Experiments with Heavy Ions in Traps

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and the SHIPTRAP-Collaboration

High-Accuracy Measurement of the g-Factor of the Bound Electron in a Highly Charged Ion

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We report on a high-accuracy measurement of the magnetic moment (*g-factor*) of the electron bound in hydrogen-like carbon (C^{5+}). Compared to our previous measurement [1] we improved the experimental accuracy by more than three orders of magnitude. This new experimental determination of the g-factor of the bound electron represents a clean test of Quantum Electrodynamics (QED), because it is not very sensitive to nuclear structure effects. The result presented here was obtained with a single hydrogen-like carbon ion ($^{12}C^{5+}$) stored in a Penning trap [2]. The experimental accuracy is high enough to verify the bound-state QED contribution to the g-factor on the one-loop level with a fractional uncertainty of 1 %. Other experimental data on the g-factor of hydrogenic systems are available only for the hydrogen atom and the $^4He^+$-ion [3] and for $^{209}Bi^{82+}$ from a measurement of the lifetime of the upper hyperfine level of the 1s ground state [4].

In a Penning trap a charged particle is stored in a combination of a homogeneous magnetic field and an electrostatic quadrupole field. The magnetic field confines the particle in the direction perpendicular to the magnetic field lines, and the electrostatic potential in the direction parallel to the magnetic field lines. The three characteristic motions that result are the cyclotron motion, the axial motion (parallel to the magnetic field lines) and the magnetron motion, which is a circular E x B drift motion perpendicular to the magnetic field lines.

The free-space cyclotron frequency $\omega_c = (Q/M)B$ of an ion with charge Q and mass M in a magnetic field B can be calculated from a combination of the trapped ion's three eigenfrequencies which are measured in the experiment. 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 by

$$\hbar\omega_L = g\frac{e\hbar}{2m_e}B = g\mu_B B. \qquad (1)$$

Using the cyclotron frequency ω_c of the hydrogen-like ion for the calibration of the magnetic field, the g-factor of the bound electron can be expressed as the ratio of the Larmor precession frequency ω_L of the electron and the cyclotron frequency ω_c of the hydrogen-like ion

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

The ratio of charge-to-mass ratios of the carbon ion (Q/M) and of the electron (e/m_e) was measured in a Penning trap to an accuracy of $2{\cdot}10^{-9}$ by van Dyck et al. [5].

The Larmor precession frequency ω_L is measured by resonant excitation (at 104 GHz) of the transition between the two spin states (spin *up* and *down*) of the bound electron in the magnetic field ($\approx$ 4 Tesla) of the Penning trap. These spin-flip transitions (*quantum jumps*) are observed via the continuous Stern-Gerlach effect [1] as small discrete changes of the axial frequency ($\Delta\omega_z/2\pi = 0.7$ Hz) of the stored ion. This dependence of the ion's axial frequency on the spin direction of the bound electron is caused by a quadratic magnetic field inhomogeneity which is superimposed on the homogeneous magnetic field of the Penning trap [6].

With the measured values of the Larmor precession frequency of the bound electron and of the cyclotron frequency of the $^{12}C^{5+}$-ion the g-factor of the bound electron in $^{12}C^{5+}$ is calculated using (2) to (see Fig. 1)

