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Mass-selective ion ejection from multi-reflection time-of-flight devices via a pulsed in-trap lift

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ABSTRACT

A method for high-resolution mass selection is presented which makes use of a multi-reflection time-of-flight mass spectrometer with in-trap lift. The new method needs no additional gating or deflection components. The concept is described in detail and demonstrated with both offline and online measurements on short-lived nuclides performed with ISOLTRAP at ISOLDE/CERN.

1. Introduction

Mass spectrometry in nuclear research [1–3] is hampered when contaminant ions are simultaneously delivered from the sources of the exotic nuclides of interest. As the contaminants are often isobars of the nuclides of interest, high mass resolving powers are needed. In addition, the ions of interest are mostly the very exotic and short-lived ones and their production yields can be as low as only a few ions per second, while at the same time the unwanted ion species – often long-lived or even stable nuclides – have a much higher abundance.

For many experiments these conditions lead to unpredictable high systematic shifts due to Coulomb interactions between the ions which can even make the measurements impossible [4]. Therefore, an efficient preparation of pure samples is extremely important.

This situation is encountered in precision Penning-trap mass spectrometry of radioactive species where relative uncertainties on the order of $\delta m/m = 10^{-8}$ or even better have been achieved. It allows to determine nuclear binding energies and thus to investigate various fundamental questions of, e.g., nuclear structure or nucleosynthesis [2]. If, however, the Penning traps are loaded not only with the ions of interest but also with additional contaminating species, this can lead to hardly controllable relative mass shifts on the order of 10^{-6} and more [4,5]. As the nuclear binding energies result from small differences between nuclear masses, their values suffer heavily from such mass shifts. Thus, it is of utmost importance to exclude sample contamination in these kinds of investigations.

Already 25 years ago, multi-reflection time-of-flight (MR-ToF) mass spectrometry has been introduced [6]. Recently, these ideas have been realized at the ISOLTRAP setup at ISOLDE/CERN [7], expanding the knowledge in nuclear structure and nuclear astrophysics by use of an MR-ToF device as a mass separator followed by Penning-trap mass spectrometry [8–10] as well as by making use of itself as a mass spectrometer [10–12]. Furthermore, it has proven very versatile as a high-resolution mass analyzer for target and ion-source developments [13], in-source ionization spectroscopy [14], and half-life measurements [15]. Furthermore, other facilities in the field of nuclear physics are using or planning to use an MR-ToF MS, see [16] and the references therein.

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In the following, we focus on the mass separation which is not only necessary for subsequent precision mass spectrometry by Penning traps but also for further investigations, such as nuclear decay studies [17].

Until recently, for the selection of separated isobaric ion species, MR-ToF devices have been combined with subsequent ion gates, most notably the Bradbury-Nielsen gate (BNG) [18–20]. In contrast, a new selection method is presented that does not rely on any such additional external device but makes use of an internal component of ISOLTRAP's MR-ToF section itself, namely its drift-tube electrode between the ion-optical mirrors. This electrode has been introduced as an "in-trap potential lift" to capture and eject ions [21]. The new selection method is based on the timing of the ejection pulse of this electrode to selectively address only the ions of interest. This technique has already been applied in several on-line experiments, e.g. during the studies reported in [10].

The next section gives a brief overview of the ISOLTRAP setup including its MR-ToF mass spectrometer/separator (MS). Section 3 reviews the in-trap lift technique and its performance for mass spectrometry. This is followed by the introduction and characterization of the new in-trap lift based selection method in Section 4. Finally, in Section 5 several examples of on-line applications illustrate its usefulness for the investigation of short-lived nuclides.

2. The ISOLTRAP experiment at ISOLDE/CERN

In the late 1980s precision mass spectrometry of short-lived nuclides was revolutionized with the installation of ISOLTRAP at the ISOLDE facility at CERN/Geneva, the first on-line Penning-trap system for this purpose [22–24]. Overviews of the ISOLTRAP setup and of its developments over the years can be found in Bollen et al. [25], Mukherjee et al. [26] and Kreim et al. [27]. Today, it comprises four ion-trapping components as schematically presented in Fig. 1.

