International Journal of Mass Spectrometry 379 (2015) 33–45

Contents lists available at ScienceDirect

International Journal of Mass Spectrometry

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

High-resolution mass separation by phase splitting and fast centering of ion motion in a Penning trap

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ARTICLE INFO

Article history:
Received 8 September 2014
Received in revised form
16 December 2014
Accepted 17 December 2014
Available online 27 December 2014

PACS:
07.75.+h
82.80.Qx

Keywords:
Penning trap
Mass-selective ion centering
Isobaric separation
Phase imaging ion cyclotron resonance
Magnetron manipulation

ABSTRACT

A new technique for fast and effective mass separation of isobaric-contaminant ions is presented based on the continuous control of the phase and magnetron radius of ions orbiting in a Penning trap. Inspired by two techniques: Phase imaging ion cyclotron resonance (PI-ICR) (Eliseev et al., 2013) and magnetron-orbit manipulation (Mortensen et al., 2013), this method does not require ion cooling. First, isobaric species are separated in the radial plane by mass-selective excitations. A radial, position-selective dipole excitation pulse is then applied to re-center only the ions of interest. This paper presents the theoretical analysis of the process with detailed simulations. Results are compared to another buffer-gas free technique: SImultaneous Magnetron and resonant COnversion (SIMCO) excitation (Rosenbusch et al., 2012). Despite a lower maximum resolving power, the new process is twice as fast as SIMCO.

1. Introduction

Nuclear physics requires the study of very exotic isotopes, those having excessive ratios of protons to neutrons. These are produced at radioactive beam facilities using a variety of nuclear reactions with accelerated projectile beams. As these reactions are not selective, radioisotope facilities all include some form of magnetic mass separation to purify the exotic-ion beam [4]. The limited production rates of exotic species are compounded by the presence of overwhelming isobaric contamination: nuclides with the same mass number but less exotic combinations of protons and neutrons. The mass resolving power required to separate neighboring exotic isobars reaches 10^4 but in many cases (including molecular cross-contamination) exceeds 10^5. Classic dipole mass separation has only limited success since the relatively large beam emittances limit resolving power to less than 10^4.

Cylindrical Penning traps can offer very high mass resolving power. The success of Penning traps lies in the manipulation of the two radial eigenmodes of the trapped-ion motion: the fast (mass-dependent) cyclotron motion and the slow (mass-independent) magnetron motion. Typically the mass separation methods in such trap use mass selective excitations leading to a centering of the ions of interest while the contaminants are radially shifted. Only the desired species remains after ejecting the ions through a diaphragm. For example, the commonly-used sideband buffer-gas cooling technique reaches a resolving power of about $\mathcal{R} = 10^5$ [5,6]. The ions are first excited by a dipolar excitation at the magnetron frequency, leading to a large magnetron radius. A quadrupolar excitation is then applied at the cyclotron frequency of the desired ions. At the resonance, this excitation provides a conversion of the magnetron motion into reduced cyclotron motion, which is damped by buffer-gas collisions. This combination allows thus the centering of the desired ions. Off resonance, the contaminants keep a large magnetron radius, that is even increased by the buffer-gas collisions [7]. An improvement of an order of magnitude of the resolving power has been demonstrated by using an octupolar excitation, however this scheme is very sensitive to the initial phase space of the ions [8–10].

Other techniques have been developed without the use of buffer-gas. One of the motivations is notably the higher achievable resolving power, required for example for isomer identification. Moreover buffer-gas can have deleterious effects, e.g. charge exchange in the case of highly charged ions. Cleaning can be

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http://dx.doi.org/10.1016/j.ijms.2014.12.007
1387-3806/

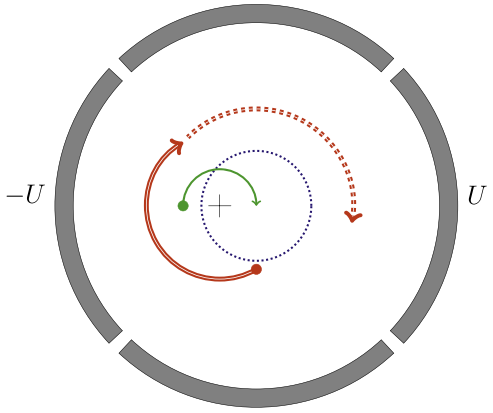

Fig. 1. Schematic illustration of the new technique, shown in the radial section of the trap. The dotted (blue) circle corresponds to the radius of the diaphragm. The contaminants (red point) are separated from the ions of interest (green point). All the ions have a pure magnetron motion. The DC pulsed dipolar excitation is applied until the trajectory of the ions of interest (green line) crosses the geometric center of the trap by shifting the electric center (black cross), while the contaminants trajectory (double solid line) remains larger than the radius of the diaphragm. At the end of the excitation, the magnetron orbit of the contaminants (double dashed line) remains outside the radius of the diaphragm. (For interpretation of reference to color in this figure legend, the reader is referred to the web version of this article.)

performed by a dipole excitation at the reduced cyclotron frequency of the contaminant, increasing the radius while the ions of interest remain at small radii. Analog schemes using various excitation profiles have been demonstrated such as a Gaussian envelope or the Ramsey excitation using time-separated oscillatory fields [11], both with a resolving power more than 10^5. However the identification of the contaminants is required for these techniques, contrary to the sideband buffer-gas cooling. They are typically dedicated to experiments involving only one contaminant species, although a broadband cleaning can be achieved using the stored waveform inverse Fourier transform (SWIFT) technique [12].