$$g_e^{exp}(C^{5+}) = 2.001\,041\,597(4). \qquad (3)$$

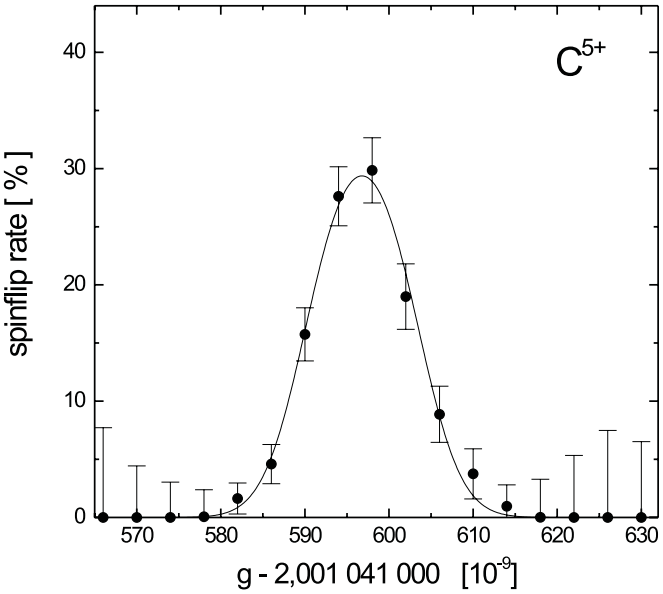

Figure 1: The g-factor of the bound electron in hydrogen-like carbon $^{12}C^{5+}$-ion is measured by resonant excitation (at 104 GHz) of the transition between the two spin states (spin *up* and *down*) of the bound electron in the magnetic field of a Penning trap.

Compared to the g-factor of the free electron $g_e^{free} = 2.002\,319\,304\,377\,(9)$ [7], the g-factor of the bound electron in the hydrogen-like charge state is changed because of the relativistic motion of the electron in the 1s-state and bound-state QED corrections. In the case of the hydrogen-like carbon ion (Z = 6) the relativistic term is $\Delta g_{rel} = -0.001\,278\,646$. The sum of all bound-state QED terms on the one-photon level gives a contribution of $\Delta g_{QED} = +0.84{\cdot}10^{-6}$. The theoretical prediction, including relativistic, bound-state QED and nuclear corrections, for the bound-state g-factor in $^{12}C^{5+}$ is

$$g_e^{th}(C^{5+}) = 2.001\,041\,591(5). \qquad (4)$$

Our present experimental result confirms the bound-state QED terms on the one-photon level with a fractional uncertainty of 1 %. The good agreement between the theoretical and the experimental values (see also Fig. 1) sets an upper limit for the size of the yet uncalculated higher-order bound-state QED corrections. In the future, we plan to extend the g-factor measurements to heavier hydrogen-like systems, up to hydrogen-like uranium U^{91+}. The measurements on heavy highly charged ions are of particular interest since the relativistic as well as the bound-state QED correction terms scale as Z^2.

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

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Mass measurements on short-lived isotopes delivered by the on-line mass separator ISOLDE are the task of the ISOLTRAP experiment at CERN. Accurate experimental mass values serve as a stringent test of nuclear models, help to improve them for predictions of nuclear properties far from nuclear stability and can reveal nuclear structure.

The ISOLTRAP system [8] installed at the on-line mass separator ISOLDE/CERN is a triple trap mass spectrometer. It consists of a radiofrequency quadrupole (RFQ) ion beam buncher, a Penning trap ion cooler and a Penning trap mass spectrometer. In the ion beam buncher the 60 keV ISOLDE ions are electrostatically retarded before they enter a linear Paul trap system where they are cooled by buffergas collisions and accumulated. After accumulation the ions are ejected as a short 2.5 keV ion bunch, which is transported to ground potential by passing through a pulsed drift tube. The low energy ion bunches are then captured with high efficiency in the first Penning trap of the ISOLTRAP system. This trap [9] acts as an ion cooler and isobar separator with a resolving power of $m/\Delta m(\mathrm{FWHM}) \approx 10^5$. In the second Penning trap the mass measurement is carried out via the measurement of the cyclotron frequency $\omega_c = q/m \cdot B$ of the stored ions. A resolving power of $m/\Delta m(\mathrm{FWHM}) > 10^6$ enables separation of nuclei in their ground or isomeric states even for very low excitation energies. The accuracy delivered by ISOLTRAP for short-lived isotopes with a half-life of $T_{1/2} = 1$ s and mass $m \approx 100$ u is typically $\delta m/m = 1 \cdot 10^{-7}$.

