The Heidelberg EBIT: 
Present Results and Future Perspectives.

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Abstract.
The Heidelberg electron beam ion trap (EBIT) is one of the three high-energy EBITs worldwide presently in operation. In this contribution, selected recent experimental results on precision spectroscopy measurements of trapped ions in the visible and x-ray wavelength regimes, respectively, will reviewed. Moreover, interference between radiative and dielectronic recombination pathways is demonstrated for Hg$^{75+...78+}$ ions and state selected electron transfer reactions in collisions of U$^{94+}$ with He is reported. Future perspectives with two new EBITs coming into operation in 2005 for the investigation of radioactive ions as well as the interaction of highly charged ions with intense photon beams from the free electron laser at DESY in Hamburg will be highlighted.
1. Introduction

Highly charged ions (HCI) are of particular interest since they are most abundant in the universe (80% of the heavy barionic matter) and since they are important for all high-temperature earth-bound plasmas. HCIs are extraterrestially observed in many astrophysical phenomenae like supernovae exploitations, active galactic nuclei (AGN), solar coronae and x-rays from HCIs have recently been observed to be emitted even from cold comets. In contrast, their production and observation on earth is restricted (for heavy HCI) to only a few laboratories, namely, huge accelerators like, e.g., at the GSI in Darmstadt (Gesellschaft für Schwerionenforschung, Germany) or to more compact devices, so-called electron beam ion traps (EBITs). In the following a description of the Heidelberg EBIT and some selected results are given. Here, we have focused attention to the photorecombination processes of highly charged mercury ions.

2. Machine

The EBIT at the Max-Planck-Institut für Kernphysik in Heidelberg [1] is one out of three operating high-energy EBITs and has a worldwide unique design (see Fig. 1). So far, electron beam energies up to 100 keV and currents of 535 mA [2] have been demonstrated. It is planned in the near future to achieve the design values, namely, 350 keV and 750 mA, respectively. Due to a better thermal shielding compared to all other machines, the helium consumption has been substantially reduced from 5 l/h (liquid helium) as reported by the EBIT-II at LLNL to only 0.2 l/h. The magnetic field strength can be varied from 3 T to 9 T. A set of independent biased trapping electrodes (drift tubes) allows one to have different trap configurations whose length can be varied from 40 mm to 200 mm. These conditions have allowed to already produce a broad variety of different ion charge states such as Hg$^{78+}$, U$^{64+}$, Xe$^{54+}$, Kr$^{36+}$, etc. Some of these ion species have been extracted from the trap after mass-to-charge ratio selection at typical energies of 10 keV/q (q: ion charge state) and used in kinematically complete atomic collisions experiments exploiting the cold target recoil ion

Figure 1. Section through the Heidelberg EBIT.
momentum spectroscopy (COLTRIMS) technique in a reaction microscope [3]. Another beam line for extracted ions has been recently used for surface interaction experiments. In particular, the electron emission for impact of slow multiply charged ions (Xe\(^{44+}\)) on an atomically clean insulating LiF(001) surface has been investigated [4].

3. Spectroscopy in the visible wavelengths

High resolution measurements in the visible wavelength regime have several advantageous applications for plasma diagnostics. For example, the ion temperature of the plasma can be determined from the Doppler broadening and the local magnetic field strength through the Zeeman splitting. In the Heidelberg EBIT a Cerny-Turner spectrometer with 2400 lines/mm grating combined with a liquid N\(_2\) cooled CCD detector is used for high precision spectroscopy in the visible range. The wavelength of the forbidden transition \(^2P_{1/2} - ^2P_{3/2}\) in Ar\(^{13+}\) (2\(s^22p\)), for example, observed in the solar corona, has been determined in the laboratory with unprecedented accuracy (\(\lambda = 441.2559(1)\) nm). A proper choice of the trap parameters, namely, low electron currents (20 – 50 mA), low axial trapping voltages (nominally 0 – 10 V) and a strong magnetic field (6.82 T) has allowed us to observe the Zeeman splitting with an experimental FWHM of 0.035 nm at 441 nm (see Fig. 2). Under such conditions it has been possible, in addition, to reduce (roughly by a factor 2) the acquisition time while achieving the same level of accuracy as in previous experimental data [5].

