Strongly interacting and tightly confined quantum systems: a new quantum technology toolbox

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. The current technological goal is to create new systems in which collective quantum effects twill be actively shaped in order to reach unprecedented levels of computational power and measurement precision and bring the second quantum revolution to the industry. However, while the basic principles behind quantum computation and sensing are well understood, harnessing the potential of large quantum systems for applications is inherently difficult. Useful quantum states are fragile to noise and require fast and extremely precise operations. For this reason, researchers are working on various artificial systems suitable for providing the quantum hardware.

Every physical platform designed for being a quantum device comes with a set of unique properties, strengths and weaknesses. Precise understanding of the system is necessary for achieving sufficient level of controllability. This project is focused on microscopic description of two quantum simulator candidates which are currently studied in several laboratories. The first system consists of ultracold polar molecules individually arranged in optical tweezer traps which are made from laser light. Molecules have rich internal structure and long-lived rotational states which can be potentially useful as qubits, and interact strongly due to their dipole moment. The second considered platform are indirect excitons, quasiparticles composed from an electron and a hole localised in different layers of the material which gives rise to a dipole moment and long-range interaction. While very different at first sight, the considered systems at the microscopic level can be described with similar tools and share several important properties such as the type of the interaction and vital role of the external trapping potential. This project aims to provide the insight into the details of the interactions in both setups required to make them useful for quantum technologies. Starting from derivation of the interaction potential taking into account strong external confinement, we will then proceed with implementation of effective numerical techniques for analysis of multiple molecular species and excitonic samples, providing guidance for experiments.

The project will contribute to better fundamental understanding of the interplay between strong long-range interactions and tight external confinement. The acquired knowledge will be used to design fast and robust quantum information processing protocols as well as to control inelastic collisions and chemical reactions in the quantum regime.