In 1999, the recently installed RFQ ion beam buncher was taken into operation and three radioactive beam times were carried out with ISOLTRAP. In parallel systematic tests have been performed on the RFQ ion beam buncher in order to investigate its properties and to optimize its parameters. Compared to the previously used beam buncher (based on a large Paul trap) it was possible to increase the efficiency for stopping and bunching of the ISOLDE beam by at least 2 orders of magnitude to reach a value of about 10%.

In the first beam time with a molten-lead target it was possible to extend the measurements on the mercury isotopic chain even further to the proton-rich side reaching ^{182,183}Hg, both of which were not yet measured before. Furthermore, the isomeric states of ^{183,187,189}Hg have been investigated.

In the second beam time measurements have been carried out on light isotopes in the mass region around $A = 35$. Using a CaO target with a cooled transfer line measurements on several Ar isotopes were performed. For ^{33,42,43}Ar the error for the measured mass could be improved by at least a factor 3.

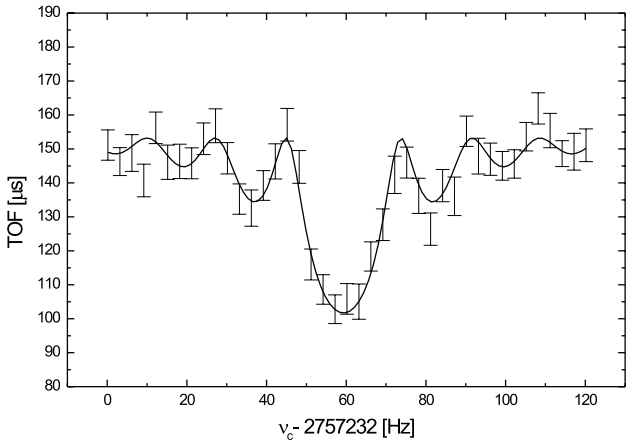

Figure 2: Cyclotron resonance of ^{33}Ar ions. The half-life of ^{33}Ar is as short as 174 ms. ^{33}Ar is therefore the shortest-lived isotope that has ever been measured in a Penning trap.

Figure 2 shows the cyclotron resonance curve for ^{33}Ar, which is an isotope of special interest because the ground state of ^{33}Ar is an endpoint of an isobaric mass multiplet. Using the ISOLTRAP data this mass multiplet is one of the best measured multiplets and can therefore serve as a stringent test of the isobaric multiplet mass equation (IMME). Further importance is due to the fact that ^{33}Ar is a test case for isospin violation corrections to superallowed mixed transitions. Furthermore, ^{33}Ar is the shortest-lived isotope ever measured with a Penning trap mass spectrometer ($T_{1/2} = 174$ ms).

In a third beam time a LaO target with cooled transfer line was used for the production of xenon isotopes. Here, ISOLTRAP investigated the entire neutron-deficient part of the Xe isotopic chain from $A = 114$ to $A = 123$. For ^{114,115,116}Xe the mass table gives no experimental data while for $^{117..122}$Xe the uncertainty is much larger than the one reached with ISOLTRAP.

In the future, the extended applicability of ISOLTRAP will be employed for the accurate determination of masses in various regions of the nuclear chart. One example is the planned exploration of the neutron-rich side of ^{208}Pb. Despite the fact that this nucleus is the classical shell model nucleus, hardly any information exists about more neutron-rich isotopes. Such isotopes are particularly important for the adjustment of the parameters of models used for the prediction of the stability of 'superheavy' isotopes.

Another example is the mass determination of very short-lived isotopes like ^{32}Ar and ^{74}Rb. The exact knowledge of the mass of ^{32}Ar makes it possible to improve the constraints on scalar weak interaction [10] while a good knowledge of the mass of ^{74}Rb helps to extend the charge dependent systematics on pure Fermi decays towards higher Z.

The SHIPTRAP Project at GSI

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The investigation of the properties of very heavy elements or of short-lived doubly magic and neighboring nuclei (e.g. ^{100}Sn) is a very important testing ground for the ability of the existing nuclear models to describe stabilization effects of the underlying shell structure.

