Description for general public

One of the challenges that contemporary physics aims to overcome is the possibility of maniupulating the matter on the quantum level. The control over the quantum properties of the matter would revolutionize many different fields of technology, for example metrology (the measurement of properties of single atoms or molecules), power engineering (lossless transport of energy e.g. due to high-temperature superconductivity) and information technology (the quantum computer, which may solve problems inaccessible to conventional computers). The precise engineering of these properties may be possible due to artificial quantum systems, such as e.g. systems of quantum dots. Quantum dots are artificial object behaving similarily to single atoms. The precise control of parameters of system of such dots (e.g. their size and spacing) would allow to obtain a material with desired properties.

One of the fundamental problems of such engineering is the sensitivity of these systems to the influence of the environment. For example, the fragile superpositions of states, necessary for quantum computing, are destroyed by process called decohrence. One of proposed ways of overcoming this difficulty is the usage of the topological phases of matter.

The topology is an abstract field of mathematics, which can be understood in a simplest way as geometry without the notion of distance. In topology the objects which can be deformed into each other in a continuous manner (e.g. a disc and a sphere) are indistinguishable of each other. Such a perspective allows to grasp some very general properties of objects, which do not change in such transformations. An example is the genus - the number of ”holes” in the object. A disc and a sphere have genus 0, and a torus, which cannot be obtained from a disc in a continuous way, has genus 1.

In recent years, the application of topology in quantum description of materials (more precisely: the electrons within the materials), is intensively studied. Their topological properties are very abstract, but they manifest itself in particular physical phenomena. Topologically different systems may at first appear similar, if we look at their bulk (i.e. interior). The differecne becomes apparent when these two materials are connected to each other - on such an interface, some interesting physical phenomena occur. The edge of the material can also be such a border, if it has different topological properties than the surrounding vacuum. These materials (more precisely: the quantum states of electrons inside it) are called topological phases of matter. One of the examples are the recently discovered topological insulators, whose bulk is insulating, but the edges conduct electricity. Because of their insensitivity to continuous deformations, the topological properties of materials are robust against perturbations.

In our research, we will consider two examples of topological phases of matter, characterized by strong correlation. This means that to describe their behaviour, one should track the behaviour of many electrons interacting with each other. It is a computationally difficult task even for supercomputers, who can usually simulate only small systems. This means that strongly correlated systems still hold many mysteries. Moreover, in strongly correlated topological phases interesting physical phenomena occur, for example so-called fractional quantum statistics. The quantum statistics describe the effect of interchanging two identical particles. All real particles (e.g. electrons) are described with one of two statistics: bosonic or fermionic. However, some quasiparticles (i.e. object which are not real particles, but behave in similar way) in strongly correlated topological phases exhibit a third one, ”anyonic”. Investigating such phenomena might extend our understanding of the basic properties of matter.

Our work will concern numerical simulation of two strongly-correlated topological phases of matter: the Haldane phase and fractional Chern insulator. The existence of the first one was confirmed experimentally in magnetic molecules. In my work, we will investigate a different proposal of its experimental realization: a chain of quantum dots, which allows more conrol over the parameters of the system and the possibilty of its analysis by optical means. The second topological phase is currently only a theoretical concept, postulated basing on computations for small systems. It was shown that its simplest variant can survive in the systems large enough to be investigated experimentally. The optimal conditions for its occurence were defined. For more complicated (and more interesting) variants, such calculations are missing. We plan to fill this gap with our project.

In summary, our calculations aim at deeper understanding of strongly correlated topological phases, and will be helpful for construcing experiments which will allow to observe their predicted properties.