Experiments with Heavy Ions in Traps

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HITRAP: A Facility for Experiments with Trapped Highly Charged Ions

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The GSI midterm project HITRAP is a planned ion trap facility for capturing and cooling of highly charged ions (HCI) produced at GSI in the heavy-ion complex of the UNILAC-SIS accelerators and the ESR storage ring. In this facility heavy highly-charged ions up to uranium will be available as bare nuclei, hydrogen-like ions or few-electron systems at low temperatures. The trap for receiving and studying these ions is designed for operation at extremely high vacuum by cooling to cryogenic temperatures. The stored highly charged ions can be investigated in the trap itself or can be extracted from the trap at energies up to about 30 keV/q.

The basic components constituting the HITRAP facility are outlined in Fig. 1. Highly charged ions are accelerated in the heavy-ion synchrotron SIS, stripped in a foil to the desired charge state and injected into the Experimental Storage Ring (ESR). For bare or hydrogen-like ions, energies of a few hundred MeV/u are required. In the ESR the ions will be decelerated to an energy of 3 MeV/u. It is planned to demonstrate this low-energy operation mode of the ESR during 2001. They will then be extracted in a fast-extraction mode as short ion bunches.

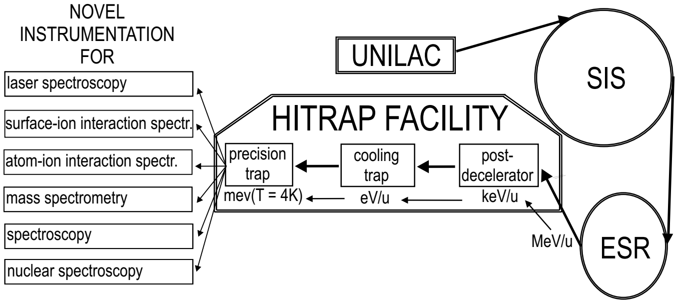

Figure 1: Schematic of the GSI accelerator complex and the planned HITRAP facility. Highly charged ions are extracted from the ESR storage ring at 3 MeV/u, decelerated in a post-decelerator to some keV/u, and then transferred into a Penning trap system.

The extracted ion bunches will be post-decelerated to a final energy of the order of 30 keV/q in a radiofrequency quadrupole structure (RFQ) or a linear interdigital H-mode (IH) drift tube structure. Recently, a RFQ decelerator has been successfully commissioned at the Antiproton Decelerator (AD) at CERN to allow antiprotons to be decelerated from an energy of 5.3 MeV down to below 100 keV. After post-deceleration the ions will be captured into a first Penning trap (Fig. 1) and cooled to a temperature of T = 4 K with a combination of electron or positron cooling and resistive cooling. The cooled highly charged ions can be extracted and transferred to physics experiments. The HITRAP facility will provide about 10^6 charges per second, i.e. about 10^4 ions/s in the case of U^{92+}.

The HITRAP physics programme includes collision studies with highly charged ions at well-defined low energies (eV/u), laser spectroscopy of hyperfine structure transitions in HCI, X-ray spectroscopy on HCI, and high-accuracy measurements to determine the magnetic moment anomaly (or *g-factor*) of the electron bound in hydrogen-like heavy ions and the atomic binding energies of few-electron systems.

For the determination of the g-factor of the bound electron in highly charged ions as a stringent test of Quantum Electrodynamics (QED) [1] a precision Penning trap has been developed in a joint effort of the University of Mainz and GSI. The g-factor of the bound electron is determined from the Larmor precession frequency ω_L of its magnetic moment in the magnetic field B, $\omega_L = g(e/2m_e)B$, and the cyclotron frequency of the hydrogen-like ion, $\omega_c = (Q/M)B$.

