REVIEW

High-accuracy Penning trap mass measurements with stored and cooled exotic ions

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Received 11 January 2009, in final form 12 January 2009
Published 15 July 2009
Online at stacks.iop.org/JPhysB/42/154015

Abstract

The technique of Penning trap mass spectrometry is briefly reviewed particularly in view of precision experiments on unstable nuclei, performed at different facilities worldwide. Selected examples of recent results emphasize the importance of high-precision mass measurements in various fields of physics.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The mass is a unique, fundamental property of an atom. Mass values provide access to nuclear and atomic binding energies, serve for comparison with nuclear models as well as for test of fundamental interactions such as quantum electrodynamics or weak interaction [1–4]. The required precision depends on the problem: while for particle identification in physics and chemistry a relative mass uncertainty $\delta m/m < 10^{-5}$ is sufficient, tests of bound-state quantum electrodynamics in heavy ions require $\delta m/m < 10^{-11}$. Table 1 gives examples of the required mass uncertainty for different applications.

In the history of mass spectrometry, the precision of atomic mass determination has shown a constant improvement of about an order of magnitude every decade [5]. Figure 1 shows as an example the decreasing uncertainty of the mass of $^{28}$Si in time using various techniques. The introduction of devices that employed frequency measurements in the 1950s [6], in particular the introduction of Penning traps in the 1980s, was a breakthrough in mass spectrometry which lead to a dramatic decrease in the mass uncertainty.

In this review, we will focus on mass determinations of exotic ions, such as short-lived radionuclides, and highly charged ions. We will briefly introduce the technique of Penning traps, describe the basic features of facilities for mass determinations of radionuclides and discuss some of the applications of precise mass determinations.

2. Principle of Penning trap mass spectrometry

Mass determination in Penning traps relies on the fact that the ratio of cyclotron frequencies $v_c = qeB/(2\pi m)$ for two ion species in the same magnetic field $B$ gives directly their mass ratio:

$$\frac{v_c(1)}{v_c(2)} = \frac{q(1)}{q(2)} \cdot \frac{m(2)}{m(1)},$$

where $q$ and $m$ are the charge state and mass, respectively, of each ion. If $^{12}$C as an atomic mass standard is taken as a reference, the mass of the unknown species is obtained in atomic mass units [7]. The ions are confined for extended periods of time in a small volume in space by a strong magnetic field and a weak electric quadrupole potential created by hyperbolically shaped electrodes (figure 2(a)) of the Penning trap. Alternatively cylindrical electrodes may be used (figure 2(b)) which are easier to manufacture and to align. Near the centre of the cylindrical trap, the potential can be well approximated by a quadrupole potential. Higher order contributions can be partially reduced by guard electrodes placed between the central ring and the outer endcap electrodes.
Figure 1. Decrease of mass uncertainties in time for $^{28}\text{Si}$ using various techniques [5].

![Graph showing decrease of mass uncertainties in time for $^{28}\text{Si}$](image)

Figure 2. (a) Hyperbolical and (b) cylindrical Penning traps.

![Penning traps diagram](image)

Table 1. Some applications of mass determinations and typically required relative mass uncertainty $\delta m/m$.

| Application of mass determination                     | $\delta m/m$ |
|-------------------------------------------------------|--------------|
| Identification of atoms and molecules                 | $< 10^{-5}$  |
| Nuclear structure                                     | $< 10^{-6}$  |
| Astrophysics                                          | $< 10^{-6}$  |
| Weak interaction studies                              | $< 10^{-8}$  |
| Metrology-fundamental constants                       | $< 10^{-9}$  |
| QED in highly charged ions                            | $< 10^{-11}$ |

[8] The quadrupole potential is given by

$$\Phi = \frac{V}{d^2}(\rho^2 - 2z^2),$$

where $\rho^2 = x^2 + y^2$ and $2d^2 = z_0^2 + \rho_0^2/2$ describe the dimensions of the trap (with $2\rho_0$ and $2z_0$ being the inner ring diameter and the closest distance between the endcap electrodes, respectively; see figure 2). $V$ is the applied potential difference between the ring and endcaps. A single particle of charge $q$ and mass $m$ oscillates in the axial direction with frequency

$$v_z = \frac{1}{2\pi} \sqrt{\frac{qV}{md^2}}.$$  

(3)

