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Nuclear Instruments and Methods in Physics Research B 204 (2003) 492–496
NIM B Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

# The proposed TITAN facility at ISAC for very precise mass measurements on highly charged short-lived isotopes

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**Abstract**

One of the necessary experimental quantities required for the test of unitarity of the fundamental Cabbibo–Kobayashi–Maskawa (CKM) quark mixing matrix can be gained from nuclear beta decay. However, the short-lived beta-decaying nuclei have to be produced on-line in order to provide a large enough sample to carry out the experiments. At the new ISAC (Isotope Separator and Accelerator) facility at the TRIUMF national laboratory in Vancouver, Canada, ideal conditions are provided for the production of some of the most interesting nuclides in that respect. The experimental information that is needed are branching ratio, half-life and Q-value of the specific beta decay. For the first two components experiments have already been carried out or are in preparation at ISAC (Phys. Rev. Lett. 86 (2001) 1454, and experiments E823 and E909 approved at TRIUMF), for the third one, we are proposing to set up a unique facility capable of high accuracy mass measurements $\delta m/m \leqslant 1 \times 10^{-8}$ on very short-lived isotopes ($T_{1/2} \leqslant 50$ ms) employing a Penning trap spectrometer coupled to an electron beam ion trap (EBIT) for charge breeding. The main goal of TITAN is mass measurements, however, the unique combination of the systems will allow to carry out high precision measurements in other fields of nuclear and also atomic physics.
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*PACS:* 06.30.Dr; 07.75.+h; 07.75.+h; 07.85.−m; 07.77.−n; 32.10.Bi
*Keywords:* Atomic masses; Binding energies; QED tests; Penning trap; Electron beam ion trap

## 1. Introduction

The binding energy of the atomic nucleus is one of the most fundamental properties of such a many body system. Accurate mass measurements serve as a testing ground for nuclear models, stimulate their further improvement and are required for weak interaction studies in nuclear β-decay. Tests of fundamental concepts like conserved vector currents and unitartity of the Cabbibo–Kobayashi–Maskawa (CKM) matrix also rely on nuclear mass values. One crucial parameter for this test is the $Q$-value of the β-decay corresponding to the difference in mass of mother and daughter nuclei. The present status of the unitarity test indicates a deviation from 1, by two sigma [1]. It is presently unclear if this is due to the applied theoretical corrections of the experimental input values or if it indicates new physics. To test and improve these

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0168-583X/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0168-583X(02)02118-3

theoretical corrections an experimental precision for the mass measurements of $\delta m/m \leqslant 1 \times 10^{-8}$ is required. We are proposing to set up a unique facility for mass measurements capable of such accuracies for very short-lived isotopes ($T_{1/2} \leqslant$ 50 ms). The spectrometer will employ a Penning trap coupled to an electron beam ion trap (EBIT) for charge breeding. This device will be set up at the ISAC online facility at TRIUMF/ Vancouver.

## 2. Set-up

The TITAN (Triumf's Ion Trap for Atomic and Nuclear science) system will consist of four main components all serving different purposes, following the principle 'separation of functions'. A block diagram of the system including other possible applications is shown in Fig. 1. In the following sections each part is described in more detail.

### 2.1. RFQ cooler and buncher

The mass separated ISAC beam is brought into a radio frequency quadrupole (RFQ), filled with buffer gas, similar to the ones used at ISOLDE/ CERN [2] or the IGISOL facility at Jyväskylä [3]. The ions are electrostatically retarded to a kinetic energy of a few eV before entering the RFQ structure. Once inside, the RF fields provide radial confinement while an additional longitudinal electric field pulls the ions slowly through the buffer gas. Interactions with the buffer gas molecules reduce the kinetic energy of the ions and thermal equilibrium is reached after about $T_{\mathrm{cool}} \approx 1$ ms. A longitudinal potential barrier at the end-section of the RFQ allows one to accumulate the cooled ions. Changing to an extraction potential allows for the emission of the cooled bunch. The purpose of this device is the quality improvement of the beam, hence higher transport efficiency and the option of beam bunching.

