PAPER

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SpecTrap: precision spectroscopy of highly charged ions—status and prospects

Tobias Murböck[1], Sebastian Albrecht[1], Zoran Andelkovic[2], Radu Cazan[2,3], Volker Hannen[4], Raphael Jöhren[4], Jonas Vollbrecht[4], Stefan Schmidt[2,5,6], Danny Segal[7], Richard Thompson[7], Manuel Vogel[1], Christian Weinheimer[4], Wilfried Nörtershäuser[2,5,6] and Gerhard Birkl[1]

[1] Institut für Angewandte Physik, Technische Universität Darmstadt, Schlossgartenstraße 7, D-64289 Darmstadt, Germany
[2] GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany
[3] Centre for Quantum Technologies, National University of Singapore, Singapore
[4] Institut für Kernphysik, Westfälische Wilhelms-Universität, D-48149 Münster, Germany
[5] Institut für Kernchemie, Universität Mainz, D-55099 Mainz, Germany
[6] Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany
[7] Department of Physics, Imperial College London, London SW7 2AZ, UK

E-mail: t.murboeck@gsi.de

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Abstract
We present the status of the SpecTrap experiment currently being commissioned in the framework of the HITRAP project at GSI, Darmstadt, Germany. SpecTrap is a cryogenic Penning trap experiment dedicated to high-accuracy laser spectroscopy of highly charged ions (HCI) near rest. Determination of fine structure and hyperfine structure splittings in HCI with an expected relative spectral resolution of 10^{-7} will offer the possibility to test quantum electrodynamics in strong fields with unprecedented accuracy. Recently, we have demonstrated trapping and laser Doppler cooling of singly charged magnesium ions in SpecTrap. We report on the status of the experimental apparatus, measurements and present the future program toward storage and cooling of HCI.

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(Some figures may appear in colour only in the online journal)

1. Introduction and setup

Highly charged ions (HCI) offer the unique possibility to investigate one- and few-electron systems in the extreme fields of the nearby nucleus. Due to the strong electron–nucleus interaction, fine structure and hyperfine structure transitions are shifted into the optical regime for certain HCI, and thus allow the use of accurate laser spectroscopy techniques. Hence, HCI are ideal systems for stringent tests of bound-state quantum electrodynamics (QED) calculations. A prerequisite for high accuracy in laser spectroscopy of trapped HCI is the reduction of Doppler broadening caused by the thermal ion motion. In experiments with HCI in storage rings the relative accuracy is limited to 10^{-4} due to momentum uncertainty [1] whereas in electron beam ion traps a relative accuracy better than 10^{-6} was achieved by means of evaporative cooling [2]. Applying Doppler laser cooling, temperatures far below that of the cryogenic surrounding at 4 K can be reached if a suitable cooling transition is available. This is in general not the case for HCI. However, they can be cooled sympathetically to sub-Kelvin temperatures when they are stored simultaneously with a laser-cooled species like Mg^+ ions. To this end, a dedicated laser system for Doppler cooling of Mg^+ ions has been developed [3]. The ions are produced in an external source, dynamically captured into the Penning trap, confined and laser-cooled. At SpecTrap, one laser beam for cooling of the Mg^+ ions and a second beam for excitation of the HCI are irradiated in axial direction while fluorescence detection takes place perpendicular to the experiment's main axis. To that end, a central hole is drilled into each segment