The aim of the SHIPTRAP project is to provide isobarically pure ion beams of low emittance and low energy. It will allow one to perform ISOL-like experiments on transuranium isotopes or other fusion reaction products, e.g. precise mass measurements, laser spectroscopy or β-spectroscopy. The system is designed to capture radioactive ions from the velocity filter SHIP at GSI and to cool them to room temperature in a volume of some mm^3 with an overall efficiency of greater than 1%.

In the experiment the radioactive ions to be investigated are separated from the primary beam projectiles in the SHIP separator. The energy of the recoil ions is reduced in degrader foils followed by a helium buffer gas cell (p $<$ 1 bar) [11]. ¿From this stopping volume either the remaining singly charged ions or the neutralized and stepwise resonantly laser-ionized ions are extracted by electric fields and a gas flow through a nozzle. From there the ions are captured with high efficiency ($>$ 50%) in two subsequent radiofrequency quadrupole (RFQ) ion guides [12] forming differential pumping stages. The last section of the second ion guide is a RFQ ion trap where the ions are collected and cooled down to an energy of about 0.05 eV.

In 1999, a RFQ was built and tested with stable singly charged ions from an off-line ion source. The characteristics of the buncher, like acceptance of the incoming beam or longitudinal and transverse emittance of the resulting beam have been investigated. According to these tests the design of an optimized RFQ rod structure, the bunching system, has been finished. After the fabrication of the parts of the RFQ rod structure the assembly and testing of this system has started. The optimized buncher will be connected to the other parts of the setup in 2000. After the buncher the ions are extracted into a Penning trap system, which will be similar to the cooler and measurement trap of the ISOLTRAP facility at CERN [8, 9]. In the cooler trap the ions are mass-selectively cooled and isomeric contamination is removed if not already achieved by resonant laser ionization. The purified and cooled ion cloud is ejected as a bunch or as a continuous beam, accelerated and guided to an experimental area where e.g. mass spectrometry, nuclear spectroscopy, high-resolution laser spectroscopy or chemical investigations can be performed. The design of the Penning trap system will be finished in early 2000. After assembly of the parts first tests can be performed with stable singly charged ions from an off-line ion source. It is planned to connect the RFQ ion buncher and the Penning traps to SHIP in the autumn 2000.

The Buffer Gas Cell and the Extraction RFQ for SHIPTRAP

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The design, construction and manufacturing of the test setup of the buffer gas cell and the extraction RFQ for SHIPTRAP is finished after a wide range of simulations. The simulations covered the following topics: stopping of the ions in the buffer gas, drag of the ions via the electric field in the cell towards a supersonic nozzle, drag of the ions through the nozzle with the gas flow, and gas flow parameters in the extraction RFQ; cooling of the ions in the extraction RFQ.

Based on the results of these simulations a prototype gas cell has been constructed which is shown in Fig. 3. After passing through a 565 μg/cm^2 Ni foil the high energy ions are stopped in argon at pressures of 50 to 200 mbar in the center of the gas cell. The electric field geometry in the gas cell is presently created by three electrodes which allow for an extraction with a good focusing of the stopped ions within 10 ms with maximum voltages of 700 V (Fig. 3). Recent simulations have shown that two additional electrodes in the area of the stopped ion cloud can improve the extraction time. To prevent the ion beam defocusing in the supersonic nozzle and to separate the effects of the electrostatic field and the gas flow on the ion beam formation, the nozzle entrance is covered by a high transmission grid at nozzle potential.