### 2.2. Electron beam ion trap

An EBIT consists of a homogeneous magnetic field, where charged particles are trapped radially and trapping electrodes with DC potentials for axial confinement. An additional electron beam on the axis generates an attractive potential for the positively charged ions, and also strips shell electrons of those trapped ions, thus charge breeding takes place. Fig. 2 shows the basic concept.

EBITs have been previously used for atomic physics investigation, namely X-ray spectroscopy (see e.g. [4]). Recently an electron beam ion source (EBIS) was employed for charge breeding to low or moderate charge states (for example +2 to +12 for Ar) of radioactive species at REX-ISOLDE [5]. The EBIT envisaged in our system, is based on a conceptual design of the Livermoore EBIT group for the INTENSE-EBIT [6]. It will operate on higher electron beam energies and larger currents allowing one to reach bare, hydrogen-like, or helium-like configurations for all elements up to uranium in very fast breeding times. Table 1 shows the parameters that are planned to be used. Based on these parameters one can calculate the breeding

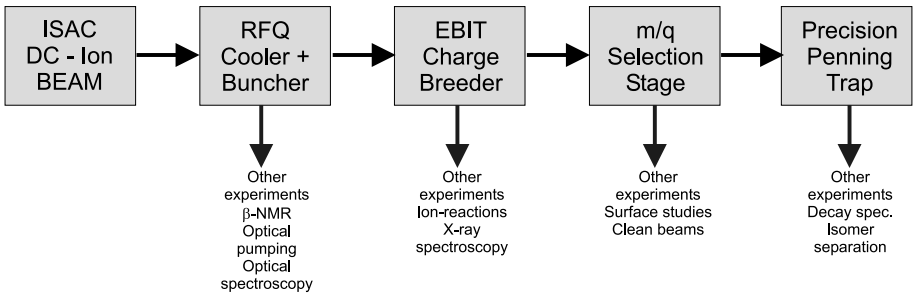


Fig. 1. Concept of the proposed ion trap facility TITAN at ISAC/TRIUMF. Other possible applications of the indvidual components are indicated.

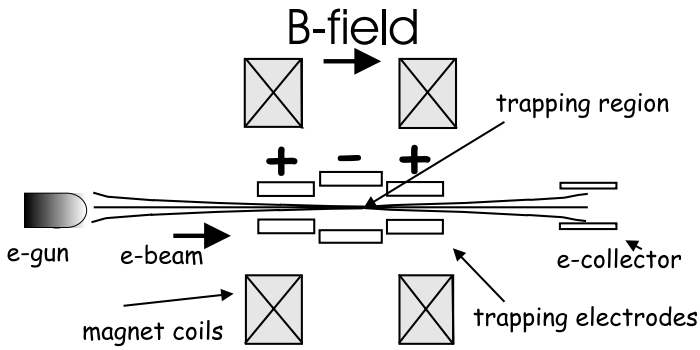


Fig. 2. Concept of an electron beam ion trap (EBIT).

Table 1
Parameters for the planned EBIT system for TITAN and expected performance values

| Parameters | |
|---|---|
| Magnetic field | 6 T |
| Electron beam energy | 30–60 keV |
| Electron beam current | 5 A |
| Beam radius (80% current, confined in the trap) | 50 μm |
| Central current flux | $3.4 \times 10^{23}/\mathrm{cm}^{-2}$ s |
| Trap length | 250 mm |
| *Expected performance* | |
| Space charge limit | $\approx 10^{10}$ ions/s for $Sn^{40+}$ |
| Acceptance of EBIT | $\epsilon \approx 6\pi$ mm mrad |
| Emittance of extracted beam | $\epsilon \approx 1\pi$ mm mrad/q |

time for a specific charge state, based on a simple Lotz formula [7], assuming sequential removal of the shell electrons. Table 2 shows the breeding times for various charge states for rubidium and tin.

