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Extreme-field physics in Penning traps

The ARTEMIS and HILITE experiments

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Abstract We present two Penning trap experiments concerned with different aspects of the physics of extreme electromagnetic fields, the ARTEMIS experiment designed for bound-electron magnetic moment measurements in the presence of the extremely strong fields close to the nucleus of highly charged ions, and the HILITE experiment, in which well-defined ion targets are to be subjected to high-intensity laser fields.

Keywords Penning traps · Highly charged ions · Extreme fields

1 Introduction

The presence of extremely strong electromagnetic fields has a wide range of effects and may, amongst others, be studied in two interesting yet distinct regimes: on a microscopic scale there are extreme electric and magnetic fields in the vicinity of an atomic nucleus, which significantly alter the properties of bound electrons. As field strengths reach close to the Schwinger limit (of the order of 10^{16} V/cm, above which field production of real

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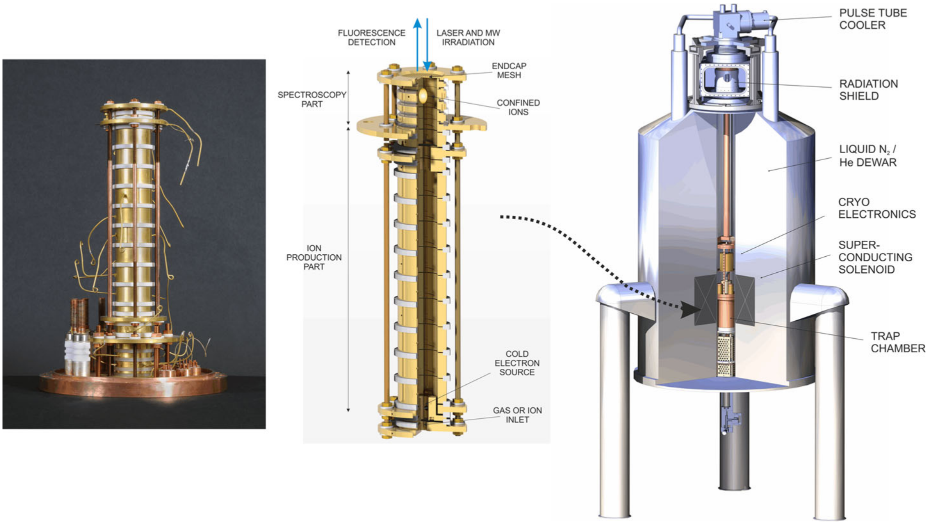

Fig. 1 Image of the ARTEMIS Penning trap (*left*), schematic of same trap (*middle*), and schematic of the complete setup with the trap located in the centre of the superconducting magnet (*right*)

electron-positron pairs would become possible), contributions from quantum electrodynamics (QED) play an important role to electronic structure, state lifetimes, and magnetic moments, and corresponding calculations can be tested with high accuracies [1]. In turn, this allows access to fundamental constants and symmetries. The ARTEMIS experiment is designed for precision measurements of bound electron magnetic moments in confined and cooled highly charged ions, and aims at measurements on the part per billion (ppb) level of accuracy for electronic g-factors and on the part per million (ppm) level of accuracy for nuclear magnetic moments. It is further designed for dedicated measurements of higher-order Zeeman effects. It is located at the HITRAP facility [2] at GSI, Germany, for access to low-energy highly charged ions. We present the concept, status, and first results.

On a macroscopic scale, extreme fields are present when atoms and ions are subjected to highly intense laser light. The electromagnetic fields in and close to a laser focus produce strongly non-linear optical effects such as multi-photon ionization to high charge states. The HILITE experiment hence features a Penning trap for the preparation and positioning of well-defined ion targets, as well as for non-destructive detection and confinement of reaction products in studies with various high-intensity and / or high-energy lasers.

2 Double-resonance spectroscopy at ARTEMIS

Precise measurements of fine structure and hyperfine structure transitions in highly charged ions allow sensitive tests of corresponding calculations in the framework of quantum electrodynamics of bound states [3]. Precisely measurable quantities comprise magnetic dipole (M1) transition energies and to some extent also lifetimes in the optical and in the microwave domain [4].

