Nuclear Inst. and Methods in Physics Research B xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Improved beam diagnostics and optimization at ISAC via TITAN's MR-TOF-MS

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ARTICLE INFO

Keywords:
Low-energy RIB
Isotopic separation on line
Beam purification and optimization
MR-TOF-MS

ABSTRACT

Determination of the constituents of the radioactive ion beam (RIB) is crucial for successful experiments at low-energy RIB facilities and as such decides the fate of many experiments. Here we present the role of TITAN's Multiple-Reflection Time-Of-Flight Mass Separator (MR-TOF-MS) and how it complements the present capabilities at ISAC-TRIUMF for yield determinations and beam delivery. This non-scanning, broadband, high-resolution mass spectrometer allows for real-time identification and quantification of all species, ranging from radionuclides with half-lives as low as a few ms to stable isotopes and molecules. In this manner it can be efficiently used to optimize RIB delivery through the ISAC mass separator for rate of the species of interest or its ratio to contamination. We present an example of this optimization approach, where the purity of secondary beams of neutron-rich titanium was improved by more than one order of magnitude based on the diagnostics capabilities of the new MR-TOF-MS and thus, allowed for high-precision mass measurements at TITAN.

1. Introduction

The study of radioactive isotopes is of high interest to understand the interplay between the electromagnetic, strong and weak interactions inside a nucleus. Systematic measurements along isotopic chains and the observed shell structure of nuclei, reflected by increased binding energies at the so-called magic neutron and proton numbers compared to the average trend, led to the development of the shell model [1]. The structure and properties of nuclei far from stability attracts large attention [2], but in contrast to nuclei closer to the stability line, experimental data are scarce. New effects such as shell quenching, weakening or disappearance of shells around the classical magic numbers and appearance of new magic numbers have been theoretically predicted [3,4] and observed in experiments [5–7].

Production of these more exotic nuclei, far away from stability, becomes more and more challenging as production cross sections as

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https://doi.org/10.1016/j.nimb.2019.04.034
Received 31 January 2019; Received in revised form 29 March 2019; Accepted 13 April 2019
0168-583X/

well as half-lives drop rapidly, while at the same time the production of unwanted species causes often overwhelming background [8].

The presence of unwanted isobaric contaminant species often prevents high-precision experiments and is a general challenge for experiments at low-energy facilities.

To cope with this high background and to provide clean beams for high-precision experiments, advanced diagnostics and separation tools are needed. These should be able to measure short-lived as well as stable isotopes in order to determine possible background, to have a high sensitivity and dynamic range to measure isotopes with low and high production cross sections, to be able to measure a wide range of masses simultaneously and have high resolving power to identify and separate all components of the ion beam. The development of Multi-Reflection Time-Of-Flight Mass-Spectrometers (MR-TOF-MS) [9] has made such diagnostics systems, with capabilities e.g. discussed in [10], available at many low-energy RIB facilities [11–14] and recently at TITAN [15].

In this article we explore the capabilities of the TITAN MR-TOF-MS to identify beam constituents and to improve beam delivery at TRIUMF's Isotope Separator and ACcelerator (ISAC) facility [16], which relies on the ISOL technique for radioactive ion beam production. We compare the information obtained with the MR-TOF-MS to that from conventional beam diagnostics techniques. The latter includes scans of the ISAC mass separator [17], recorded on a Faraday cup, and decay measurements at the ISAC Yield Station [18].

Further we demonstrate how to optimize the mass separator magnet for two scenarios. The first is to maximize the yield of the desired ion of interest, and the second is to optimize the signal-to-background ratio as much as an order of magnitude. We illustrate these concepts with data measured during radioactive beam experiments.

2. Experimental facilities

2.1. ISAC

At ISAC [16] radioactive ions are procured via the ISOL method. A high-energy (480 MeV), high-intensity ($< 100\,\mu$A) proton beam is extracted from TRIUMF's main cyclotron and transported to one of two production targets. Species extracted from the target are ionized with a surface ion source and, in this case, TRIUMF's Laser Ionization Source (TRILIS) [19]. An overview of the experimental facilities is given in Fig. 1 and a detailed description of the experimental conditions is given in the respective publications of Ti and V mass measurements [20,21] and in a forthcoming publication for the results presented in Fig. 4.

