Ion crystals in a linear Paul trap

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Large ion crystals containing as many as 10^5 laser-cooled $^{24}Mg^+$ ions arranged in 10 cylindrical shells around a central string have been observed in a linear Paul trap. For smaller crystals consisting of approximately 3500 ions, the varying linear charge densities along the trap axis give rise to well-defined transition regions between the different shell-structures. These structures and the transition regions as a function of linear density are in good agreement with molecular dynamics simulations. The micromotion of the ions in such smaller crystals is also investigated through comparison with MD-simulations. Finally, the degree and progression of ordering in the plasma have been observed for various temperatures and compared with MD-simulations. Good qualitative agreement is again obtained.

1. Introduction

The introduction of laser-cooling has made it possible to cool down systems of trapped ions in Paul [1,2] and Penning [3] traps to sufficiently low temperatures for an ordered state to appear. These trapped and cooled ion clouds are examples of strongly coupled one component plasmas [4]. Theoretical studies of their behaviour have been conducted mainly with the help of molecular dynamics simulations [5,6] yielding results showing how the structure and state of the ion plasma depend on the number of ions, the average kinetic and potential energy of the ions and the shape of the confining potential. These results have been experimentally confirmed earlier in both Paul traps [7], and in Penning traps [8]. Here we report the observation of formation and structure of large ion crystals in a linear Paul trap. These results are compared to molecular dynamics simulations.

2. Experimental setup

In the experiment $^{24}Mg^+$ ions are laser cooled and trapped in a linear Paul trap. The trap is a quadrupole trap consisting of 4 parallel, cylindrical, gold-plated steel rods, each axially partitioned into three parts. The central part of the electrodes has a length of 25 mm, the end-caps are 15 mm long, and the diameter of the rods is 0.4 mm. The distance from the trap axis to the surface of the electrodes is 1.75 mm. An RF field applied across two diagonally opposed rods leads to confinement in the transverse dimensions. The confinement along the axis is obtained by applying a DC-potential on the 8 end caps. For the experiments described here, an RF frequency of $\Omega = 2\pi \times 4.2$ MHz, and an RF amplitude $U_{\mathrm{RF}} = 30$–50 V were employed. The radial confinement is much stronger than the confinement along the axis, leading to the formation of very prolate crystals.

The Doppler cooling technique is used to cool the axial motion of the ions, using the $3s^2S_{1/2}$–$3p^2P_{3/2}$ transition. The 280 nm light to excite this transition is obtained by frequency doubling the 560 nm output beam from a dye laser. The doubling is done in an external cavity, using a KDP crystal. After passing through a series of lenses and a pinhole for spatial filtering, and an AOM to stabilize the power, the laser beam is split up into two equal intensity beams by a polarization beamsplitter. The two beams are sent into the trap region, counter-propagating along the trap-axis. Typically, resulting beams of 3–8 mW, having nearly Gaussian spatial distributions and waists of 0.5 mm are directed into the ion cloud. The transverse motion is cooled sympathetically through Coulomb scattering between the ions.

The fluorescence light from the ions is used for diagnostics. A photo multiplier tube monitors the fluorescence intensity, and the cloud is imaged onto a liquid nitrogen cooled, 1024×1024 pixel CCD-camera, through a lens system giving 9 times magnification. The spatial distribution of the cloud is thereby measured with a resolution of 2.7 μm.

3. Experimental results

With the present setup, we are able to trap and crystallize ion clouds ranging from a few ions to more than 10^5 ions. The corresponding dimensionless linear density λ, defined as the linear ion density times the Wigner–Seitz radius, $a_{\mathrm{W-S}} = (3/(4\pi n_0))^{1/3}$, where n_0 is the zero temperature ion density, ranges from $\lambda = 0.5$ to $\lambda = 150$, the latter being a factor of 5 larger than what has been reported earlier in linear and ring-shaped [7] Paul traps. Molecular dynamics simulations of infinitely long ion plasmas in a cylindrically symmetric potential reveal that as the linear density is increased the ions arrange themselves in increasingly complex structures, starting from a single string on axis and evolving into structures consisting of multiple, concentric shells, with or without a central string [5,11]. The largest crystal observed in our trap so far consists of a central string surrounded by 10 concentric shells [9]. Simulations predict that for very large crystals, the central structure becomes independent of the size of the crystal (i.e., surface effects are negligible in the central region), and a BCC structure begins to form. Such behaviour has been observed in Penning traps [8] with the number of ions exceeding 2.7×10^5. Since the crystals in our trap are very prolate, one would expect that a larger number of ions would be needed for the bulk behaviour to appear. This supposition is supported by MD-simulations [10].

