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Cooling, identification and spectroscopy of super-heavy element ions

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Abstract. We briefly discuss some possibilities for cooling, identification and spectroscopy of super-heavy element (SHE) ions based on recent results obtained from studies of atomic and molecular ions in linear rf traps. Since these investigations only relied on the charge and the mass of the ion of interest, we believe it should be straight forward to adopt most of the techniques for SHE ion research.

PACS. 27.90.+b $220 \leq A$ – 32.10.Bi Atomic masses, mass spectra, abundances, and isotopes – 32.30.-r Atomic spectra – 39.30.+w Spectroscopic techniques

1 Introduction

In the past decade, there has been an increasing research activity involving cold and trapped ions. The advancements have taken place partly due to the prospect of building quantum computers based on trapped ions [1–3], partly due to the increased interest in cold molecular ion research [4–9]. By exploiting the strong Coulomb interaction between trapped ions, directly laser cooled atomic ions have, e.g., been found very efficient to sympathetically cool the translational motion of molecular ions [4]. Several methods based on the collective motion of cold ion ensembles have, furthermore, been developed for *in situ* non-destructive identification of atomic and molecular ions [5,6,9]. Finally, new ideas for spectroscopic studies of single atomic and molecular ions have been demonstrated or proposed [10–13]. The aim of this short article is to give an overview of the basics of these recent developments and their potential use in SHE ion research.

2 Sympathetic cooling of ions

Sympathetic cooling of one ion species by another was first demonstrated nearly two decades ago were laser cooled Be^+ ions where found to cool co-trapped Hg^+ ions in a Penning trap to a temperature of ∼1 K [14]. More recently, sympathetic cooling of both atomic [15–17] and molecular [4,6,9,16] species to a temperature of ∼10 mK has been reported. At such low temperatures so-called Coulomb crystals are formed [18–20]. The typical time it takes to cool ions from an initial temperature of ∼1000 K to ∼10 mK is of the order of ∼100 ms [21,22], and due to a typical trap potential depth of several eV, the lifetime of the sympathetically cooled ions can easily be of the order of days. Since in rf traps, motional stability only exists for ions with charge-to-mass ratios within a certain range for given applied trap dc and ac potentials [23], not all ion species can be co-trapped. While in theory any singly charged ion with a mass larger than that of the laser-cooled singly charged atomic ion can stay trapped and be cooled, experimental work in linear rf traps has shown that only when the mass of the sympathetically cooled ion is less than ∼3 times the mass of the directly cooled ion, effective sympathetic cooling is observed. Similarly, if the mass of a singly charged sympathetically cooled ion is less than ∼1/3 of the coolant ion, the sympathetic cooling is not effective. Higher mass ions can, however, be trapped and effectively sympathetically cooled if a higher charge state is used. Coulomb crystals containing doubly charged ions have, e.g., been realized [16]. Since SHEs have masses of ∼300 a.m.u., singly charged SHE ions with lifetimes of $\gtrsim$100 ms should easily be sympathetically cooled into a Coulomb crystal by using either laser cooled Ba^+, Yb^+ or Hg^+ ions. A brief introduction to the function of a linear rf trap as well as the properties of single- and two-component crystals in such traps are given, e.g., in reference [16].

3 Identification of sympathetically cooled ions

When experimenting with ion species that do not have a closed optical transition in the visible or near-visible

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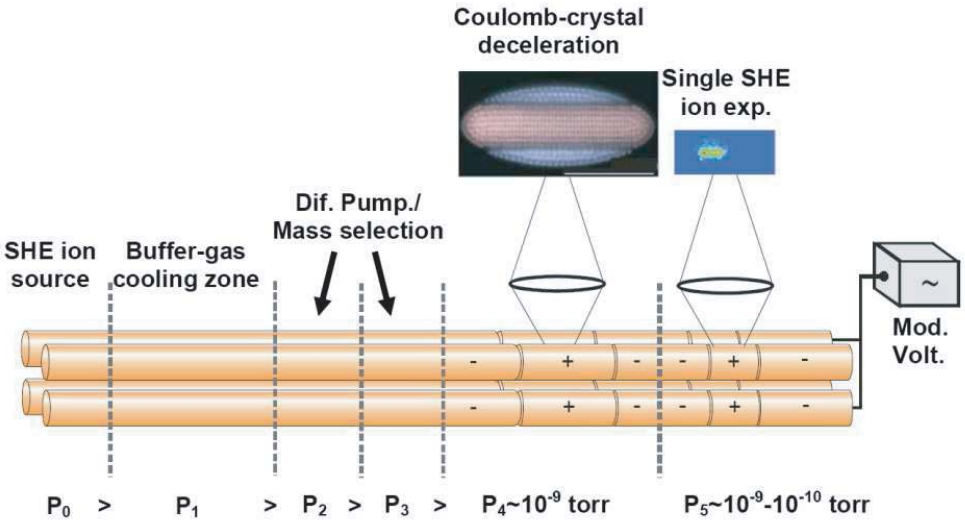