$$g = 2 \cdot \frac{\omega_L}{\omega_c} \cdot \frac{Q/M}{e/m_e}. \qquad (1)$$

Our measurement of the g-factor of the electron in hydrogen-like carbon ($^{12}C^{5+}$) yielded a value of $g_e^{exp}(C^{5+}) = 2.001\,041\,596(5)$, in excellent agreement with the theoretical value of $g_e^{th}(C^{5+}) = 2.001\,041\,591(7)$ [2]. Further improvement of the theoretical [3] as well as the experimental accuracy will make it possible to determine the atomic mass of the electron with an unprecedented precision of a few parts in 10^{-10}. In 2000 we performed a g-factor measurement on hydrogen-like oxygen ($^{16}O^{7+}$). The preliminary experimental value of $g_e^{exp}(O^{7+}) = 2.000047017(8)$ is in excellent agreement with the theoretical prediction of $g_e^{th}(O^{7+}) = 2.000\,047\,022(5)$. This is our second high-accuracy test of bound-state QED. At the HITRAP facility, the g-factor measurements will be performed up to the heaviest hydrogen-like ions, where the product of proton number and fine-structure constant ($Z\alpha$) approaches unity. This will provide a crucial test of QED calculations in extreme electromagnetic fields.

High Accuracy Mass Determination of unstable Nuclei with the Penning Trap Mass Spectrometer ISOLTRAP

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The Penning trap mass spectrometer ISOLTRAP is installed at ISOLDE/CERN. It provides mass measurements of short-lived nuclides with very high accuracy. Accurate experimental mass values serve for testing nuclear models, help to increase their predictive power for nuclides far from stability and can reveal nuclear structure. Additionally, some mass values represent important input parameters for Standard Model tests and astrophysical calculations.

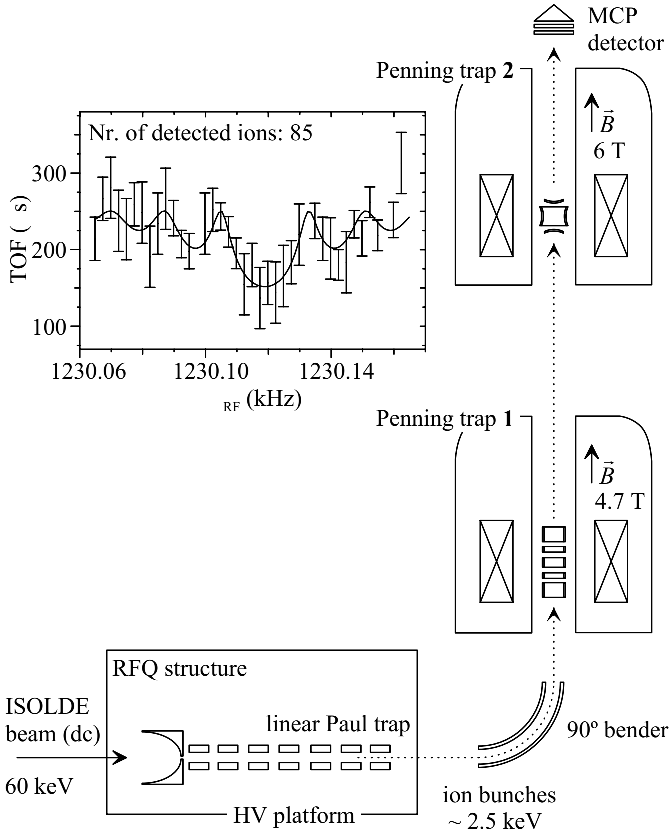

Figure 2: Experimental setup of the ISOLTRAP spectrometer. The inset shows the cyclotron resonance curve for ^{74}Rb. Plotted is the time of flight (TOF) of the ions from the trap to the ion detector as a function of the applied radiofrequency with the theoretical line shape fitted. This spectrum contains roughly one fourth of all ^{74}Rb data obtained during a recent run.

