Experiments with Heavy Ions in Traps

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

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We report on the first measurement of the magnetic moment (*g-factor*) of the electron bound in a highly charged hydrogen-like ion. The experimental determination of the g-factor of the bound electron represents a clean test of Quantum Electrodynamics, because it is not very sensitive to nuclear structure effects. Experimental data on the g-factor of hydrogenic systems are available only for the hydrogen atom and the $^4He^+$-ion [1] and for $^{209}Bi^{82+}$ from a recent measurement of the lifetime of the upper hyperfine level of the 1s ground state [2]. The result presented here was obtained with a single hydrogen-like carbon ion ($^{12}C^{5+}$) stored in a Penning trap [3]. The experimental accuracy is already high enough to verify the relativistic contribution to the g-factor on the 10^{-3} level. In the near future we expect to test the bound-state QED contributions in light hydrogen-like ions with improved accuracy. Later on, the measurements will be extended to heavy hydrogen-like ions (up to U^{91+}).

In a Penning trap a charged particle is stored in a combination of a homogeneous magnetic field and an electrostatic quadrupole field [4]. 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 amplitudes of these three eigenmotions are reduced below 50 μm by cooling the particle to a temperature of T = 4 K.

The free-space cyclotron frequency ω_c of an ion with charge Q and mass M in the magnetic field B

$$\omega_c = \frac{Q}{M} B \tag{1}$$

can be calculated from a combination of the trapped ion's three eigenfrequencies ω_+, ω_z and ω_-, which are measured in the experiment, via

$$\omega_c^2 = \omega_+^2 + \omega_z^2 + \omega_-^2 . \tag{2}$$

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

$$\hbar \omega_L = g \frac{e\hbar}{2m_e} B = g \mu_B B. \tag{3}$$

Using the cyclotron frequency ω_c of the hydrogen-like ion (equ. 1) 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

$$g = 2 \cdot \frac{\omega_L}{\omega_c} \cdot \frac{Q/M}{e/m_e}. \tag{4}$$

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 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 as small discrete changes of the axial frequency ($\Delta\omega_z/2\pi = 0.7$ Hz) of the stored ion (see Fig. 1). 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]. The quadratic component is produced by a nickel ring at the center electrode of the Penning trap. This quantum jump method was first used by Dehmelt et al. in his g-2 experiment with a single trapped electron [7].

With the measured values of $\omega_L/2\pi = 103\,958.1(2)$ MHz for the Larmor precession frequency of the bound electron and $\omega_c/2\pi = 23.755\,28(5)$ MHz for the cyclotron frequency of the $^{12}C^{5+}$-ion the g-factor of the bound electron in $^{12}C^{5+}$ is calculated using (4) to

$$g_e^{exp}(C^{5+}) = 2.001\,040(4). \tag{5}$$

Compared to the g-factor of the free electron $g_e^{free} = 2.002\,319\,304\,377\,(4)$ [7,8], 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. The relativistic correction was first calculated by Breit who solved the Dirac equation for the bound system [9]. In the case of the hydrogen-like carbon ion (Z = 6) the relativistic term is $\Delta g_{rel} = -0.001\,278\,646$. Our measurement confirms this term at a level of $3 \cdot 10^{-3}$.

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 accuracy of our measurement ($2 \cdot 10^{-6}$) is not yet sufficient to verify the bound-state QED terms. The theoretical prediction, including relativistic, bound-state QED and nuclear corrections, for the bound-state g-factor in $^{12}C^{5+}$ is [10]

$$g_e^{th}(C^{5+}) = 2.001\,041\,59 \tag{6}$$

Our experimental result is in excellent agreement with this theoretical value. In the near future, we plan to improve the accuracy of the g-factor measurement to about 10^{-8} by spatially separating the functions of inducing and detecting the spin-flip transitions. Furthermore, we plan

