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FT-ICR: A non-destructive detection for on-line mass measurements at SHIPTRAP

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Abstract. The SHIPTRAP facility is set up behind the velocity filter SHIP at GSI. One of the main physics goals is the direct mass determination of trans-uranium nuclides by Penning trap mass spectrometry. In this contribution the applicability of the non-destructive Fourier Transform-Ion Cyclotron Resonance (FT-ICR) detection technique to mass spectrometry of short-lived nuclides is discussed.

PACS. 07.75.+h Mass spectrometers – 27.90.+b $220 \leq A$

The SHIPTRAP facility [1,2,3] is designed to provide clean and cooled beams of singly charged radioactive ions produced in a fusion-evaporation reaction and separated by the velocity filter SHIP [4]. The scientific program comprises mass spectrometry, atomic and nuclear spectroscopy, and chemistry of elements with $Z > 92$, which are not available at ISOL- or fragmentation facilities. Since predicted mass values in this region often vary by about 1 MeV, direct experimental values serve as a test of theoretical models. Furthermore, they allow for the calculation of shell corrections in the stabilized, deformed region around $Z = 108$, as well as at the shell closure of the superheavy elements.

The mass m of an ion with charge q stored inside a Penning trap is determined via a measurement of its cyclotron frequency $\nu_c = qB/(2\pi m)$, where B denotes the magnetic field strength. For unstable nuclides this is up to now only achieved with the destructive time-of-flight-ICR detection method [5]. One of the main limitations to the experimental investigations is the low production rate of most of these exotic superheavy nuclides, in many cases less than one per minute. However, several nuclides in the trans-uranium region exhibit particular long half-lives. There are 173 known nuclides above uranium with a half-life longer than one minute, and beyond fermium 37 nuclides fulfill this requirement. This allows for comparatively long observation times, enabling an increased precision in the frequency determination. Here, a sensitive and non-destructive method, like the Fourier Transform-ICR [6] technique, is ideally suited for the identification and characterization of these species. The induced image currents of charged particles stored in a Penning trap with segmented electrodes are picked up and Fourier analyzed. This mass spectroscopic technique is applied throughout in the field of analytical chemistry and is routinely achieving an accuracy at the sub-ppm level for different elemental compositions in a wide mass range [7]. The FT-ICR setup at SHIPTRAP is especially optimized for the sensitive detection of single, short-lived ions with $A > 200$. The main characteristics are: Ions are stored in an orthogonalized hyperbolic Penning trap [8] and their signals are detected with a narrow-band tuned circuit.

With FT-ICR the complete frequency spectrum is obtained after loading the trap only once, whereas in TOF-ICR a minimum number of ions $N_{\text{ion}} > 500$ is required. In order to reach a relative mass uncertainty $\delta m/m \propto 1/(\nu_c \cdot T \cdot \sqrt{N_{\text{ion}}})$ [9] the loss in ion statistics N_{ion} of rare species from SHIP is overcome by a prolonged observation time T due to longer half-lives and the possibility of multiple measurements due to the non-destructive character of the method. The signal-to-noise ratio of *one* singly charged ion detected with a standard room temperature setup is estimated: An ion with mass $A = 250$ revealing a reduced cyclotron frequency ν_+ of about 420 kHz ($B = 7\,\text{T}$, $U = 10\,\text{V}$) is expected to give $S/N \approx 0.9$ which lies below the detection limit. For any given ion species q/m the S/N is proportional to the factor $\sqrt{Q/(TC)}$. Here Q denotes the quality factor of the tuned circuit, T the temperature, and C the capacitance of the overall detection system. Changing the technology of the tuned circuit from resistive to superconducting material leads to an estimated increase in S/N by a factor of 3.2. A reduction of the temperature from 300 K to for example 77 K results in a factor of 2.0. The capacitance C is given by

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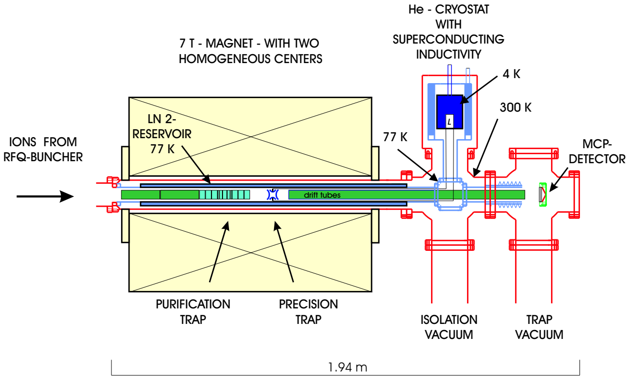

