

Tunable ultracold quantum matter with long-ranged interactions

Abstract for the general public

Quantum mechanics lies at the heart of all modern technologies. Understanding the basic laws governing the behaviour of matter at the nanoscale allowed for construction of devices such as the transistor which revolutionised electronics. It is currently believed that utilizing collective quantum effects for technological purposes can lead to the so-called second industrial quantum revolution. Researchers are thus working on multiple platforms suitable for providing the quantum hardware, from superconducting circuits to photonics.

One particularly appealing system for fundamental studies of quantum many-body physics is based on ultracold atoms. These atoms are first trapped as an extremely dilute gaseous cloud, and then cooled to temperatures near absolute zero. At such extreme conditions the atoms have so little kinetic energy that they can be trapped using laser light, as they feel a tiny force drawing them to a region with higher or lower light intensity, depending on their property called polarizability. In ultracold systems, thermal fluctuations play only a negligible role and the quantum nature of matter becomes evident. An early example of the potential of cold atoms was creation of Bose-Einstein condensate, an exotic state of matter in which all the participating atoms are described by a macroscopic wave function and form a matter wave. Recently, it also became possible to trap single cold atoms using optical tweezer technology and use them as qubits for quantum computing purposes.

For several reasons, it is an appealing idea to switch from atoms to molecules. This is due to strong molecular interactions and their rich internal state structure, opening new possibilities for fundamental studies as well as applications. This project focuses on strongly interacting molecular systems as paradigmatic example of tunable quantum matter. Its main goal is to explore control possibilities for ensembles of molecules, both in the gas phase and in an array of optical tweezers. Using these new tools, we will look for the possibilities to generate highly entangled states of many particles. We will collaborate closely with experimental groups to find suitable parameter regimes for demonstrating exotic phenomena such as the formation of quantum droplets. The project will improve our understanding of systems with long-ranged interactions and make a step towards their future technological applications.