Penning-trap experiments for spectroscopy of highly-charged ions at HITRAP

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Penning-Trap Experiments for Spectroscopy of Highly-Charged Ions at HITRAP

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Abstract. Highly charged ions offer the possibility to measure electronic fine structures and hyperfine structures with precisions of optical lasers. Microwave spectroscopy of transitions between Zeeman substates further yields magnetic moments (g-factors) of bound electrons, making tests of calculations in the framework of bound-state QED possible in the strong-field regime. We present the SPECTRAP and ARTEMIS experiments, which are currently being commissioned with highly charged ions in the framework of the HITRAP facility at GSI, Germany. We present the scientific outline, the experimental setups and first results with confined ions.

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1. Introduction

Precise measurements of fine structure (FS) and hyperfine structure (HFS) transitions in highly charged ions allow sensitive tests of corresponding calculations in the framework of quantum electrodynamics of bound states [1, 2, 3]. Observables comprise magnetic dipole (M1) transition energies and lifetimes in the optical (FS and HFS) and in the microwave domain (Zeeman substructures). Their scaling with the nuclear charge of the ion makes them suitable for experimental access within a broad range of ion species. Here, we discuss the SPECTRAP experiment for optical spectroscopy and the ARTEMIS experiment for microwave spectroscopy of confined highly charged ions. Generally, the obtainable spectroscopic resolution depends crucially on effects of line shift and broadening, foremost on first-order Doppler effects, which need to be minimized by phase-space cooling of the ions' motions. To this end, the Penning trap experiments presented here feature techniques for extended ion storage and cooling prior to spectroscopic measurements. Both experiments are foreseen to dynamically capture externally produced ions at the HITRAP facility [5] at GSI, Germany.

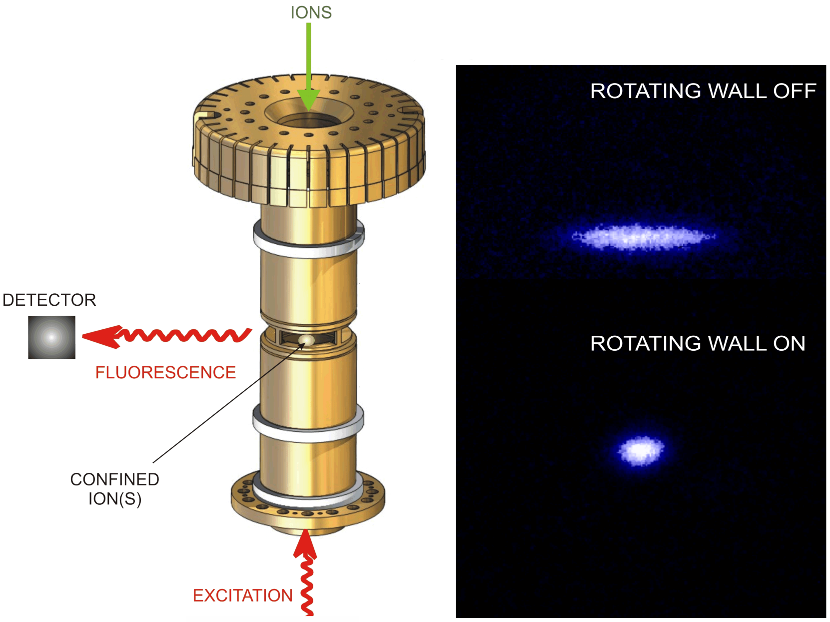

Figure 1. SPECTRAP Penning trap schematic (left) and CCD images taken of confined ions when a rotating wall for ion centering and compression is applied [4].

