Transport properties of ultracold bosons in optical lattice

PhD thesis abstract

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In this thesis the problem of transport in strongly correlated boson systems in optical lattices was considered.

Optical lattices are created through interference of counter-propagating laser beams. In the resulting periodic potential, atoms of Bose-Einstein condensate can be trapped due to the AC Stark shift. Bose-Einstein condensates are achieved in atomic gases of bosonic alkali metals cooled to temperature near absolute zero ($\sim 10^{-9}$ K). Optical lattice systems can be used as quantum simulators of crystalline materials, where the laser light interference pattern acts as a periodic crystalline lattice and the ultracold atoms act as the charge carriers. Optical lattice systems have a great advantage of being clean systems – with minimal number of defects and impurities. Additionaly, the lattice parameters, such as dimensionality and geometry, or the on-site potential, can be easily modified. Moreover, there is a possibility of tuning the strength and sign of interactions between atoms. Latest experimental achievements allow for simulation of the effects of the magnetic field acting on charged particles (synthetic magnetic field) in neutral atomic environment in regimes unattainable in solid-state experiments. In recent years there appeared first experimental set-ups, where the transport properties of cold-atomic systems can be measured. These achievements have given the author the motivation for studying transport of strongly interacting boson lattice system and writing this thesis.

The description of strongly interacting bosons in optical lattice is given by the Bose-Hubbard model. This model predicts a quantum phase transition (at zero temperature) between the superfluid and Mott insulator states. Ordered, superfluid state is characterized by the long-range phase coherence and delocalization of particles, while in the disordered state, the Mott insulator, the phase coherence vanishes and bosons localize in the lattice sites.

In this thesis, the quantum rotor approach was employed to solve the Bose-Hubbard model. As opposed to methods based on the mean field approach, this method takes into account the spatial correlations, thus allowing to study the influence of geometry and dimensionality of the lattice on the current-current correlation function, which is related to transport properties of the system. Moreover, quantum rotor approach allows for description of both the superfluid and Mott insulator phases, and, as a result, determination of the conductivity as a function of the Bose-Hubbard model parameters. Especially, the value of the universal conductivity in two-dimensional systems can be determined.

Another problem considered in the thesis concerned the influence of the multiband energy structure on the conductivity. Such structure arises due to the introduction of the lattice basis, for example by the presence of the synthetic magnetic field. In this case, the conductivity can be separated into two parts – intra- and interband. The interband contribution appears only in the case of systems with multiband energy structure and can dominate over the intraband contribution even by several order of magnitude. The influence of the temperature on conductivty was also studied – it turns out that the conductivity is modified in different ways depending on the phase of the system. In non-zero temperature the interband conductivity exhibits additional trasport channels, which result from the coupling of thermally excited quasiparticles to the external field.