FACILITY FOR ANTIPROTON AND ION RESEARCH

SPARC COLLABORATION

TECHNICAL DESIGN REPORT -FINAL VERSION-

THE SPECTRAP EXPERIMENT
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TECHNICAL DESIGN REPORT

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ABSTRACT

This document describes the SPECTRAP Penning trap experiment for optical precision spectroscopy of confined and cooled highly charged ions. It presents the methods and apparatus for measurements of strong-field effects on the electronic level structure of atomic ions with spectroscopic resolutions near the natural linewidths of electronic transitions. As such, SPECTRAP allows to benchmark corresponding calculations in the framework of strong-field QED with high significance and with a broad range of ion species and charge states.
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1. PHYSICS CASE AND METHODS

Laser spectroscopy of optical transitions in highly charged ions provides unique access to relativistic effects in few-electron systems and allows stringent benchmarks of quantum electrodynamics (QED) in the extreme electric and magnetic fields as they exist only in the vicinity of ionic nuclei [1,2]. Such experiments represent a bridge between extreme-field physics and precision determinations of fundamental constants and symmetries [3]. Experimentally, magnetic dipole transitions in highly charged systems have first been studied in electron-beam ion traps (EBITs) by emission spectroscopy and later by laser excitation and fluorescence detection experiments [4], which have obtained relative precisions of a few permille up to several parts per million (ppm) for the wavelength determination. Direct laser spectroscopy of heavy highly charged ions has so far only been performed at the experimental storage ring ESR with hydrogen-like bismuth $^{209}$Bi$^{82+}$ [5] and lead $^{207}$Pb$^{81+}$ [6], as well as more recently with lithium-like bismuth $^{209}$Bi$^{80+}$ [7]. This measurement in combination with the measurement on hydrogen-like bismuth will allow the first determination of the so-called specific difference between the hyperfine splittings [8]. The measurement of the transition in $^{209}$Bi$^{80+}$ is an important step, but it will not provide sufficient accuracy for a high-precision determination of the QED effects in the specific difference since the wavelength determination for both transitions (H-like and Li-like) is still limited in accuracy due to the large Doppler effects caused by the relativistic ion motion in the storage ring. This will be considerably improved once high-Z highly charged ions are available at rest in clean environments, which allow high-precision laser spectroscopy. To this end, the SPECTRAP experiment has been conceived [9,10].

The precision achieved in laser spectroscopy of confined ions crucially depends on the width of the optical transition of interest and the mechanisms that lead to additional broadening, e.g., Doppler broadening. The study of narrow forbidden (M1) transitions with high accuracy requires the elimination of Doppler broadening. This can be achieved by first-order Doppler-free techniques like two-photon transitions or by confinement and application of suitable cooling techniques. There is a variety of corresponding methods for phase-space cooling of ion motions, for a detailed overview see, for example, [11]. Evaporative cooling of highly charged ions has been used for laser spectroscopy of Ar$^{19+}$ in an EBIT [4] and has also been demonstrated in a Penning trap using re-trapped highly charged ions produced in an EBIT [12]. The techniques to be employed at SPECTRAP have in part been pioneered at the SMILETRAP [13] Penning trap experiment which is dedicated to precision mass measurements of highly charged ions [14] and has contributed to the development of techniques for recapture, cooling [15], and manipulation [16] of externally produced highly charged ions. SPECTRAP makes use of both resistive cooling [17-20] and laser cooling [21] of such ions. The former is a very effective cooling mechanism for highly charged ions, while the latter is most suitable for singly charged ions with a level scheme suitable for laser cooling such as Mg$^+$. However, laser-cooled ions can then be used for sympathetic cooling [12] of simultaneously confined highly charged ions down to the Lamb-Dicke regime [22]. Such studies allow entering the ppb region of relative accuracies in the transition wavelength determination and are of immense value as input information for related studies like the spectroscopy scheme used in the ARTEMIS experiment for high-precision measurements of magnetic moments [23,24]. The SPECTRAP experiment is designed to accept externally produced atomic ions of all species and charge states.
2. GENERAL SETUP OVERVIEW

The experiment is centered around the cryogenic Penning trap arrangement inside the homogeneous field region of a superconducting magnet. It is designed for dynamic capture of externally produced low-energy ions. In the trap, confined ions are cooled and irradiated with laser light for the spectroscopy to be performed. Optical fluorescence signals are guided radially outward to a photon detector or EMCCD-camera outside of the trap and magnet vessel arrangement, while the ion content of the trap and its motional states are detected non-destructively by pick-up of their image charges. The trap is schematically depicted in figure 1, its properties will be discussed in detail in the following section.

