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Hybrid quantum systems of ultracold atoms and ions

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Ultracold atoms and trapped ions are among the most studied physical systems in experimental quantum physics. On the one hand, ultracold neutral atoms form coherent ensembles of a great number of particles whose interactions, dimensionality and motion can be precisely controlled by well-established techniques. On the other hand, trapped ions constitute smaller samples that can be efficiently confined for long periods of time. Due to Coulomb repulsion, trapped ions crystallize in spatially well-separated structures, hence granting the possibility of detecting and addressing a single ion more easily with respect to neutral atoms. Together, atom-ion quantum mixtures are promising candidates for investigating several open problems in experimental quantum physics and condensed matter physics from a different standpoint [1].
In addition to the features of each individual quantum system, this hybrid system gives rise to atom-ion interactions, which are more long-ranged than atom-atom ones. Atom-ion interactions can represent an extremely useful tool in order to simulate condensed matter problems, to explore new hardware for quantum technologies, to investigate fundamental chemical reactions, and to advance metrology standards. Elastic collisions between ions and atoms can be exploited to sympathetically cool the ions and try to reach the elusive s-wave scattering regime, in which atom-ion collisions can lead to a quantum coherent evolution of the composite system.

Creating an ultracold atom-ion quantum mixture represents a remarkable experimental challenge, since two complex setups must be integrated in the same apparatus. Moreover, the ultracold atom-ion mixtures realized so far were not brought to the s-wave scattering regime because of the so-called "micromotion", a driven motion affecting the dynamics of the ions trapped in Paul traps.
From the experimental point of view, the main levers upon which to act in order to reach the s-wave scattering regime are basically two. The choice of the atomic species and the trapping strategy for confining the ions. For what regards the pair of atomic species, these must be carefully chosen on the basis of their mass ratio and the characteristics of their mutual interaction. We opted for fermionic Lithium for the atoms and Barium for the ions, since in their ground states they are chemically stable against charge-exchange reactions. For what concerns the ions'trapping strategy, the micromotion arising in radiofrequency traps is formed by different contributions and could be reduced by applying static and dynamics electric fields. We designed our trap with four radiofrequency electrodes and six DC electrodes of different shapes for generating a trapping potential along the three orthogonal directions. For the micromotion compensation, extra DC voltages can be applied to each of these ten electrodes.
Even if the experiment is currently under construction, the "ion"side of the apparatus has already been implemented. Since it is able to work independently from the rest of the setup, the first attempts of ion trapping and cooling in Italy are already possible.

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[1] Quantum gas experiments - exploring many-body states, chap. 12, C. Sias, M. Kohl (2016).

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