(1) A linear radio-frequency quadrupole (RFQ) ion trap [28] for cooling and bunching the quasi-continuous ISOLDE ion beam of up to 60 keV. The ions are ejected in 3.2-keV pulses to the ISOLTRAP components downstream.
(2) The MR-ToF mass analyzer for mass measurements and beam purification as described in detail in the next section.
(3) The so-called preparation Penning trap [29,30] were mass-selective buffer-gas centering [31] is applied to prepare the ions for mass measurement in the precision Penning trap. This method is used to center and cool the ions of interest and, if necessary, to further purify them from contaminations with mass resolving powers on the order of $R = 1 \cdot 10^5$ within a few 100 ms [32]. Additionally, the preparation trap has been used to access nuclides that are not or only barely produced directly in the ISOLDE target, by use of in-trap decays, i.e. capturing the recoiling daughter nuclides from the corresponding beta-decaying precursor nuclides [33].
(4) The precision Penning trap for mass measurements of high accuracy. This is achieved by determination of the cyclotron frequency $\nu_c = qB/(2\pi m)$ of the ion of interest in a homogenous magnetic field B and comparing it to the cyclotron frequency of a reference ion with well-known mass. These measurements are based on the time-of-flight ion-cyclotron resonance (ToF-ICR]) technique [29,34,35] with single rf-pulse-type or Ramsey-type excitation patterns [36]. Excitation times of the ion motion from a few tens of milliseconds [9,37] up to several seconds have been applied, the latter resulting in resolving powers of well over $R = 10^6$ [38] and relative statistical uncertainties down to $\delta m/m = 10^{-8}$ [39]. Recently, the phase-imaging ion-cyclotron resonance (PI-ICR) method [40,41] has been implemented by which even higher resolving powers and lower mass uncertainties can be obtained. Furthermore, the precision Penning trap has provided isomerically pure ion bunches to a decay-station extension which can be mounted downstream as the last component of the setup [42,43].

The present study is focused on the MR-ToF mass analyzer. The insets of Fig. 1 show a cut view of a simplified CAD model of the

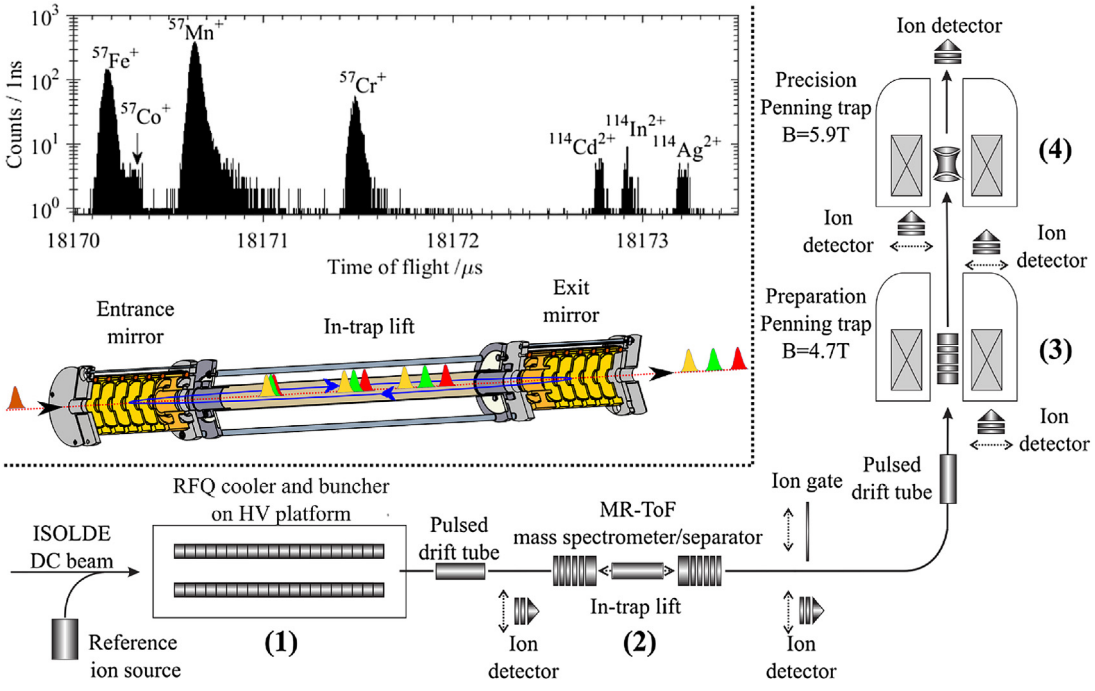

Fig. 1. Schematic overview of the ISOLTRAP setup. For more details, see text. **Lower inset:** The MR-ToF device composed of the electrostatic mirror electrodes and the in-trap lift. An ion bunch containing different ion species is injected and captured between the mirror electrodes. With increasing storage time the different ions species separate. **Upper inset:** Time-of-flight spectrum of $A/z = 57$ isobars after 1000 revolutions in the MR-ToF MS. A total of 30773 ion counts were accumulated in 2706 experimental cycles.