Ultracold quantum mixtures of ions with atoms, molecules, and Rydberg atoms: novel hybrid systems and applications

Summary for the general public

Michał Tomza

I. RESEARCH PROJECT OBJECTIVES

The cold and ultracold systems attract great interest because the quantum nature of the world is visibly manifested at ultralow temperatures, that is temperatures below 1 miliKelvin, and research on such systems gives a new insight into the quantum theory of matter and matter-light interaction. Ultracold gases are also ideal systems for engineering highly nontrivial states of matter because they allow one to prepare, manipulate, and measure with great accuracy strongly interacting quantum systems. The development of laser and cooling techniques resulted in the birth and successful advances of the field of ultracold quantum gases in recent decades. After many spectacular successes in research on ultracold atoms, the scientific community has recently drawn its attention to the research on ultracold molecules, Rydberg atoms, ions, and their mixtures with ultracold atoms.

The aim of the project is to propose novel hybrid systems based on ultracold quantum mixtures of atomic ions with atoms, molecules, and Rydberg atoms and to investigate theoretically their properties, interactions, dynamics, and potential applications in frontier research. We suppose that such quantum mixtures can find many interesting applications in contemporary physics and chemistry of ultracold quantum matter. Possible applications range from investigating chemical reactions and production of molecular ions to simulating quantum phenomena of few-body and many-body physics. Many novel ways of engineering, that is, controlling and manipulating properties of these systems can also be proposed.

II. WORK PLAN

We will employ state-of-the-art *ab initio* techniques of quantum chemistry and molecular physics, as well as develop and implement new concepts and methods. We will start from investigating electronic structure and cold collisions of atomic ions interacting with atoms, choosing the systems that are the most relevant for ongoing experiments. The calculated electronic structure data will be next employed to investigate the state-selective formation and control of diatomic molecular ions with magnetic and laser fields. We will propose new efficient formation pathways using both photoassociation and magnetoassociation. We will show how the external fields can be exploited to control cold collisions and formation pathways. We will investigate the interactions and chemical reactions of doubly charged alkaline-earth-metal ions immersed in ultracold atomic quantum gases. We will characterize energetics and channels of chemical reactions in ionic three-body systems. We will study interactions, cold collisions, and chemical reactions of atomic ions with diatomic molecules and diatomic molecular ions with atoms. We will also explore weakly bound ionic three-body systems, where an atomic ion is immersed into ultracold gas of Feshbach molecules. We will investigate novel hybrid systems of atomic ions combined with Rydberg atoms, as well as Rydberg excitations in atomic and molecular ions. The last part of the project will be devoted to many-body physics of an atomic ion trapped together with several Fermi atoms in a one- and three-dimensional harmonic potential. Finally, we will propose new applications of atomic ions for quantum sensing and probing properties of ultracold gases.

III. MOTIVATION

Hybrid systems of laser-cooled trapped ions and ultracold atoms combined in a single experimental setup have recently emerged as a new platform for fundamental research in quantum physics and chemistry. These systems combine the best features of the two well-established fields: trapped ions and ultracold atoms. In the project, we will investigate mixtures of atomic ions with atoms, molecules, and Rydberg atoms - the systems that are interesting from the fundamental point of view, yet not well explored. A detailed knowledge of cold interactions, collisions, chemical reactions, and impact of external fields in these mixtures will result in novel ways of engineering ultracold controllable ion-neutral systems and their applications in studying various quantum phenomena. The obtained theoretical results will explain, guide and motivate ongoing and upcoming experimental works. In the end, all anticipated efforts will bring a better understanding of the quantum nature of the world at the microscopic level, essential for all branches of physics and chemistry.