The obtainable spectroscopic resolution depends crucially on effects of line shift and broadening, prominently on first-order Doppler effects, which need to be minimized by

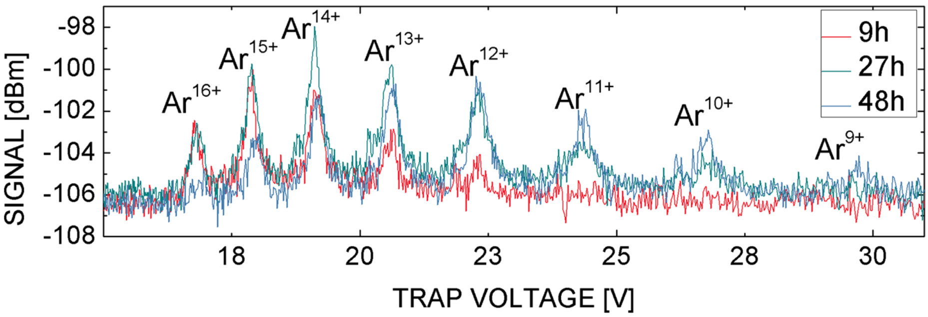

Fig. 2 Spectrum of in-trap created and confined argon ion charge states as a function of time upon creation

phase-space cooling of the ions' motions. To this end, ARTEMIS features techniques for extended ion storage and cooling prior to spectroscopic measurements.

The ARTEMIS experiment applies a laser-microwave double-resonance spectroscopy scheme which allows to precisely measure the Zeeman substructure of the fine or hyperfine structure of the ion under consideration [5]. From this, the magnetic moments (g-factors) of bound electrons can be determined for ions with non-zero nuclear spin, with precisions on the ppb scale, and in a somewhat complimentary approach to the Stern-Gerlach type measurements which have been successfully performed with various hydrogen-like ions [6–9]. At the same time, this information yields the nuclear magnetic moments with precisions on the ppm scale. A nice feature when applied to few-electron systems is the absence of diamagnetic shielding of the nucleus by outer electrons, hence these measurements enable benchmarks of shielding models. The principle of the laser-microwave double-resonance technique is to use fluorescence light from a closed optical transition as a probe for the microwave excitation between corresponding Zeeman sublevels. Different level schemes allow different preparation and measurement procedures, as has been discussed in detail in [5]. The envisaged experimental resolution allows to measure also quadratic and cubic contributions to the Zeeman effect, as has been detailed out in [10], and which allow the first laboratory access to individual higher-order contributions on the magnetic sector. The Penning trap in use for this kind of spectroscopy is a dedicated development to the end of maximizing the optical fluorescence yield, a so-called 'half-open' Penning trap [11]. It also features an ion creation part in full similarity to a cryogenic mini-EBIS [12], in which test ions such as Ar^{13+} are produced. This part of the trap is designed for dynamic capture of ions from an external source like an EBIS or from the HITRAP facility [2] via a low-energy beamline [14, 15]. We are currently commissioning the system with internally produced ions, see the charge spectrum in Fig. 2. It shows first measurements of the axial detection signal of the same ion cloud at three different storage times after ion creation. In the present spectrum, the signal is picked up by a resonant circuit at a frequency of $\omega = 2\pi \cdot 635\,\text{kHz}$ while the trap voltage U is ramped from 32 V to 16 V with a scanning speed of $\mathrm{d}U/(\mathrm{Ud}t) \approx 10^{-2}/\text{s}$. From the observed space charge shift of the ion signal, we estimate an ion number density of about $10^6/\text{cm}^3$ which is roughly one third of the expected electric space charge limit for that trap. Since three spectra of the same ion cloud are taken at different times, one can estimate the residual gas pressure. Assuming a cross section for electron capture from residual gas of $3.25 \cdot 10^{-15}\text{cm}^2$ for ions like Ar^{13+} [13], the observed charge state lifetime of roughly 20 hours results in a value for the residual gas pressure of

