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A high-performance multiple-reflection time-of-flight mass spectrometer and isobar separator for the research with exotic nuclei

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ABSTRACT

A novel multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) and isobar separator for the research with exotic nuclides at low-energy rare isotope beam facilities has been developed, commissioned and characterized. It can be used (i) as broadband mass spectrometer with medium resolution, (ii) as highly accurate mass spectrometer for direct mass measurements and (iii) as high-resolution mass separator. The device features a worldwide unique combination of performance characteristics: a mass resolving power of 600,000 (FWHM), a mass measurement accuracy of $\sim 10^{-7}$, large ion capacities in excess of 10^6 ions per second, a transmission efficiency of up to 70%, single-ion sensitivity, and cycle frequencies of up to 400 Hz have been achieved. The spatial separation of close-lying isobars with an intensity ratio of 200:1 and a binding energy difference as small as 4 MeV have been demonstrated. The MR-TOF-MS is ideally suited for experiments with rare and very short-lived nuclei at present and future in-flight, ISOL or IGISOL facilities, such as the FRS Ion-Catcher and SHIP/SHIPTRAP at GSI, TITAN at TRIUMF, IGISOL at the University of Jyväskylä and the Low-Energy Branch of the Super-FRS at FAIR.

1. Introduction

In recent years much progress has been made in the research with exotic nuclei [1,2]. Experiments with exotic nuclei yield key information about nuclear structure and about the origin of the chemical elements in the universe. Further advances, such as closer access to nuclides along the nucleosynthesis pathways, will be achieved at next-generation accelerator facilities, which are presently under construction (such as the Facility for Antiproton and Ion Research FAIR in Darmstadt, Germany, SPIRAL2 at GANIL, France and the Facility for Rare Isotopes FRIB at Michigan State University, USA) or already in operation (RI-beam factory RIBF at RIKEN, Japan). It is difficult to produce very exotic nuclei in sufficient amounts and purity and to study their properties. Even existing facilities face serious challenges for experiments with exotic nuclei in the form of life time limitations caused by the cycle time of the experiments and the overwhelming amount of contaminants produced together with the nuclides of interest. These challenges will intensify at future facilities, as the primary beam intensities are increased and more exotic species can be produced.

A new approach to precision experiments with exotic nuclei is the production and in-flight separation of the nuclei and their subsequent slowing-down and thermalization in gas-filled stopping cells [3]. It enables precision experiments with ions almost at rest, including mass measurements in ion traps, high-resolution decay spectroscopy, and laser spectroscopy, while retaining the advantages of the in-flight method of fast and universal production. Alternatively, exotic nuclei can be made available with low kinetic energies at conventional ISOL or at IGISOL facilities. At all these low-energy rare isotope beam (RIB) facilities the fast, universal, sensitive and broadband identification of ions is an additional challenge, which must be met in order to efficiently perform and optimize experiments.

Time-of-flight mass spectrometry (TOF-MS) allows for fast and broadband measurements as well as for high transmission efficiency and single-ion sensitivity. It is hence an ideal tool to address these issues. However, hitherto the mass resolving power obtained by TOF-MS has been limited to a few ten thousand, which is not sufficient for the resolution of most atomic isobars. The most important limitation is the turn-around time [4] caused by the initial, viz. thermal, velocity spread of the ions prior to acceleration. It leads to different flight times even for otherwise identical

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ions, which have initially different velocity components along the direction of extraction. For a given ion temperature, the turn-around time can only be reduced by increasing the extraction field strength. However, the energy spread of the ions, and hence the extraction field strength, cannot be made arbitrarily large, otherwise chromatic aberrations would limit the quality of the energy focusing [4,5] and hence the ion optical resolving power. Furthermore, the detector bandwidth also sets a lower limit to the peak width.

A method to overcome the limitation in resolving power is to extend flight path using devices with multiple passes [6]. Assuming the time-of-flight errors due to initial conditions, Δt_0, which include in particular the turn-around time, and the time-of-flight errors in each turn in the time-of-flight analyzer due to aberrations, Δt_a, are independent of each other, the resolving power of a multiple-pass TOF-MS is given by

$$\left(\frac{m}{\Delta m}\right)=\frac{t_0/N_a+t_a}{2\sqrt{\left(\frac{\Delta t_0}{N_a}\right)^2+(\Delta t_a)^2}} \quad (1)$$

where t_0 is the time-of-flight from the start position to the detector without any flight path extension, t_a is the time-of-flight for a single turn in the analyzer and N_a is the number of passes in the analyzer. Clearly, in the case of a large number of passes, $N_a \to \infty$, the overall mass resolving power tends towards the ion optical resolving power $t_a/(2\Delta t_a)$, which can be made orders of magnitude larger than the resolving power achievable in single-pass TOF-MS.

