Sympathetic Cooling and Crystallization of Ions in a Linear Paul Trap

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Abstract. Coulomb crystals, containing up to a few hundred ions of which more than 50 % were cooled sympathetically by the Coulomb interaction with laser cooled Mg^+ ions, have been produced in a linear Paul trap. By controlling the balance of the radiation pressure from the two cooling lasers, the Coulomb crystals could be segregated according to ion species. Previuos studies of ion crystals and molecular dynamics simulations suggest that the temperture may be around 10 mK or lower. The obtained results indicate that a wide range of atomic and molecular ions, which due to their internal structures are not amenable to direct laser cooling, can be effectively cooled and localized (crystalized) in linear Paul traps. For high resolution spectroscopy of such ions this may turn out to be very useful.

INTRODUCTION

Trapped ions, when cooled sufficiently, form spatially ordered structures (Coulomb crystals). For smaller crystals, where surface effects play a role, shell and string like structures are equilibrium states [1–3], while molecular dynamics (MD) simulations of infinite single component plasmas, predict a body centred cubic (BCC) structure [4] as the equilibrium state. In both Paul and Penning traps string and shell structures have been produced by applying laser cooling [5–11], and recently BCC structures at the centre of very large ion crystals in Penning traps have been reported [12,13]. Since only ions with simple level schemes accesible to lasers can easily be laser cooled, most atomic ion species and all molecular ions, due to their complex vibrational and rotational structure, are excluded from this type of cooling. Hence, to date only very few singly charged atomic ion species have been laser cooled and crystallized. The equation of motion in vaious traps allow, however, ions in several different charge states and with a wide range of masses to be trapped simultaneously, which make sympathetic cooling though the Coulomb interaction possible.

Previously, several authors have investigated sympathetic cooling, where directly laser cooled ions were used to cool ions of different species through mutual Coulomb interaction [14–17]. In most of these experiments, the typically achieved temperatures of the sympathetic cooled ions were some 100 mK, which did not lead to ordering of the whole plasmas. However, in a few cases a few dark sites in crystals consisting of laser cooled $^{24}Mg^+$ were attributed to indirectly cooled impurity ions [18,19]. Recently, a crystal consisting entirely of Ca^+ was observed to stay crystallised when some of the constituent ions were decoupled from the cooling laser by being optically pumped into a metastable dark state [9].

In this proceeding, Coulomb crystals in a linear Paul trap consisting of upto a few hundred ions where the fraction of sympathetically cooled ions is greater than 50 % are presented. In one case particular intersting for spectroscopy, 14 sympathetically cooled ions were maintained in an ordered string structure by only one directly cooled $^{24}Mg^+$ ion. We have not measured the temperature of the sympatetically cooled ions in the crystals, but since ordering is observed it must be below temperatures previously reported in experiments with comparable large fractions of sympathetically cooled ions [15–17]. Recent studies of the formation of $^{24}Mg^+$ ion crystals [10] and molecular dynamics (MD) simulations of infinitely long cylindrical plasmas [20] indicate that the temperature may well be around 10 mK or lower. The radiation pressure of the cooling lasers has furthermore made it possible to segregate the ions according to species. Besides the potential interst of such mixed Coulomb crystals within plasma physics, the very cold and well-localized sympathetically cooled ions are

CP457, *Trapped Charged Particles and Fundamental Physics*
edited by Daniel H. E. Dubin and Dieter Schneider

very interesting in connection with high resulution spectroscopy, where both transit time broadening, Doppler shift/broadening as well as laser induced light shifts can be problematic.

