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ION TRAPS - RECENT APPLICATIONS AND DEVELOPMENTS

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ABSTRACT

Paul and Penning traps are now widely applied in chemistry and physics laboratories. They are used as storage devices, as tools for precision spectroscopy and metrology, and as mass spectrometers. Direct mass measurements of short-lived Rb, Sr, Cs, Ba, Fr and Ra isotopes were performed at the on-line mass separator ISOLDE at CERN/Geneva by means of a tandem Penning trap system. The ions from ISOLDE are captured and cooled in a first trap and transferred to a second trap. Here the mass of the trapped ions is determined by measuring their cyclotron frequency. Resolving powers exceeding $m/\Delta m$ (FWHM) = 10^6 could be achieved. Mass values of about 60 isotopes have been determined with accuracies of typically $\delta m/m = 10^{-7}$. For the first time in the history of mass spectrometry the isomeric and ground state of a nucleus has been resolved.

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1. Introduction

A long time ago powerful techniques were developed for three-dimensional confinement of ions by combined static magnetic and electric fields (Penning trap [1]) or by time-varying electric fields (Paul or radio frequency quadrupole trap [2,3]), also called quite often QUISTOR = quadrupole ion storage trap. The tremendous impact of these devices was acknowledged in 1989 by the award of the Nobel Prize to H. Dehmelt and W. Paul.

The quadrupole radio frequency mass analyser [4], a two-dimensional variant of the Paul trap, is well known and since long time commercially available. However, only in the last decade have the application of ion traps as storage devices and their use for high-precision measurements become an important issue. This break-through was made possible by the development of ultra-high vacuum technology, of fast computers, and, finally, of superconducting magnets with high stability and homogeneity over a large volume. It should be noted that over one hundred Penning trap systems are presently also in use by chemists for the investigation of chemical reactions by mass spectrometry. The Paul trap as well is now commercially available in combination with a gas chromatograph and is widely applied by chemists.

Recently the injection of ions from the outside world into ion traps and their capture with high efficiency have been achieved [5,6]. Hence, rare species can now be investigated such as radioactive isotopes, antiprotons or clusters like C_{60} , produced by accelerators, on-line isotope separators or special ion sources.

This publication will concentrate on Penning traps which allow the determination of the mass of stored charged particles with high resolving power and accuracy. This is accomplished by observing the cyclotron motion of the ion in a magnetic field. The principle of Penning traps will be briefly discussed as well as techniques for ion injection, cooling and detection of the cyclotron resonance. The Paul trap is treated in more detail in Ref. [7-9].

Some recent applications will be briefly presented as examples for the wide applicability of ion traps. These are the investigation of cluster properties [10], the mass measurement of the antiproton performed at the antiproton storage ring LEAR/CERN [11], and, in more detail, the mass determination of short-lived isotopes at the on-line isotope separator ISOLDE/CERN [12]. In the latter experiment the ground and isomeric state could be mass resolved for the first time. Since the ion in the nuclear ground state or in the isomeric state can be selectively ejected from the trap by radio frequency, the Penning trap acts as an isomer separator.

Future applications include the measurement of the gravitational mass of the antiproton [13], ultra-precise doublet mass spectrometry by use of clusters [14], mass spectrometry and other investigations of highly charged ions produced in EBIS or ECR ion sources [15], and the coupling of ion traps to heavy-ion accelerators like GSI/Darmstadt [16].

More information on ion traps for high-precision mass spectrometry and their use at accelerators and isotope separators can be found in the proceedings of the "Workshop and Symposium on the Physics of Low-Energy Stored and Trapped Particles" [17] and the proceedings of the "Workshop on Physics with Penning Traps" [18].

2. Principle of Ion Traps

Electromagnetic forces are used for confinement of charged particles. For both the Penning and the Paul trap a quadrupole potential

$$\Phi_2 = \frac{a_2}{2} (2z^2 - r^2) \quad (1)$$

is used with $r^2 = x^2 + y^2$. Such a quadrupole potential can be set up by electrodes which follow the equipotential surface given by eq. (1). In general this configuration consists of three electrodes: Two endcaps and one ring electrode which are hyperboloids of revolution (e.g., with $r_0 = \sqrt{2} z_0$, see Fig. 1) specified by

$$z^2 - r^2/2 = \pm z_0^2 \quad (2)$$

where z_0 is half the distance between the two end electrodes. If the voltage of the endcap electrodes relative to the ring electrode is V_0 , then the coefficient for the quadrupole term can be conveniently expressed as

