High-precision mass measurements for fundamental applications using highly-charged ions with SMILETRAP

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Abstract. The Penning trap mass spectrometer SMILETRAP takes advantage of highly-charged ions for high-accuracy mass measurements. In this paper recent mass measurements on Li and Ca ions are presented and their impact on fundamental applications discussed, especially the need for accurate mass values of hydrogen-like and lithium-like ions in the evaluation of the electron $g$-factor measurements in highly-charged ions is emphasized. Such experiments aim to test bound state quantum electrodynamics. Here the ionic mass is a key ingredient, which can be the limiting factor for the final precision.

1. Introduction

A fundamental property of an atomic system is its mass, which is due to the relation to the nuclear and atomic binding energies, a carrier of unique information, similar to the fingerprint of a human. High-precision atomic masses have a wide range of applications in modern physics, which include the determination of fundamental constants, verification of nuclear models, test of the Standard Model, metrology and many more [1]. They can also be used for testing atomic structure calculations and determining electron binding energies in order to detect QED effects directly [2]. The leading devices in the field of high-accuracy mass spectrometry are the Penning trap mass spectrometers [1], mainly due to the fact, that they provide long observation times and the dynamics of the ion motion in the combined electric and magnetic fields of a Penning trap are well understood [3]. Nowadays, atomic masses can be measured in Penning traps to a precision of $\delta m/m = 1 \times 10^{-11}$ in the case of certain stable isotopes [4, 5], and to better than $1 \times 10^{-8}$ in the case of short-lived radionuclides even with half-lives well below 1 s [6].

Different types of Penning trap mass spectrometers are installed worldwide, serving different fields of physics [1]. Common to all of them is that the mass measurement is turned into a frequency comparison, employing well-established frequency measurement techniques like the non-destructive Fourier-Transform Ion-Cyclotron-Resonance (FT-ICR) [7, 8] or the time-of-flight cyclotron resonance (TOF-ICR) detection method [9, 10]. Since the mass dependent true cyclotron frequency $\nu_c = qB/(2\pi m)$ is directly detectable in a Penning trap, with $q/m$
being the charge-to-mass ratio, this simple formula is the principle of mass measurements at SMILETRAP [11], which is specialized for mass measurements using highly-charged ions [12] with high resolving power \( \nu_c/\Delta \nu_c = 10^8 \). The resonance width \( \Delta \nu \) is inverse proportional to the observation time \( \Delta \nu = 1/T_{rf} \). Thus, by using e.g. 10+ ions instead of singly charged ions, an order of magnitude can be gained in the precision of the ion’s mass. In order to calibrate the magnetic field \( B \), the frequency of a reference ion with well-known mass is measured almost simultaneously and the mass of the ion of interest is obtained from the ratio of these two frequencies:

\[
m_{ion} = \frac{\nu_{ref}}{\nu_{ion}} \frac{q_{ion}}{q_{ref}} m_{ref}.
\]  

(1)

To deduce the mass of the neutral atom one has to add the mass \( q_{ion}m_e \) of the missing electrons and their total atomic binding energies \( E \):

\[
m_{atom} = m_{ion} + q_{ion}m_e - E.
\]

In this paper, the emphasis is on ionic masses \( (m_{ion}) \), which are a necessary ingredient for the evaluation of the \( g \)-factor experiments of the electron bound in hydrogen-like and lithium-like ions [13]. The \( g \)-factor experiment has the objective to test and benchmark theoretical QED calculations [14]. The value of \( g \) can be obtained from:

\[
g = 2 \frac{\omega_L q m_e}{\omega_c e m_{ion}},
\]

(2)

where the spin precession (Larmor) frequency \( \omega_L \) and the true cyclotron frequency \( \omega_c \) can be precisely measured in the \( g \)-factor experiment [15], and \( m_e \) is the mass of the electron. The ionic mass \( m_{ion} \) is measured directly at SMILETRAP and thus there are no errors introduced by electron binding energy calculations as discussed in Ref. [2]. So far the hydrogen-like \( ^{12}\text{C}^{5+} \) [16] and \( ^{16}\text{O}^{7+} \) [17] are the heaviest ions used in the \( g \)-factor experiment. In both cases the ionic mass was accurately known, and the dominant contribution to the total uncertainty in \( g \) came from the uncertainty in the electron mass. From these measurements a new electron mass was extracted [18]. The present uncertainty in the electron mass is \( \delta m/m = 4.4 \times 10^{-10} \) [19]. The proposed new \( g \)-factor experiments involving medium heavy ions like \( ^{40}\text{Ca}^{17+},^{19+} \) [13] will benefit of the new high-precision electron mass \( m_e \), thus they require ion masses with similar uncertainties as the electron mass (see Eq. 2). If we consider the ratio of \( g \)-factors of hydrogen-like ions of different isotopes of the same element, the dependence on the electron mass can be eliminated, and nuclear contributions can be determined. An isotope effect in the \( g \)-factor \( \Delta g = g_1/g_2 - 1 \) can thus be introduced to characterize these contributions. It was shown in Ref. [20] that an isotope effect in the \( g \)-factor would be measurable already between \( ^{24}\text{Mg}^{11+} \) and \( ^{26}\text{Mg}^{11+} \), thanks to the high-precision mass values measured with SMILETRAP for both isotopes [20]. The size of the isotope effect in the \( g \)-factor, is expected to be even more pronounced in the case of \( ^{40}\text{Ca}^{19+} \) and \( ^{48}\text{Ca}^{19+} \) [2].