EXPERIMENTAL SETUP

The experimental setup is practically identical to the one described in the contribution by J. S. Hangst *et al.* in this proceeding and is described in details in ref. [10]. In the experiments, the ions are confined in a linear Paul trap [21] operating at a RF frequency of $\Omega = 2\pi \times 4.2$ MHz and a RF amplitude of $U_{RF} = 15 - 100$ V, which give values of the stability parameter q within the range [0.07,0.5] for $^{24}\mathrm{Mg}^+$ ions. Since loading of the trap is done by electron bombartment of an atomic magnesium beam sent through the trap center, ions from the background gas are produced as well and will be trapped if their charge to mass ratio gives rise to values of q below the stability limit of 0.9. The fraction of trapped background gas ions can be controlled to some extent by varying the atomic beam flux. The $^{24}\mathrm{Mg}^+$, and in some cases also $^{26}\mathrm{Mg}^+$, ions are laser cooled axially by Doppler cooling on the $3s^2S_{1/2} - 3p^2P_{3/2}$ transition. Sympathetic cooling of the transverse degrees of freedom of the laser cooled ions as well as all degrees of freedom of the other trapped ions is accomplised through the Coulomb interaction between the ions. When cooling a single species two counter propagating laser beams at the same frequency and with adjustable intensity balance are sent into the trap region, while when cooling two isotopes an extra laser beam at a separately tunable frequency is overlapped. The positions of the ions are monitored by imaging the fluorescence light onto an image-intensified video camera, the time resolution of which is 20 ms. The camera system views the trap perpendicular to the trap axis.

EXPERIMENTAL RESULTS

We have observed sympathetic crystallization of crystals containing of up to some 200 ions where 60% of the ions were cooled indirectly. Fig.1 shows a sequence where ions are loaded into the trap using two counter propagating lasers resonant with $^{24}\mathrm{Mg}^+$ and $^{26}\mathrm{Mg}^+$, respectively. Due to the net radiation pressure force exerted on the cooled ions in the direction of the laser beams, the crystal is spatially segregated according to species. Since this forces can at most displace the ions some 50 μm along the axial trap potential, we conclude that the dark regions between the two magnesium isotopes in Fig. 1 must be filled with other ionic species. The visible magnesium ions are clearly crystallized at the boundary of the dark region, indicating that the dark ions in the dark region are also crystallized, since the Coulomb interaction is long range and the otherwise chaotic motion at the centre of the crystal would lead to heating of the entire ion plasma. By using two counter propagating laser beams resonant with one of the magnesium isotopes and temporarily changing their power balance, we can cause the visible ions to move back and forth though the centre. The movement takes the form of discrete hops from one well-defined site to another, in agreement with a full ordered plasma.

Previous studies of larger $^{24}\mathrm{Mg}^+$ crystals of similar shapes Ref. [10] show that the onset of spatial ordering happens at a plasma coupling parameter comparable to the value predicted for infinitely long cylindrical plasmas [20]. The plasma coupling parameter is defined as:

$$\Gamma = \frac{E_{Coul}}{k_B T},$$

where T is the temperature and E_{Coul} is the nearest neighbour Coulomb energy. From the simulation presented in Ref. [20] fully ordered shell structures are expected when $\Gamma \geq 100$. With the trap parameters used in the present experiment this lower limit of Γ sets an upper temperature limit of about 10 mK. Due to the strong coherent transverse micro-motion of the ions, the maximum transverse kinetic energy of the outer shell ions in the last image of Fig. 1 corresponds to a temperature of a few Kelvin. Since the coupling of transverse micro-motion into the axial motion is found to be extremely small for very prolate crystals, this leads to small additional first order Doppler shifts along the trap axis, while the second order Doppler shifts will be larger than implied by the estimated temperature for crystalization.