The ISOLTRAP Penning trap mass spectrometer (Fig. 2) consists of three main parts: a) a linear gas-filled radiofrequency quadrupole (RFQ) trap for retardation, accumulation, cooling and bunched ejection at low energy [4], b) a gas-filled cylindrical Penning trap for further cooling and isobaric separation [5], and c) an ultra-high vacuum hyperbolic Penning trap for isomeric separation and the mass measurement [6]. The mass measurement is performed via the determination of the cyclotron frequency $\omega_c = q/m \cdot B$ of the ion with mass m and charge q revolving in the magnetic field of strength B. The accuracy of the measured mass values is typically $\delta m/m = 1 \cdot 10^{-7}$.

Six radioactive beam times were carried out in 2000. In the first beam time, an uranium carbide target was used in conjunction with the resonant ionisation laser ion source (RILIS) to measure the mass of neutron-rich tin isotopes. The isotopes ^{128,129,130,132}Sn were investigated. Particularly, the mass of the doubly magic ^{132}Sn is of interest for astrophysical calculations along the r-process path.

The second beam time was dedicated to neutron-deficient Sr isotopes. The mass of ^{76}Sr and ^{77}Sr could be measured by determining the mass of SrF$_2$ molecules. ^{76}Sr is a possible waiting point on the astrophysical rp-process path.

One major project in 2000 was the measurement of the Q-value of the superallowed β-decay of ^{74}Rb. Two beam times were performed to measure the mass of ^{74}Rb (Fig. 2) and its daugther nucleus ^{74}Kr. ^{74}Rb is the shortest-lived nuclide ever investigated in a Penning trap ($T_{1/2} = 65\,\mathrm{ms}$). The accuracy of its mass value is governed by statistics and resolving power, which are limited by production rate and half-life. The relative accuracy reached for the mass of ^{74}Rb is about $3.4 \cdot 10^{-7}$ (i.e. $\approx 25\,\mathrm{keV}$). The measurement of ^{74}Kr was performed with an unprecedented relative accuracy of only $3 \cdot 10^{-8}$. Additionally, the masses of the krypton isotopes with $A = 73$ and 75 were measured.

One beam time was performed using a molten lead target to complete the picture of binding energies for the neutron-deficient mercury isotopes. The isotopes ^{179,180,181}Hg were measured for the first time closing the gap in the binding energy sytematics.

The last beam time in 2000 was used to measure the mass of ^{34}Ar produced in a CaO target. This value is needed with very high accuracy in the context of the FT-value systematics for superallowed Fermi β decays. ISOLTRAP succeeded in measuring this mass with an uncertainty below 1 keV.

Future mass measurements will be performed in astrophysically interesting regions like the neutron-rich Cd and Sn isotopes, the neutron-deficient Y isotopes and around the rp-process waiting points ^{68}Se and ^{72}Kr. Additionally, the measurements in the context of fundamental tests will be continued measuring ^{32}Ar. Future technical developments focus on the improvement of the overall efficiency by improving the detector setup as well as different parts of the ion transfer.

Status of the SHIPTRAP project: A capture and storage facility for heavy radionuclides from SHIP

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The ion trap facility SHIPTRAP is being set up to deliver very clean and cool beams of singly-charged recoil ions produced at SHIP at GSI [7]. SHIPTRAP consists of a gas cell for stopping and thermalizing high-energy recoil ions from SHIP, an rf ion guide for extraction of the ions from the gas cell, a linear rf trap for accumulation and bunching of the ions, and a Penning trap for isobaric purification. The recent development for the SHIPTRAP stopping chamber and the extraction system is described in a separate section later in this report.

The Buncher

The ion bunching system is a 1 m long Radio Frequency Quadrupole (RFQ) immersed in a low-pressure buffer gas. The four rods have a diameter of 9 mm at a distance between two opposite rods of 7.86 mm. The rods are divided into 34 segments. With proper choice of applied voltages, one creates a potential slope with a harmonic potential well at the end of the quadrupole structure. When the ions lose energy in collisions with the buffer gas, they accumulate in this trap and can be extracted as a short bunch of cool ions. The radial motion in the RFQ is described by the Mathieu equations, where the solutions are characterized by the two dimensionless parameters a and q, but only $q = \frac{2eV_{rf}}{m\omega_{rf}^2 r_0^2}$ depends on the rf-amplitude. Presently we use the RFQ in a rf-only mode with no additional bias ($a = 0$). The ion motion is stable only in a certain range of q, for other values the amplitudes of the motion grow infinitely. For a certain rf amplitude V all ions of different masses whose q is below the stability limit of $q = 0.908$ pass through the buncher.