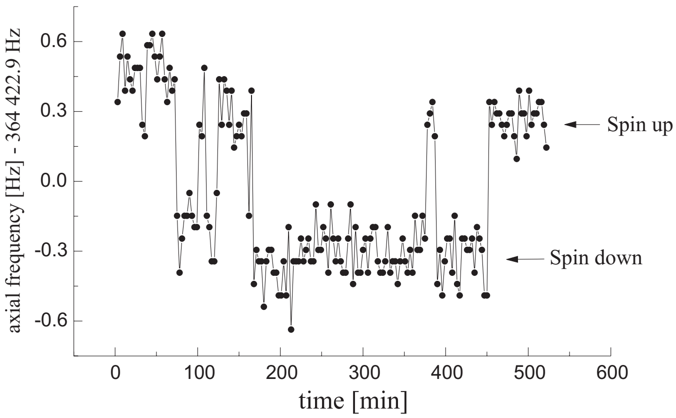

Figure 1: The Larmor precession frequency ω_L is measured by resonant excitation (at 104 GHz) of the transition between the two spin states (spin *up* and *down*) of the bound electron in the magnetic field of a Penning trap. The spin-flip transitions (*quantum jumps*) are observed as small discrete changes of the axial frequency ($\Delta\omega_z/2\pi = 0.7$ Hz) of the stored $^{12}C^{5+}$-ion.

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 is 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 [11] installed at the on-line mass separator ISOLDE/CERN is a triple-trap mass spectrometer. It consists of an ion-beam prebuncher, a Penning trap ion cooler and a Penning trap mass spectrometer. The prebuncher stops and accumulates the 60 keV ISOLDE ion beam and transfers it into low-energy ion bunches. In the last two years a Paul trap system has been used for this purpose. The first Penning trap [12] acts as an ion cooler and isobar separator with a resolving power of $m/\Delta m_{(FWHM)} \approx 10^5$. In the second Penning trap the mass determination is carried out via the measurement of the cyclotron frequency $\omega_c = (q/m)\cdot B$ of the stored ions. A resolving power of the spectrometer of up to $m/\Delta m_{(FWHM)} \approx 10^7$ enables separation of nuclei in their ground and isomeric states even for very low excitation energies. The accuracy achieved in the ISOLTRAP measurements is about $\Delta m/m = 1\cdot 10^{-7}$ [13].

In 1998 no new mass measurements were performed. Work concentrated on an important upgrade of the experimental set-up and the evaluation of the data taken in the previous two years. A new prebuncher system was designed and installed at the ISOLTRAP experiment. The new system is based on a linear quadrupole rod structure (Fig. 2). Compared to the previous Paul trap system it promises a significant increase in efficiency of the spectrometer. The system is now fully implemented in the ISOLTRAP system and has been undergoing first tests with ISOLDE beam. The final commissioning of the system is under way and it will be operational for first runs with radioactive beam in 1999.

All data taken in the past two years were analysed and an Atomic Mass Evaluation (AME) was carried out. The new ISOLTRAP mass values of isotopes of mercury and other elements in the vicinity of lead improved considerably the knowledge of nuclear binding energies in a large mass region since they serve as very accurate anchorage for alpha-decay chains with known Q-values. Due to the new mass data it is now possible to make a solid study of the trends of the binding energies in this region. Such a study was carried out for the two-neutron separation energies in the isotopic chaines of Pt, Hg, Pb, Po, Rn and Ra [14, 15]. The results were compared with the result of shell model calculations and with other nuclear structure information obtained from atomic and nuclear spectroscopy. It was found that there is good coherence between these informations and the trends observed in binding energies. The results for the lead and radium isotopes support a spherical ground state. In the case of the platinum, mercury and polonium isotopes a deviation from a linear trend for the two-neutron separation energies was observed which can be interpreted as being due to a mixing of spherical and deformed states, while in the case of the radon isotopes a similar behavior is likely to result from the onset of ground-state deformation.

In the future, the improved efficiency of ISOLTRAP will be employed for the accurate determination of new and exotic mass regions. One of the goals for 1999 is the 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 (like ^{215}Pb and ^{217}Bi, recently discovered at ISOLDE) are for example important for the adjustment of the parameters of models used for the prediction of the stability of 'superheavy' isotopes.