Fig. 1. Sketch of a possible experimental set-up for studies of sympathetically cooled SHE ions. The set-up consists of several sections, which are discussed in the text. Differential pumping will be very important since in the final step where, e.g., experiments using single SHE ions will take place, a pressure of at least 10^{-9} torr is needed.

range, which is the case for many singly- and multi-charged atomic ions due to the large energy level splitting and for molecular ions due the rovibrational sub-structure, standard absorption or fluorescence spectroscopy is not an option for identifying the sympathetically cooled ions in typical Coulomb crystals (up to ∼10 000 ions). Destructive time-of-flight techniques based on releasing the ions from the trap would make it possible through a mass measurement to identify the ions. Alternatively, one can use the fact that trapped cold ion ensembles have a series of collective oscillation frequencies, which can be resonantly excited without loosing the ions by applying time-varying perturbing electric fields to some of the trap electrodes [5,6,9]. For larger ensembles, one can typically only determine the masses of the non-laser-cooled ions with a precision of a few percent from resonance spectra, since the actual resonance frequencies depend on the trapping potential, the number of ions as well as the composition of the ion ensemble [5,9]. This mass resolution will typically not be sufficient for SHE ion experiments. However, in the ultimate situation of two ions, i.e. one single laser-cooled ion and one sympathetically cooled ion, one can achieve a much more precise non-destructive determination of the mass of the sympathetically cooled ion. In recent experiments, we have demonstrated relative mass resolutions of $\sim 10^{-4}$ [6], which is sufficient for many chemical physics experiments. This technique should also fairly easily be applied to determine the number of nucleons in a trapped SHE ion. Furthermore, investigations relying on only two trapped ions make it very easy to determine the charge-state of the SHE ion, since the equilibrium position of the laser cooled ion (visible due to the fluorescence light) will depend on the charge of the SHE ion.

4 Spectroscopy of sympathetically cooled ions

As stated above, standard absorption or fluorescence spectroscopy is generally not possible for sympathetically cooled ions. In the case of molecular ions, spectroscopic signals can, however, easily be obtained through Resonance Enhanced Multi-Photon Dissociation (REMPD) [7,8]. REMPD is a destructive process that only gives a single event per ion. This event can, though, be detected with nearly 100% efficiency either by monitoring the change in the Coulomb crystal ion composition or by observing the loss of trapped molecular ions [7,8]. This method has in recent experiments been used to acquire information on the rotational state distribution of sympathetically cooled molecular ions [7,8]. Another related destructive method, Resonance Enhanced Multi-Photon Ionization (REMPI), can be used to gain spectroscopic information on molecular as well as atomic ions. Again a nearly 100% detection efficiency can be obtained by monitoring the change in the structure of the Coulomb crystal due to the production of doubly charged ions [16]. The generally large ionization potential for singly charged ions limits the potential use of this technique, though. With low production rates of SHE ions, the destructive nature of the REMPI detection scheme does not seem very favorable. In the case of one single laser-cooled ion and one sympathetically cooled ion, one can exploit that it is possible to reach a situation where a single photon absorbed by the sympathetically cooled ion will lead to excitation of a common motional mode of the two-ion system [10,12]. Though the absorption of the light cannot be directly measured, the excitation of the motional mode can be detected by the laser-cooled ion using the so-called electron-shelving technique [10,12]. This detection scheme is non-destructive, and hence the trapped and sympathetically cooled ion can be "recycled". This technique has already been used successfully to perform high-resolution spectroscopy on an Al^+ ion [12], and proposals for doing spectroscopy [11] and internal state preparation [13] of molecular ions have been reported. Though it is technically rather demanding, there seems to be no fundamental reason why such methods cannot be applied to SHE ions as well.

5 Experimental considerations for SHE ion investigations

Being a non-expert in the art of producing and extracting SHE ions for further investigations, it is not very clear how one constructs an optimum experimental set-up for spectroscopic studies of SHE ions. However, the quadrupole structure of linear rf traps makes it tempting to extend this structure to accommodate at least several preparation steps needed before the SHE ions reach the "spectroscopic trap". In Figure 1, a sketch of a possible implementation is presented. After the SHE ions have left the ion source region, they may be guided through a buffer gas zone for reducing the ions' kinetic energies and for having them end up in the desired charge state. Next, they could pass a few stages of differential pumping, including charge-to-mass selecting filters. Before entering the "spectroscopic trap", the SHE ions may furthermore have their kinetic energies reduced by passing through a larger ion Coulomb crystal [24] (see the also contribution in this Special Issue by M. Bussmann et al.). Finally, various of the techniques described in the previous sections might be implemented to study the SHE ions in detail.

6 Conclusion

In conclusion, we have briefly described various ways in which SHE ions in the future can be cooled, identified and studied spectroscopically in rf linear traps. Since most of the techniques have already been applied either on other atomic or molecular ions, we believe that for SHE ions with a sufficiently long lifetime, the techniques should work as well.

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