The geometry of the supersonic nozzle with a diameter of the throat of 0.6 mm is optimized to drag ions through it

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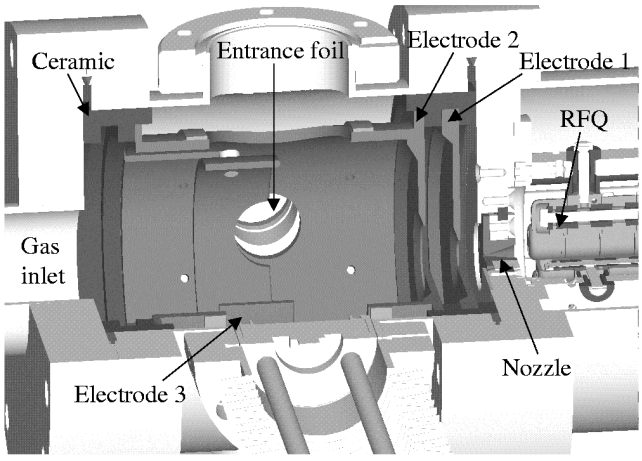

Figure 3: The SHIPTRAP buffer gas cell and part of the extraction RFQ.

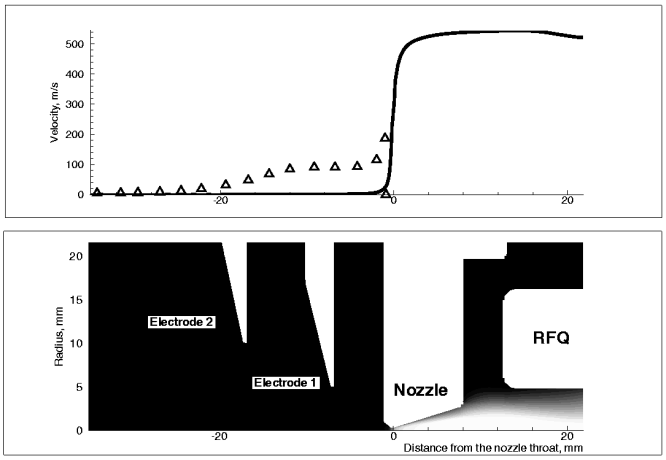

Figure 4: Ion velocity profile at the axis of the gas cell, caused by the electric field (triangles) and the drag of the gas flow (solid line). Schematic of gas cell electrodes, nozzle and first part of the RFQ, the arrowed solid lines are the gas streamlines (lower part).

into the RFQ with minimum losses on the nozzle wall and in times below 1 ms. The supersonic part of the nozzle with an opening half angle of 19° is designed to adapt the shape of the gas/ion jet to the aperture of the RFQ. The upper part of Fig. 4 shows the different components of the ion velocity at the axis of the cell. Upstream of the grid position (2 mm in front of the nozzle) the ion velocity is caused by the electric field. Downstream of the grid where the electric field is equal to zero the ions are transported by the gas flow. Here, the gas velocity has to be high in order to ensure short transport times. The lower part of Fig. 4 shows the geometry of gas cell electrodes, nozzle and first part of the RFQ. The arrowed solid lines are the gas streamlines.

The Ni foil was tested to stand the pressure difference of 200 mbar between gas cell and beam line vacuum. The setup of the gas cell and the extraction RFQ is in progress. The first offline test will be to optimize the gas cell geometry and parameters with an Er filament and laser ionisation in the gas cell [13] in order to simulate the stopped ion cloud. In parallel the stopping and straggling of ions through a Ni foil and noble gas will be investigated at the Munich Tandem accelerator in order to optimize the dimensions of the cell and to investigate different degrader configurations.

Optical Spectroscopy of Trans-Fermium Elements at SHIPTRAP

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The investigation of atomic, nuclear and chemical properties of heavy elements with Z $\geq$ 100 presents a great challenge since new experimental methods are required. Heavy elements are produced via nuclear fusion reactions with rates of sometimes only a few atoms per week. Their lifetimes are short, sometimes only in the order of ms. A suitable experimental method, based on laser spectroscopy and gas phase ion chemistry was developed at the Universität Mainz [11] and installed at the MP-Tandem accelerator facility in Heidelberg. This setup was used to perform preparatory experiments for the determination of the ionization potentials of No and Lr at SHIPTRAP.