The secondary beams are consecutively mass separated by two dipole mass separators, first, by the ISAC Pre-Separator and, second, ISAC's high-resolution mass separator [17], reaching mass resolving powers of 600 and 2500, respectively. The magnetic field of the mass separator is scanned and the total beam current is measured using a Faraday cup behind the exit slits of the pre-separator. A section of such a scan of the pre-separator magnet is shown in Fig. 2a for isotopes with a mass-to-charge ratios between 39 and 58 u as measured during the Ti/V experiments. In case low intensity beams need to be quantified the ISAC beam line is equipped with channeltron detectors along the beam path, which allow single ion counting. In order to controllably adjust the overall beam intensity at a given mass number, calibrated attenuators and slits behind the high-resolution mass separator can be insert into the beam path.

Tuning both mass separators to the mass-to-charge of an isotope of interest, the beam is delivered to the ISAC Yield Station [18] or to TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) [22].

2.2. ISAC yield station

At the Yield Station the RIB is accumulated on an aluminized Mylar tape surrounded by a plastic scintillator detector assembly, achieving a high detection efficiency for β particles, and a high-purity germanium (HPGe) detector, used for detection and identification of nuclide-specific γ-rays. The incoming RIB can electrostatically be blocked while the decay curve of the accumulated activity can be monitored using β and γ detection. The cycle of 'accumulation-measurement-tape movement' is repeated until sufficient statistics for a half-life measurement and identification of isotope specific γ lines is reached. An example spectra, showing the decay of ^{54}Ti, is given in Fig. 2b.

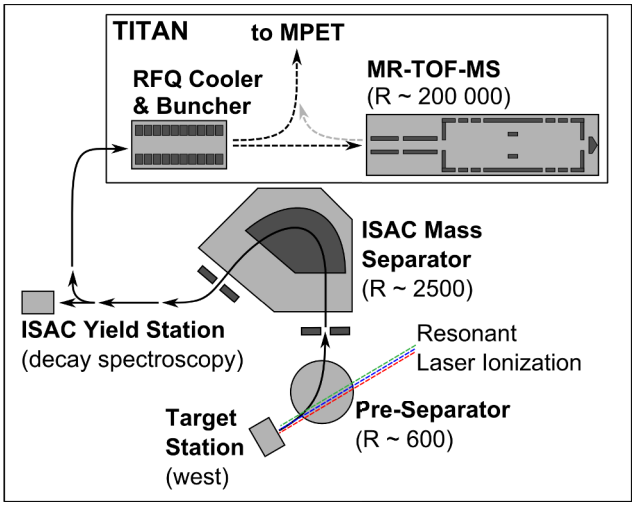

Fig. 1. Overview of the experimental facilities described herein. The beam transport is shown from the production target, through the ISAC magnetic mass separators, to the Yield Station and to the TITAN mass measurement system. Subsystems of the TITAN experiment employed herein, an RFQ Cooler & Buncher and the new MR-TOF-MS, are shown. Continuous ion beams are indicated by solid arrows, whereas bunched beams are shown by dashed arrows.

2.3. TITAN MR-TOF-MS

TITAN [22] has specialized in fast mass spectrometry of singly and highly charged, short-lived exotic nuclei and in-trap decay spectroscopy.

At TITAN the continuous RIB is first accumulated, cooled and bunched in a helium-gas-filled Radio Frequency Quadrupole (RFQ) cooler-buncher [23]. From there ion bunches are sent to the MR-TOF-MS. In the MR-TOF-MS the ions are identified by their specific mass-to-charge ratio, determined by the time-of-flight method [24,25]. Long time-of-flights and thus high resolving powers are achieved by storing an ion bunch between two electrostatic ion mirrors preserving the initial time spread over large flight path [9]. The TITAN MR-TOF-MS, based on the design of the system used at GSI, Darmstadt [10,26], consists of a gas-filled RFQ beam line [27], a RF injection trap and an electrostatic time-of-flight mass analyzer [28]. In order to achieve a large unambiguous mass range the potential of the ion mirrors are switched for injection and ejection of ions into the analyzer in combination with the Time-Focus-Shift (TFS) turn method [29].