In Fig. 4a. in the contribution by Hangst *et al.* is shown a video frame of a single $^{24}\mathrm{Mg}^+$ ion in a string with 14 non-fluorescing ions, which are either ions from the background gas or other magnesium isotope ions. The evidence for the string comes about by monitoring the various positions the single $^{24}\mathrm{Mg}^+$ ion visits due to diffusion in a 2 min. video sequence. A composite picture of the positions visited by the visible ion fits perfect with simulated positions of a string of 15 singly charged ions at zero-temperature (See fig 4b. in contribution by

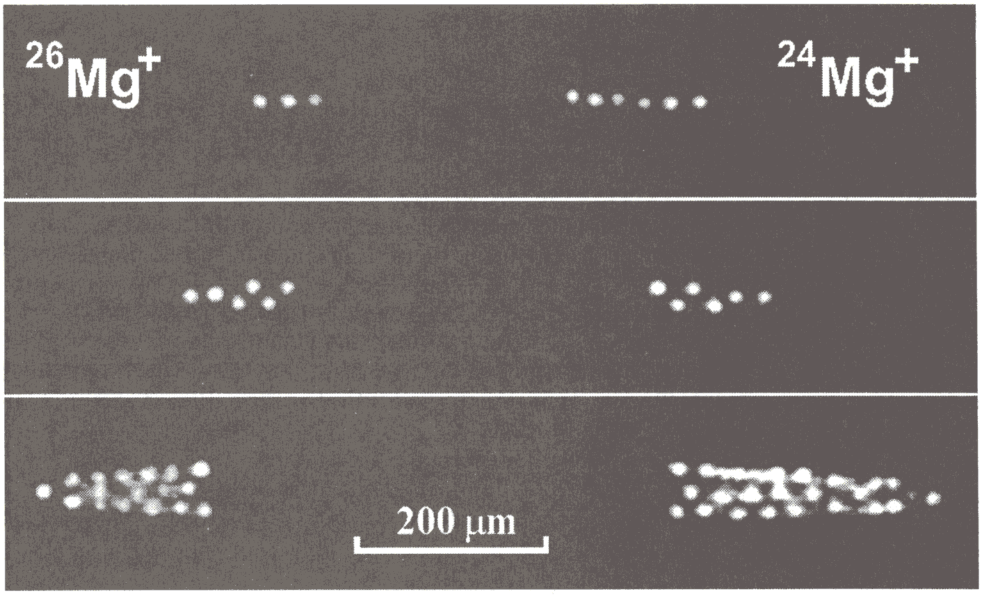

FIGURE 1. Three successive images taken during a loading sequence. The $^{24}\mathrm{Mg}^{+}$ ions are pushed to the right and $^{26}\mathrm{Mg}^{+}$ ions to the left by their respective near resonant cooling lasers. The central region contains sympathetically cooled ions.

J. S. Hangst *et al.*). Since each video frame always shows the visible ion in a single position, the rearangement time of the string after an detectable disturbance must be faster than the frame integration time of 20 ms. This is in accordance with typical reordering times (~1ms) found in molecular dynamics (MD) simulations. For the observed positional diffusion of the visible ion with a jump rate of 0.36 per second there are two probable processes: Occasional elastic collisions with background gas atoms/molecules and random walk of the ions induced by the photon scattering events through laser cooling. For the experimental background pressure of approx. 10^{-10} Torr, we estimate 0.03 elastic collisions per ion per second [22]. If each such collision leads to a positional jump this can explain the observed jump rate. However, future experiments conducted at various pressures as well as MD simulations should reveal the importance of the two mechanism for positional jumps. We have initiated MD simulations where the RF field of the trap, collisions with the background gas and the random momentum kicks given to the ions in the photon scattering processes are included.

CONCLUSION

In conclusion, we have demonstrated that in a linear Paul trap it is possible to make Coulomb crystals consisting of up to at least a few hundred ions where more than 50% of the ions are cooled sympathetically. We have proven it is possible to create and keep a string of 15 cold ions where only a single ion is directly cooled. Earlier studies of the formation of $^{24}\mathrm{Mg}^{+}$ ion crystals and MD simulations indicate that the temperture may well be around 10 mK or lower. Our findings indicate that a wide range of atomic and molecular ions, can in a substantial amount be effectively cooled and localized by the use of linear Paul traps. This points towards improvements in spectroscopic studies of such ions.

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