$$a_2 = \frac{V_0}{2z_0^2} \quad (3)$$

Penning Trap: A homogeneous magnetic field is used for radial confinement. The axially symmetric static electric quadrupole field

$$E_r = a_2 r ; E_z = -2a_2 z \quad (4)$$

prevents the ions from escaping along the magnetic field lines and hence leads to the axial confinement of the particle of charge q and mass m which oscillates with a frequency of

$$\omega_z^2 = 2 \frac{q}{m} a_2 \quad (5)$$

Due to the additional electric force the radial ion motion is not a pure cyclotron motion with frequency ω_c given by

$$\omega_c = \frac{q}{m} B \quad (6)$$

but a superposition of two harmonic eigenmotions: A slow drift around the trap axis called magnetron motion with frequency ω_- and a modified cyclotron motion with frequency ω_+ given by

$$\omega_{\pm} = \frac{\omega_c}{2} \pm \sqrt{\left(\frac{\omega_c}{2}\right)^2 - \frac{\omega_z^2}{2}} \quad (7)$$

More detail can be found in Ref. [19-24].

Paul Trap: No magnetic field is used in this trap, but V_0 is in this case an oscillating quadrupole field applied between the ring electrode and the end caps, generally in addition to a DC voltage.

$$V_0 = V_{\text{RF}} \sin \omega_{\text{RF}} t + V_{\text{DC}} \quad (8)$$

The Paul trap is an ideal and inexpensive device when only storage and precision spectroscopy are desired. The absence of a magnetic field is advantageous to metrology and optical spectroscopy experiments. However, it has only limited resolving power for mass spectrometry. This type of trap and its applications are described in detail in Ref. [2,3,7-9,17-20,22,24].

3. Applications of Ion Traps

Out of the numerous applications of ion traps only a few examples will be discussed here to illustrate the powerful features of ion traps. These are:

- (i) Storage of charged particles in a very well controlled environment nearly free of unwanted perturbations for long periods of time.
- (ii) The possibility of performing experiments on few or even single ions. Thus perturbations by ion-ion Coulomb interaction are reduced or totally eliminated and very rare species can be investigated.
- (iii) Extreme reduction of the Doppler effect due to the possibility of very effective cooling.
- (iv) Use of the ion trap as a mass spectrometer of very high resolving power and accuracy.

ad (i): Since the ions can be stored over long periods of time the transit time line broadening usually limiting the resolution in atomic beam experiments can be reduced or even eliminated. Hence, the hyperfine splitting in ionic ground states could be measured by optical pumping and RF transitions with extreme accuracies [7,25]. Such a precision makes ion traps attractive for metrology and might lead to a replacement of the present ^{133}Cs frequency standard by an ion trap. Considerably higher accuracies of frequency standards can in principle be obtained by use of optical instead of RF transitions.

ad (ii): The long storage time and highly efficient detection schemes enables experiments on few or even single ions. Best known is the g-2 experiment on a single stored electron or positron which provided us with the most accurate fundamental constant known today [24]. Furthermore the efficient use of charged particles in traps enabled the investigation of rare species like anti-particles (antiproton [6,11], positron [24]), short-lived isotopes (see below) or exotic particles like the $^{12}\text{C}_{60}$ cluster [10]. The C_{60} cluster, known as Buckminsterfullerene, consists of 60 carbon atoms placed on the surface of a sphere with icosahedral symmetry and looks like a soccer ball.

ad (iii): Several cooling techniques (for detail see Ref. [26]) have been developed in order to reduce the Doppler broadening, to localize the charged particles near the trap center, to achieve crystallization of an ion cloud in the trap, or to increase the capture efficiency for externally produced particles.

Conceptually simplest are cooling by synchrotron radiation in Penning traps for light particles (e^- , e^+) and cooling by buffer gas collisions in Paul traps (see also Ref. [9]). Resistive cooling is based on the dissipation of energy of the stored ion in an external resistor. The energy is generally taken out of the axial motion via the mirror currents induced in the endcap electrodes. This cooling mechanism works efficiently only for particles with high q/m ratio and requires a tuned circuit. Synchrotron cooling of electrons, cooling of antiprotons by electrons and resistive cooling have been applied at LEAR for a 1000-fold improvement in the accuracy of the mass of the antiproton [11]. Cooling of highly charged ions by synchrotron radiation cooled positrons is proposed for work at heavy ion accelerators [16].