In first tests (no axial trapping) in the rf-only mode with a calibrated ion source a transmission of about 95% was achieved. Figure 3 shows a transmission plot for Ar^+ ions. The driving field frequency was set to $\nu_{rf} = 600$ kHz.

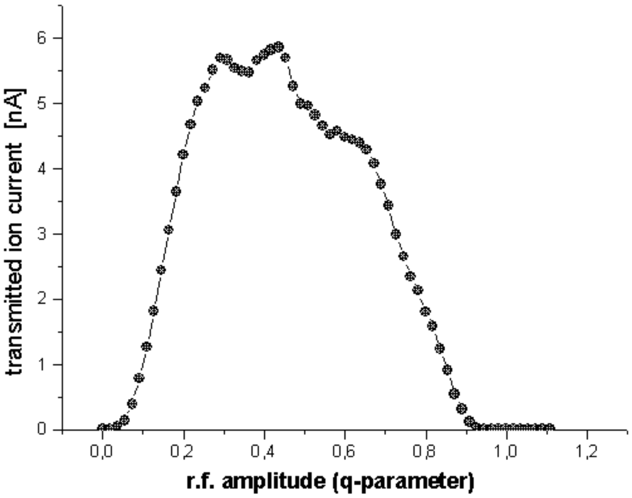

Figure 3: Transmission plot in rf-only mode for Ar^+ ions.

The basic task of the buncher at SHIPTRAP is to cool the ions from the stopping chamber and to collect them. Since the buncher will therefore be operated under buffer gas it is necessary to investigate the influence of gas on the ion motion. The average effect of ion collisions with buffer gas molecules can be approximated by a frictional drag force. This leads to the usual form of the Mathieu equation but with an added velocity dependent term. Figure 4 shows three measured transmission curves at different pressures. One can see a tendency that the right edge of the stability diagram is shifted to higher q-values. Due to the damping of the ion motion one can apply higher quadrupole field strength until the ion motion becomes unstable. The information how much the stability region is increased under buffer gas operation is important since one tries to use the limited mass resolution of the RFQ in rf-only mode to suppress contamination of lighter ion species.

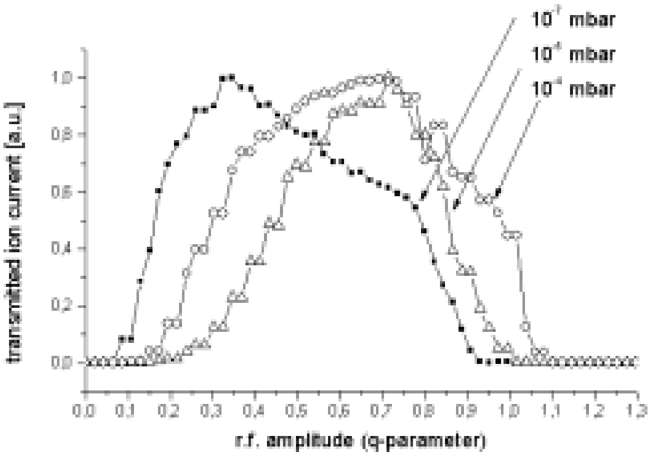

Figure 4: Influence of buffer gas on the transmission curve

The Penning Trap System

Two Penning traps will be installed at SHIPTRAP, which are both housed in one superconducting magnet. The first Penning trap, a 207.5 mm long cylindrical trap with 32 mm open diameter, captures the ions from the buncher, cools and isobarically purifies them. The design is based on the one used for this purpose at the ISOLTRAP facility at ISOLDE [6]. In such a system the contaminating isotopes are very effectively suppressed due to the high mass resolving power of the cooling process. The second Penning trap, also cylindrical but shorter and with higher homogeneity in the electric and magnetic fields, will serve for precision mass measurements. The traps have been constructed, built and assembled in 2000. They are now ready for the first tests.