In Fig. 2c the mass-to-charge spectra for the mass number 54 is shown. In this measurement ions were cooled for ≈ 13 ms in the RF injection trap and injected into the mass analyzer, where they underwent 512 turns before impinging on a MicroChannel Plate (MCP) detector. The individual species produced ion bunches with peak width of about 17 ns FWHM after times of flight of about 7.4 ms, corresponding to mass resolving power of $\approx 200,000$. Single ion counting with a TDC (Ametek Mod. 9353 Time Digitizer/ MCS) or measurements of the average charge per species with an ADC (Signal Recovery FASTFLIGHT2) allow identification and quantification of the individual species.

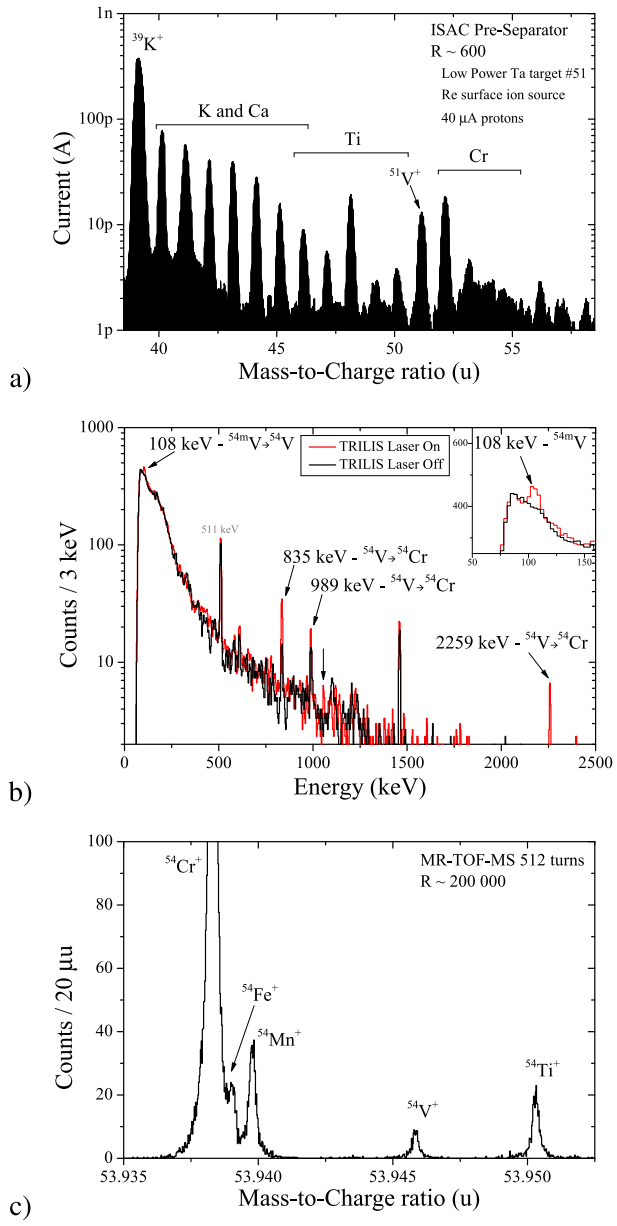

Fig. 2. Complementarity of the beam diagnostics capabilities of a) scans of the ISAC pre-separator, b) γ detection at the ISAC Yield Station and c) mass measurement at the TITAN MR-TOF-MS for a radioactive beam of ^{54}Ti.

3. Comparison of beam-composition determinations

The information gained by the mass separator, the Yield Station and the MR-TOF-MS can be seen to be highly complementary as they give access to different properties of the secondary beam.