A pulsed 50 Mev Er^{7+} beam with a mean ion current of $\bar{I}$ = 0.6 pnA was implanted in a buffer gas cell, filled with 50 mbar Ar (Fig. 5). To maximize the number of ions which come to rest between the entrance and the exit foil (titanium, 1.8 mg/cm^2) the beam energy was adjusted by a rotatable 400 μg/cm^2 carbon degrader. The ions partly neutralize during the slowing down process inside the gas. Using electric fields inside the gas cell all charged particles were removed during the clean-up period, see Fig. 6(a). Only neutral Er atoms remain stored in the buffer gas for about 40 ms, the diffusion time of the atoms to the walls of the cell. During this time **R**esonance **I**onization **S**pectroscopy (RIS) was performed using an Excimer pumped Dye laser (Coumarin 47) for the ground state excitation. Ionization was accomplished with the split pump laser running on XeF (351/353 nm). The resonantly ionized Er atoms are guided by altered electric fields towards a nozzle and ejected with the buffer gas jet into a segmented rf-**Q**uadru**p**ole-**I**on **G**uide (QPIG) of 3 mm inner diameter with rods of 3 mm diameter. Being trapped in the rf potential the ions were separated from the gas and transmitted to the high vacuum section of the mass analyzer (Balzers QMG 311) and the channeltron detector.

In order to investigate the overall features of the system in a first experiment only one laser pulse was supplied to the optical cell with a variable delay time between 3 ms and 72 ms (Fig. 6(b)). The delay time t_d = 2.8 ms between the laser trigger and the maximum of the ion signal corresponds to the transport time from the stopping volume to the detector. The decrease of the ion pulses with increasing delay is due to diffusion losses. The width of the ion signal (FWHM=1.0 ms) and the transport time depend critically on the offset voltages between the nozzle and the first two QPIG segments. At typical gradients between two segments of 2 V, small variations in the order of 100 mV result in a total loss of the time structure at only minor changes of the efficiency. The initial energy of the

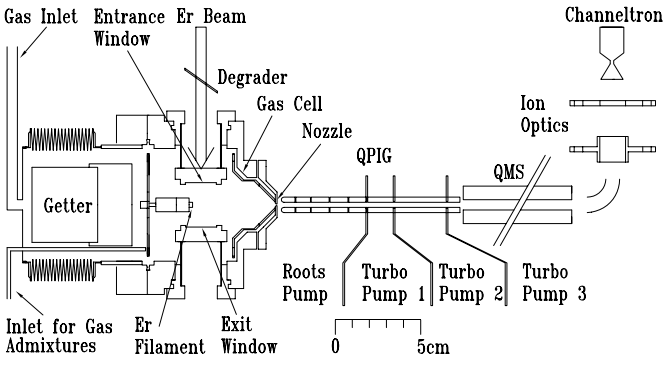

Figure 5: Experimental setup for RIS at Er. An Er-filament was used for mass and wavelength calibration. Both laser beams were transported via one fiber optic to the gas cell. The beam spot was expanded to 1.5 cm diameter and was irradiated from top.