Summary

After an intense simulation and construction phase all components are set up and under test. SHIPTRAP will start operation in autumn 2001. The experimental programme which is envisaged by the SHIPTRAP user community promises to give new insights into the nuclear, atomic and chemical properties of the elements heavier than einsteinium.

The gas cell and extraction RFQ for SHIPTRAP

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Set-up

The prototype of the gas cell for SHIPTRAP follows the concept of extracting the ions via the gas flow and guiding electrostatic fields. These two mechanisms can be simulated separately in first order due to the special feature of a high transmission grid in front of the nozzle. This grid prevents a loss of ions in the defocusing field inside the nozzle and improves the focusing inside the cell due to a spherical shape. The extraction RFQ separates the ions from the neutral gas. The prototype gas cell has a length and a diameter of 100 mm. The guiding field inside the cell is created by three electrodes and a spherical grid covering the supersonic nozzle with an inner diameter of 0.6 mm. The subsonic part of the nozzle has a conical shape to achieve gas velocities high enough to drag the ions through the nozzle [8].

The design of the extraction RFQ and the electronics profits from the work done at ISOLTRAP and GSI in the past three years [4]. Compared to the structures used there the extraction RFQ of SHIPTRAP is a short structure with 12 segments and a total length of 120 mm. The diameter of the rods is 11 mm with an aperture (diameter) of 10 mm. The ions are mass selective detected in a QMS followed by a MSP (Micro Sphere Plate) [9]. The test set-up is shown schematically in Fig. 5.

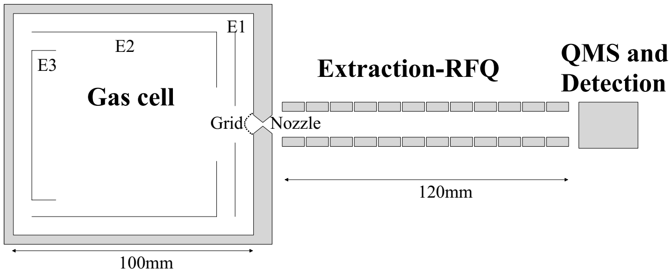

Figure 5: Test set-up for the SHIPTRAP gas cell. It consists of three electrodes (E1, E2, E3) and a nozzle covered by a high transmission grid, the extraction RFQ as a differential pumping section and the QMS and Detection section for a mass selective ion detection.

Simulations

The simulations covered the following topics: stopping of the ions in the gas (SRIM); drag of the ions via the electrical field in the cell towards a supersonic nozzle (SIMION); drag of the ions through the nozzle via the gas flow (VARJET, solving the full system of time dependent Navier-Stokes equations [10]).

First stopping simulations indicate that, whatever gas is used, a majority (50 to 90%) of most radionuclides of interest could be stopped within a spheroid of 40 mm diameter and 70 mm length (for ^{232}Th at 100 keV/u in He at 50 mbar). To these values one has to add the horizontal and vertical SHIP-beam dimensions of 50 mm and 30 mm. These simulations imply the minimum dimensions for the innermost electrode of the final gas cell for SHIPTRAP.

Measurements

First measurements with laser ionized Ni and Er in the gas cell were performed to optimize the voltages in the cell and the RFQ. Based on this the extraction times in dependence of the gas pressure and the voltage inside the cell were studied. A voltage difference of 10 V was applied between the first and last segment of the extraction RFQ together with an rf-voltage of 200V$_{\mathrm{pp}}$ at 1.2 MHz to guide the ions to the mass selective ion detection system. Figure 6 shows the measured time of flight (TOF) of Ni and Er ions at different pressures and voltages in the cell.