SMILETRAP is so far the only operating Penning trap mass spectrometer that was built to exploit the precision gain by using highly-charged ions. Other Penning trap mass spectrometers under construction, which are dedicated to highly-charged ions are HITRAP [21] at GSI, Darmstadt, TITAN [22] at TRIUMF, Vancouver, and MATS [1] in Mainz/Darmstadt.

2. Short description of the experimental setup

The experimental setup and the associated physics program has been reviewed in Ref. [11], therefore, only a short description will be given here.

The highly-charged ions for mass measurements at SMILETRAP are produced in an electron beam-ion source, CRYYSIS [23]. The well defined ionization time in this type of ion source leads to a narrow charge state distribution. The extracted short ion pulses have little energy spread (5-10 eV) and low emittance. These characteristics make this beam very well suited for a Penning trap mass spectrometer.
The proper ion charge state is selected by scanning the current of a 90° double focusing magnet, which also bends the beam vertically towards the trap setup. The \( q/m \) separated beam is captured and retarded to ground potential in a cylindrical Penning trap [24]. This preparation trap is placed inside an electromagnet with a field of 0.25 T. To stop the ion pulses coming from CRYYSIS, the entire preparation trap is floated on a high potential equal with the extraction potential of CRYYSIS.

The most important part of the mass spectrometer is a hyperbolic Penning trap [25], placed inside a 4.7 T homogeneous \( B \)-field of a superconducting magnet.

Out of the few thousand ions ejected from the preparation trap typically about one hundred ions are captured in-flight in the precision trap. To remove the ions with high axial energy an evaporative cooling technique is used. This involves lowering the trapping potential from 5 V to a few mV by ramping up the potential of the central ring electrode of the precision trap. After the axially hottest ions have left the trap, the potential is restored. The process can be repeated until only 1–2 ions remain in the trap. They are then subject to an azimuthal quadrupolar radio-frequency excitation. During the excitation the magnetron and modified cyclotron motion couple, which leads to a gain in the radial energy. After ejection this energy gets converted into axial energy in the fringe field of the magnet [10]. The excitation frequency is scanned around the true cyclotron frequency, and after each excitation the ions are ejected from the trap towards the drift section, and the time of flight to a detector located 500 mm upstream of the trap center is recorded. Then ions are loaded again into the trap and the process is repeated. The resonance frequency \( \nu_c \) shows up as a well-pronounced minimum in the time-of-flight spectrum. A typical measurement with SMILETRAP for a single nuclide and charge state involves a few thousand scans corresponding to 20 000 or more ions of each species, requiring a data acquisition time from one day up to one week or longer.

3. Examples of mass measurements

2005 was an especially successful year in the history of SMILETRAP. The masses of \(^6\text{Li}\) and \(^7\text{Li}\) have been measured with a relative uncertainty of \(10^{-9}\) and an unexpected large deviation of 1.1\(\mu\)u, \(i.e.\) 14\(\sigma\), in the \(^7\text{Li}\) mass was uncovered, see Fig. 1 and Ref. [26].

We improved the \(Q\)-value of the tritium \(\beta\)-decay, based on mass measurements of \(^3\text{H}\)\(^{1+}\) and \(^3\text{He}\)\(^{1+}\). At present it is the most precise value with an uncertainty of only 1.2 eV [27].

The masses of \(^{40}\text{Ca}\)\(^{17+}\) and \(^{40}\text{Ca}\)\(^{19+}\) needed for the determination of the electron \(g\)-factor bound in these systems have been measured, see Fig. 1 and Ref. [28]. They serve as a test for bound state QED calculations [13].

![Figure 1](image-url)

**Figure 1.** Left: The atomic mass of \(^7\text{Li}\) compared to previous literature values. Right: The atomic mass of \(^{40}\text{Ca}\) derived from mass measurements of 17+ and 19+ ions, compared to the previous best literature value [29].
4. Conclusion and outlook

Smilettrap is the only Penning trap mass spectrometer where ions with charge states higher than 8+ were used for mass measurements. Ions in the mass range 1–200 u and charge states from 1–52+ have been successfully measured already, involving about 30 different nuclides. A relative mass uncertainty as low as a few parts in $10^{10}$ has been achieved in many cases.

To study even heavier masses and higher charge states, the Smilettrap facility will be connected to the new REBIT [30] ion source, which is already operating in the new physics building AlbaNova, just about 1 km from the present location, the Manne Siegbahn Laboratory. At the same time certain upgrades will be performed, e.g. a new cylindrical Penning trap for ion preparation and cooling will be installed. A precision gain by one order of magnitude can be expected since the cooled ions will allow to use longer observation times in combination with the application of the Ramsey-method for ion excitation [31].

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