![Averaged spectrum of the M1 forbidden transition \(^2P_{1/2} - ^2P_{3/2}\) of the Ar\(^{13+}\) ion. The four dashed blue lines correspond to the \(\pi\)-components and the two solid green to the \(\sigma\)-components of the Zeeman splitting.](image)

Figure 2. Averaged spectrum of the M1 forbidden transition \(^2P_{1/2} - ^2P_{3/2}\) of the Ar\(^{13+}\) ion. The four dashed blue lines correspond to the \(\pi\)-components and the two solid green to the \(\sigma\)-components of the Zeeman splitting.

In Fig. 2, the two highest peaks correspond to the \(\sigma\)-components, thus, \(\Delta M = 0\) in the case of M1 transitions, and the other four peaks in the wings are due to the
π-components ($\Delta M \pm 1$). Through the measured line splitting, the Landé factors $g_J$ of the two involved levels ($J = 1/2$ and $J = 3/2$) of the $2s^22p$ state can be determined with error bars in the order of $10^{-3}$.

In order to further substantially improve the reached resolution, an experimental setup for high precision laser spectroscopy has also been installed and tested. Here, the hyperfine transitions in the ground state of heavy hydrogenic ions are of particular interest. In the past, such studies have fuelled intense discussions on the contributions of the nuclear magnetization distribution and QED effects to the observed transition wavelengths.

4. Photorecombination

Asymmetric resonance line profiles characterized by the so-called Fano parameters are observed whenever resonant and non-resonant pathways interfere. Indeed, we have observed the interference between the radiative (direct) and dielectronic (indirect) recombination of highly charged mercury ions ($\text{Hg}^{75+...78+}$) in collisions with free electrons. The interference, observed for the first time for well-defined charge states, has been characterized with unprecedented precision for the most dominant charge states in the trap [6].

In the radiative recombination (RR), a free electron is captured into a vacant state of an ion emitting a photon (diagonal bands in Fig. 3). The dielectronic recombination (DR) is a resonant process where a free electron is captured and a bound electron is simultaneously excited. Later, the intermediate excited state is stabilized via photon emission (bright spots in Fig. 3). At energies close to the DR resonances, it is not possible to know if the system has passed through the intermediate excited state (DR) or if it went directly to the final state (RR). Both pathways are then indistinguishable and, therefore, quantum interference can occur.

In this experiment a high magnetic field of 8 T was used and the electron beam energy was scanned very slowly (37 V/s) across the KLL resonances (45 – 54 keV) of mercury ions in order to maintain the electron-impact ionization in equilibrium with the recombination processes at each beam energy. Here, both the emitted photon and the electron beam energies are simultaneously recorded for each event. The photon energies have been measured with a solid-state germanium detector while the electron acceleration energy was determined by means of two high-precision voltage dividers ($\approx 20$ ppm). After an appropriate data acquisition time, two-dimensional maps (photon energy versus electron energy) of the photorecombination rate are obtained (see Fig. 3). By projecting narrow slices of this map onto the electron beam energy axis, it is possible to study the resonances for ions in a specific charge state, because the photon energies on the different slices of each RR band correspond to different ion charge states according to their ionization potentials.

In order to fit the asymmetric experimental data, we used a Fano profile function (see e.g. [6, 7]) convoluted with a normalized Gaussian distribution to account for the
electron beam energy spread (≈ 60 eV). As clearly seen in Fig. 4, the observed and calculated Fano factors are in good agreement with each other. The asymmetry of the observed strongest resonances (Be$_3$ and B$_1$ in Fig. 4b) was characterized with relative error bars of only 6 %. Two of the results due to Be-like resonances were found to be in disagreement with Multi-Configuration Dirac-Fock (MCDF) calculations [8].

