ULTRACOLD ATOM-ION COLLISIONS

Amelia Detti

Recently scientists have reached the ability to create **hybrid quantum systems** and to study their physical behaviors by making two different quantum systems interact in the same experimental setup. When the systems are isolated, they undergo evolutions governed by their unperturbed Hamiltonians. However, when the systems interact, the evolutions of both systems are perturbed, leading to the emergence of new physical properties and behaviours. An ultracold degenerate gas of neutral atoms interacting with trapped ions composes an **atom-ion hybrid quantum system**, which can be used as a new platform to study quantum physics and to realize new quantum technologies.

Atom-ion physics is based on atom-ion interaction, which is substantially different from the interaction between neutral atoms. Neutral atoms have not permanent electric dipole, but when they approach each other, they develop an induced electric dipole and this leads to an interaction potential that scales with R^{-6}, where R is the interparticle distance. Ions, instead, have electric charge resulting in a different atom-ion interaction potential, scaling with R^{-4}, due to the electrostatic force between the ion's electric monopole and the atom's induced dipole [2]. Because of this longer-ranged asymptotic scaling, atom-ion interactions have typically a range that is two orders of magnitude larger than atom-atom interactions (hundreds of nm instead of a few nm).

The aim of this project is to realize a quantum hybrid system of atoms and ions in the ultracold regime, i.e. at temperatures for which atom-ion collisions are in the s-wave scattering regime. With this new physical system it will be possible to study atom-ion interactions for the first time in the ultracold regime, leading to the possibility of tuning atom-ion interactions through the so-far-elusive atom-ion Feshbach resonances [1]. Moreover, the atoms will collisionally cool an ion-based hardware of a quantum computer to ultralow temperatures. This cooling mechanism would be innovative in comparison to state-of-the-art ion-based quantum technologies in which it is necessary to stop the evaluation processes in order to optically cool the quantum hardware.

The quantum hybrid system will be composed by **a Lithium degenerate gas and one or more Ba^+ (Barium) ions**. This choice ensures the non-existence of charge exchange collisions, inelastic processes for which an electron is exchanged between the two colliding particles. In fact, since the absolute ground state of the atom and the ion is a Ba^+-Li compound, charge-exchange reactions are energetically forbidden. Additionally, the large mass ratio ensures an efficient cooling of the ion in the ultracold gas. With this novel experimental setup it will be possible to study for the first time a number of phenomena that have been so far only theorized. Trapping ions without micromotion will make it possible to cool down the ions at the same temperatures of the Lithium's buffer gas, through **sympathetic cooling**. It will be possible to characterize for the first time atom-ion collisions in the full quantum regime, by measuring the atom-ion scattering length, and it will be possible to test the efficiency of sympathetic cooling in ion-based hardwares of quantum technologies. This alternative cooling scheme will be tested by encoding a qubit in the internal Zeeman levels of the $^{138}Ba^+$ $S_{1/2}$ ground state, and by searching for conditions (for instance through Feshbach resonances) for which the scattering length is the same for any superposition of the internal states of the ion, which will therefore act as a decoherence-free ultracold bath. Realizing this new experimental setup will allow us not only to study the physics of atom-ion collisions at ultralow temperatures, but will also pave the way for the investigation of many-body systems in presence of localized impurities.

[1] Z. Idziaszek et al. Phys. Rev. A 79, 010702(R) (2009)
[2]C. Sias, M. Koehl arXiv.1401.3188 (2014)