SHIPTRAP: A Capture and Storage Facility at GSI for Heavy Radionuclides from SHIP

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The investigation of the properties of very heavy elements and of short-lived doubly magic and neighboring nuclei

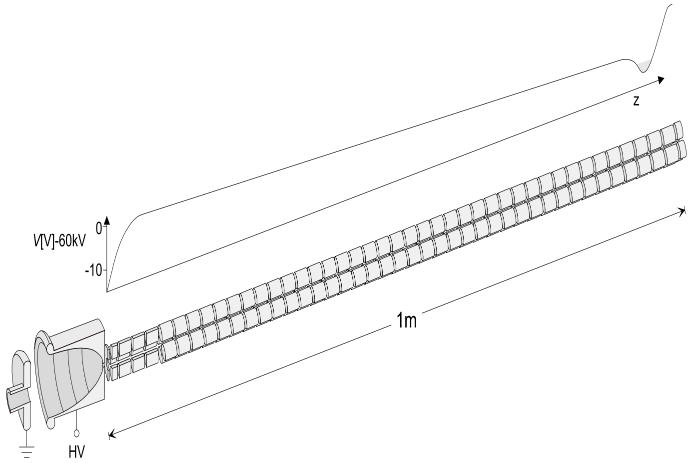

Figure 2: The new ISOLTRAP ion beam prebuncher. It is based on a gas filled linear radiofrequency quadrupole structure with a lens system for electrostatic retardation of the 60 keV ISOLDE beam. A dc potential along the axis of the system allows the accumulation of ions close to the exit side of the system from where the ions can be extracted in short ion bunches.

(e.g.^{100}Sn) is a very important testing ground for the ability of the existing nuclear models to describe stabilisation 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 γ-spectroscopy. The system is designed to capture radioactive ions from the velocity filter SHIP at GSI and to cool them in an ion trap 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 ($p \leq 1$ bar), see Fig. 3. From this stopping volume either the remaining singly charged ions or the neutralised and stepwise resonantly laser-ionised 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 ion guides forming differential pumping stages. The last section of the second ion guide is built as a RFQ rod trap where the ions are collected and cooled down to an energy of about 0.05 eV. Then the ions are extracted into a Penning trap system, which will be similar to the cooler trap of the ISOLTRAP facility at CERN. In this trap the ions are mass selectively cooled, and isomeric contamination is removed if not already achieved by resonant laser ionisation. 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 or high-resolution laser spectroscopy or chemistry can be performed.

In 1998 the design of the RFQ rod structure which serves as a bunching system has been finished. After assembly this part will be tested in early 1999 at the SHIPTRAP facility. The tests will be performed with stable singly charged ions from an ion source. The characteristics of the buncher, like acceptance of the incoming beam or longitudinal and transverse emittance of the extracted beam, will be investigated. The optimised buncher will then be connected to the other parts of the set-up.

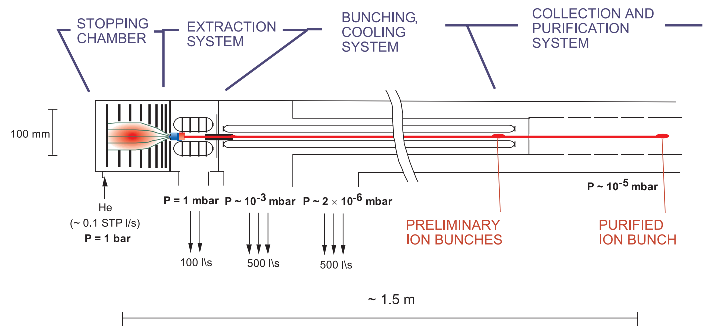

Figure 3: Overall configuration of the SHIPTRAP facility. It consists of a stopping chamber containing a noble gas, an extraction system, a rfq structure for accumulation and bunching and a Penning trap for isobaric purification.

