Towards hybrid systems of ultracold atoms and ions

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Ultracold atoms and trapped ions have proven to be extremely valuable resources for getting new insights on fundamental physical phenomena. With their large separation due to Coulomb repulsion, trapped ions can be individually addressed and coherently manipulated. Ultracold gases, instead, provide large atomic samples where trapping potentials and interactions can be controlled externally, making them well suited for systematic studies of many-body quantum phenomena. Combining the strengths of these two systems can lead to new advances in impurity physics, out-of-equilibrium dynamics, quantum information, optical metrology and ultracold chemistry.

In a hybrid quantum system, ultracold atoms and trapped ions are combined in a single experimental apparatus, thus realizing an innovative platform to experimentally investigate open problems of quantum physics from a new standpoint. This hybrid system not only brings together the advantages of each single physical system, but also gives rise to atom-ion interactions which are two orders of magnitude more long-ranged than atom-atom interactions. Despite of the strong interest in atom-ion experiments in the recent years, atom-ion systems have not yet been brought to a full quantum regime since it has not been possible to create a long-living coherent coupling between atoms and ions [1].

We address these topics by presenting an overview on our hybrid system of ultracold Li atoms and Ba^+ ions together with the recent advances on our experimental apparatus. The main innovative point of our system with respect to previous setups is the choice of the mixture $^{138}Ba^+$ and ^6Li: the mixture has no charge transfer losses and the large mass ratio facilitates the sympathetic cooling of the ions in the RF trap. Moreover, ^6Li can be prepared in the absolute ground state in a fully polarized state to avoid three-body recombination processes and spin-exchange. Finally, ^6Li features broad Feshbach resonances, suitable for many-body studies. All these reasons make the mixture of Ba^+ and ^6Li a good candidate for reaching the long-searched coherent coupling regime.

Having this closed system at hand permits to access the s-wave scattering regime, where several ion-atom Feshbach resonances are expected [2]. The observation of Feshbach resonances allows reaching the ultimate level of control over atom-ion interactions, permitting new advances in quantum simulations, ion-based quantum computing and ultracold chemistry, to mention a few.

One of the most interesting prospects for this hybrid system is the systematic study of controlled impurities in a Fermi gas. The concept of impurity is one of the most general notions of physics and it is fundamental for describing properties of most materials. Additionally, models with a single localized impurity have been used to address fundamental problems on the non-equilibrium dynamics of many-body systems. A celebrated example is given by the Anderson orthogonality catastrophe [3]. By immersing a single ion in a quantum gas, it would be possible to directly observe the emergence of the Anderson orthogonality catastrophe in the time-domain by monitoring the evolution of the impurity ion [4]. The observation of the Anderson orthogonality catastrophe in the time-domain is so far lacking and it would give important insights into the dynamics of an out-of-equilibrium many-body system as well as provide a conceptual framework for understanding several fundamental phenomena in solid state physics.

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