Laser cooling utilizes the tiny energy defect gained in each optical pumping cycle (which happens, however, at a fast rate) with the laser wavelength tuned just below a strong optical resonance. It has been applied to ions stored in Paul as well as in Penning traps. Temperatures as low as some 10 μ K have been achieved [27]. A disadvantage of laser cooling is that it is not generally applicable. Only a few elements have an appropriate level scheme in the ionic state for laser cooling with presently available cw tunable laser systems.

A new cooling technique has been developed in the course of the experiments concerning the determination of masses of short-lived isotopes in a Penning trap [28]. It is generally applicable and mass selective (see section 4.3) but reaches only the temperature of the buffer gas used.

ad (iv): Today, ion traps are frequently applied as mass spectrometers. Highest resolving power and accuracy are obtained by Penning traps (eqs. (4)-(6)). Until now, the application of high-accuracy Penning trap mass spectrometers has been restricted to light particles as in the proton/electron mass ratio [29,30], the mass of the antiproton [11], or the mass of light ions [25,31]. In the following section, high-accuracy mass measurements of heavy atoms are described in more detail.

Mass spectrometry of heavy ions is an important novel application of Penning-type ion traps used mainly by chemists. These commercially available instruments are called Fourier transform ion cyclotron resonance (FT-ICR) spectrometers or simply Fourier transform mass spectrometer (FT-MS). They are mainly applied to the investigation of chemical reactions via mass spectrometry [32,33]. In these instruments, the stored ions are excited to a large cyclotron radius by a white RF radiation and the mirror signals induced in the segmented ring electrode are recorded. The transient signal is Fourier-transformed and the spectrum of the (modified) cyclotron frequencies yields a mass spectrum of the stored ion cloud. Although extreme resolving powers of up to several 100 millions have been reported [34], the accuracy in mass determination is restricted to $\delta m/m \geq 10^{-6}$. This is due to several reasons: The cubic trap geometry generally used results in electric field imperfections; magnetic and electric field imperfections become important since the ion cloud is excited to large cyclotron radii reaching close to the detection plates which replace the ring electrode of hyperboloidal traps; the requirement of a rather large number of stored ions (minimum 100 - 1000 ions of one species) leads to ion-ion interactions and space charge shifts in the observed modified cyclotron resonance [35].

4. The Penning Trap as a Mass Spectrometer for Short-Lived Heavy Isotopes

The majority of masses of radioactive isotopes has been measured by determination of Q-values in nuclear reactions or in nuclear decay. For a long time the use of direct mass determination has been limited to stable isotopes or isotopes close to stability. This changed in the 70's with magnetic spectrometers put on-line to isotope separators. The Orsay group [36] succeeded in measuring the masses in long isotope chains of alkali elements. They impressively demonstrated the possibilities embedded in direct mass determination of isotopes far from stability.

The persisting demand for more precise masses of short-lived isotopes (or exotic particles) has prompted in recent years the development of new techniques for direct mass spectrometry. A general feature of these new devices is an evolution from measurements of voltage ratios to measurements of time and frequency. Time-of-flight mass spectrometry is performed by the facilities TOFI at Los Alamos [37] and SPEG at Ganil [38], and is planned at ESR at GSI [39,40].

The Penning trap technique is another powerful approach based on frequency measurements. The experiments reported here were performed by use of a tandem Penning trap mass spectrometer at the on-line mass separator ISOLDE/CERN. Very accurate mass results were obtained for Rb, Sr, Cs, Ba, Fr, and Ra isotopes.

4.1 Mass Determination via the Cyclotron Resonance

The principle used in the Penning trap mass spectrometer at ISOLDE/CERN is to determine the resonance of the cyclotron frequency ω_c of an ion in a homogeneous magnetic field via eq. (6).

An important relationship between the radial frequencies in a pure electric quadrupole field and a homogeneous magnetic field is

$$\omega_c = \omega_+ + \omega_- \quad . \quad (8)$$

The ion motion in a Penning trap can be directly excited at this sum frequency by means of an azimuthal quadrupole field. This excitation couples magnetron and cyclotron motion so that a periodic conversion from one motion into the other can be achieved [23,35]. After the excitation time T_{RF} an initially pure magnetron motion is transformed into a pure cyclotron motion. In general this transformation leads to a large change in radial energy (since $\omega_+ \gg \omega_-$) which is detected by a time-of-flight technique described below. The width of the cyclotron resonance curve $\Delta\nu_c(\text{FWHM}) \approx 0.9/T_{RF}$ is determined by the Fourier-limit of the driving RF-field switched on for a time T_{RF} . For example, a singly charged ion with mass number $A = 100$ in a field of $B = 6$ T has $\nu_c \approx 1$ MHz. Exciting it for $T_{RF} = 900$ ms yields a line width of $\Delta\nu_c \approx 1$ Hz corresponding to a resolving power of 10^6 . Of course this theoretical limit can only be achieved if line broadening effects due to poor vacuum or trap imperfections are much smaller.