![Figure 1: Schematic of the Penning trap (with cut-out for better visibility) and illustration of its use.](image)

The trap itself and its cryo-electronics are cooled to liquid helium temperature by the cold bore of the superconducting magnet, i.e. the heat sink which maintains the magnet's superconductivity also cools the cold magnet bore and with it the trap and the attached electronics. The bore needs to have an inner diameter of 3 inches or more to host the trap as well as the ion optics for guidance and deceleration of externally produced ions, which enter the setup from the top. Figure 2 shows a schematic overview of the superconducting magnet setup with the trap in the centre.
Fig. 2: Schematic overview of the SPECTRAP superconducting magnet setup with the Penning trap from figure 1 in the centre of the homogeneous field region.

The experimental cycle including ion creation, transport, deceleration and capture is defined by a control and data acquisition software based on LabVIEW, which uses, amongst others, two DG535 digital delay generators and three DS345 synthesized function generators to provide the trap electrode triggers, the frequencies for the system clock, ion excitation and laser scan, and controls the SR430 multichannel scaler used for time-of-flight measurements. Figure 3 shows the setup overview in terms of the experimental control and data acquisition with the most important instruments indicated.

Figure 3: Overview of the experimental control and data acquisition system in SPECTRAP.
3. THE TRAP AND ITS ELECTRONICS

The trap is a cylindrical open-endcap five-pole Penning trap with an additional capture electrode on either end. It confines the ions radially by the superconducting magnet’s axial field and axially by an electrostatic potential well created by appropriate voltages applied to the trap electrodes. These consist of oxygen-free copper and are galvanically gold-plated to avoid oxidization and to minimize electrostatic patch effects. The electrical insulation is guaranteed by Macor rings and sapphire balls in between electrodes. The ring electrode is split into four segments to allow ion cyclotron frequency detection, ion excitation and implementation of the rotating wall compression technique. We have performed R&D studies of this technique in an identical trap at Imperial College, a detailed analysis of the achieved compression and related effects can be found in [21]. Each ring segment is equipped with a 4.8 mm hole for detection of fluorescence light. This diameter was chosen as the maximum size that does not compromise the stability of the electrode segments. The holes offer 100% transmission for photons and create a acceptable loss in the harmonicity of the potential. The sides facing the correction electrodes are equipped with three small blind holes to hold the sapphire balls for electrode separation. The complete electrode stack is mounted on four parallel rods, forming the corners of a square that is defined by the cuts of the ring electrode. The rods establish mechanical contact with the trap only on the mounting flanges, which are grounded and compress the electrode stack longitudinally. Assembled further out, but parallel with the main rods are four support rods, which hold the platform for the trap’s optical components (see figures 4 and 10). The main aluminum flange offers a stable support for the trap assembly. It is mounted on the bottom of the superconducting magnet’s liquid helium reservoir for thermal contact, for more technical details see [25]. For the sake of low temperature-related electronic noise, several components are operated at cryogenic temperatures. They are designed to fit directly under the trap and the liquid helium reservoir.

Figure 4: Complete trap assembly with the Penning trap, its thermal contacts via the top and bottom plates, the optical components for imaging of the fluorescence light, the holders for the cryo-electronics boards (aluminum support flange) and the resonator coil housings below the copper mounting plate. This image is roughly a third the actual size.

The electronics include [25]:

- filters for all signal lines going towards the trap electrodes
- pre-amplifiers for axial and cyclotron frequency signals going from the trap electrodes
- a so-called “arrival detector”, for detection of short (Schottky) pulses of the incoming ions.
Since a single charge typically only creates a voltage signal of the order of a few nV in the trap electrodes, the Johnson noise of a 10 kΩ and 10 kHz bandwidth resistor at room temperature of the order of μV surpasses this signal already by three orders of magnitude. Even though the trap and the attached amplifiers are kept at cryogenic temperature, noise that is picked up from the outer components and transmitted to the trap electrodes can significantly disturb ion motion and detection. Hence, all lines connecting the cryogenic parts with the room-temperature electronics are equipped with dedicated noise filters, see figure 6.

The trap and its electronics are designed for maximum acceptance with respect to capture, storage, cooling and electronic detection of ions. It can be seen from figure 7 that the frequency of the ion axial motion can be tuned to resonance with at least one of the axial coils for all mass-to-charge ratios up to 35. This is necessary both for effective resistive cooling and non-destructive detection of the ion axial motion, and it sets the upper limit for the mentioned techniques. However, ions with yet higher m/q ratio can still be stored and used for experiments. The detection is in that case limited to destructive or optical methods, and sympathetic cooling must replace resistive cooling.
Figure 7: Left: trap voltage necessary to bring the axial motions of ions with different mass-to-charge ratios into resonance with one of the two resonant circuits. Right: maximum voltage that can be applied between the end caps in order to ensure stable confinement conditions at a given magnetic field.