### 2.3. $m/q$ selection stage

Contaminants of isobars are always present at online facilities operating with a moderate resolution separator. Installing an $m/q$ selection system after the EBIT enables one to filter out one specific isotope at one charge state. A device that could be employed for such purposes is a Wien filter, where a separation according to velocity can be performed. An example of how to use the combination of charge breeding and Wien filter for the case of mass 100 isobars is listed in Table 3. For such a scenario, where one adjusts the electron beam energy in the EBIT, it is possible to produce a pure beam, e.g. for $^{100}$Sn, even with moderate resolving power for the Wien filter.

Table 2
Breeding time for various charge states assuming the above device parameters and sequential stripping of electrons

| Element and charge state | Breeding time (ms) |
|---|---|
| $Rb^{27+}$ Ne-like | 2 |
| $Rb^{35+}$ He-like | 10 |
| $Rb^{36+}$ H-like | 50 |
| $Sn^{40+}$ Ne-like | 3 |
| $Sn^{48+}$ He-like | 34 |

Table 3
Example of how to produce a contaminant free beam of $^{100}$Sn employing the EBIT with an electron beam energy of $E_{e^-} = 30$ keV and a Wien filter. The ionization energy for He-like configuration and the highest charge state at 30 keV are listed

| Isotope | $T_{1/2}$ | Ionization potential (keV) | Charge state | $m/q$ |
|---|---|---|---|---|
| $^{100}$Sn | 660 ms | 34.4 | $48^+$ | 0.48 |
| $^{100}$In | 6.1 s | 32.8 | $47^+$ | 0.47 |
| $^{100}$Mo | Stable | 32.8 | $42^+$ | 0.42 |

### 2.4. Penning trap

The mass measurement of an ion confined in a Penning trap is accomplished by determining its cyclotron frequency. The cyclotron frequency $\omega_c$ of an ion with charge to mass ratio $q/m$ in a magnetic field with strength $B$ is given by

$$\omega_c = \frac{q}{m} B. \tag{1}$$

The resolving power for mass measurements is given by

$$R = \frac{m}{\delta m} \approx \frac{T_{RF} q B \sqrt{N}}{m}, \tag{2}$$

where $T_{RF}$ is the RF-excitation duration in the trap, in practice limited by the nuclear half-life and $N$ is the number of detected ions. From Eq. (2) it is clear that the possibilities to enhance the resolving power are: use of large magnetic fields, longer measurement periods (gaining only with $\sqrt{N}$) and use of highly charged ions.

The cyclotron frequency is increased by the charge state $q$ when using highly charged instead of singly charged ions. Fig. 3 shows a comparison of the achievable resolution $\delta m/m$ for singly and highly charged ions as a function of RF excitation time for various numbers of detected ions. From this comparison it is obvious that such a system allows one to reach $q$-times higher accuracies as compared to operating with singly charged ions, as for example in the case for ISOLTRAP. Similar accuracies can be reached, using a factor $q^2$ less beam time or, most attractively, mass measurements can be performed on isotopes with $q$-times shorter half-life. In that way the necessary precision for the previously mentioned fundamental test can be achieved. It is planned to use a standard 6 T NMR magnet with warm bore and 0.1 ppm maximum central field variation over a 10 mm diameter spherical volume where the ions are stored. It is intended to allow for a second homogeneous region in the magnet, where preparations, such as cooling could be performed.

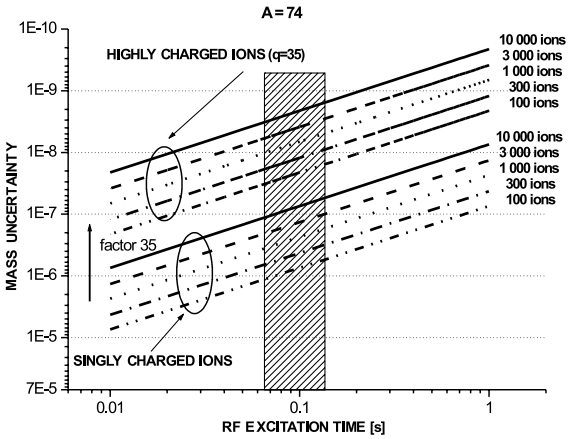


Fig. 3. Resolution $\delta m/m$ as a function of RF excitation time for $^{100}$Sn and $^{74}$Rb. Shown are sets of curves for different number of detected ions, for singly and highly charged ions. The shaded block indicates the typical RF time, corresponding to two nuclear half-lives.