Scans of the ISAC pre-separator are an important tool for beam development. They show the total beam extracted from a target and allow for a fast overall characterization, as shown in Fig. 2a. However due to the limited resolving power of the magnetic separator and sensitivity of the Faraday cup, they cannot distinguish between different isobars or detect low-intensity species. Due to their low ionization energy alkali and alkaline-earth metals, as well as lanthanides, are surface ionized well and have been found to dominate the beam composition.

The decay and spectroscopy measurements at the Yield Station are the standard tool for beam identification and quantification at ISAC. The Yield Station is well suited to determine the yield of high-intensity radioactive species out of a strong stable or long-lived background, but it is limited to yields in the order of a ~ 10 particles per second (pps). Sensitive only to the radioactive decay, the Yield Station requires accurate and high-quality nuclear decay properties of the nuclide of interest and cannot measure the fraction of stable or longlived isotopes. On the other hand, yield measurements at the Yield Station are also not hampered by stable contamination.

In the MR-TOF-MS species are identified by their mass-to-charge ratio and the yield of each species can be determined directly without relying on decay schemes. Reaching high resolving powers the TITAN MR-TOF-MS can resolve almost all species of the radioactive ion beam. As the identification does not rely on the decay of an isotope, long-lived or even stable isotopes can be identified and quantified within a short measurement time of several minutes, as shown in Fig. 2c. The highly sensitive MR-TOF-MS is capable of handling high amounts of background, with ion-of-interest to background ratios on the order of 1: 10^5, as well as to identify species with low yields down to a few particles per minute. In addition, being a non-scanning broadband technique, the MR-TOF-MS can measure all isotopes or even nuclear isomers with a half-life longer than a few ms and excitation energy of several hundred of keV at the same time. On the other hand, the MR-TOF-MS technique cannot measure high-intensity beams and requires attenuation in order to reduce the overall beam intensity. This can be achieved by the calibrated beam attenuators and slits part of the ISAC beam line. In order to measure absolute yields the efficiency of the ISAC beam transport, the TITAN cooler & buncher and the MR-TOF-MS need to be determined. For the results presented herein the total efficiency amounts to ≈ 2%, but has been improved since [30].

While the scan on the Faraday cup can be used to optimize transmission of the beam, we remain unaware of the beam composition and often optimize on contaminant species such as alkaline or stable, see Fig. 2a. The Yield Station can easily pick out a radioactive signature from a large background and is best to identify shorter lived constituents (half-lives < 30 min). In Fig. 2b γ-ray transitions from ^{54}V are clearly seen, but not long-lived ^{54}Mn($t_{1/2}$ = 312 days) and stable and ^{54}Cr. For many experiments and processes, sensitive to space charge, the long-lived species are best measured in an MR-TOF-MS, which can measure them as well as the short-lived ion of interest in a comparable or shorter time than the Yield Station; Fig. 2c, which demonstrates this capability, was measured in 10 min. Moreover, with a demonstrated sensitivity to yields of < 1 pps, TITAN's MR-TOF-MS is needed for very low-yield beams.

However, as ion of interest to background frequently exceed 1: 10^8, measurements at the Yield Station and MR-TOF-MS have been found to be well complementary to each other.

3.1. The yield of ^{54}Ti

The yield measurements of ^{54}Ti, shown in Fig. 2, using the three different techniques gives a nice example of beam identification at ISAC.

In the magnet scan K and Ca as well as stable Ti, V and Cr are measured with intensities above 1 pA each.