For smaller crystals the variations in linear density along the axis are sufficient for us to be able to see the transitions between many different crystal shell structures in one single image (see figure 1a). From MD-simulations of infinitely long cylindrical

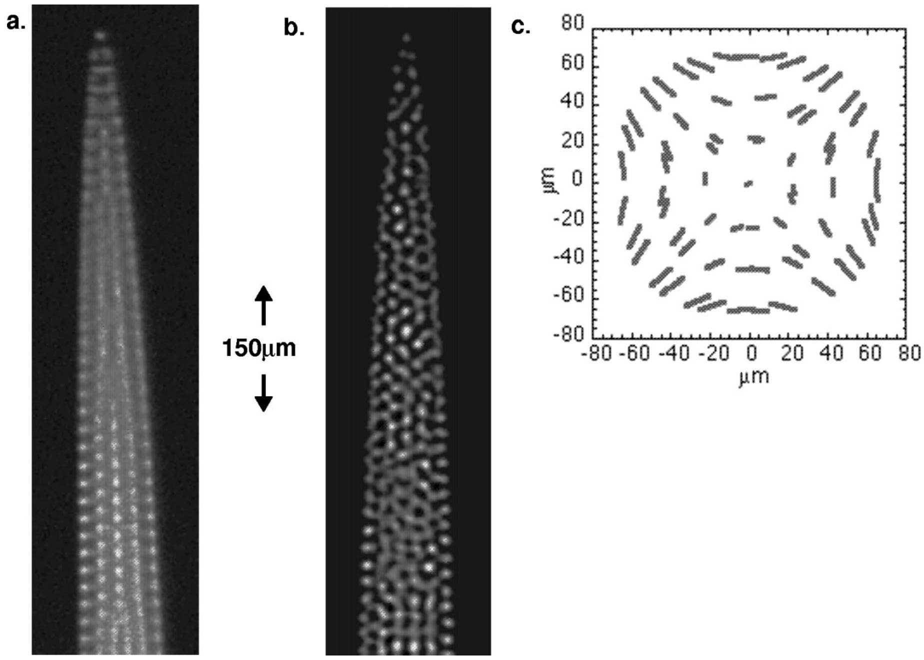

Figure 1. a. Image of an ion crystal containing approximately 3500 ions taken with a 2 s integration time. b. Molecular dynamics simulation of a crystal with the same ion-number and aspect-ratio as the crystal shown in a, averaged over one full cycle of the RF field. c. Cross-section from the center of the same MD-simulated crystal illustrating the micromotion of the ions.

crystals, it is known how these structures should depend on linear density [5,11]. Comparison of the position of transition points in our experiment and the transition points found from simulations of infinitely long crystals, show very good agreement [9]. For further comparison between theory and experiment, MD-simulations with a finite-size crystal, containing 3500 ions, of dimensions comparable to the crystal shown in figure 1a was made. The micromotion of the ions was included in this MD-simulation. Figure 1b shows the resulting 2-D projection of ion positions integrated over a full period of the RF field to reproduce the averaging inherent in the experimental imaging. The transition points between different shell structures again show good agreement both with our experiment and with MD-simulations of infinitely long crystals. In both the experimental image and the simulation it seems that the ions at the edge of the crystal are quite well-defined, compared to the inner ones. One reason for this is the variation of the direction of the micromotion, with respect to the imaging plane. In figure 1c a cross-section from the center of the MD-simulated crystal is shown. The ions at the top move in the image plane, whereas the ions at the side move perpendicular to the image plane, and hence have well-defined positions under the time average performed in both simulation and experimental imaging.

We have also studied the formation of the crystals. The state of the ion plasma is a direct function of the plasma coupling parameter, i.e., the ratio of inter particle potential and average kinetic energies of the ions in the plasma [4]. The ion plasma enters a liquid like state for coupling parameters $\Gamma \simeq 2$, and an ordered crystalline state for $\Gamma \simeq 180$. By taking pictures at different laser detunings, and hence at different plasma temperatures, the state of the ion plasma at different coupling parameters can be observed. As predicted by MD-simulations [12] the crystallization starts at the outer shells and then progresses inwards as the coupling parameter is increased [9].

4. Outlook

The size of the crystals observed so far is not sufficient for the formation of central BCC-structures to be seen, but we are attempting to push the limit on crystal size by increasing the available laser power. At the present, investigations into the behaviour of sympathetically cooled impurity ions, mainly Mg-isotopes: $^{25}Mg^{+}$ and $^{26}Mg^{+}$, and doubly-charged Mg-ions, are taking place. Data acquisition with an image-intensifier system will make more detailed, time dependent studies in crystal formation and ion plasma phase transitions possible.

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