Furthermore, the measurements showed a clear dependence of the ion focusing towards the nozzle and the grid in front of the nozzle. The grid allows to achieve faster extraction times due to higher voltages applicable in the cell. These higher voltages lead to a stronger defocusing of the ions. However, this drawback can be compensated by the better focusing properties of the grid.

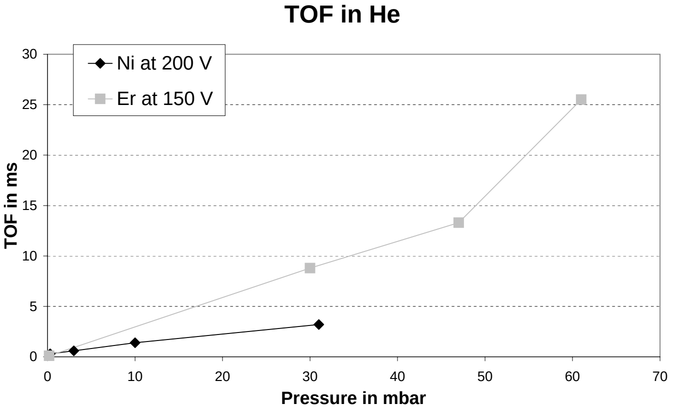

Figure 6: Measurement of the TOF of Ni and Er ions in dependence of gas pressure and voltage inside the cell (electrode E2).

An improved gas cell, based on these experiences is under construction. The new cell will allow higher voltages in the cell and is designed to stop and extract 90% of the ion cloud.

Optical Spectroscopy and Ion Chemistry of Trans-Fermium Elements at SHIPTRAP

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An ultra-sensitive laser spectroscopic method is being developed for the investigation of the completely unknown atomic structure of the elements No and Lr. First experiments will be performed on No which will be produced via the reaction ^{208}Pb(^{48}Ca,2n)^{254}No. The reaction products, separated by SHIP, will be stopped in a buffer gas cell in which Resonance Ionization Spectroscopy (RIS) is performed with detection of the ionization process by the α-decay of ^{254}No. The technique is similar to that developed for RIS on fission isomers [11]. To determine the stopping distribution of the 40 MeV No recoils, a 40 MeV ^{238}U^{8+} beam from the tandem van-de-Graaff accelerator at the MP-Tandem accelerator facility in Heidelberg was implanted in a buffer gas cell. The range distribution and the lateral straggling of the ions in the gas was measured for different gas pressures. The normalized count rate of the movable semiconductor detector is shown in Fig. 7 as a function of the distance from the entrance foil.

The code SRIM2000 predicts a 30% shorter range which might originate from assuming a too high effective charge state of the ions during the slowing-down process. Similar derivations between measurements and calculations have been found for the straggling. These results have been taken into account for the design of the buffer gas cell. The cell has been constructed, and first vacuum and high voltage tests have been carried out successfully [12].

Furthermore, we plan to study ion chemical reactions of heavy elements such as ^{254}No and ^{256}Lr in a buffer gas cell with well-defined admixtures, e.g. O_2, H_2O, CH_4, CO_2.

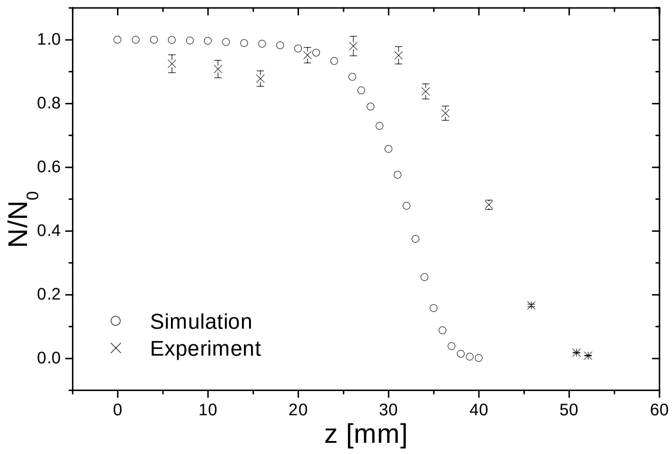

Figure 7: Range distribution of the U ions in Ar at a gas pressure of 250 mbar (×). The calculation (○) is based on the code SRIM2000 [13].

