Topological Defects and Self-Bound Solutions in Mixtures of Ultracold Bose and Fermi Gases with Density Functional Theory

As we know since the discovery of quantum mechancs, the physics at small length scales or large energies is governed by laws different to those we experience through everyday interaction with the world. The physics of individual atoms is therefore richer and less intuitive than the physics of macroscopic objects. For example, particles fall into two separate categories: bosons or fermions, which has a tremendous impact on their properties.

However, as was predicted by A. Einstein, a gas of bosons can, at very low temperatures, display collective properties governed by a single quantum mechanical wave function. This is so because, at very low temperatures, almost all bosons occupy the same quantum state, allowing for experimental observation of quantum mechanical effects in labolatory.

Since the experimental realisation of the Bose-Einstein Condensate in 1995, it is possible to study the quantum effects in low temperature atomic gases, and the new branch of research emerged: a study of ultracold quantum gases. Since then the experimental techniques developed so far, that we can now engineer quantum systems trapping quantum gases in optical traps, often in the form of a lattice of a desired topology. This allowed for experiments on model, simple systems, testing theoretical predictions for more complcated phenomena from condensed matter physics.

One of the quantum effects present in ultracold gases is superfluidity. This effect is manifested as a lack of friction when a fluid flows through a vessel. It was observed in superfluid Helium and is closely related to superconductivity of electrons in a solid state. But, in the case of fermions, the mechanism is different: at low temperatures, fermions of opposite spin and momenta form pairs, whose size is typically much larger than average separation between the particles. Such pairs are called Cooper pairs and are responsible for superfluid properties at low temperatures.

One of the unusual properties of superfluid systems is presense of topological defects: stable topological objects that cannot dissolve easily. An example is a vortex, a whirl o superfluid flow that is caracterized by a quantized circulation. If fermions are in unequal numbers of spin-up and down particles, than an exotic superfluid is predicted, which is characterized by spatial oscillations. However it has not been directly observed to this day. Another interesting object is a quantum droplet: an analogue of a droplet of a liquid such as water. It is caracterized by a constant density inside and a surface tension. It was shown that such fascinating objects can exist in the Bose-Einstein Condensate.

All of these objects were studied intensively in superfluid systems of bosons and fermions. In this project I want to study the properties of superfluid mixtures, where a Bose and a Fermi superfluids coexist. How the presence of the other component affects the properties of the defects? Is a bound state in a form of a droplet possible? I would like to answer these questions.

To this end, I plan to apply the powerful method known from condensed matter physics, called Density Function Theory, that has been adapted to superfluid Fermi systems. This time, however, I would like to apply it to a mixture of bosons and fermions and see whether or not the presence of both gases affects the existence or stability of topological defects or droplets. I would also like to see if it would be possible to enhance the non-uniform superfluid in an imbalanced Fermi gas, which could potentially lead to an observation of this new phase. This project should further our understanding of the superfluid effects in quantum gases.