In the radial direction, we have a superposition of two motions with frequencies

$$v_+ = \frac{v_c}{2} + \left(\frac{v_c^2}{4} - \frac{v_z^2}{2}\right)^{1/2},$$

(4)

and

$$v_- = \frac{v_c}{2} - \left(\frac{v_c^2}{4} - \frac{v_z^2}{2}\right)^{1/2},$$

(5)

where $v_+$ is called the reduced cyclotron frequency and $v_-$ is the magnetron frequency. Typically $v_+$ is in the MHz range, $v_-$ is a few kHz and $v_z$ is several 10 kHz. The superposition of these three eigenfrequencies leads to a motion as illustrated in figure 3. For more details on the principles of Penning traps, see [9, 10]. The cyclotron frequency as required for mass determination is not an eigenfrequency of the particles’ motion. It can, however, be obtained by the sum of $v_+$ and $v_-$. Deviations of the potential from the ideal quadrupole shape shift the eigenfrequencies and may lead to errors in mass determination. Brown and Gabrielse have shown that the relation

$$v_c^2 = v_+^2 + v_-^2 + v_z^2,$$

(6)

known as the Brown–Gabrielse invariance theorem, is independent of potential perturbations to first order [11, 12].

The detection of the motional frequencies can be performed in different ways. In the non-destructive detection technique, the particle remains in the trap and does not get lost in the detection process. Repeated measurements can be carried out with relatively long observation times by picking up the voltage induced in the trap electrodes by the oscillating charged particles employing sensitive electronics with a very high quality factor $Q$. A Fourier transform of the induced voltage reveals the motional frequency. Another advantage of this
method is that, thanks to its high sensitivity, it requires a very small number of simultaneously stored ions. Measurements on single particles have been demonstrated which eliminate potential frequency shifts arising from the Coulomb field of simultaneously confined ions. The trapped ion can be cooled to low energies by keeping its oscillation in resonance with a tank circuit attached to the trap and kept at liquid helium temperature (resistive cooling). Then the oscillation amplitude is of the order of a few microns and residual potential imperfections or magnetic field inhomogeneities seen by the ion play only a very small role. In fact, the highest precision in mass spectrometry has been obtained using this technique [13–17].

Because of the time required to cool the trapped ions and to accumulate sufficient signal strength (transients) for a good signal-to-noise ratio in the Fourier spectrometer, this non-destructive detection method is not suited for investigation of very short-lived radionuclides with half-lives below 1 s [18]. Instead, a destructive detection method for detecting the cyclotron resonance has been developed [19] and is known as the time-of-flight ion-cyclotron-resonance technique (ToF-ICR). The ToF-ICR is a destructive technique in the sense that the trapped ion is lost in the detection process and the trap has to be reloaded in each cycle. The technique involves manipulating the ions’ eigenmotions and probing the cyclotron frequency using an external radiofrequency field and measuring the flight time of the ions ejected from the trap to a detector. Since we focus on experiments with unstable nuclei, we shall describe this technique in more detail. The ion motion can be manipulated by external radiofrequency fields. With dipolar excitation (see figure 4(a)) typically the amplitude of an eigenmotion is enhanced, while quadrupolar fields (see figure 4(b)) are used to couple two eigenmotions. Within the ToF-ICR technique, the trapped ions are first prepared by a phase-locked dipolar excitation to a defined radius of the magnetron motion [20]. At this stage, the orbital magnetic moment $\mu$ and the corresponding energy $E = \mu B$ are small. By applying a resonant quadrupolar radiofrequency excitation signal with properly chosen amplitude and duration on the segmented ring electrode, the radial motions couple and the magnetron motion is completely converted into the modified cyclotron motion leading to a large increase in radial energy. The excited ions are ejected from the trap towards an ion counting detector (see figure 5). While travelling through the fringe field of the magnet, the ions get accelerated due to the gradient force:

$$\vec{F} = -\vec{\mu}(\nabla \vec{B}) = -\frac{E_r}{B} \frac{\partial B}{\partial z} \hat{z}. \quad (7)$$

The force is proportional to the orbital magnetic moment and thus to the radial energy $E_r$. The magnetic moment and the radial energy of the ions are the largest at resonance, when the frequency of the exciting field equals the true cyclotron frequency ($\nu_c$) which leads to a reduction in the time of flight from the trap to the detector. The total time of flight from the trap centre ($z = 0$) to the detector ($z = z_1$) for a given radial energy $E_r$ is given by

$$T_{\text{tot}}(\omega_q) = \int_0^{z_1} \sqrt{\frac{m}{2(E_0 - qU(z) - \mu(\omega_q)B(z))}} \, dz, \quad (8)$$

where $\omega_q$ is the frequency of the exciting field, $E_0$ denotes the initial axial energy and $U(z)$ and $B(z)$ the electric and magnetic potential differences, respectively.