2. Optical Spectroscopy with SPECTRAP

An experimental scheme has been outlined for laser spectroscopy measurements with well-localised highly charged ions nearly at rest [6]. This is achieved by ion confinement in a cryogenic Penning trap [7] with an optically transparent ring electrode for radial access, see also figure 1. For these experiments, a cylindrical open-endcap Penning trap with an additional capture electrode at either end has been chosen. An externally produced ion bunch is dynamically captured, confined and cooled by resistive and sympathetic cooling [8, 9]. To this end, the trap is pre-loaded with singly charged Mg ions which are laser-cooled close to the Doppler limit, i.e. to temperatures of several tens of mK. This has been achieved by use of a frequency-quadrupled 1118 nm diode laser, and hints towards ion crystalisation have been found, see figure 2, and the detailed discussion in [9]. So far, highly charged argon ions up to Ar^{16+} have been co-loaded from an external electron beam ion source (EBIS) [10, 11, 12] for commissioning of the setup, and systematic measurements of the system's properties have been performed. An identical sister trap at Imperial College London has been used for detailed studies of ion compression by the rotating wall technique, which will be employed to further increase the fluorescence yield by dynamic ion cloud compression [4]. Figure 3 shows the principle of the rotating dipole field created by phase-shifted sinusoidal signal applied to different segments of the ring electrode and the observed increase in fluorescence yield from the confined ion cloud when the rotating wall is switched on. The Penning trap is complemented by fluorescence detectors capable of single-photon counting in the range from UV wavelengths (with commercial photo-multiplier tubes) up to the near-infrared region (with Si-APD detectors operated at cryogenic temperatures, see [13]). In the framework of the HITRAP facility, measurements of the hyperfine structure transitions in heavy, highly charged ion like Pb^{81+} and Bi^{82+} are foreseen [6].

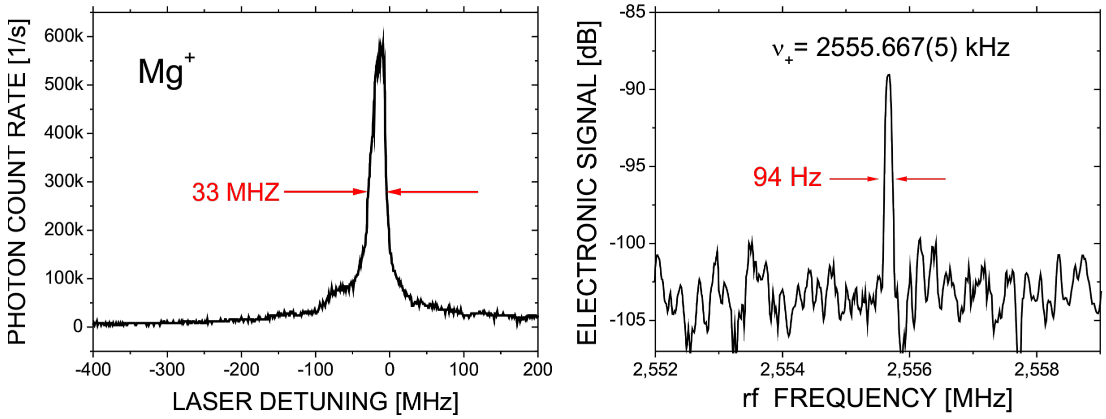

Figure 2. Axial optical laser cooling signal of confined Mg^{+} ions in SPECTRAP (left) indicating an ion temperature of around 60 mK, and radial electronic detection signal of confined Mg^{+} ions (right).

3. Microwave Spectroscopy at ARTEMIS

The ARTEMIS experiment employs a laser-microwave double-resonance spectroscopy scheme which foremost allows to precisely measure the Zeeman substructure of the fine or hyperfine structure of the ion under consideration [14]. From this, the magnetic moments (g-factors) of bound electrons can be determined with precisions on the ppb scale. This