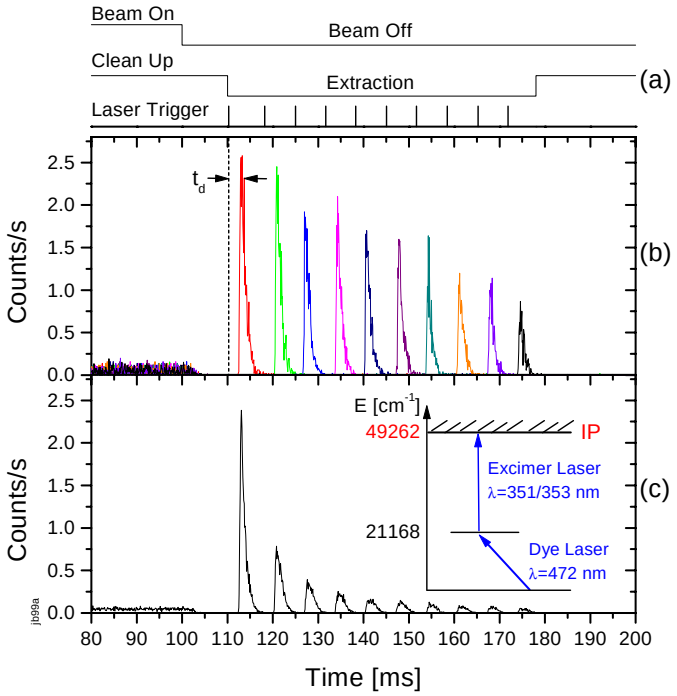

Figure 6: Timing of the primary beam (100 ms/100 ms), the electric field and the laser trigger (a). The time-resolved ion signal (m=170 u) for 10 single laser pulses (b), and the corresponding signal for a sequence of 10 laser pulses (c).

ions from the gas jet is not sufficient for transmission to the high vacuum section. The ions are stopped by collisions in the first vacuum section. If no acceleration voltages are applied transport times of more than 200 ms were measured, and a strong formation of hydrocarbon ions inside the ion guide system was observed.

In a second experiment the efficiency of the system was measured. A train of 10 laser pulses with a separation of 6.8 ms resulted in the intensity distribution shown in Fig. 6 (c). ¿From the intensity ratio of two subsequent ion pulses, taking into account the correction for diffusion losses, a RIS efficiency $\epsilon_{RIS} = 50\%$ was determined. The total efficiency of the system, defined as the ratio of the mean count rate of the channeltron detector $\dot{N}_d$ to the primary ion current $\dot{N}_p$, yields

$$\epsilon = \dot{N}_d/\dot{N}_p = 4 \cdot 10^{-5}$$

In comparison, an efficiency

$$\epsilon_{calc} = \epsilon_{stop} \cdot \epsilon_{neutral} \cdot \epsilon_{overlap} \cdot \epsilon_{RIS} \cdot \epsilon_{cell} \cdot \epsilon_{trans} = 6 \cdot 10^{-4}$$

is expected which was calculated with the following partial efficiencies. The stopping efficiency of the ions in the gas cell amounts to $\epsilon_{stop} \approx 0.2$, as estimated with a Monte-Carlo simulation. The fraction of ions which come to rest as neutrals is assumed to be in the order of 13% [14]. No increase of neutralization according to plasma effects is expected at the low beam current of 1-3 pnA in our experiment [15]. The fact that the count rate in our experiment increases linearly with the beam intensity supports this assumption. The spatial overlap of the laser with the stopping distribution amounts to $\epsilon_{overlap} = 0.3$. The transport efficiency $\epsilon_{trans} = 0.15$ through the QPIG and QMS was determined off-line, as well as the efficiency $\epsilon_{cell} = 0.5$ of the electric field extraction in the gas cell.

The calculated efficiency is at variance with the measured one. A large factor may originate from a too optimistic assumption of the extraction efficiency since this was measured with a point-like distribution while the stopped Er ions are more or less homogeneously distributed. However, in the next step of the experiment in which Er is produced via the reaction $^{161}\mathrm{Dy}(\alpha, 2n)^{163}\mathrm{Er}$, using a 80% enriched ^{161}Dy target inside the buffer gas cell, this factor may be regained. Due to the low recoil energy of 500 keV, 90% of the products are stopped within a range of 2 mm. In addition, a neutralization efficiency of more than 90% is expected in the plasma created by the α beam [15]. For this experiment a total efficiency in the order of one percent may be expected.

During the experiments with the IGRIS setup it became apparent that this spectrometer can also be used to study chemical reactions of ions in the gas phase. First studies were carried out with gas admixtures of O_2 and CH_4. Reference measurements are under way using a Fourier Transform Mass Spectrometer (FT/MS) at the Institut für Kernphysik of the Universität Mainz.

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