## 3. Other applications

The proposed TITAN facility will allow for applications of stable and unstable, cooled and bunched beams, for single and highly charged ions. Some possible experiments are given as examples.

### 3.1. Online laser spectroscopy

Laser spectroscopy on series of exotic isotopes gives very important information of fundamental nuclear properties, such as charge radius or deformation parameters. The experiments traditionally carried out at online facilities such as ISOLDE [9] suffer from low production yields further away from the valley of stability and low signal-to-noise ratio. If carried out at TITAN/ISAC, such an experiment could make use of a singly charged radioactive beam, prepared in the RFQ cooler and buncher. The beam-quality, e.g. the longitudinal and transversal energy spread, would be improved. Moreover, the bunched beam allows one to trigger on the expected signal, suppressing the background significantly. Experiments at the University of Jyväskylä [10] demonstrated the tremendous improvements in sensitivity due to the buncher, where experiments were performed on only 50 ions/s. Possibilities arise with the higher yields at ISAC extending the known information towards the drip-lines and going to even shorted half-lives, for example the halo-nucleus $^{11}$Li with $T_{1/2} = 8.6$ ms.

### 3.2. Surface studies with hollow atoms

Hollow atoms are systems with full electron shells but inverted configurations [11]. They can be

formed by letting a highly charged ion, with very high potential energy ($E_{pot} \approx 50$ keV) and little kinetic energy ($E_{kin} \approx 200$ eV) approach a metal surface. Due to the high charge state of the ion a mirror potential is induced, accelerating the ion towards the surface. In close proximity to the conductor, electrons are 'sucked' into orbits of the ion, but due to the excess of potential energy, they go into Rydberg states. Upon impact with the surface, the energy is released. In the neutralization process characteristic X-rays or Auger electrons are emitted. Recording of these as a function of time and hence deposition depth, allows one to gain information of the layer itself. The TITAN facility could provide highly charged stable ions during phases when the radioactive ISAC beam is provided to other experiments. Experiments for surface studies are becoming more and more important and are allowing the development of applications in the semiconductor industry, such element specific surface cleaning can be done, without radiation damage [12], due to the very moderate kinetic energy.

### *3.3. Fundamental atomic physics with X-ray spectroscopy*

The production of highly charged ions in the EBIT in specific atomic configurations and the correlated de-excitation or recombination processes give rise to characteristic X-rays. By observing those with a spectrometer fundamental questions can be addressed. The advantages of the TITAN EBIT are twofold: if the foreseen electron current can be reached, the device would be the world's brightest X-rays EBIT source and secondly, the unique possibility of carrying out experiments on stable and short-lived isotopes would allow investigations of the influence of the nucleus.

## 4. Conclusion

The proposed TITAN facility will be capable of performing high accuracy mass measurements on very short lived isotopes, allowing one to reach the necessary precision for ruling out the limitations of theoretical corrections for fundamental tests, such unitarity of the CKM-matrix. The other experimental input data for these corrections are presently being investigated in an ongoing program for super-allowed β-decay candidates at ISAC [8]. With ISAC being operational at the full intensity, employing a 100 μA DC proton beam, a 20-fold increase in production yield as compared to ISOLDE is expected. The gain in using highly charged ions as well as the high production yields will make the proposed mass spectrometer unique worldwide and will allow the extension of high-accuracy mass measurements to very short-lived isotopes far off stability. Due to the combination of an RFQ, EBIT and Penning trap at the online facility ISAC an enormous potential for other applications arise, for example in the fields of nuclear-, atomic- and solid-state physics and also in chemistry. A letter of intent to the experimental evaluation committee at TRIUMF in December 2001 was very well received and preparations for a proposal to NSERC are under way. The first stage of the TITAN system, the RFQ cooler is presently being built and the complete facility is expected to be assembled in 2005.

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