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A new setup and methods for the fast production of ultracold atoms for atom-ion experiments

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Summary

Isolated quantum systems offer an ideal platform to study fundamental aspects of quantum physics and test emergent technological applications. Recent improvements in experimental techniques have made it possible to join different quantum systems in a single experimental setup, allowing for the study of their interaction and their enriched dynamics. Hybrid quantum systems of atoms and ions aim at bringing together ultracold atoms, which constitute the ideal many-body system, and trapped ions, which represent the ideal single-body system. In these setups a key emerging feature is the atom-ion interaction, which originates from the dipole induced by the ion's charge on the approaching atom. Atom-ion systems have been proposed for a number of different experiments in the fields of quantum computation, quantum simulation, astrophysics, quantum chemistry, and metrology.

Atom-ion quantum systems require the integration of two complex setups, each dedicated to producing either cold atoms or cold ions. These two particles have considerable different production time scales: on the one hand, ions are generally produced by photo-ionization of hot atoms, and are trapped in deep Radio Frequency (RF) traps where fast cooling techniques (such as sideband cooling) are employed to bring the ion to its ground state of motion. The whole process can be completed in less than a second; furthermore, the same ion can be cooled and reused multiple times in an experiment. On the other hand, atoms must be first slowed and trapped using magneto-optical techniques, and are brought to degeneracy using evaporative cooling. In general, this process can take up to tens of seconds. Therefore, the preparation of a cold cloud of neutral atoms represent the major bottleneck to achieve a high repetition rate to perform repeated measures.

This thesis examines a novel scheme for the fast cooling of neutral ^{6}Li atoms. This new cooling scheme makes use of deep optical potentials generated using a cavity-enhanced optical lattice and resolved single-photon sideband cooling to cool particles toward their ground state of motion. First, a mathematical model of sideband cooling in optical potentials is developed. The model describes the vibrational state of particles trapped in non-harmonic state-dependent optical potentials. Numeric simulations performed using wavefunction Monte Carlo show that, in experimentally feasible conditions, it is possible to reduce the particles' vibrational energy by more than 95 % of its initial value using a laser frequency sweep a few

ms long.

A two-mirror high-finesse optical resonator was designed to be used for sideband cooling and evaporative cooling of the ^{6}Li atoms. The resonator is made of vacuum-compatible materials and it is installed inside the chamber where ^{6}Li atoms are prepared. The assembled resonator was characterized using optical techniques: the cavity finesse and linewidth were determined to be 28 800(80) and 78.6(2) kHz, respectively. Thanks to such a high finesse, a low-power laser diode coupled to the cavity can achieve an optical lattice sufficiently deep to perform single-photon sideband cooling. Due to the small cavity linewidth, considerable work has been done to characterize the coupled laser and its noise power spectrum.

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