The presented technique avoids the use of buffer-gas and is independent of the number of contaminants species. This is an important advantage since experiments (of limited duration) require considerable time to be devoted to the identification of contamination for its elimination. The technique exploits the ability of recentering ions selectively in the radial plane of the trap with a pulsed dipolar excitation [2], shifting the electric center of the trap and thus only acting on the ion magnetron motion. The excitation is applied until the magnetron orbit of the ions of interest reaches the geometric center of the trap, as shown in Fig. 1.

Section 2 gives an overview of the theoretical background of the ion motions in a Penning trap. In Second 3, the technique is presented in detail with the theoretical analysis of each step. The power of separation and the limitations of the technique are then described. Section 4 presents the comparison of the technique with the SIMCO excitation [3], with which resolving powers up to $7 \cdot 10^5$ have been achieved. Its theoretical analysis has been done by Kretzschmar [13]. This excitation does not make use of buffer gas cooling and is independent of the number of contaminants species, as the process described in this paper. SIMCO is therefore used as a reference to quantify the efficiency of the presented technique.

2. Theoretical background and criteria of selectivity for the isobaric separation technique

An ideal Penning trap confines charged particles by combining a strong magnetic field $B\vec{e}_z$ along the trap axis (conventionally chosen as the z-axis) and an electric potential $\phi = \frac{U_0}{d^2}(2z^2 - r^2)$ produced by a set of electrodes. U_0 is the potential depth of the well and d its characteristic length, that depends on the geometry of the electrodes. In a such device, a charged particle with a mass m and a charge q exhibits an axial oscillation at the frequency ω_z and two radial circular modes: the magnetron motion with frequency ω_- and the reduced cyclotron motion with frequency ω_+:

$$\omega_z = \sqrt{\frac{qU_0}{md^2}} \tag{1}$$

$$\omega_\pm = \frac{1}{2}\left(\omega_c \pm \sqrt{\omega_c^2 - 2\omega_z^2}\right) \tag{2}$$

where $\omega_c = qB/m$ is the cyclotron frequency. These frequencies obey the hierarchy:

$$\omega_- \ll \omega_z \ll \omega_+ \sim \omega_c \tag{3}$$

The Newtonian equation in the radial plane can be expressed in complex coordinates $u = x + iy$ [14]:

$$\ddot{u} + i\omega_c\dot{u} - \frac{1}{2}\omega_z^2 u = 0 \tag{4}$$

Solving (4) leads to the evolution of charged particles in the radial plane of the trap:

$$u(t) = R_+ e^{-i(\omega_+ t + \phi_+)} + R_- e^{-i(\omega_- t + \phi_-)} \tag{5}$$

where R_+, R_- and ϕ_+, ϕ_- are respectively the modified cyclotron and magnetron radii and phase. The radial motion is then a combination of two circular orbits. The particle moves within a circular ring between the inner radius $\left|R_+ - R_-\right|$ and the outer radius $R_+ + R_-$. The radial size of the cloud R_c is defined by the maximum outer radius.

The expression of the total radial motion defines the criteria of selectivity for isobaric separation using a diaphragm:

$$R_{+,i} + R_{-,i} < R_d \tag{6}$$

$$R_{+,c} + R_{-,c} > R_d \tag{7}$$

where R_d is the radius of the diaphragm and the subscripts i and c respectively refer to the ions of interest and the contaminants. If both species of ions fulfill these conditions, the desired ions go through the diaphragm, while the contaminants do not. In principle it is the absolute value of difference in radii of relation (7). In the following discussion, we will consider that the time of the transport through the diaphragm is longer than the cyclotron period, so that the contaminants are dumped on the diaphragm or on its inner surface if the criterion (7) is fulfilled. Note that this assumption on the different timescales is typically confirmed. Moreover, the initial radius of the cloud R_c is assumed smaller than the radius of the diaphragm R_d.

In case of isobaric ions, we will assume that the difference of cyclotron frequencies $\delta = \omega_{c,i} - \omega_{c,c}$ is negligible compared to the magnetron frequency. Thus, the magnetron frequencies of all the species are equal to first order and the difference of reduced cyclotron frequencies is equal to δ to first order.

3. Description of the technique

For ions initially centered in the radial plane, the phase splitting technique uses a sequence of three azimuthal excitations:

1 a: A dipolar excitation at the reduced cyclotron frequency $\omega_{+,i}$ of the desired ions is first applied. This mass-selective excitation increases the modified cyclotron radius of the ions. During this step, the different species evolving with a pure reduced cyclotron motion, are separated in the radial plane.

1 b: A supplementary step can also be added without excitation. As the motion of the species is purely cyclotron, their angular