PhD in Metrology

Research Title: Experimental realization of a quantum mixture of atoms and ions

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Context of the research activity	Experimental quantum physics relies on the ability to realize and control quantum systems that can be isolated from the environment. Among the many physical systems that are currently studied, ultracold atoms and trapped ions are probably the most formidable sources of coherent matter available in a laboratory. On the one hand, ultracold atoms form very large ensembles of particles that behave coherently, like a "laser of matter", but it is extremely challenging to manipulate them at the single-particle level. On the other hand, trapped ions form much smaller clouds that can be more easily controlled at the single particle level since Coulomb repulsion ensures a relatively large spacing between particles. Notably, trapped ions and cold atoms represent the hardware of the best optical clocks realized so far. In a hybrid quantum system of atoms and ions, 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. An atom-ion hybrid system not only brings together the advantages of each single physical system, but moreover gives rise to atom-ion interactions, which are two orders of magnitude more long-ranged than atom-atom interactions. The first experiments on quantum mixtures of atoms and ions date to less than ten years ago, and now several groups in the world are

	exploring the many features of this novel physical system. However, despite of the strong interest in atom-ion experiments, atom-ion systems have not yet been brought to a full quantum regime since it has not yet been possible to create a long-living coherent coupling between atoms and ions.

Objectives	The aim of the project is to run a novel atom-ion hybrid system in which full control of atom-ion interactions is achieved by entering in the so-far unexplored regime of ultracold temperatures. The key point of our strategy is to use a new type of ion trap that will allow us to realize for the first time an energetically closed atom-ion system, so that atom-ion physics in the quantum regime will be explored. The machine, which is currently under construction and should be terminated by the end of 2019 – early 2020, will make it possible to study fundamental interactions between charged and neutral particles for the first time in the quantum regime. It is important to note that this is a fundamental physical goal, since these interactions are ubiquotous in Nature; for instance, they are considered responsible for the formation of molecular compounds in astrochemical environments like interstellar clouds. The project aims at completing the construction of the experimental machine – a unique opportunity for a student to acquire knowledge in fundamental experimental techniques like laser physics, optics, electronics – and at realizing experiments with a quantum atom-ion mixture. A first series of experiments will focus on studying atom-ion interactions and use them in the context of quantum technologies and quantum computing. First, it will be possible to observe and characterize the so-far elusive atom-ion Feshbach resonances, i.e. a technique to exploit quantum interference to tune interactions by using a magnetic field. Second, in the ultracold regime the motional state of the ion will be cooled sympathetically to its ground state, with an efficiency larger than the best value that is currently achievable. Finally, by encoding a qubit in two of the ion's internal states and by using appropriate Feshbach resonances, it will be possible to create a decoherence-free environment for the qubit, implementing therefore a crucial step toward a continuously-cooled quantum computer, in which computation does not need to be interrupted to cool the “quantum hardware”. In a second series of experiments, novel mechanisms for the creation of molecular ions will be explored: it has been predicted that a trapped ion in an ultracold gas will act as a “nano-trap” for the atoms by spontaneously associating hundreds of atoms in a weakly bound state of the atom-ion molecular potential. Additionally, the formation of charged molecules through controlled chemical reactions will be investigated, with the aim of demonstrating cooling and manipulation of the collisionally-created

	molecular compounds. Finally, we note that, while ion trapping experiments are spread in the world, and their important contribution to the advancements of physics was recognized by the 2012 Nobel prize, experimental investigations with trapped ions are absent in Italy. Our experimental group is the first one attempting ion trapping in Italy, therefore bringing a critical resource for future technologies to Italy for the first time.

Skills and competencies for the development of the activity	The most important quality for a Ph.d. candidate is her/his strong will in learning new physics and new experimental methods. Basic knowledge in either electronics, optics or programming (i.e. Mathematics, C/C++, etc.) would result in a smoother approach to the project, but this should not be consireded a pre-requisite. The thesis work will be carried out in a small team (currently formed by the PI, two post-docs and two more senior Ph.D. students) and the student will be supervised and trained in learning all the techniques that are necessary for the lab operation. Considered the research topic, a master thesis in Physics is preferrable, although a candidate with a master thesis in Engineering and a strong interest in quantum physics could also be successful.