In the γ-ray spectrum an increase in the γ lines corresponding to well known transitions in ^{54}Cr can be seen, indicating an increased ionization and yield of ^{54}Ti, when switching the resonant laser system for Ti on and off. However, the only previously reported characteristic γ line at 900(100) keV [31] for the decay of ^{54}Ti cannot be observed, but an increase in a γ transition at 108 keV can be seen, matching the decay of a known 0.9 μs isomeric state in ^{54}V [32]. Due to its very short half-life, this isomeric state could not have been produced and transported to the Yield Station directly, but can only be populated via the decay ^{54}Ti → ^{54m}V. In the literature no feeding of ^{54m}V from ^{54}Ti has been reported. However, the clear increase in this γ line with laser ionization indicates a missing transition in the decay of ^{54}Ti → ^{54}V. A measurement of the decay half-life of ^{54}Ti based on the total β decays detected

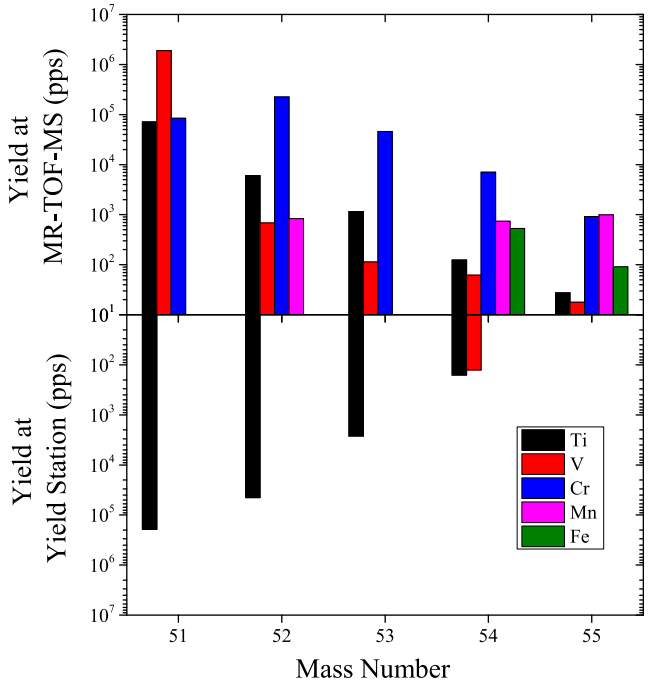

Fig. 3. Yields of all components of the radioactive beam determined with the TITAN MR-TOF-MS after the optimization of the beam purity in addition to the yields of neutron-rich Ti isotopes determined at the ISAC Yield Station.

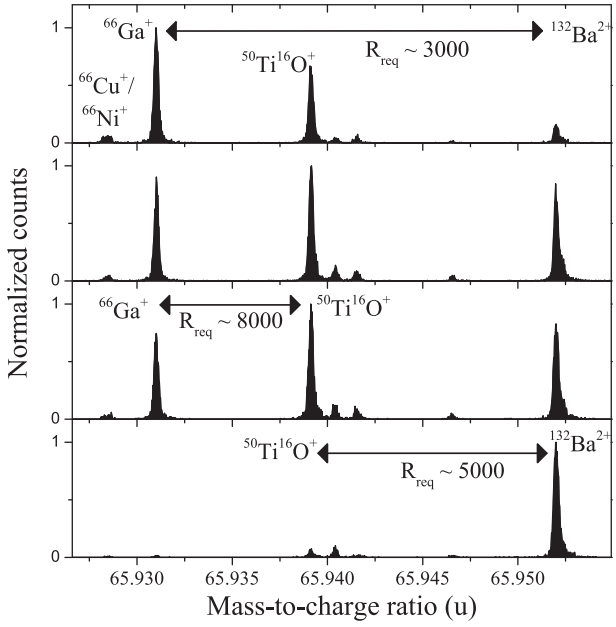

Fig. 4. Beam composition of $^{50}Ti^{16}O^+$ as detected with the MR-TOF-MS after 400 turns inside the mass analyzer. The time-of-flight spectra has been calibrated using the time of flight and mass of $^{66}Ga^+$. From top to bottom the set current of the ISAC mass separator was adjusted in mA steps in order to fine tune the beam composition.

by the scintillator assembly of the Yield Station, showed a discrepancy of the half-life, compared to the literature value of 2.1 s, by ~ 3σ. From the measurements it becomes clear that there is crucial spectroscopy information missing in the literature for ^{54}Ti.

