Ion Coulomb-crystals: A medium for storage of quantum states of light?

Anders Mortensen, Frank K. Jensen, Dirk Voigt, and Michael Drewsen
Institute of Physics and Astronomy, University of Aarhus, Ny Munkegade, DK-8000 Aarhus C, Denmark
drewsen@ifa.au.dk.

Abstract:

Following the idea of a recent paper [M. D. Lukin, S. F. Yelin, and M. Fleischhauer, Phys. Rev. Lett. **84**, 4232 (2000)], a two-species ion Coulomb-crystal inside an optical cavity is proposed as a medium for storage of the quantum state of a light pulse.

1. Introduction

Recently, two independent experiments have demonstrated that a pulse of coherent light can be temporarily stored as a collective excitation of a cold atomic ensemble [1,2]. The idea behind these experiments suggests that not only coherent light pulses, but also light with non-classical characters can be stored. Both experiments relied on a very large reduction of the group velocity of the light pulse as well as on the atomic medium being optically thick in the absence of a control laser beam. It has, however, been shown that these requirements can be relaxed if the atomic ensemble is placed within a high-finesse optical cavity [3], where the light pulse, due to multiple reflections, will pass the atoms several times.

In the present contribution, we consider the prospect of implementing the idea of Ref. [3] using a two-species ion Coulomb-crystal inside an optical cavity as a medium for storage of quantum states of light.

2. Coulomb-crystals

When trapped ions are cooled below a certain critical temperature (typically about ten milli-Kelvin) they start to form spatially ordered structures sometimes referred to as ion Coulomb-crystals or just ion crystals. Such crystals of various sizes containing single atomic ion species have now for more than ten years been investigated in various types of traps. Recently, also multi-component crystals, and in particular two-component crystals (bi-crystals), have attracted attention. In quantum optics, short strings of several ion species have, e.g., been proposed applied in the implementation of a quantum computer [4], while larger bi-crystals have so far mainly been considered interesting objects either in non-neutral plasma physics [5] or in atomic and molecular physics [6]. In the latter case, the possibility of sympathetic translational cooling of various atomic or molecular ion species, through Coulomb interactions with ion species that are directly laser-cooled, is very attractive. It has been demonstrated that the translational temperature of the sympathetically cooled ions can easily be below 100 mK and that the two species at such low temperatures in, e.g., linear Paul traps generally separates radially with the lighter ions situated closest to the trap axis [5,6]. Figure 1 below, which shows a picture of a bi-crystal of laser cooled Ca^+ ions surrounding an invisible cylindrical shaped core of O_2^+ ions, illustrates this point.

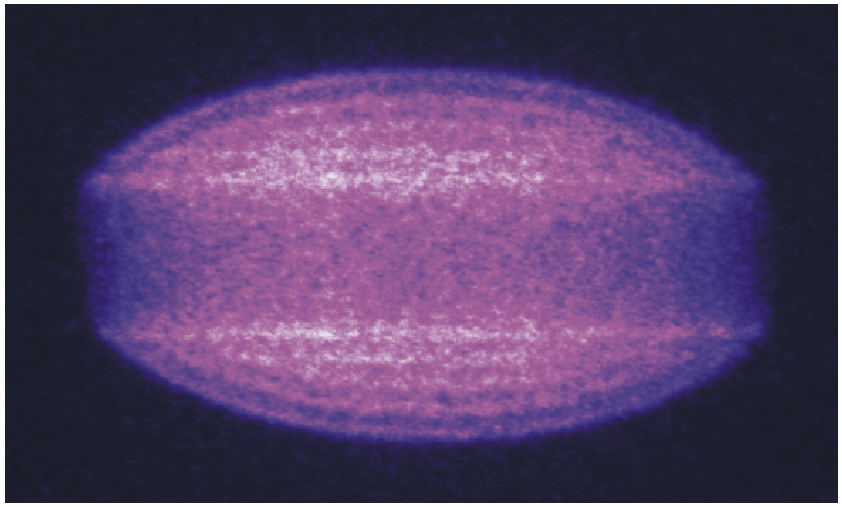

Fig. 1. A picture of an ion bi-crystal consisting of an invisible cylindrical core of O_2^+ ions surrounded by heavier fluorescing $^{40}Ca^+$ ions.

3. The ion crystal quantum memory

In order to implement the idea of Ref. [3], a relatively strong coupling between the atoms and the cavity mode is needed and the atoms should stay within the mode volume at least during the storage and read-out process. Ions in the nearly cylindrical shaped core of an ion bi-crystal situated within the TEM_{00} mode volume of a high-finesse optical cavity fulfill these criteria even for times up to seconds. Furthermore, in order to make the storage of quantum states of light possible, it is necessary that the storage medium consists of effective three-level Λ-atoms where one transition is nearly resonant with the quantum light. Since the wavelength of the transitions between the metastable 3d D-states and the 4p P-states of the Ca^+ isotopes are in the region of 850 nm, where tunable sources of non-classical light already exist, such ions seem to be a good choice for a storage medium. To realize the quantum memory, we envision a bi-crystal consisting of a cylindrical core of Ca^+ ions sympathetically cooled by surrounding laser-cooled heavier isotopes of Ca^+ or other ion species such as Sr^+, Yb^+, or Ba^+. In a linear Paul trap, the length of the core of the bi-crystals can be at least up to a few millimeters long, and the ratio of the length to the diameter can be matched to the cavity mode by changing the trap parameters. With typical ion densities of 10^8 cm^{-3}, a medium of about 1000 ions seems to be feasible. Since this is relatively few compared to the number of atoms in the experiments of Ref. [1,2], an ion Coulomb-crystal memory device will only be able to store light pulses consisting of up to tens of photons with high fidelity. However, for some quantum information applications this could be sufficient.

In the presentation, details on an actual realization of a memory device based on a linear Paul trap will be discussed.

[1] C. Liu, Z. Dutton, C. H. Behroozi, and L. V. Hau, “Observation of coherent optical information storage in an atomic medium using halted light pulses”, Nature **409**, 490-493 (2001).

[2] D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, “Storage of light in atomic vapor”, Phys. Rev. Lett. **86**, 783-786 (2001).

[3] M. D. Lukin, S. F. Yelin, and M. Fleischhauer, “Entanglement of atomic ensembles by trapping correlated photon states”, Phys. Rev. Lett. **84**, 4232-4235 (2000).

[4] E. Peik, J. Abel, Th. Becker, J. von Zanthier, H. Walther, “Sideband cooling of ions in radio-frequency traps”, Phys. Rev. A **60**, 439-449 (1999).

[5] L. Hornekær, N. Kjærgaard, A. M. Thommesen, and M. Drewsen, ”Two-component Coulomb crystals”, Phys. Rev. Lett. **86**, 1994-1997 (2001).

[6] K. Mølhave and M. Drewsen, “Formation of translationally cold MgH^+/MgD^+ molecules in an ion trap” , Phys. Rev. A **62**, 0011401(R)1-4 (2000).

[7] E. S. Polzik, J. Carri, and H. J. Kimble, “Spectroscopy with squeezed light”, Phys. Rev. Lett. **68**, 3020-3023 (1992).