Optical Spectroscopy of Trans-Fermium Elements at SHIPTRAP

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The investigation of atomic, chemical and nuclear properties of new heavy elements is a real challenge. Heavy elements are produced in nuclear fusion reactions with rates of sometimes only a few atoms per week. Their lifetimes are short, sometimes only in the order of ms. At present, the most advanced method for the investigation of the properties of heavy elements is chemistry with single atoms in aqueous solutions [16] and in the gas phase. This technique provided already detailed chemical information for $Z = 105$ and recently also for $Z = 106$ [17]. The goal of such experiments is to compare their chemical properties with homologous elements. It is well-known that relativistic effects play an increasingly important role for the heaviest elements around $Z = 100$. Therefore, the atomic and chemical properties of these elements may substantially differ from what would be expected from periodicity considerations. These relativistic effects are caused by a shrinkage of the wave functions of inner shell electrons which influences the binding energies of the valence electrons.

The electron configurations of valence electrons can be predicted by Multi-Configuration Hartree-Fock-Dirac calculations and other methods [18]. These ab-initio calculations can be checked by chemistry experiments. A more direct test of these calculations would be an investigation of the atomic properties, e.g. the first ionisation potential and the atomic level schemes, rather than chemical properties. However, very powerful experimental methods are required to obtain reliable results since the half-lives are short and no excited atomic levels are known. For production rates of about 10 atoms/s the Radiation Detected Resonance Ionisation Spectroscopy (RADRIS) technique in a buffer gas cell can be employed for the investigation of radioactive nuclides with half-lives as short as 1 ms, as demonstrated by spectroscopic investigations of the ^{240f,242f}Am fission isomers [19].

However, the detection by radioactive decay limits the RADRIS technique to nuclides with half-lives of less than a few minutes. Therefore, this method has been developed further into Ion-Guide detected Resonance Ionisation Spectroscopy (IGRIS). Here, the radioactive-decay detection is replaced by a mass selective direct detection of the ions, similar to the Ion-Guide Quadrupole Mass Separation (IGQMS) technique [20] in which the ions leaving the buffer gas cell are separated from the gas jet and mass analysed in a quadrupole mass filter [21]. The combination of resonance ionisation spectroscopy and mass analysis of the extracted ions provides information on both the nuclear charge number as well as the mass number of the ions. Application of this technique at the SHIPTRAP project offers the unique possibility to investigate atomic, nuclear and ion-chemical properties of very heavy elements.

The IGRIS technique at SHIPTRAP gets even more complicated since no excited atomic states are known. Therefore, as a first step, studies are planned for fermium ($Z = 100$) at the MPI für Kernphysik in Heidelberg using the reaction ^{249}Cf(α,2n)^{251}Fm with a large cross section of 20 mb. For these experiments a compact apparatus will be used which was constructed and successfully tested at the Universität Mainz [22]. At SHIPTRAP the elements Md, No and Lr ($Z = 101$ - 103) can be investigated. They can be produced with cross sections in the order of μb by the reactions ^{238}U(^{19}F,5n)^{252}Md, ^{208}Pb(^{48}Ca,n)^{255}No and ^{209}Bi(^{48}Ca,n)^{256}Lr.

During the experiments with the IGRIS set-up it became apparent that this spectrometer can also be used to study chemical reactions of ions in the gas phase. Such reactions occur between ions and buffer gas admixtures as O_2, H_2O, CO_2, etc. They provide informations about electron configurations and the size of valence orbits of the ions as demonstrated in investigations of the reactivity of transition-element ions such as Hf^+, Ta^+ or W^+ with O_2, H_2O, CH_4, C_2H_6 and CO_2 [23, 24]. A large fraction of about 87% of the fusion reaction products, delivered from SHIP, comes to rest in the buffer gas cell as singly charged ions. About two orders of magnitude less ions are needed for the gas phase ion chemistry than for laser spectroscopy. It is expected that the investigations can be extended to short-lived transactinides with $Z > 106$ and $t_{1/2} < 100$ ms which are out of reach for gas chromatographic methods.

Reference measurements with the homologue elements and the various gas admixtures present in the buffer gas cell are of great importance for the understanding of the ion-chemical reactions in the cell. Such measurements can easily be performed with a Fourier Transform Mass Spectrometer (FT/MS) which is available at the Institut für Kernphysik of the Universität Mainz.

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