4. THE MAGNET AND ION GUIDING

The envisaged magnet is a vertical, cold-bore superconducting magnet with a Helmholtz arrangement of coils to allow optical access in the central horizontal plane through the trap centre via 6 optical ports ordered in three pairs, two of which are perpendicular to each other and the third is in a 30° arrangement with respect to those. These may be used for radial laser excitation and/or detection of fluorescence photons perpendicular to the magnetic field. The magnet can be run in a persistent mode at up to 6 Tesla central field strength at a current-to-field efficiency of 0.1 T/A. The central field homogeneity is required to be better than 50 ppm over a 1 cm³ region mainly for reasons of ion manipulation and electronic detection. If cooling to the superconducting state is done by (pulse-tube) cryo-coolers, mechanical vibration needs to be kept under control. This potential issue can be circumvented when using liquid helium shielded by a liquid nitrogen vessel. Then, low coolant consumption is essential for continuous operation. Helium re-liquefaction is highly desired, as precision spectroscopy requires extended periods of confinement and measurements. It is hence desirable to do helium re-liquefaction on-site, for example by a re-condenser attached to the system. The central magnet bore of 3 inch diameter hosts the Penning trap with its cryo-electronics and a pair of pulsed drift tubes (DT1 and DT2 in figure 8) for ion deceleration from a few keV/q to close to rest. In its upper extension there is also a set of ion-optical elements for focusing and steering of the ion beam incoming from external ion sources. The details of this are shown in figure 8.

Figure 8: Diagram of the SPECTRAP beamline with ion optical elements.

Ex - Einzel lens, Q - quadrupole bender, M - multipole, EMx - electron multiplier, D - deflector, DTx - drift tube
5. OPTICAL SYSTEMS

5.1. Laser cooling of Mg$^+$ for sympathetic cooling of highly charged ions

Laser cooling of Mg$^+$ is performed on the $^2S_{1/2}$ to $^2P_{3/2}$ transition at 279.6 nm. We have developed a laser system based on a Koheras Boostik fiber laser, which produces up to 0.6 W of single-mode radiation at 1118 nm. The fourth harmonic of this radiation provides about 20 mW at the desired wavelength of 279.6 nm. Hence, two subsequent frequency doubling stages are installed as shown in figure 9, details can be found in [26]. The 1118 nm laser light is guided through two wave plates and a Faraday isolator in order to avoid any backscattered light disturbing the laser oscillator. The first frequency doubling stage involves a lithium triborate (LBO) crystal with non-critical phase matching. The SHG cavity is locked to the fiber-laser frequency using the Hänsch-Couillaud locking scheme. Thanks to the non-critical phase matching, the output is a round Gaussian beam with an excellent beam profile, easy to mode-match and couple into the second doubler. The second SHG-stage is constructed using a beta-barium borate (BBO) crystal with critical phase matching.

![Diagram of optical system](image)

Figure 9: Schematic overview of the experimental setup for generation of 279.6 nm laser light needed for Doppler cooling of Mg$^+$. LBO and BBO are the non-linear crystals. Details can be found in [22].

5.2. Fluorescence collection

The central holes in the ring electrodes (4.8 mm diameter) are located 14 mm away from the main trap axis. They define a solid angle of 0.09 sr, which is a fraction of $7 \times 10^{-3}$ out of the total solid angle of $4\pi$. A collection system consisting of a spherical mirror and a plano-convex lens, as depicted in figure 10, collimates the light emitted from the centre towards the optical detection system. In that way, one part of the light is directly collected by the lens, while another part is reflected back into the trap centre by the mirror and then also collected, thus increasing the overall fluorescence signal. With four holes in the ring electrode it is possible to establish two perpendicular detection axes, which can be simultaneously used for fluorescence detection.
The technical realization of fluorescence detection, i.e. the type of detector in use, depends on the wavelength regime under investigation. For the set of intended studies, three ranges are of relevance, as can be seen in table 1. With the UV and near optical region covered by standard commercial photo multiplier tubes, effort is focused on efficient detection also in the infrared region. Corresponding development is being performed in collaboration with the University of Münster, for details see [27].

<table>
<thead>
<tr>
<th>Model</th>
<th>PerkinElmer C1993P</th>
<th>RMD S0814</th>
<th>Hamamatsu H10330</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Channel PMT</td>
<td>Si-APD</td>
<td>NIR PMT</td>
</tr>
<tr>
<td><strong>Active area</strong></td>
<td>15 mm diameter</td>
<td>8 mm x 8 mm</td>
<td>1.6 mm diameter</td>
</tr>
<tr>
<td><strong>Wavelength range</strong></td>
<td>200 nm - 400 nm</td>
<td>400 nm - 1050 nm</td>
<td>950 nm - 1650 nm</td>
</tr>
<tr>
<td><strong>Quantum Efficiency</strong></td>
<td>&lt; 18 %</td>
<td>&lt; 70 %</td>
<td>~ 10 %</td>
</tr>
<tr>
<td><strong>Dark count rate</strong></td>
<td>&lt; 10 Hz</td>
<td>&lt; 100 Hz</td>
<td>~ 150 kHz</td>
</tr>
</tbody>
</table>

Table 1: Characteristics of the main three detector types to be used in SPECTRAP (PMT is for photo-multiplier tube, APD for avalanche photo diode and NIR for near infra-red).

REFERENCES