4.2 Trap Imperfections

With regard to the high accuracy aimed for it is important to find and understand the causes of shifts in the cyclotron resonance frequency leading to systematic errors. Most of these frequency shifts arise from the trap itself and are due to deviations of the electric trapping field from a pure axial quadrupole field, magnetic-field inhomogeneities and misalignment of the trap relative to the magnetic-field axis. (The effect of ion-ion interaction will be discussed later). A careful investigation allowed the construction of a Penning trap with very low magnetic and electric field imperfections [35].

4.3 Ion Capture and Cooling

In order to perform mass determinations on unstable isotopes delivered by an on-line mass separator a mechanism is required to capture these ions in the trap. Two possibilities exist for capturing an ion from the outside world in a Penning trap. Either a retardation electric field is applied until the ion is brought to rest or a buffer gas is used to reduce the ion energy by friction. Both schemes are applied in the ISOLDE mass experiment. In the trap where the cyclotron resonance is determined, a short ion bunch is captured in flight by the first mechanism [5]. This bunch is provided by another Penning trap which acts as an ion beam buncher and cooler for the continuous ISOLDE beam. In this trap, high temperature ions are stopped and cooled by buffer gas collisions. Buffer gas collisions in a Penning trap lead to the desirable decrease of the amplitudes of the axial and cyclotron motion but at the same time to an increase of the magnetron orbit due to the negative energy of this motion (Fig. 2). In order to circumvent this process an additional oscillating quadrupole field at frequency ω_c is applied which re-centers the ions [28]. This new cooling technique is mass-selective since the cyclotron frequency is involved.

4.4 The Experimental Set-Up and its Performance

Figure 3 shows the experimental set-up at the on-line mass separator ISOLDE. It consists of two main parts, the lower Penning trap (trap #1) acting as ion beam buncher and cooler, and the upper high-precision trap (trap #2) in which the mass determination takes place. The first trap is placed in a vacuum chamber mounted in an electromagnet with a magnetic field of $B = 0.7$ T. The continuous 60 keV ISOLDE beam is collected on a rhenium foil mounted in the lower endcap of this trap. The foil is rotated by 180° and current-heated for 500 ms so as to surface-ionize the collected material. By buffer gas collisions the ions are stopped and cooled by the mechanism explained above. Use of He gas at a pressure of $p = 10^{-3}$ to 10^{-4} mbar results in a capture efficiency of $\epsilon_{\text{capture}} \geq 10^{-4}$. A mass resolution of $m/\Delta m(\text{FWHM}) = 500$ is obtained in this trap, sufficient to remove isotopic contaminations present in the ISOLDE beam.

After a cooling period of 200 ms a voltage pulse is applied to the trap to eject the ions. The ion bunch is accelerated to 1 keV, transferred to the upper Penning trap with an electrostatic lens system and again retarded. The potential of the lower endcap is first switched to a low value allowing the ions to enter the trap and then raised again in order to capture them. The ion transfer between two Penning traps can be performed with nearly 100% efficiency.

The high-precision trap (Fig. 4) is constructed from oxygen-free copper and is gold plated. Glass ceramics are used for insulation. All parts are machined as thin as possible in order to minimize magnetic field inhomogeneities due to the susceptibility of the materials. Deviations from the ideal quadrupole field are compensated by correction electrodes installed between the ring electrode and the endcaps and at the holes required in the endcaps for injection and ejection of ions (Fig. 4). The azimuthal quadrupole field for the excitation is created by splitting the ring electrode into four quadrants. The trap itself is placed off-center with respect to the incoming beam axis so as to capture the ions at a magnetron orbit of radius $\rho_- \approx 1$ mm. After excitation of their motion by the RF-field the ions are pushed out of the trap and drift along the magnetic field lines to an ion detector placed in the weak fringe field of the magnet. The radial energy gained by the excitation is converted into axial energy in the inhomogeneous part of the magnetic field. Therefore the measurement of the drift time as a function of the applied radio-frequency yields a resonance curve with a minimum at $\omega_c = \omega_+ + \omega_-$, corresponding to a maximum of gained radial energy. As an example, Fig. 5 shows a resonance curve obtained for ^{120}Cs ($T_{1/2} = 64$ s). As expected from the excitation time of $T_{\text{RF}} = 1.8$ s a Fourier-limited linewidth of $\Delta\nu_c = 0.5$ Hz is achieved, corresponding to a resolving power of $R = 1.5$ million. This measurement took 7 minutes with a total of 2000 ions detected. The overall efficiency (ratio of the number of detected ions to the number of ions implanted in the foil) was determined to be $\epsilon_{\text{total}} = 5 \cdot 10^{-5}$. An accuracy of $\delta m/m = 2.1 \cdot 10^{-7}$ could be achieved for this isotope, corresponding to $\delta m = 24$ keV.