When the exciting quadrupolar field is applied with constant amplitude $U_q$ for a fixed time interval $T_{rf}$, the resulting energy gain $E_r$ is [21]
Figure 6. Calculated conversion of a pure magnetron motion into a pure cyclotron motion by a radial quadrupolar rf field at frequency \( v_+ = v_+ + v_- \). The time for one full conversion is \( T_c \). Parts (a) and (b) show the first and second halves of the conversion, respectively.

\[
E_r = \frac{\sin^2(\omega_b T_{rf})}{\omega_b^2} \tag{9}
\]

with

\[
\omega_b = \frac{1}{2} \sqrt{(\omega_{rf} - \omega_c)^2 + (\omega_{conv}/2)^2}. \tag{10}
\]

The conversion frequency \( \omega_{conv} \) is given by

\[
\omega_{conv} = \frac{U_q}{r_0^2} \cdot \frac{1}{4B}. \tag{11}
\]

where \( U_q \) corresponds to the maximum potential of the quadrupole radiofrequency field measured on a circle with radius \( r_0 \). Hence, the effect of the coupling is a periodic conversion of the perturbed cyclotron and the magnetron oscillations [21] as shown in figure 6.

In the ToF-ICR technique the energy gain is directly transformed into a change in time of flight, and for optimum energy conversion into the cyclotron motion a minimum in flight time is observed at the frequency of the unperturbed cyclotron frequency. Upon variation of the coupling frequency a resonance line is obtained whose shape can be calculated [21], as shown in figure 7. The full width at half-minimum is given by \( \Delta v_{1/2} = 1/T_{rf} \).

3. Experimental facilities

A number of trap experiments worldwide, as shown in figure 8, have been constructed or are planned to determine masses of exotic species, i.e. short-lived radionuclides or highly charged ions. These experiments to a large degree are complementary; they differ mainly by the way the ions are produced and transported to the trap at the corresponding facilities [22, 23]. Some of them are designed to work with extremely short-lived isotopes. For example, at the TITAN experiment at TRIUMF recently a measurement was carried out on \(^{11}\)Li with a half-life of \( t_{1/2} = 8.8 \) ms, so far the shortest lived nuclide for which a mass measurement has ever been performed with a Penning trap [24]. The SHIPTRAP experiment at GSI is dedicated to high-precision mass measurements of trans-uranium elements and rare isotopes produced in fusion-evaporation reactions where the so far heaviest element, \(^{254}\)No, has been measured in a Penning trap [25]. The LEBIT experiment at NSCL/MSU exploits short-lived rare isotopes produced by fast-beam fragmentation [26]. JYFLTRAP at the IGISOL facility of the University of Jyväskylä focuses on exotic radioactive ion beams of refractory elements, neutron-rich nuclides and super-allowed beta emitters [27]. The CPT mass spectrometer investigates neutron-deficient nuclei produced in fusion-evaporation reactions using beams from the Argonne Tandem Linear Accelerator System (ATLAS) [28]. The recently commissioned TRIGA-TRAP
experiment at the research reactor TRIGA Mainz will perform high-precision mass measurements on thermal neutron-induced fission products, exotic neutron-rich nuclides and actinides [29]. Highly charged ions are used in some facilities, e.g. SMILETRAP in Stockholm, where the so far highest charge state measured was $^{204}$Hg $^{52+}$ [30]. Using highly charged ions increases the precision of the mass determination since the cyclotron frequency scales linearly with the charge state, whereas the full width of the resonance line is determined only by the duration of the excitation $T_{rf}$.