In the mass-to-charge spectra of $^{54}Ti^+$ at the MR-TOF-MS all components of the ion beam are resolved and produce clearly visible and separated peaks. The identity of the Ti peak can be similarly validated by turning on and off its TRILIS ionization. Therefore the yields of $^{54}Ti^+$, as well as $^{54}Cr^+$,^{54} Mn^+ and $^{54}V^+$, can be determined directly from the spectra without detailed knowledge of their nuclear structure.

3.2. Yields of neutron-rich Ti

The Yield Station and the MR-TOF-MS were both used for yield measurements of neutron-rich Ti from mass number 51 to 54. Due to the high sensitivity of MR-TOF-MS a yield of ^{55}Ti could be determined in addition to the yields of all species of the ion beam at the respective mass numbers.

In Fig. 3 the individual yields of neutron-rich Ti and V and stable Cr, Mn and Fe are shown. The results of the Yield Station and the TITAN-MR-TOF-MS agree. Any difference can be understood in the difference of the optimization procedure used to tune the beam to the measurement station as described in the next section. The overview highlights the complementarity of the Yield Station and the MR-TOF-MS. The combination of both methods allows better understanding of the production of secondary beams and will guide future beam development.

4. Optimization of the mass separator with the MR-TOF-MS

Making use of the fast high-resolution diagnostic capabilities of the MR-TOF-MS enables real-time yield and beam composition measurements. This can be used to fine tune and optimize the beam transport from the target to the experiment, herein TITAN. Of particular interest is the application for fine adjustment of the ISAC mass separator itself because it is the dominant mass-selective ion optics element.

4.1. Optimized delivery of the ion of interest

In Fig. 4 an example of a magnet optimization of stable species using the TITAN MR-TOF-MS is shown. The constituents of the ion beam at mass number 66 delivered from ISAC, consisting of three stable species (singly charged $^{66}Ga^+$ and $^{50}T^{16}O^+$ and doubly charged $^{132}Ba^{2+}$) are well resolved. Initially the beam is dominated by $^{66}Ga^+$. Small mA adjustments of the set current and thus the magnetic fields of the ISAC mass separator were used to maximize the yield of one of the components of the RIB. The measurements as shown in Fig. 4, took less than 15 min in total and effectively isolated the $^{66}Ga^+$ or the $^{132}Ba^{2+}$ component from each other.

A separation of $^{66}Ga^+$ and $^{132}Ba^{2+}$ requires a resolving power of $R_{req} \approx 3000$, which can be achieved by the separator. The ratio between $^{66}Ga^+$ and $^{132}Ba^{2+}$ can be adjusted by two orders of magnitude. A separation of $^{66}Ga^+$ and $^{50}T^{16}O^+$, requiring $R_{req} \approx 8000$, cannot be reached.

This example demonstrates that in merely minutes a suitable combination of magnetic field and slit settings can be achieved to maximize delivery of the ion of interest and to meet the necessary experimental requirements.

4.2. Optimized signal-to-background

As the ion of interest becomes increasingly exotic, the resolving power required to separate ion of interests and stable contaminant decreases. However, the signal to background ratio decreases strongly and may prevent measurements.

Optimizing the signal-to-background ratio can be as critical as the absolute yield itself for many experiments, especially for those whose beam delivery or measurement is sensitive to space charge, as e.g. Penning trap mass spectrometry. The goal, then, is to enhance the purity of the ion of interest in the RIB delivered by ISAC to the experiment by adjusting the mass separator magnet in mA steps.