Multiple-pass devices have been proposed in multiple-turn configurations with sector fields [7] and in multiple-reflection configurations with electrostatic ion mirrors [8,9]. The use of a multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) [6] for direct mass measurements of very short-lived, exotic nuclei has been proposed more than a decade ago [10]. First implementations of an MR-TOF-MS at the Justus-Liebig-University Gießen (Germany) and at RIKEN (Japan) yielded mass resolving powers of up to 65,000 [11–13]. The mass spectra obtained with these devices were however characterized by strong tails, limiting the application to separation of ion species with similar abundance. We have overcome this limitation by employing an advanced coaxial four-electrode design [14,15]. Even for uncooled ion populations with the emittance of an electron impact ion source excellent peak shapes characterized by a mass resolving power of 100,000 at FWHM and 35,000 at 10% height of the peak were achieved in a very compact MR-TOF-MS prototype at Justus-Liebig-University Gießen [16,14,17]. An MR-TOF-MS can not only be used to perform mass measurements, but it can also be employed as a mass separator. We have proposed to use an MR-TOF-MS in conjunction with a Bradbury-Nielsen Gate [18,19] as isobar separator [20,21], and we have demonstrated the spatial separation of isobars in an MR-TOF-MS for the first time [22,14]. Furthermore, we have proposed to employ an MR-TOF-MS for diagnostics purposes at rare isotope facilities [14,23]. Our device served as proof-of-principle for future MR-TOF-MS experiments with exotic nuclei at the GSI Helmholtzzentrum für Schwerionenforschung GSI, Darmstadt (Germany) and the Facility for Antiproton and Ion Research (FAIR). Similar projects are pursued at the RI-beam factory RIBF at RIKEN (Japan) [24,25] and at ISOLDE/CERN in Geneva [26,27], and first direct mass measurements of short-lived nuclides have been performed [28,29].

Here, a next-generation device is presented, which reaches an unprecedented performance level for MR-TOF-MS. It has been developed for experiments at SHIP/SHIPTRAP [30], the FRS Ion Catcher [31] at GSI and at the Low-Energy Branch (LEB) [32] of the Super-FRS at FAIR. Based on the technology of this MR-TOF-MS, an MR-TOF isobar separator for the TITAN experiment at the ISAC facility at TRIUMF (Vancouver, Canada) [33] has been constructed and commissioned at the Justus-Liebig-University Gießen and is being installed at the TITAN facility. A duplicate of the MR-TOF-MS for GSI and FAIR is being built for MLLTRAP [34].

The MR-TOF-MS includes several novel components and extends existing approaches in several important points [14,6]. (i) It has an advanced ion optical layout with a simple, yet ion optically advantageous time-of-flight analyzer and an additional post-analyzer reflector. The combination of these two elements yields a flexible high-performance mass spectrometer, which is easy to optimize and to operate and which can be switched instantaneously between modi with different resolving power. (ii) A novel triple-stage injection trap enables efficient ion accumulation, fast cooling and ejection of the ions without significant collisional reheating. Application of a rectangular radiofrequency (RF) voltage allows for a shift of the potential of the ions and turning off the RF voltage during ejection, which removes detrimental mass-dependent time-of-flight variations. (iii) The MR-TOF-MS can be used for broadband measurements at medium resolution, for high-resolution mass measurements, and as an isobar separator, transmitting an arbitrary combination of ions of interest, while constantly monitoring the ions to be removed. (iv) A novel dynamic energy buncher enables efficient recapturing of the selected ions, which can then be accumulated and transmitted to experiments downstream of the device. (v) The MR-TOF-MS has a compact, mobile setup. Due to the shift of the ion potential in the injection trap its operation is independent of the entrance potential of the incoming ions. It can thus be used easily with only minor modifications at different accelerator facilities, and setup times are a few hours only.

Prior to its construction, the MR-TOF-MS was designed using extensive simulations using the programs SIMION [35] and ITSIM [36,37]. The general design of the device and its operation modes have been introduced in [14]. For an in-depth description of the setup of the MR-TOF-MS, its operation and the performance characteristics see [38]; its ion optical design is presented in [15].

2. Setup

2.1. Overview

The setup of the MR-TOF-MS is shown schematically in Fig. 1. Ions are introduced into the mass spectrometer through straight and curved radiofrequency quadrupole (RFQ) ion guides [21]. In the injection trap system the ions are accumulated, cooled by collisions with the buffer gas and injected as bunches into the time-of-flight analyzer. In the analyzer the ions are trapped and travel back and forth between the two reflectors of the analyzer for a selectable number of turns. Then they are ejected, pass through the post-analyzer reflector and alternatively (i) impinge on an isochronous secondary electron multiplier for measurement of their time-of-flight (mass measurement mode) or (ii) pass through a Bradbury-Nielsen Gate (BNG) [18,19], in which contaminant ions can be deflected and only the ions of choice are transmitted (mass separator mode). The mass resolving power is determined by the number of turns in the time-of-flight analyzer (see Eq. (1)). Without reflections in the analyzer (pass-through mode) a medium mass resolving power (several thousands) is obtained; with hundreds of turns in the analyzer (multiple-turn mode) a mass resolving power of several 10^5 is achieved. In the future, the energy spread of the selected ions will be reduced in an energy buncher [14], such that the ions can be recaptured efficiently in an RFQ and trap system and delivered to experiments downstream of the device. The re-accumulation serves to

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