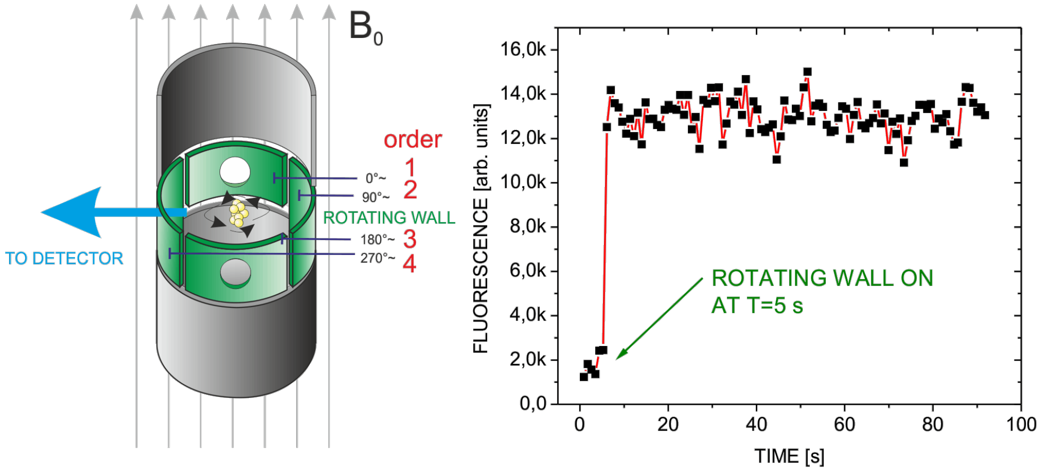

Figure 3. Schematic of the rotating wall field acting on confined ions (left) and observed increase of fluorescence when the field is switched on (right) [4].

spectroscopy scheme is conceptually different from the Stern-Gerlach-type experiments which have successfully been performed with single hydrogen-like and lithium-like ions such as C^{5+} [15], O^{7+} [16], Si^{13+} [17] and Si^{11+} [18], and yields also 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 such measurements will enable benchmarks of shielding models. The principle of the laser-microwave double-resonance technique is to use fluorescence light from an optical transition as a probe for the microwave excitation between corresponding Zeeman sublevels. Different level schemes allow different preparation and measurement procedures, as we have discussed in detail in [14]. Quadratic, and partially also cubic, contributions to the Zeeman effect are within our foreseen experimental resolution, as

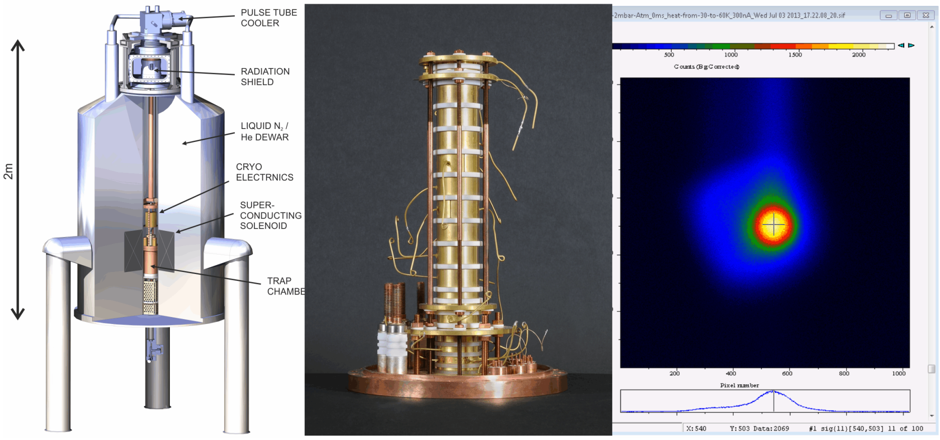

Figure 4. Schematic view of the superconducting magnet setup, the Penning trap used for spectroscopy, and a CCD image looking into the trap during ion production.

has been detailed out in [19]. These allow laboratory access to individual higher-order contributions on the magnetic sector, in a regime not accessible before. A general setup overview is shown on the left hand side of figure 4, the centre frame of that figure shows a photograph of the Penning trap arrangement, and on the right hand side, a CCD image of light emitted along the trap axis during ion charge breeding is shown. The Penning trap in use for the laser-microwave spectroscopy is a dedicated development to the end of maximizing the optical fluorescence yield, a so-called 'half-open' Penning trap [20]. The electrode arrangement also features an ion creation part in full similarity to a cryogenic mini-EBIS [21], in which we currently produce test ions such as Ar^{13+}. This is shown in figure 5, where the measured charge state spectrum of the same in-trap-produced argon ion cloud is shown at three different times after creation. We are currently commissioning the system with such internally produced ions. A connection to the HITRAP low-energy beam line [22, 23] is under construction and measurements with heavy, highly charged ions up to U^{91+} are foreseen. From the observed charge state lifetime against electron capture from residual gas of roughly one day for ions such as Ar^{13+} (see figure 5), we derive a background pressure of less than 10^{-13} mbar and corresponding lifetimes of several hours for ions of even the highest charge states, which is sufficient for the intended measurements.