In addition to their practical importance in plasmas, heavy HCIs are of particular interest due to large quantum electrodynamic (QED) contributions and nuclear size effects, as for instance to their energy levels. In the case of the 1s-electron in mercury (Z = 80), these corrections are as large as 160 eV and 50 eV, respectively. The projections mentioned above allowed us to absolutely determine the excitation energies of the resonances under study after few considerations. Here, the negative space charge potential which reduces the electron beam energy has been estimated by standard formulae to be 142 eV at the experimental running conditions of 160 mA (fixed during the whole experiment) and 46 kV (first He-like resonance). As the space charge potential is a function of the electron velocity, it slightly changes over the scanned energy region, which had to be taken into account. The effect of the compensation of the space charge potential by the stored positive ions is conservatively evaluated to be in the range of (30 ± 10) %. These two numbers yield a systematic error bar in addition to the statistical one for the measured resonances of ± 14 eV. This error bar can be reduced to only ± 4 eV by refering our energy scale to the theoretical value for the almost completely symmetric 1s2s$^2$ (intermediate state) He-like resonance. Here, several state-of-the-art calculations agree within the experimental statistical error bars.
Figure 4. Experimental (grey curve) and fitted (red curve) data for two different slices of the RR \( n = 2, J = 1/2 \) band in comparison with a normalized non-convoluted theoretical cross section (green and blue curves). (a) Projection of the middle slice (cut 1 in Fig. 3) where primarily Be-like ions are observed. (b) Projection of the lowest slice in the same RR band (cut 2) where two strong resonances due to Be- and B-like ions are present.

By comparing the observed results for the highest charge state (He-like) with MCDF calculations [8], good agreement is obtained for all of them even when they are up to 5 keV away from the reference energy. However, when inspecting the data for the lower charge states, namely, Li-, Be- and B-like, distinct discrepancies appear. In particular, the theoretical values for the Be-like resonance energies show significant deviations of about 15 eV from the experimentally observed energies. A second set of theoretical predictions also based on MCDF calculations [9], where an optimal level approach was used, has yielded a substantial reduction (8 eV) of these discrepancies in the Be-like system.

5. Collisions

Collisions between slow highly-charged ions and neutral atoms are ideally suited to investigate the dynamics of multi-electron transitions on very short time scales of femtoseconds or even below. In capture reactions with highly-charged ions, one or more electrons are transferred from the target atom with large cross sections most likely into highly excited states of the projectile ion. The quantities of interest are the dynamics of this electron transfer, \( i.e. \) its impact parameter dependence, the specification of the populated states in the projectile ion as well as the relaxation dynamics of multiply excited states.

In this type of experiments, we have used a “reaction microscope”, where the three-
dimensional momentum vectors of all reaction products are measured in coincidence with high resolution in combination with the Heidelberg EBIT to produce highest ion charge states. In single electron capture, the recoil-ion momentum along the beam direction $P_{\parallel}$ contains information about the energy difference $Q$ between the initial and final multi-electronic states [10]. Figure 5 shows the Q-value spectrum (i.e. the converted $P_{\parallel}$ distribution of the target ions) for single electron capture in collisions of 5 keV/amu $^\text{U}^{64+}$ ions with He. With an achieved momentum resolution of 0.1 a.u. for the recoiling target ion, which corresponds to a Q-value resolution of better than 5 eV, we were able to resolve the projectile states of the $^\text{U}^{63+}$ ion with respect to their principal quantum number $n$ (indicated in Fig. 5). It was found, that only a small number of projectile levels are populated, with a maximum for the transition into the $n = 22$ state.

