Ultracold ytterbium atoms in programmable optical microtraps: quantum simulations of highly correlated states of matter with single atom control

Fields of research: Ultracold atoms, Quantum simulation, Quantum information, Many-Body physics

Type of research: Experimental

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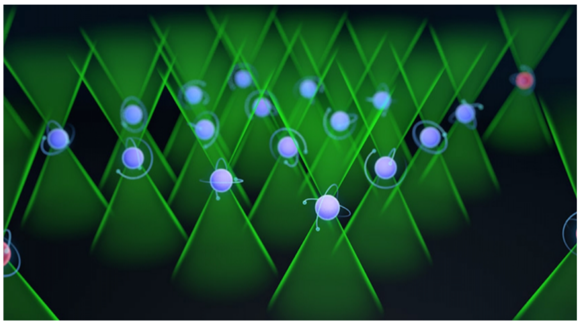
Recent years have seen impressive scientific progress in controlling engineered quantum systems, leading to a paradigm shift coined the *second quantum revolution* [1], and revitalizing Feynman's idea of a *quantum simulator* [2]. Fundamental constituents of matter, such as atoms, photons and electrons, can nowadays be precisely manipulated in laboratories, allowing to test fundamental laws, as well as to lay the foundations of new technologies. In particular, ultracold atomic gases have become a unique playground for the investigation of highly correlated quantum phenomena [3]. An exceptional degree of controllability and long coherence times, together with new tools enabling the detection of each individual atom in state-of-the-art *quantum gas microscopes*, make ultracold gases a mature quantum simulation platform. This is ideal for exploring non-equilibrium dynamics in quantum systems [4], and tackling open issues across condensed matter theory, quantum many-body physics,and quantum information sciences [5]. Individual atoms can be trapped in defect-free optical potentials, let free to move and interact with tunable strengths, and addressed or imaged one by one to reconstruct the quantum correlations of their many-particle wavefunction, revealing the emergence of collective behaviors or the dynamics of excitations.

Among the many atomic species that have been cooled down to quantum degeneracy, those having a helium-like electronic structure, i.e. *two-electron atoms* such has ytterbium or strontium, have attracted much theoretical and experimental interest. This is motivated by their rich level structure, which provides exciting opportunities for exploring a wide range of quantum phenomena. Two-electron atoms possess two long-lived electronic states: the electronic ground state and a metastable excited state with a lifetime exceeding 10 seconds. These states are termed *clock* states, because the ultranarrow optical transition that connects them has been exploited to realize the most precise atomic clocks available nowadays [6]. For this, atoms are trapped in an optical lattice, i.e. a periodic array of potential wells created by a laser light interference pattern, while the relative population of the clock states can be manipulated coherently in an extremely precise fashion by using a laser source with an ultra-narrow linewidth, i.e. a *clock* laser. The availability of two stable electronic levels in each atom has also inspired a variety of approaches for engineering previously inaccessible fundamental many-body systems [7,8] and quantum information schemes [9,10]. Novel ideas are stimulated by the very different ways in which atoms in the two clock states interact both with light and with other atoms. For example, atoms can be trapped selectively, allowing to localize an atom depending on its internal state [11]. This is in direct analogy to electrons in a crystal lattice occupying two different *orbital* bands, an essential ingredient of fundamental condensed-matter models such as the Kondo and the Anderson model. In parallel, owing to the technological toolbox developed in modern atomic clocks, platforms based on two-electron atoms are extremely promising for attacking qualitatively new problems in quantum matter. For example, they are an ideal entry point for exploring the role of entanglement at the many-body level.

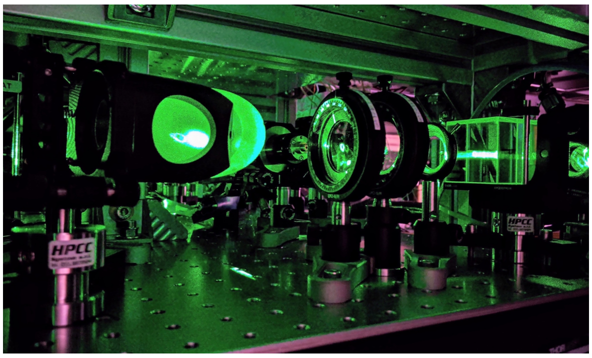
A new-generation experimental apparatus for manipulating single ytterbium atoms

Over the last few years, a new generation of cold-atom machines has emerged, based on arrays of single atoms held in reconfigurable optical micro-traps [12,13]. Such programmable devices combine two central benefits, which are typically conflicting: they showcase exquisite single-atom control,



while at the same time showing excellent scalability to mesoscopic system sizes containing more than 100 atoms.

The proposed PhD project targets the development of a new cold-atom experimental setup for the creation of fermionic ytterbium arrays of >100 atoms in programmable optical potentials. This will constitute a large and robust defect-free quantum register, an excellent starting point for both quantum information processing and quantum simulations. The apparatus will include the laser and optical systems for the cooling, trapping and imaging of single ytterbium atoms. It will also involve an ultra-high vacuum system and the hardware for the automatized control of the experimental sequence. Our quantum simulation experiments will mainly target the realization of fermionic mesoscopic systems assembled ‘atom by atom’, enabling the exploration of paradigmatic transport and dynamical phenomena with full information on the system’s quantum state. For example, we will study the decoherence and transport dynamics of the analogous of a *quantum dot*, created by pinning one or more single atomic spin impurities within an atomic ensemble by a tightly focused laser trap, while letting impurity state interact with its surroundings [14].



The candidate will have the unique opportunity to build a strong expertise across different fields of research: laser physics, atomic physics, many-body physics and quantum information. The PhD candidate will work in the laboratory located in Basovizza within a team of 3-4 people, collaborating to the design and the implementation of the new machine, and being responsible for independently developing fundamental parts of the experiment. Once the team will obtain a cold ytterbium sample, the candidate will focus on demonstrating new techniques for single-atom microscopy and perform experiments and numerical simulations on the controlled manipulation of the external and internal atomic states. She/he will be encouraged to concentrate on physical topics of interest under a continuous interaction with the supervisor, and will have the occasion to collaborate with theorists on the conception and implementation of new proposals for optimally harnessing the developed experimental techniques.

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