Historically, the first one of these on-line facilities is ISOLTRAP at ISOLDE/CERN, which was initiated more than two decades ago [31, 32] and reaches relative mass uncertainties of $\delta m/m < 10^{-8}$ [33]. It has produced a vast number of results on unstable isotopes and may serve as a typical example for a Penning trap mass spectrometer experiment; thus, we shall briefly describe its main features. Figure 9 shows the general layout of the ISOLDE facility. The unstable nuclides are produced by nuclear spallation, fission or fragmentation reactions induced by 1.4 GeV protons arriving at the target station of either the general purpose separator (GPS) with a mass resolving power of $m/\Delta m \approx 1000$ or at the high resolution separator (HRS) with $m/\Delta m \approx 5000$ [34]. After diffusion the radionuclides are ionized by surface ionization, plasma discharge or resonant laser ionization, depending on the species of interest. The beam is then guided at 30–60 keV to a linear radiofrequency quadrupole (RFQ) trap filled with buffer gas [35]. It acts to bunch and cool the incoming continuous high energy beam by collisions with the buffer gas. After a time of several ms, a bunch of ions is extracted. These bunches can be efficiently transported and captured in the first cylindrical Penning trap (preparation trap in figure 10), where mass-selective buffer gas cooling is performed. This involves that the magnetron radius of all ion species regardless of their mass is increased to a larger diameter than the size of the exit aperture of the trap by a dipolar excitation at the magnetron frequency. A mass selective quadrupolar excitation on the cyclotron frequency centres the ion of interest in the presence of the buffer gas. This leads to ion purification since only the centred ions of reduced radius can leave the trap while other ions with large magnetron radius are held back. The mass resolution of this purification step is about $10^5$. Finally, the ions are re-captured in the second trap (precision trap in figure 10), where the mass measurement takes place. The cyclotron resonance is detected by the time-of-flight technique described previously. The mass resolution depends on the excitation time and is typically of the order of $10^6$–$10^7$, allowing us to resolve even low-lying isomeric states [36–38]. Alternating with the ions of interest, stable reference ions such as alkaline ions from a surface ion source or carbon cluster ions produced by laser ablation from a carbon pellet are loaded into
4. Selected applications

Here we present a number of examples which emphasize that high precision mass measurements contribute significantly to various fields of physics.

4.1. Nuclear structure studies and test of the isobaric-multiplet mass equation

The mass of a nucleus is less than the sum of the masses of the individual protons and neutrons. The difference between the sum of the masses of \( Z \) protons \( Zm_p \) and \( N \) neutrons \( Nm_n \) and the measured mass of the bound system \( m \) is the nuclear binding energy \( B \):

\[
B(N, Z) = (Zm_p + Nm_n - m(Z, N))c^2.
\]  

It depends on details of the nuclear composition. Mass measurements with fractional uncertainties below \( 10^{-6} \) allow discussing the hills and valleys of the binding energy appearing across the nuclear chart in view of nuclear models [2, 41–45].

As a specific case, we take the case of light nuclei with isobaric analogue states. They have nearly identical wavefunctions and the charge-dependent energy difference of these states can be calculated by first-order perturbation theory assuming only two-body Coulomb interaction. This leads to the isobaric-multiplet mass equation (IMME) which gives the mass \( m \) of a member of an isospin multiplet as a function of the isospin \( z \)-component \( T_z = (N - Z)/2 \) [46, 47]:

\[
M = a + bT_z + cT_z^2.
\]  

It is generally assumed that the quadratic term in this equation is adequate. The so far most stringent tests of this assumption have been performed at ISOLTRAP using mass measurements on \(^{32}\text{Ar} \) (\( T_1/2 = 98 \) ms), \(^{33}\text{Ar} \) (\( T_1/2 = 173 \) ms), \(^{35}\text{K} \) (\( T_1/2 = 178 \) ms) and \(^{36}\text{K} \) (\( T_1/2 = 342 \) ms) with fractional uncertainties of a few parts in \( 10^{-8} \) together with mass excess values of the other states of the \( T = 2 \) quintet in \( A = 32 \) and \( A = 36 \) and the \( T = 3/2 \) quartet in \( A = 33 \) and \( A = 35 \), respectively [48, 49]. An assumed cubic \( dT_z^3 \) term in equation (13) was found to be consistent with zero within the error bars for three out of four cases, as shown in figure 11. Only for the \( A = 35, T = 3/2 \) case was a non-zero \( d \) coefficient of \(-3.2(1.1) \) keV found, for which the reason is still unclear [49].

