Multi-spieces ion Coulomb-crystals

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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. Such crystals of various sizes containing single atomic ion species have now for more than ten years been investigated in various types of traps (See e.g. Ref. [1, 2, 3, 4] and references therein). Though crystals containing few impurity ions have been observed since the first experiments, so far not much attention has been paid to experimental studies and applications of ion Coulomb-crystals of multi-species ions [5, 6]. The present contribution contains recent experimental work on this subject as well as possible applications in molecular ion physics and quantum optics.

When loading a trap, e.g., by electron bombardment of an atomic beam, besides singly charged ions of the various isotopes of the chosen element, doubly charged ions as well as background gas ions will be created. In our experiments when loading Mg^+ ions into the trap, often more than half of the trapped ions are of other types. However, just by laser cooling the $^{24}Mg^+$ ions, multi-species Coulomb-crystals can be created through sympathetic cooling of the other ions present [5]. Due to the radial separation of cold ions with various charge to mass ratios in the trap, we have, by monitoring the fluorescence from both $^{24}Mg^+$ and $^{26}Mg^+$ ions in such crystals, been able to prove that Coulomb-crystals containing a significant amount of at least five different ion species have been produced.

Coulomb-crystals of two or more *specific* ion species, with one suitable for laser cooling and the neutrals of others being gasseous at room temperature, can typically be achieved relatively easily. First, the laser coolable ions are produced by electron bombardment followed by removal of unwanted impurity ions by a series of changes in the trap parameters. Next, a gas of one specific element is leaked into the vacuum chamber at a pressure much higher than the background gas pressure, and is followed by a short periode of electron bombardment which essentially only produces ions of the introduced gas. Finally, the introduced gas is pumped out. The last steps in the procedure can be repeated with other gasses. By this technique, we have as test cases produced multi-species ion Coulomb-crystals consisting of $^{24}Mg^+$ ions and, e.g., Ne^+, Ar^+, and N_2^+ ions, which are all not easily laser cooled.

In some specific cases, Coulomb-crystals containing molecular ions can also be produced through reactions between trapped ions and neutrals. In recent experiments two-species Coulomb-crystals of Mg^+ and MgH^+ ions [6], Ca^+ and CaH^+, and Ca^+ and CaO^+ have been demonstated in our laboratory. In Ref. [6], it was shown that it is possible to create Coulomb-crystals of one thousand ions of which more than 95% was MgH^+ ions. Since the trapping lifetime of the very cold and spatially well-localized molecular ions is at least several tens of minutes, optical spectroscopy of the molecular ions by monitoring the fluorescence may be feasible. Furthermore, Coulomb-crystals containing molecular ions are attractive objects for dissociation and ionization studies including coherent controlled photon-induced processes. A nearly 100% detection efficiency for such processes can be obtained by observing the change in spatial distribution of the laser cooled ions present.

Loading of the trap by a combination of electron bombardment and resonant two-photon ionization [7] is yet another way in which we are able to create nearly isotopically pure two-species Coulomb-crystal, from now on referred to as bi-crystals. The details in the photo-ionization scheme is presented in another conference contribution by N. Kjærgaard *et al.* By producing $^{40}Ca^+$ ions by electron bombardment and $^{24}Mg^+$ ions by a resonant two-photon ionization process, we have been able to produce bi-crystals of various shapes and relative contents. As also predicted by molecular dynamics simulations, these bi-crystals form various interesting structures with well-defined boundaries between the two ion species. By letting the Mg^+ ions react with H_2 molecules, we have furthermore been able to produce bi-crystal of MgH^+ ions sympathetically cooled by Ca^+ ions.

Resonant multi-photon ionization may also become an interesting tool in quantum optics experiments, since, e.g., strings of various isotopes of one or more elements can be loaded into a trap in specific numbers, without introducing unwanted impurity ions. In connection with a recently proposed quantum computing implementation based on $^{25}Mg^+$ ions sympathetically cooled by laser cooled $^{115}In^+$ ions [8], the photo-ionization technique seems very attractive.

In conclusion, we believe that multi-species Coulomb-crystals are very interesting objects to be studied, and that they can become important objects in fields of molecular physics and quantum optics.

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