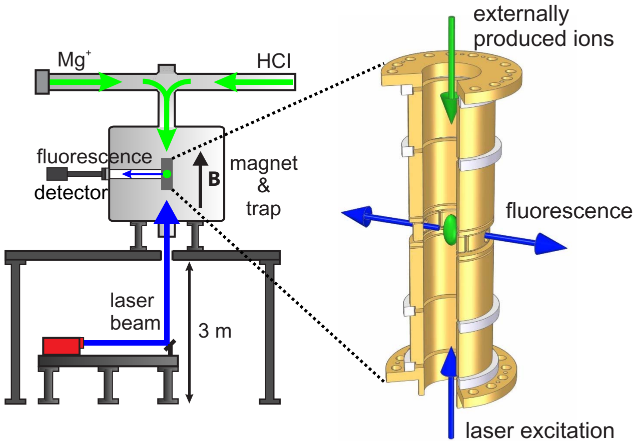

Figure 1. The figure shows a schematic drawing of the SpecTrap experimental setup (left) and a detailed view of the Penning trap (right). The ions are externally produced and excited with a laser beam irradiated in axial direction. A central hole in each ring segments allows fluorescence detection perpendicular to the experiment's main axis.

of the trap's four-fold split central ring electrode, allowing us the detection of fluorescence light with detectors positioned outside the magnet enclosure (see figure 1). Details about the experimental concept have been given in [4]. The split ring electrode also allows us to drive the ion cloud with a rotating dipole field. This rotating wall technique compresses the ion cloud and strongly enhances the signal-to-noise ratio of fluorescence detection, as we have demonstrated in [5]. HCI will become available from external sources such as a dedicated electron beam ion source (EBIS) or from the HITRAP facility [6, 7] at GSI, Darmstadt. HITRAP will be able to provide HCI decelerated from relativistic energies to a kinetic energy of 5q keV. We expect to be able to trap up to 10^5 ions of any species and charge state.

2. Results

Systematic measurements with Mg^+ ions have previously been performed with SpecTrap and are presented in detail in [8]. Ion detection has been accomplished by both optical and non-destructive electronic methods. Single ion fluorescence detection was demonstrated and yields an accurate method for a determination of the total number of stored ions. So far, we have succeeded in loading the trap with up to about 2500 Mg^+ ions. Electronic detection of Mg^+ has been performed by coherent excitation of the reduced cyclotron motion. This measurement also reveals the ion oscillation frequency and thus the magnetic field strength required for a detailed analysis of the obtained spectroscopic data. Applying laser Doppler cooling to Mg^+, temperatures as low as 60 mK have been achieved, and evidence for the formation of Coulomb crystals was observed. Recent measurements yield a storage time constant of Mg^+ ions in our trap of the order of 1 h.

3. Prospects

These initial experiments have proven the functionality of SpecTrap for dynamic capture, confinement and laser cooling of ions as demonstrated with externally produced Mg^+. Next steps comprise the optimization of the trapping and cooling performance and an in-depth characterization of the ion cloud characteristics. To that end, the efficiency of the Mg^+ ion source will be increased to raise the number of trapped ions up to 100 000 ions. A higher number of stored magnesium ions will ease the Mg^+ cloud detection and be advantageous for sympathetic cooling of HCI in future experiments. Though the laser system has proven sufficient for Doppler cooling of Mg^+, its frequency stability will be further improved. A new seed laser will allow for higher stability and reliability in cooling the magnesium ion cloud. With the additional operation of the rotating wall at SpecTrap, advanced control of the ion cloud properties such as shape and density become possible [5]. The compression of the ion cloud to the center of the trap also increases the light collection efficiency and overlap with the cooling laser beam. The functionality of the rotating wall in SpecTrap will be investigated with Mg^+ ions to be ready for use with HCI. A good candidate for first measurements with HCI is boron-like argon, which can be readily produced by an EBIS located at the low-energy beamline of the HITRAP facility. As soon as the HITRAP facility is operational, ions of the highest charge states such as hydrogen-like bismuth (Bi^{82+}) and lithium-like bismuth (Bi^{80+}) will be available for the proposed tests of QED in strong fields [9]. A dedicated laser system for spectroscopy of hydrogen-like bismuth has already been set up and characterized in detail [10]. Detection systems for single photons with wavelengths ranging from the UV (244 nm) to the near infrared (1555 nm) have been developed and tested in collaboration with the University of Münster [11, 12].

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