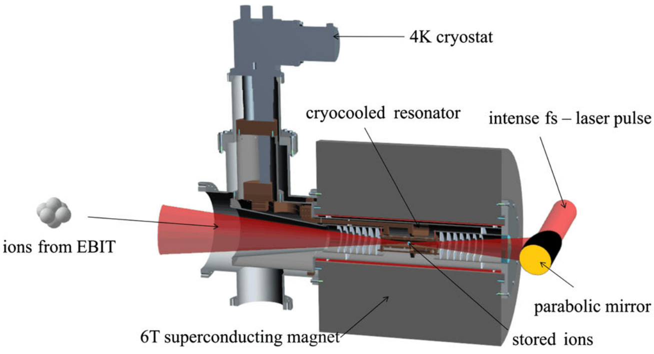

Fig. 3 Schematic of the HILITE experiment (*left*) and image of the actual setup (*right*)

about 10^{-13} hPa, which will allow storage of the highest charge states from the HITRAP facility for several hours, sufficient for the envisaged measurements.

3 High-intensity-laser reaction studies with HILITE

An important effect of high electromagnetic field strengths in atomic physics is non-linear ionization. Laser ionization is a widely investigated topic and there are several experiments and theories concerned with the high-energy [16–18] and high-intensity [19–21] photo-ionization regimes. For the sake of a clean reaction environment, it is desirable to work with ion targets prepared in a well-defined state concerning the charge distribution, position, shape, species and spatial density. To this end, we have conceived and built a dedicated Penning trap setup for ion-target preparation and non-destructive detection. The setup is designed to be compact (see Fig. 3), such that it may be moved readily to laser facilities such as FLASH [22], PHELIX [23], JETI 200 and POLARIS [24] or others, which cover a broad range of possible ionization parameters.

3.1 Experimental setup

The HILITE Penning trap is located inside the bore of a horizontal superconducting magnet with a maximum magnetic field of 6 T. The trap is a mechanically compensated open-endcap Penning trap [25, 26] which consists of an eight-fold segmented ring electrode and a pair of endcap electrodes with a separation of $2z_0 = 17.4$ mm. For dynamic capture of ions, additional electrodes are mounted on either end of the trap, which have a conical opening to accept laser beams up to an aperture of f/5. The inner trap diameter is 20.0 mm and hence the experiment is transparent for non-focused (laser) beams up to that diameter. The main concern of the experiment is to be able to prepare ion targets for laser irradiation and non-destructively detect the reaction products. To that end, a number of trap-specific techniques are combined which shall briefly be described.

3.2 Ion selection, cooling and positioning

Typically, ion ensembles which are produced inside a trap or captured from external sources may contain different atomic or molecular constituents in different charge states. Since each ion species of a certain charge-to-mass ratio q/m has a specific axial oscillation frequency in the trap, it is possible to excite any species selectively. The so-called SWIFT-technique (Stored Waveform Inverse Fourier Transform) [27] allows to excite any combination of q/m-regions resonantly and simultaneously. If the excitation amplitude is sufficiently large, the unwanted ions are resonantly ejected from the trap, leaving a cloud which consists of desired ion species only. The phase space of this remaining ion cloud can be cooled by resistive or sympathetic cooling, as detailed out in [28]. Axial positioning of the ion cloud as a whole is possible by use of a trap voltage asymmetry, i.e. an effective non-zero voltage across the endcaps. In this way, the centre of the ion oscillation is shifted with respect to the geometrical trap centre, and can be positioned with a resolution on the micrometer scale with respect to the laser focus. Details about the possibilities and requirements have been given in [29].

3.3 Ion target density and shape

To the end of defining the spatial density of the ion cloud, we employ the so-called 'rotating wall technique' [30–32]. In combination with a choice of the axial trapping potential, it can further be used to define the aspect ratio of the ion cloud. The ion cloud, always being an ellipsoid of rotation under these circumstances, may be deformed continuously from an oblate form (flat disc perpendicular to the central trap axis), to a spheroid and further to a prolate form (cigar shape along the central trap axis). To this end, a rotating dipole field is created by phase-shifted sinusoidal rf-signals applied to opposing segments of the ring electrodes. It produces a torque on the ion cloud as a whole and forces the global rotation frequency of the ion cloud to the revolution frequency ω_r of the rf-drive. This frequency uniquely determines the density n of the ion cloud, which has its maximum n_{max} at ω_r equal to half the free cyclotron frequency of the ions. The density n_{max} is determined by the values of the confining field strengths, and fundamentally limited to

$$n_{max} = \frac{\epsilon_0 \cdot B^2}{2m}, \tag{1}$$

the so-called 'Brillouin-limit' [33, 34]. The maximum ion number density for Xe^+ ($m = 132\,u$) at a magnetic field strength of $B = 6\,T$ is about $7 \times 10^5\ mm^{-3}$.