In Fig. 5, we show the evolution of beam purity, here for neutron-rich Ti. For ^{51}Ti, improvement was neither required nor attempted. However, for ^{54}Ti, ^{54}Cr was the dominant species and required a resolving power of $R_{req} \approx 4000$ to separate. While larger than the

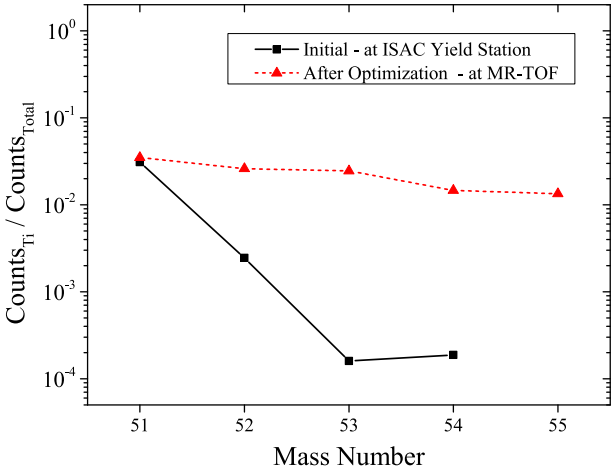

Fig. 5. Relative beam composition of neutron-rich Ti isotopes at different mass numbers as initially delivered by ISAC and after fine adjustment of the ISAC mass separator using the TITAN MR-TOF-MS for beam diagnostics. For neutron-rich Ti isotopes more than one order of magnitude in beam purity could be gained.

capability of the ISAC mass separator, the ratio ^{54}Ti: ^{54}Cr could be optimized to 1: 70, within the capabilities of TITAN's Penning trap. This is an improvement in purity by about a factor of 80.

In general, for neutron-rich Ti isotopes an improvement in beam purity of more than one order of magnitude was achieved by fine tuning the ISAC mass separator based on the beam diagnostics of the TITAN MR-TOF-MS. At the same time the improvement in beam purity reduced the overall intensity of neutron-rich Ti only by about a factor 2–7, as shown in the comparison of yields between the Yield Station and the MR-TOF-MS in Fig. 3. The largest reduction in intensity occurs closest to stability, for ^{52}Ti, where high separation powers are needed to separate Ti from stable Cr ions. However, here yields are sufficiently high such that a reduction in intensity was fully outweighed by the mandate for purer RIB for high-precision ion trapping experiments.

5. Conclusion and outlook

Yield measurements at RIB facilities are an important tool to drive future beam development. Measurements at the ISAC Yield station and the new TITAN MR-TOF-MS have shown to be well complementary to each other and the combination of both techniques allows for new species to be identified at ISAC and make available to experiments.

Further we show that mass spectrometry, in particular the new MR-TOF-MS technique, is a great tool for beam diagnosis at low-energy radioactive beam facilities. Due to the element and decay properties independent diagnosis capabilities the yields of all species of a radioactive beam can be measured at once, cutting down measurement time and opening new possibilities for target development. Using this identification and quantification scheme the existing mass separator at ISAC could be fine tuned, improving its effective separation capabilities. Cleaner secondary beams of neutron-rich Ti could be provided. The improvement in ion-of-interest to background ratio of more than one order of magnitude is enabled due to the new diagnostics capabilities added by the MR-TOF-MS.

In the future using the TITAN MR-TOF-MS as a high-resolution isobar separator itself, the purity of secondary beams can be improved further. This will enable additional high precision experiments, which currently suffer from strong isobaric background, at the TITAN facility.

Acknowledgments

We would like to thank H.L. Crawford for fruitful discussions on the decay of ^{54}Ti and the TRIUMF beam delivery and development groups for the development and preparation of the neutron-rich Ti beams. This work is supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Foundation for Innovation (CFI), the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under grant 249121/2013-1, the Helmholtz Association of German Research Centers through the Nuclear Astrophysics Virtual Institute (VH-VI-417), Justus-Liebig-Universität Gießen and GSI under the JLU-GSI strategic Helmholtz partnership agreement, the Hessian Ministry for Science and Art (HMWK) through the LOEWE Center HICforFAIR, the US National Science Foundation under Grant PHY-1419765, the Deutsche Forschungsgemeinschaft (DFG) under Grant FR 601/3-1, the German Federal Ministry for Education and Research (BMBF) under Contract No. 05P12RGFN8, 05P15RGFN1 and 05P19RGFN1 and the Canada-UK Foundation. TRIUMF receives federal funding via the National Research Council of Canada (NRC).

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