4.2. Nuclear astrophysics studies

One of the problems in nuclear astrophysics is a detailed understanding of the formation of matter in stars. Three main scenarios are presently considered as follows. Slow neutron capture (s-process) is responsible for the creation of nuclei close to the valley of stability. Rapid neutron capture (r-process) causes the formation of heavy nuclei such as uranium and thorium. Finally, rapid proton capture (rp-process) creates nuclei close to the proton drip line. The s-process is believed to be well understood, primarily because the masses and the lifetimes of the involved nuclei are well
known. Concerning the rp-process (or the recently discussed vp-process) many masses of interest have already been addressed; see e.g. [50–52]. However, many open questions appear in our understanding of the r-process since masses of isotopes containing about 30 neutrons more than in the heaviest measured isotope of the same element are unknown. Presently, these masses are not accessible to Penning trap mass measurements by existing radioactive beam facilities. Therefore, nuclear astrophysics relies on nuclear mass models and predictions. Improvement of the models and the reliability of the predictions require the measurement of masses as far away from the stable area as possible. Most important is the region where the r-process comes closest to stability. This is the case in the vicinity of magic neutron numbers. Crucial candidates are, e.g., $^{78}$Ni, $^{80}$Zn, $^{132}$Sn and $^{208}$Pb. Two recent experiments at ISOLDE have determined the masses of $^{80,81}$Zn [53] and $^{132,134}$Sn [54], respectively, with uncertainties of $10^{-7}$ and below and represent cornerstones in our understanding of the r-process.

4.3. $^3$H–$^3$He mass difference

The $\beta$-decay of $^3$H

$$^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}$$  \hspace{1cm} (14)

is used for attempts to determine the mass of the electron (anti)neutrino. Due to a low mass difference, i.e. Q-value, and a relatively short half-life ($t_{1/2} = 12.32$ years), the $^3$H decay reaction is rather advantageous. Such an experiment involves the measurement of the decay spectrum of tritium at the highest energies near the endpoint energy, which is given by the mass difference between $^3$H and $^3$He. A finite neutrino mass would change the shape of the spectrum. The spectrum has been measured and presently the upper limit of the electron neutrino mass is $m_{\nu_e} < 2$ eV/$c^2$ at 95% C.L. [55].

The $^3$H–$^3$He mass difference is an input parameter in the fitting process of the decay spectrum. It has already been determined in a Penning trap in 1993 [56], and today’s best value recently measured at SMILETRAP is 18589.8 (1.2) eV [57]. A new $\beta$-spectroscopy experiment, KATRIN, is presently being set up at Forschungszentrum Karlsruhe, Germany, and aims at lowering the $m^2(\nu_e)$ uncertainty by another factor of 100, thus reaching a sensitivity limit $m_{\nu_e} < 0.2$ eV/$c^2$ [55, 58]. Consequently, measurements of the $^3$H and $^3$He masses to below $10^{-11}$ are necessary to match the requirement of the KATRIN experiment. Efforts in this direction are pursued at MPI-K Heidelberg in collaboration with University of Washington, Seattle.

4.4. Bound-state QED tests

The g-factor of the electron bound in simple atomic systems can be calculated in the frame of bound-state quantum electrodynamics (BS-QED). A comparison of experimental and theoretical values represents a stringent test of the calculations [59]. Experiments have been performed on hydrogen-like $^{12}$C$^5+$ [60] and $^{16}$O$^7+$ [61]. In a Penning trap, the electrons’ spin precession frequency $\omega_L = g(ge/2m_e)B$ as well as the ions’ cyclotron frequency $\omega_c = (ge/m)B$ have been measured to about $10^{-9}$. The g-factor follows as

$$g = \frac{\omega_L}{\omega_c} \cdot \frac{m_e}{m}.$$  \hspace{1cm} (15)

Obviously, the value of the ion mass $m$ is required to be of the same precision as the frequencies for g-factor determination. This is the case for carbon and oxygen. The BS-QED contributions scale approximately with the square of the nuclear charge $Z$ for hydrogen-like ions. Experiments on systems with higher $Z$ would therefore allow testing the BS-QED part to a higher degree [62]. Experiments on Ca$^{19+}$ are under way [63] and higher-$Z$ ions are considered in the near future at the GSI-HITRAP facility [64]. The corresponding masses need to be determined accurately. In the case of $^{40}$Ca for example, this has already been performed at SMILETRAP with an uncertainty of $6 \times 10^{-10}$ [65].