4.4 Mass Measurements

Several cyclotron resonances were observed for each isotope under investigation. The calibration of the magnetic field was performed via the cyclotron resonance of a stable reference isotope of well known mass. In order to achieve highest accuracy a careful search for systematic errors was performed before, during and after the runs. Within the quoted accuracy no systematic shifts due to field instabilities and imperfections were found. The only systematic shift of ω_c observed at a level of $\delta m/m \approx 10^{-7}$ is due to ion-ion interaction of simultaneously stored ions of different masses.

Beside the isotopes in their ground state, isomers and isotopes of neighbouring elements are produced in the ISOLDE targets. Isobaric products are partly eliminated by the chemical selectivity of the ionization process either in the ISOLDE ion source or by the surface-ionizer in the first trap. In some cases with sufficient difference in half-lives between two isobars, the shorter-lived isotope can be allowed to decay on the foil in trap #1 before starting the mass measurement. This method was also applied to isotopes with significantly different half-lives of ground and isomeric states.

In cases of mass differences of $\Delta m \geq 1$ MeV, contaminant ions were removed from trap #2 by selectively exciting them to large cyclotron orbits by a dipole field at ω_+ . This technique was applied to isobars. For isotopes with a half-life of the isomeric state comparable to that of the ground state none of the above techniques are applicable. Then the only possibility is to keep the number of stored ions as small as possible in order to minimize the effect of the ion-ion interaction. This procedure and the high resolving power of the Penning trap mass spectrometer allowed the isomeric and ground state of a nucleus to be mass resolved, the particular cases being ^{78}Rb and ^{84}Rb (Fig. 6).

Table 1 summarizes the isotopes investigated so far with the Penning trap mass spectrometer. The stable isotopes ^{39}K , ^{85}Rb , ^{87}Rb , and ^{133}Cs were used for calibrating the magnetic field. Masses could be determined for the first time for ^{78}Sr , ^{79}Sr , $^{122\text{m}}\text{Cs}$, ^{124}Ba , ^{126}Ba , and ^{230}Ra . The high performance of the Penning trap mass spectrometer allowed the determination of mass values with accuracies of $\delta m/m \approx 10^{-7}$ for all isotopes. The measurements performed on neutron-deficient Cs isotopes increased the accuracy of the masses far from stability by one order of magnitude [12]. Figure 7 shows a comparison between an adjustment of all mass data available in the Cs region and the Q_β /reaction data (top), the results of mass measurements with a Mattauch-Herzog spectrometer [36] (middle), and our data (bottom). The excellent agreement of the Penning-trap results with the Q_β and reaction data for nuclei near stability demonstrates the reliability of the Penning-trap technique. Its most outstanding feature is the very high and constant accuracy maintained even for isotopes far from stability. This high accuracy serves to resolve the conflict between the mass values from Q_β -studies and values by a Mattauch-Herzog-spectrometer [36]. In addition, wrong mass values due to an underestimation of the errors of Q_β -values, were found for ^{130}Cs and ^{135}Cs , both close to stability.

The performed measurements not only improved the accuracy of the mass values of the investigated nuclei but also improved those of neighbouring isotopes of other elements due to the manifold links between them.

4.5 The Penning Mass Spectrometer at the New PS Booster ISOLDE Facility

The future aim of the ISOLDE mass experiment is to extend the mass measurements to elements which can not be surface-ionized. A first step forward has already been achieved with the development and successful test of a Paul trap beam collection system [9]. This system can retard and collect the continuous ISOLDE beam. After cooling by buffer gas collisions the ions are extracted as an ion bunch. The buncher will allow us to investigate all isotopes of those elements which are not surface-ionizable and are produced relatively free of isobaric contamination. With the planned development of a highly efficient pulsed laser-induced-surface-ionization (LISI) source for positive and negative ions, the mass determination of isotopes of surface-ionizable elements can be extended to regions

far away from stability. Furthermore the investigation of isotopes of halogenes will become possible. In addition, the LISI ion source would enable the creation of carbon clusters over a large mass scale. These clusters can be used for the calibration of the magnetic field. Hence not only direct but also absolute mass determinations will be performed.