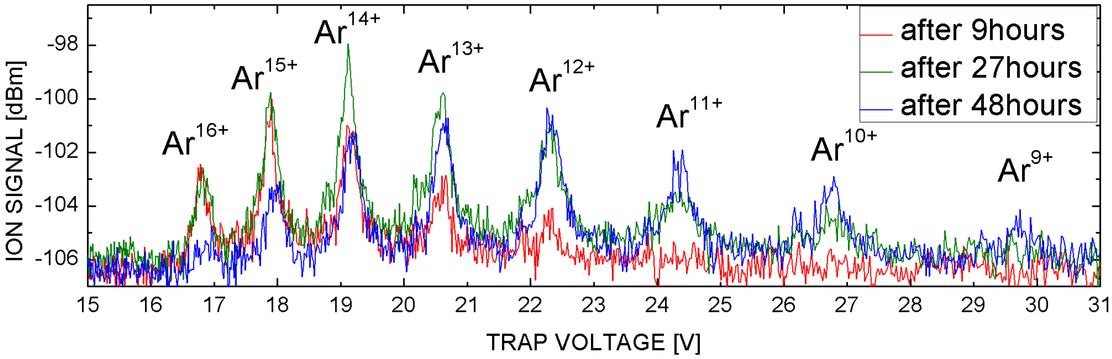

Figure 5. Ion charge state spectrum of the same ion cloud at different times after in-trap ion creation.

References

[1] V.M. Shabaev et al., Phys. Rev. A 56, 252 (1997)
[2] V.M. Shabaev et al., Phys. Rev. A 57, 149 (1998)
[3] T. Beier, Phys. Rep. **339**, 79 (2000)
[4] S. Bharadia, M. Vogel, D.M. Segal and R.C. Thompson, Appl. Phys. B **107**, 1105 (2012)
[5] H.-J. Kluge et al., Advances in Quantum Chemistry **53**, 83 (2007)
[6] M. Vogel, D.F.A. Winters, D. Segal and R.C. Thompson, Rev. Sci. Instr. **76**, 103102 (2005)
[7] G. Gabrielse, L. Haarsma and S.L. Rolston, Int. J. Mass Spectr. Ion Proc. **88**, 319 (1989)
[8] T. Murböck et al., Phys. Scr. **T156**, 014096 (2013)
[9] Z. Andelkovic et al., Phys. Rev. A **87**, 033423 (2013)
[10] G. Zschornack et al., Rev. Sci. Instrum. **79**, 02A703 (2008)
[11] B. O'Rourke et al., Journal of Physics: Conference Series **163**, 012103 (2009)

[12] A. Sokolov et al., J. Inst. **5**, C11001 (2010)
[13] R. Jöhren et al., JINST **7** P02015 (2012)
[14] W. Quint, D.L. Moskovkin, V.M. Shabaev and M. Vogel, Phys. Rev. A **78**, 032517 (2008)
[15] H. Häffner et al., Phys. Rev. Lett. **85**, 5308 (2000)
[16] J. Verdú et al., Phys. Rev. Lett. **92**, 093002 (2004)
[17] S. Sturm et al., Phys. Rev. Lett. **107**, 023002 (2011)
[18] A. Wagner et al., Phys. Rev. Lett **110**, 033003 (2013)
[19] D. von Lindenfels et al., Phys. Rev. A **87**, 023412 (2013)
[20] D. von Lindenfels et al., Hyp. Int. **227**, 197 (2014)
[21] J. Alonso et al., Rev. Sci. Instr. **77**, 03A901 (2006)
[22] D. von Lindenfels et al., Can. J. Phys. **89**, 79 (2011)
[23] Z. Andelkovic et al., submitted to Nucl. Inst. Meth. A (2015)