3.4 Ion detection and ion counting

For spectrometry of the confined ions species we use the FT-ICR (Fourier Transform Ion Cyclotron Resonance) technique. It relies on a pick-up of image currents created by the ion motion, analyzed by Fourier transformation to yield information on the charge-to-mass spectrum of the trap content and the relative ion numbers [35]. As such, it is a non-destructive detection method which keeps the analysed ions confined in the trap. We detect ions by broadband analysis of the induced currents inside ring electrodes as well as inside endcap electrodes for the radial and the axial ion oscillations, respectively. The currents are pre-amplified by a low-noise cryogenic amplifier which works at 4.2 K. Additionally, we employ three different resonators directly attached to the trap electrodes to achieve a higher signal for certain frequencies. The first is a helical resonator, which amplifies multiples of a fundamental frequency, so that all charge states of one species can be measured simultaneously with similar and high sensitivity. The second and third resonators are RLC-circuits, which are optimized for axial frequencies. The resonant frequencies are 229 kHz and 702 kHz, which are chosen to cover the detection of all charge states of all ions up to xenon within the range of possible trap voltages. Additionally, we intend to employ low-noise high-sensitivity charge amplifiers on electrodes at either side of the trap for charge counting of (educt) ions entering and (product) ions leaving the trap. These are to be gauged by destructive ion counters.

3.5 Laser ionization

In general, there are two regimes for the ionization with high-intensity photon fields, multiphoton ionization (MPI) and field ionization (FI), which are distinguished by their Keldysh parameter [36]. For high-power lasers with visible or near-infrared (NIR) radiation, field ionization dominates, and ionization probabilities can be calculated from experimental parameters [38]. One envisaged experiment with the HILITE setup uses a laser beam focused by an off-axis parabolic mirror with a silver coating through a laser window into the trap vacuum. We have chosen a fused silica window due to its high purity and high damage threshold. For lasers up to a peak intensity of 0.1 TW at an e^{-2}-beam diameter of 35 mm, non-linearities of fused silica can be neglected. The focus parameters are optimized for a maximum yield of high charge states. Typically, we can store up to 10^5 ions in an ion cloud with an axial extension of about 500 μm and a diameter of about 125 μm. Following [37], we have calculated the beam shape as well as the intensity distribution inside the focal volume assuming a laser beam quality factor of $M^2 = 1.6$ (spatial profile close to Gaussian) and an f-number of f/16. Using this spatial laser intensity distribution, for a pulse energy of 10 mJ at a pulse duration of 40 fs, we expect about 4000 stored Ar^+ ions to become ionized up to a Ar^{8+} [38]. For low charge states, all particles along the laser axis can be ionized easily and the number of ionized particles is limited by the geometries of ion cloud and laser beam. Product ions remain stored in the trap for further studies or further ionization. Currently, HILITE is being prepared for initial tests to be performed with ions from an external electron beam ion source (EBIS) and an offline test laser.

4 Summary

The ARTEMIS Penning trap experiment located at the HITRAP facility at GSI, Germany, is currently being commissioned with in-trap produced test ions like Ar^{13+}. In a next step, laser-microwave double-resonance experiments within the fine structure and its Zeeman sublevels of this ion will be performed, to the end of measuring the magnetic moment of the electron bound in a boron-like ion. At a later stage, similar measurements with ions of higher charge states up to U^{91+} from the HITRAP facility are foreseen. The HILITE experiment, currently under construction at the same site, will be tested with offline ions from the HITRAP low-energy beamline and an offline laser before being operated at high-intensity laser facilities.

Conflict of interests The authors declare that they have no conflict of interest.

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