can be simulated using the fact that the wave function of a charged particle in the presence of the gauge potentials acquires an additional phase. Analogous phase can be imprinted on neutral atoms, e.g. via Floquet engineering – a technique based on periodic driving of the system. This allows to study the strongly correlated systems with nontrivial topology in optical lattices.

In the non-interacting regime, the ultracold atoms in optical lattice can be described by the tight-binding model. The influence of the gauge fields can be included by introducing an appropriate phase change accompanying particle hoppings between lattice sites. In this thesis two particular cases of this model are considered: the Harper model, which describes a square lattice in a homegeneous magnetic field and is well-known for its fractal energy structure, and the Haldane model, which allows to study the different band topologies in a honeycomb lattice system. The tight-binding model can be extended

by taking into account interaction between the atoms. Strong localization of states on lattice sites allows to restrict the range of interaction between the atoms to the single-site only. In the case of atoms with Bose statistics, this allows to describe the system by the Bose-Hubbard model. The Bose-Hubbard model captures the essential physics underlying the quantum phase transition between Mott insulator and superfluid, which occurs in systems of ultracold bosons in optical lattices. This phase transition results from competition between the kinetic energy and on-site repulsive interaction. In the superfluid state the system exhibits long-range phase coherence, on the other hand the Mott insulator state is characterized by a finite energy gap and noncompressibility. The presence of the gauge field significantly modifies the transition point. Additionally, gauge fields influence the transport properties of these systems. Both of these aspects are studied in this thesis with the help of the quantum rotor approach, which allows to solve Bose-Hubbard model, while including the influence of spatial correlations beyond mean field approximation.