The reaction products will be identified mass selectively by the Ion Guide Quadrupole Mass Separation (IGQMS) technique [14, 15]. Presently, we are working on establishing the method on chemically homologue elements.

In a first step, ion-molecule reactions will be studied with a Fourier Transform Mass Spectrometer (FT/MS) under well-defined experimental conditions [16]. In first experiments erbium reactions with O_2 have been investigated. The ions are created by laser ablation from a solid target using a pulsed CO_2 laser, cooled by an argon buffer gas push and stored in a FT-ICR cell at constant O_2 gas pressure. An ejection sweep cleans the cell from all ions with the exception of erbium ions which react with oxygen. The results are shown in Fig. 8. The ratio of Er^+ to ErO^+ intensity, as obtained after various reaction times, is shown in Fig. 9. From the exponential decay of the Er^+ signal a reaction constant can be deduced.

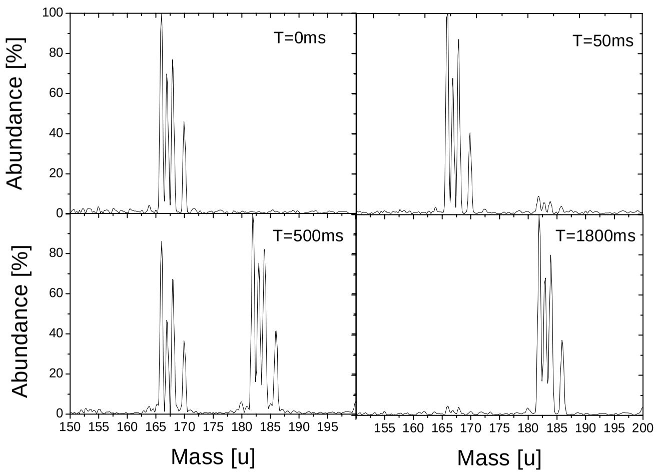

Figure 8: Er^+ and ErO^+ mass spectra at reaction time T as indicated. The groups around mass number 167 and 183 belong to Er^+ and ErO^+, respectively.

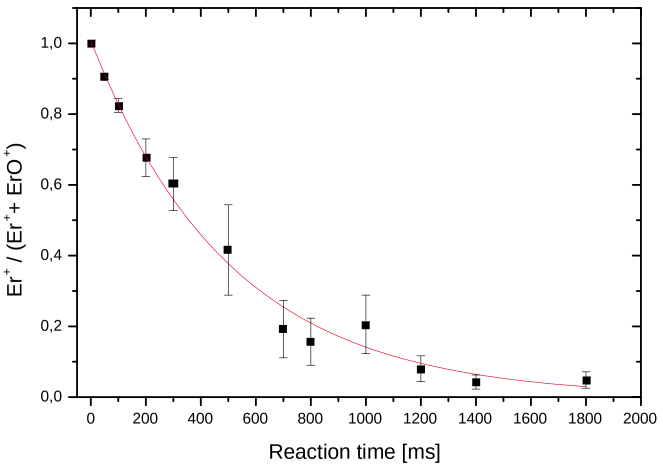

Figure 9: Intensity ratio of Er^+ to (Er^++ ErO^+) as function of the reaction time.

In a second step the results from these FT-ICR experiments which are obtained under clean experimental conditions will be compared with results obtained in the inert buffer gas cell to which the reaction gas is admixed. Energetic erbium ions from a Tandem van-de-Graaff accelerator will be implanted into the buffer gas cell. Ion-chemical reactions will be investigated in 'hot' and 'cold' surroundings. 'Hot' surrounding is expected if erbium thermalizes directly as an ion. If it thermalizes as an atom, which subsequently is resonantly ionized by the laser, the surrounding is 'cold'.

Acknowledgement

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