![Figure 5. Q-value spectrum of U$^{64+}$-He collisions.](image)

An important advantage of the described technique compared to others is that the complete information is measured simultaneously with an inherent relative normalisation. Moreover, we are not restricted to optically allowed transitions, like many traditional methods, and we observe even multiply excited states before they decay.

### 6. Future

A high-current (5 A) EBIT [11] has been constructed by the Heidelberg EBIT group which will be used for charge-breeding purposes in the framework of the TITAN project at TRIUMF (Vancouver, Canada). In fact, this machine (TITAN-EBIT) has already reached electron beam currents of roughly 200 mA at electron beam energies of 13 keV
during its first days of operation in spring 2005. This project aims to trap short-lived radionuclides produced at the ISAC facility into a high-precision Penning trap at high charge states in order to determine the nuclear mass after they have been stripped in the TITAN-EBIT. The mass measurement is performed by accurately determine the cyclotron frequency of the trapped ions [12].

By increasing the charge state of an ion the relative accuracy of the mass determination can be enhanced. On the other hand, to reach a desired accuracy the excitation times (usually limited by the nuclear half-life of the ions under investigation) can be shorter and the required count rates can be smaller when the charge of the ions is larger. Both the number of ions and their nuclear half-life are limiting factor in investigating radionuclides very far from the valley of stability. In addition, it is planned to perform high-resolution spectroscopic measurements in the visible and x-ray region meanwhile the ions are being bred. These type of studies will provide, for the first time, relevant information on isotopic shifts and nuclear size effects of a wide variety of highly charged ions.

The new VUV-FEL (free electron laser) photon beams at the TESLA Test Facility (TTF) in Hamburg will open new frontiers in the study of photon interactions with HCIs. Photon intensities varying from $10^{15}$ to $10^{17}$ W/cm$^2$, photon energies from 10 to 10,000 eV at a pulse width between 50 and about 300 fs are some of the characteristic parameters of the new light source. Here, the use of an EBIT will allow one to study photoexcitation and multiphoton processes with all types of trapped HCIs. Thus, another EBIT (TESLA-EBIT) which is almost completed will be moved to the TESLA facility at the end of this year. The TESLA-EBIT includes (also the TITAN-EBIT) a cryogen-free 6T superconducting magnet, a large bore-hole of 10 cm diameter and up to seven side ports for spectroscopy and injection.

It is planned, in the first run, to measure the $2s_{1/2} - 2p_{1/2}$ fine-structure intervals in Li-like ions of argon ($Z = 18$), krypton ($Z = 36$) and xenon ($Z = 54$). This transition, which have never been measured for elements heavier than xenon (excluding uranium), contain QED contributions which range from 0.1 eV in Ar to up to 42 eV in Li-like uranium. An expected energy resolution below $10^{-4}$ as well as high excitation rates and, therefore, superior counting statistics, will allow one to increase (by one or two orders of magnitude) the accuracy of the existing measurements and to test QED for three-electron heavy ion systems.

7. Conclusion

Summarizing, we have demonstrated the capability of the Heidelberg EBIT to perform high-precision measurements with trapped ions in both, the visible and x-ray wavelength regimes, as well as with extracted slow ions in ion-atom collisions. The high resolution achieved in the observation of the solar corona argon line at 441 nm and, thus, its Zeeman splitting, has provided indirect information on the Landé factor by means of visible spectroscopy. The measurements with mercury ions have allowed, for the
first time in heavy HCIs, to characterize the asymmetrical line profiles of state-selected DR resonances due to the quantum interference between DR and RR processes. Here, significant discrepancies when comparing the measured resonance energies with theoretical predictions showed up for the case of Be-like resonances.

An increase of the resolution in the electron capture experiments with the extracted ions is expected by using ultra-cold atoms from a magneto optical trap. This improvement (factor four to ten) will result in spectroscopic information on heavy highly excited HCIs not accessible by other methods. Two new EBITs to be operated with radioactive ions and at the VUV-FEL, respectively, will come into operation during 2005.

8. References

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