A future plan is to use laser-induced desorption and resonance ionization for the investigation of isotopes of refractory elements only available as daughter products. These techniques will extend the applicability of the Penning trap method to most of the isotopes produced at the new ISOLDE facility now being constructed at CERN [41]. They will allow a systematic study to very high accuracy of the nuclear binding energy as a function of a broad range of neutron and proton numbers.

5. Future Applications of Ion Traps

Looking into the future at applications of ion traps for physics, one can expect that ion trap techniques will play an increasingly important role in combination with specialized ion sources, isotope separators, accelerators and storage rings. Quite a number of future experiments will make use of the unique features (see section 3) of these devices.

At Los Alamos, M. Holzscheiter et al. [13,18] are preparing an experiment in order to compare the gravitational mass of the antiproton with that of the proton. It is planned to use several traps for capture, accumulation and cooling of the antiprotons delivered by the Low-Energy Antiproton Ring LEAR/CERN. The time of flight to a detector in the earth's gravitational field will be measured after launching the antiprotons from a Penning trap.

Several groups are working on the formation of antihydrogen starting from stored clouds of antiprotons and positrons [42]. Again, Penning traps are applied in order to accumulate these particles at ultra-low energies.

At several bureaus of standards, work is going on to re-define the kilogram. The kilogram is the last basic unit represented by a human artifact and not by a microscopic property of an atom. One idea is to use the mass of the ^{28}Si atom as an atomic mass unit and to relate this microscopic quantity to the macroscopic one by a more accurate Avogadro's constant [43]. In order to tie the present microscopic mass unit, i.e. $1/12^{\text{th}}$ of the mass of ^{12}C , to that of ^{28}Si , the mass ratio of these two isotopes has to be measured with an accuracy exceeding 10^{-8} . This will be done by doublet mass spectrometry in a Penning trap. Either cluster ions ($^{28}\text{Si}_3^{+}/^{12}\text{C}_7^{+}$) with $m/q = 84$ can be used [14] or highly charged isobars ($^{28}\text{Si}^{7+}/^{12}\text{C}^{3+}$) with $q/m = 4$ [15]. In the latter case, highly charged ions are to be produced in the Penning trap itself as achieved by Van Dyck [31] or a Penning trap has to be coupled to an EBIS or ECR ion source. Such combinations are now being prepared at Livermore [44] and by a Mainz/Stockholm collaboration [15]. As already proven by the EBIT (electron beam ion trap) at Livermore [45], such facilities are new, powerful tools for the study of single or few electron systems.

Very recently, the coupling of ion traps to the experimental storage ring ESR at GSI has been proposed [16]. This Heavy Ion Trap (HITRAP) facility should allow the capture, cooling and storage of highly-ionized stable and radioactive ions such as U^{92+} . These ions nearly at rest in space will enable new experiments such as:

- * Precise mass measurements of short-lived isotopes due to the proportionality of the resolving power to the charge state. Since the production mechanism of the fragment separator FRS at GSI is independent of the chemical properties of the produced isotope, the isotopes of refractory elements will also be available for investigation.
- * Ultra-precise mass measurements of highly-ionized atoms. The comparison of the masses of bare, hydrogen-, helium-like ions and so on will allow for the first time an experimental proof of the calculation of atomic binding energies at high Z where relativistic and QED effects become important.
- * Easy preparation and analysis of the charge states of stored ions.
- * Experiments on a single highly-ionized ion.
- * Reaction studies with charged particles, atoms, and photons.
- * Crystallisation of the ion cloud as already observed for singly charged ions.
- * Nuclear physics experiments where spatial confinement and separability of β^- and γ^- rays are essential.