4.5. Fundamental constants

Precise mass measurements provide possibilities of improving the value of some fundamental constants or of finding alternative ways of their determination. One of these constants is the electron mass. It was determined several years ago by the comparison of the cyclotron frequencies of electrons and carbon ions which serve as a mass reference [66]. Recently, an alternative method has led to a somewhat more precise value: the g-factor of the electron bound in hydrogen-like ions has been determined on $^{12}$C$^5+$ [60] and $^{16}$O$^7+$ [61] as mentioned above. The theory of bound-state quantum electrodynamics allows us to calculate the g-factor to high precision [67]. If we take the calculated value for $g$ as granted, we obtain with the measured frequencies $\omega_L$ and $\omega_c$ from equation (15) a value for the electron/ion mass ratio. Since the masses of carbon and oxygen are known with high precision, a value for the electron mass follows. The combined value from both
experiments is $m = 0.0055487599093(3)$ u [68]. This may be improved in the near future when experiments on low-Z H-like ions are performed [59]. Here, the BS-QED contributions as well as other corrections from nuclear structure are small and their uncertainty will not contribute significantly to the theoretical $g$-factor. Potential candidates might be $^{12}_{8}M_{e}^{+}$ [10]. Their masses have been determined by the SMILETRAP Penning trap mass spectrometer with relative uncertainties of $\delta m/m = 10^{-9}$ [69].

Another important quantity is the fine structure constant $\alpha$ which defines the strength of the electromagnetic interaction. Its most precise value comes from a comparison of the experimental and theoretical values of the free electrons’ $g$-factor [70]: $\alpha^{-1} = 137.035999084(51)$ (0.37 ppb). Since it relies on very difficult and complex calculations, it would be desirable to obtain a value for $\alpha$ independent of QED theory. A possible way represents a combination of different quantities which can be determined independently [71]:

$$\alpha^{-1} = \frac{2R_{\infty}}{c} \cdot \frac{h}{m_{e}c} \cdot \frac{m_{Cs}}{m_{p}} \cdot \frac{m_{p}}{m_{e}}.$$ (16)

The Rydberg constant $R_{\infty}$ is known to be $6.6 \times 10^{-12}$ [72]; $h/m_{e}$ has been determined by photon recoil to $7.3 \times 10^{-9}$ [73]. The last part in equation (16) relates to measurements of mass ratios $m_{Cs}/m_{p}$ and $m_{p}/m_{e}$. Future improvements of all quantities appearing in equation (16) may lead to an independent determination of $\alpha$ with somewhat comparable accuracy as the QED-related value [74–76].

4.6. Neutrino-less double $\beta$-decay

In double $\beta$-decay ($\beta\beta$) processes, two electrons are emitted from a nucleus and the charge increases by 2. While the simultaneous emission of two neutrinos is an allowed second-order process of weak interaction, neutrinoless double $\beta$-decay can only occur if neutrinos are massive Majorana particles [77]. It would represent a violation of the classical standard model. In order to set a limit on the neutrinoless decay mode, one needs to know the $Q$-values of the respective decays. The presently best-studied candidate is $^{76}$Ge. The $Q$-value for the double-$\beta$ decay has been determined by mass measurements of $^{76}$Ge and $^{76}$Se in a Penning trap with uncertainties below $10^{-9}$ [78]. The $Q$-value of 2039.006(50) deduced from this experiment deviates by several standard deviations from the value obtained from decay energy measurements [79]. This makes the report of an indication of an observed neutrinoless double $\beta$-decay in [79] and the deduction of a finite mass for the electron neutrino between 170 and 630 meV somewhat questionable. Other $Q$-values of double-beta decays that have been addressed recently by high-precision Penning trap mass spectrometry are those of $^{100}$Mo [80] and $^{136}$Xe [81].

Technical improvements are needed towards this goal. These include using new excitation schemes of the ion motion in the trap like Ramsey excitation [82–84] or octupolar excitation [85, 86], higher charge states by charge breeding processes [87–89], laser cooling of ions, sympathetic ion cooling by simultaneously trapped cold electrons [64] and trap operation at cryogenic temperatures [29, 90]. Some of these improvements are already implemented in operational facilities; others are being considered for new facilities under construction. The problem remains to get access to those isotopes whose production rate is too small for present mass spectrometers. New facilities coming up such as EURISOL/France, FAIR/Germany, FRIB/USA and RIKEN/Japan will use improved techniques for ion sources, synchrotrons, fragment separators and storage rings, respectively, in order to enhance the intensity of radioactive beams by several orders of magnitude. This will substantially widen the range of accessible nuclides and will allow future experiments of fundamental interest.

Acknowledgments

Financial support by the German Federal Ministry for Education and Research (BMBF) under contract 06MZZ215 and by the Helmholtz Association for National Research Centers (HGF) under contract VH-NG-037 is acknowledged. Sz Nagy acknowledges the support of the Alliance Program of the Helmholtz Association.

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