

The aim of this project is to determine the properties of the Kitaev-Heisenberg model upon doping, focusing in particular on the original two-dimensional model and the extended version that best describes real materials. By determining the existence and the boundaries of the topological superconducting state, I will provide new insight for future applications in quantum computers. This project involves the usage of numerical simulations to study quantum magnetism.

Magnetism is present in our everyday lives. Without looking into complex technological devices, everyone has been in contact with magnets as a kid and one might even have some magnets hanging on their fridge door. The microscopical entities that govern magnetic behaviour are called spins. Such spins are an intrinsic property of quantum particles and follow quantum mechanical rules. Pictorially, one represents them with arrows that can point in different directions. The magnets on the fridge have these microscopic spins pointing in the same directions (aligned), so the total sum of all spins is non-zero. The spins, however, can also end up in different configurations. These configurations, or phases, depend on the microscopical forces, or interactions, that act on the spins. For example, there might be an interaction between spins that makes them point to opposite direction (antialign). In this case, the total sum of the spins, also known as magnetisation, will be zero and so we cannot measure it macroscopically. However, because all spins antialign in this so-called antiferromagnetic order, there is a defined microscopic structure that can be detected through special experimental techniques, for example inelastic neutron scattering. While in these cases the resulting spin orientation is clearly predictable, in some others this intuitive prediction is not possible. For example, one can consider spins that can only point in two directions: up or down. Let us then consider a triangle with antiferromagnetic interactions, so that the favoured configuration is when two spins point to opposite directions: we can place the first spin to point up, then the second will point down, but what will the third do? It cannot satisfy pointing opposite to both the other two spins at the same time. We call such systems in which the interactions lead to several possible available configurations frustrated spin systems. Due to having so many possible configurations, it is often hard to solve such models mathematically, so that numerical methods become fundamental to determine their properties. These systems can host various different phases. Among the most interesting are spin liquids. In such a phase, the spins never form any ordered configuration.

One model that realises such a state is the Kitaev model, introduced by A. Kitaev in 2006. This model can be solved exactly and shows a spin liquid ground state. This liquid is particularly interesting because it hosts Majorana (quasi)particles, which are simultaneously the particle and its anti-particle. More interestingly, it was then found that the same kind of interaction appears also in real materials, together with another one known as Heisenberg interaction. The latter is the one present also in the fridge magnets. Because of the coexistence of these two couplings, we call the model Kitaev-Heisenberg. The properties of this model have been extensively studied. Moreover, it has been established that also other interactions need to be considered to describe real materials, leading to an extended Kitaev-Heisenberg model. The interesting spin liquid behaviour has been reported experimentally when materials are put in magnetic field. Nonetheless, one aspect of this model has not been analysed: what happens when we remove some spins and put moving charges instead? Some studies show that another peculiar state of matter might appear: superconductivity. This is a state of matter where electric resistance goes to zero. In the case of doped Kitaev-Heisenberg model, the expected superconducting state has also another peculiarity: it is a topological state. Topological superconductors are of great interest as they can be used in quantum computation, because they exhibit peculiar excitations that can be used as qubits, which are special quantum bits for quantum computers.