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References

- [1] F.M. Penning, *Physica* 3 (1936) 873
- [2] W. Paul, O. Osberghaus and E. Fischer, *Forsch. Berichte des Wirtschaftsministeriums Nordrhein-Westfalen* Nr. 415 (1958) and *Rev. Mod. Phys.* 62 (1990) 531
- [3] E. Fischer, *Z.Phys.* 156 (1959) 1
- [4] W. Paul and H. Steinwedel, *Z. Naturforsch.* A8 (1953) 448
- [5] H. Schnatz, G. Bollen, P. Dabiewicz, P. Egelhof, F. Kern, H. Kalinowsky, L. Schweikhard, H. Stolzenberg and H.-J. Kluge, *Nucl. Instr. and Meth.* A251 (1986) 17
- [6] G. Gabrielse, X. Fei, L.A. Orozco, R.L. Tjoelker, J. Haas, H. Kalinowsky, T. A. Trainor and W. Kells, *Phys. Rev. Lett.* 63 (1989) 1360
- [7] G. Werth, *Phys. Scrip.* T22 (1988) 191 and submitted to *Nucl. Instr. and Meth.*
- [8] M. Wada, submitted to *Nucl. Instr. and Meth.*
- [9] R. B. Moore, submitted to *Nucl. Instr. and Meth.*
- [10] P.A. Limbach, L. Schweikhard, K.A. Cowen, M.T. McDermott, A.G. Mashall and J.V. Coe, submitted to *Rapid Comm. Mass Spectrometry* (1991)
- [11] G. Gabrielse, X. Fei, L.A. Orozco, R.L. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor and W. Kells, *Phys. Rev. Lett.* 65 (1990) 1317
- [12] H. Stolzenberg, St. Becker, G. Bollen, F. Kern, H.-J. Kluge, Th. Otto, G. Savard, L. Schweikhard, G. Audi and R.B. Moore, *Phys. Rev. Lett.* 65 (1990) 3104
- [13] M. V. Hynes, *Phys. Scripta* T22 (1988) 195
- [14] M. Lindinger, St. Becker, G. Bollen, K. Dasgupta, R. Jertz, H.-J. Kluge L. Schweikhard, M. Vogel and K. Lützenkirchen, *Z. Physik* D20 (1991) 441
- [15] R. Jertz, G. Bollen, H.-J. Kluge, L. Schweikhard, H. Stolzenberg, I. Bergström, C. Carlberg and R. Schuch, *Z. Physik* D (in print)
- [16] H.F. Beyer, G. Bollen, F. Bosch, P. Egelhof, B. Franzke, R.W. Hasse, H.-J. Kluge, G. Kozhuharov, T. Kühl, D. Liesen, R. Mann, P.H. Mokler, A. Müller, R.W. Müller, G. Münzenberg, H. Poth, L. Schweikhard, R. Schuch and G. Werth, (GSI, Darmstadt) GSI-90-20 Report (1990)
- [17] Proc. of the "Workshop and Symposium on the Physics of Low-Energy Stored and Trapped Particles", Stockholm, Sweden 1987, *Phys. Scrip.* T22 (1988)
- [18] Proc. of the "Workshop on Physics with Penning Traps", Lertorpet, Sweden 1991, *Phys. Scrip.* (in preparation)
- [19] P.E. Toscheck, *New Trends in Atomic Physics* (eds. G. Grynberg and R. Stora) Les Houches XXXVIII (North-Holland, Amsterdam, 1984) p. 381
- [20] D.J. Wineland, W.M. Itano and R.S. Van Dyck, *Adv. At. Mol. Phys.* 19 (1984) 135
- [21] L.S. Brown and G. Gabrielse, *Rev. Mod. Phys.* 58 (1986) 233
- [22] R.C. Thompson, *Meas. Sci. Technol.* 1 (1990) 93
- [23] G. Bollen, R.B. Moore, G. Savard and H. Stolzenberg, *J. Appl. Phys.* 68 (1990) 4355
- [24] H.G. Dehmelt, *Adv. At. Mol. Phys.* 3 (1967) 53 and 5 (1969) 109, *Rev. Mod. Phys.* 62 (1990) 525
- [25] J.J. Bollinger, D.J. Heinzen, W.M. Itano, S.L. Gilbert and D.J. Wineland, *IEEE Trans. Instr. and Measur.*, 40 (1991) 126
- [26] M.H. Holzscheiter, *Phys. Scrip.* T22 (1988) 73
- [27] F. Diedrich, J.C. Bergquist, W.M. Itano and D.J. Wineland, *Phys. Rev. Lett.* 62 (1989) 403
- [28] G. Savard, St. Becker, G. Bollen, H.-J. Kluge, R.B. Moore, Th. Otto, L. Schweikhard, H. Stolzenberg and U. Wiess, *Phys. Lett.* A158 (1991) 247
- [29] G. Gräff, H. Kalinowsky and J. Traut, *Z. Phys.* A297 (1980) 35