Fig. 1. Schematic of the SHIPTRAP cryogenic trap setup [10]. Two Penning traps are placed inside a vacuum tube that is cooled by a liquid N_2 flow. The ion motion is detected with a superconducting, tuned circuit L in an external liquid He dewar. A flexible bellow (right side) is used in order to compensate the length contraction of the vacuum chamber during initial cooling down. The drift tubes and the microchannel plate (MCP) allow for an ejection of ions and a subsequent time-of-flight determination.

the distance of the tuned circuit to the trap and therefore defined by the design.

The drawback in the reduced bandwidth of this detection scheme is that only a limited mass range of $A \approx \pm 10\,\mathrm{u}$ is accessible, else the tuned circuit has to be modified and exchanged. Hence, the FT-ICR detection will be exclusively dedicated to the nuclides ($T_{1/2} > 1\,\mathrm{s}$) that are produced in rare amounts at SHIP. Nevertheless fusion products with higher production cross-sections can be alternatively studied with the destructive time-of-flight method. In addition the delivery of purified, rare nuclides from SHIPTRAP to subsequent experimental setups is envisaged in the future. Hence, the trap system had to be kept open at the exit side which determined the position of the detection inductivity and the design of the setup inside the warm bore of the superconducting magnet. The cryogenic Penning trap system that has been built [10] is schematically shown in fig. 1. The double trap setup, consisting of a cylindrical purification trap for isobaric cleaning and a hyperbolic precision trap for the frequency determination is kept at liquid nitrogen temperature. The precision trap (see fig. 2) is made of hyperbolically shaped electrodes, which guarantees a high harmonicity of the storage potential across a large volume. Even in the case of exciting the ion motion to a large radius in order to detect with sufficiently high signal-to-noise ratio, the ion will experience an harmonic electrostatic potential and a narrow resonance linewidth $\Delta\nu_{\mathrm{ion}}$ can be achieved. This resonance signal is picked up with a tuned, superconducting inductivity L made from NbTi which is placed in an external liquid helium dewar (4.2 K).

By this means the signal-to-noise ratio in the cryogenic setup with combined liquid N_2- and He-cooling will be improved by at least a factor of seven compared to a room temperature setup. This implies an increase in sensitivity which enables the detection of a single ion as well as successive measurements with the same ion. Furthermore, the improved background pressure inside the precision trap guarantees a longer coherence time of the ion motion during the detection period.

Fig. 2. Precision trap with hyperbolic electrodes. The characteristic trap dimensions are $\rho_0 = 6.38\,\mathrm{mm}$ as the minimum radius and $z_0 = 5.5\,\mathrm{mm}$ as the minimum distance from the trap center to the endcaps. Electrodes are isolated via customized sapphire pieces. The ring electrode is azimuthally segmented into an electrode pair for excitation ($2 \times 40°$) and detection ($2 \times 140°$).

In contrast to a TOF-ICR measurement, where the true cyclotron frequency ν_{c} is determined, here the trap eigenmotion with the reduced cyclotron frequency ν_+ is monitored. Using the expansion $\nu_+ \approx \nu_{\mathrm{c}} - V_0/(2\pi 2d^2 B)$, for the characteristic trap dimension d ($d^2 = (1/2)(z_0^2 + \rho_0^2/2)$), the true cyclotron frequency can be deduced from few measurements at different storage potentials V_0 and an extrapolation to zero. In order to calibrate the strength of the magnetic field B, reference ions with precisely known mass values will be studied in alternate measurements. For this purpose singly ionized carbon clusters ($^{12}\mathrm{C}_n^+, 1 \leq n \leq 23$) provide the ideal tool for *absolute* mass calibration. The advantages in conjunction with a FT-ICR detection at SHIPTRAP are twofold: In the first place, reference masses covering the entire nuclear chart are obtained [11]. Hence, systematic effects can be studied and since the calibration mass is at most six mass units different from the mass to be determined, the resulting mass-dependent frequency shifts are reduced [12]. In the second place, the short time needed for a complete frequency determination with FT-ICR permits more frequent calibration measurements and reduces the effect of the temporal magnetic-field drift.

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