- [30] R.S. Van Dyck, F.L. Moore, D.L. Farnham and P.B. Swinberg, *Phys. Rev. A* 40 (1989) 6308 and references therein
- [31] R.S. Van Dyck, Jr. D.L. Farnham and P.B. Schwinberg, submitted to *J. Mod. Optics* (1991)
- [32] M.B. Comisarow and A.G. Mashall, *J. Chem. Phys.* 62 (1975) 293
- [33] A.G. Marshall and P.B. Grosshans, *Anal. Chem.* 63 (1991) 215A
- [34] M. Alleman, H. Kellerhals and K.P. Wanczek, *Int. J. Mass Spectrom. Ion Processes* 46 (1983) 139
- [35] St. Becker, G. Bollen, F. Kern, H.-J. Kluge, R.B. Moore, G. Savard, L. Schweikhard and H. Stolzenberg, *Int. J. Mass. Spec. Ion Proc.* 99 (1990) 53
- [36] A. Audi, A. Coc, M. Epherre-Rey-Campagnolle, G. Le Scornet, C. Thibault, and F. Touchard, *Nucl. Phys.*, A449 (1986) 491
- [37] D.J. Viera et al. *Phys. Rev. Lett.* 57 (1986) 3253
- [38] A. Gillibert et al. *Phys. Lett.* B176 (1986) 317
- [39] B. Franzke, *Nucl. Instr. Methods* B24 (1987) 18
- [40] Y. Fujita et al., *Proc. 11th Int. Mass Spectrom. Conf.*, Bourdeaux, ed. P. Longevialle (Heyden, London 1989) Vol 11a, p. 640
- [41] E. Kugler, H. Haas, A. Przewloka, H.L. Ravn, D.J. Simon and K. Zimmer, submitted to *Nucl. Instrum. Meth.*
- [42] *Proceedings "Antimatter '87"*, Karlsruhe 1987, *Hyp. Int.* 44 (1988)
- [43] B.N. Taylor, *IEEE Trans. Instrum. Meas.* 40 (1991) 86
- [44] R.E. Marrs in Ref. [18]
- [45] M.A. Levine et al., *Nucl. Instrum. Meth.* B43 (1989) 431

Table 1: Isotopes for which cyclotron resonances have been determined with the Penning trap mass spectrometer. The stable isotopes ^{39}K , ^{85}Rb , ^{87}Rb , ^{133}Cs have been used for the calibration of the magnetic field.

Isotope	Mass Number
K	39
Rb	75, 76, 77, 78, 78m, 79, 80, 81, 82m, 83, 84, 84m, 85, 86, 87
Sr	78 79 80, 81, 82, 83, 87
Cs	118, 119, 120, 121, 122+122m, 122m 123, 124, 125, 126, 127 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140
Ba	124 126 138, 139, 140, 141, 142, 143, 144
Fr	209, 210, 211, 212, 221, 222
Ra	226, 230

Figure Captions

- Fig. 1: Quadrupole ion trap. A dc voltage V is applied between ring electrode and endcap electrodes for axial confinement of the ions. A homogeneous magnetic field in the direction of the symmetry axis (z -direction) serves for radial confinement in the case of a Penning trap and a radio frequency quadrupole field in the case of the Paul trap.
- Fig. 2: Runge-Kutta integration of the equation of motion in a plane perpendicular to the magnetic field for an ion in a Penning trap. A damping force proportional to velocity is taken into account which models the collisions with He buffer gas. The cross represents the center of the trap, the circle the initial magnetron radius. Top: A fast damping of the cyclotron motion and a slow increase of the magnetron motion are observed. Bottom: The effect of an additional quadrupole field resonant at ω_c is shown. Both cyclotron and magnetron radii are decreased.
- Fig. 3: Experimental set-up of the tandem Penning trap mass spectrometer at the ISOLDE on-line mass separator.
- Fig. 4: Cross-sectional view of the high-precision Penning trap (trap #2) used in the ISOLDE tandem mass spectrometer.
- Fig. 5: Cyclotron resonance of ^{120}Cs ($T_{1/2} = 64 \text{ s}$) with a resolving power of 1.5 million.
- Fig. 6: Cyclotron resonances and nuclear level scheme for ^{84}Rb and $^{84\text{m}}\text{Rb}$. The mass difference determined to be 463(7) keV is in full agreement with the known energy of the isomeric transition.
- Fig. 7: Mass data of Cs isotopes. The zero lines are the result of an adjustment of all mass data available. The deviations from the adjusted values are plotted for the available Q_β and reaction data (top), for the results obtained by a Mattauch-Herzog mass spectrometer (middle), and for the data obtained by the Penning trap mass spectrometer with ^{133}Cs as reference isotope (bottom).

Fig. 1

Fig. 2

Fig. 4

Fig. 5

Fig. 6

Fig. 7