A Mechanism for Poor High Mass Performance in Fourier Transform Mass Spectrometry

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The discovery of a mass-dependent electrical mechanism for signal loss of high mass ions in Fourier transform mass spectrometry is reported. Theoretical calculations and experimental evidence show the existence of resonances involving the z -motion and radial motion of the ion. The resonances are intrinsic in the cubic trap. This results in energy transfer between modes, expansion of the ion cloud, and a corresponding loss of signal. Quadrupolar trapping potential wells are proposed as a solution. (*J Am Soc Mass Spectrom* 1992, 3, 460-463)

Fourier transform mass spectrometry (FTMS) has proved to be a high mass, high resolution, multichannel analyzer [1-3]. For example, resolving powers of 60,000 and 53,000 were reported for abundant ion populations of m/z 5922 and 9745, respectively. This has motivated the coupling of high mass ionization techniques such as electrospray and matrix-assisted laser desorption with the Fourier transform technique [4, 5].

Nevertheless, the potential of the technique is seldom achieved for small ion populations such as those generated with biomolecules [1, 6-8]. Indeed, Hunt et al. [1] have shown that large populations of the cesium iodide cluster of m/z 5848.7 can be detected at resolutions in excess of 30,000, whereas horse cytochrome c at m/z 12384 is detected with a resolution of less than 100. Degradation of high mass performance is likely due to electrical effects because the relative strength of the magnetic field decreases as mass increases. Scaling experiments show that moderation of these effects is possible [9]. Elimination of peak splitting and optimization of resolution were achieved by an increase in ion number or simple compensation of the trapping plates.

We report in this communication the discovery of an electrical mechanism that leads to degradation of performance at high mass in the cubic trap. The mechanism involves a mass-dependent parametric resonance that involves the radial and z -motion of the ion and, apparently, is similar to mechanisms observed in magnetic bottles [10]. In this article, radial motion refers to the ion's displacement, due to the

superposition of the magnetron and trap-shifted cyclotron motions, from the z -axis. The radial motion is periodic with a frequency that is the trap-shifted cyclotron frequency minus the magnetron frequency [11]. The resonance results in radial expansion of clouds of ions having specific ranges of mass-to-charge ratios and is intrinsic in the operation of the cubic trap in that it occurs, apparently, when no excitations are applied. Hunt, Russell, and co-workers [12] suggested, without demonstration, that radial expansion of the ion cloud would result in loss of ion-phase coherence and signal degradation. This is supported by the experimental and theoretical evidence presented below. Other mechanisms that lead to radially expanded cloud are associated with ion desorption, injection [12], and initial thermal kinetic energy [13].

The location of the parametric resonances in the mass spectrum can be rationalized when the coupling between the radial and z -motion is weak and trap center assumptions apply. As an ion z -mode oscillates in an inhomogeneous electric trap field, the radial electric force on the ion is modulated in time. If there is a component in the modulation that has a frequency the same as the radial motion of the ion, a parametric resonance exists, and the radial motion of the ion becomes unstable and can grow. This would be analogous to overt parametric excitation of the ions as employed in ref 11. Because there is symmetry in the inhomogeneity about the $z = 0$ plane, the components of the radial electric force modulation are expected to have frequencies that are even harmonics of the fundamental z -mode frequency. In the trap center approximation, the radial frequency (eq 1) is equated with the z -mode harmonic that is $2n$ times the z -mode fundamental (eq 2) [14], $n \in \{1, 2, 3, \dots\}$, to give the relation in eq 3 between the critical mass and the mass

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m of singly charged ions that are affected by the resonance.

$$\omega_+ - \omega_- = \frac{qB}{m} \sqrt{1 - \frac{m}{m_c}} \quad (1)$$

$$\omega_z = \sqrt{\frac{4q\alpha V_T}{ma^2}} \quad (2)$$

$$m = \left(\frac{1}{2n^2 + 1} \right) m_c \quad (3)$$

In eq 3, $m_c = qB^2 a^2 / 8\alpha V_T$ is the critical mass [15], a is the cell length, $\alpha = 1.3869$ is a geometry constant, and V_T is the trapping potential.

Numerical calculations for a 0.0254-m cubic trap at a 1-V trapping potential were performed in concert with experiment to locate and gauge the strength of the resonances. First, Beauchamp's [16] phenomenological equation was rewritten as a first order differential equation (eq 4).

$$\frac{d\vec{X}}{dt} = \vec{f}(\vec{X}, t) \quad (4)$$

Solutions to the continuity eq 5 [17] give the first order change in the state $\vec{X}$ at time t with respect to the initial state coordinates X_{i0} at t_0 and, therefore, specify solution trajectories of eq 4 close to a chosen trajectory.

$$\frac{d}{dt} \left[\frac{\partial \vec{X}}{\partial X_{i0}} \right] = \frac{\partial \vec{f}}{\partial \vec{X}}(\vec{X}(t), t) \left(\frac{\partial \vec{X}}{\partial X_{i0}}(t) \right) \quad (5)$$

$i \in \{1, \dots, \dim \vec{X}\}$

Dragt refers to eq 5 as variational equations [18] and makes use of them in the treatment of chromaticity in small storage rings [19].

The chosen trajectory for eq 4 is determined by starting the ion at rest on the z axis; thus, the chosen trajectory lies on the z axis. The starting position between the trap center and a trap plate determines the initial z -mode amplitude A_z , which is given here in a form normalized by the maximum possible z -mode amplitude. Because the cubic trap is symmetric with respect to a 90° rotation about the chosen trajectory on the z axis, the number of equations in eq 5 were reduced from 36 to 12. Furthermore, owing to this symmetry and Gauss' law, the expression of the trap electric field in eq 5 is completely determined by the electric potential along the z axis.

A variable-order, multistep predictor-corrector method [20] was used to integrate numerically the combined system of eqs 4 and 5 for a time of 50 ms after ionization, but before excitation. For these calculations, the reduced collision frequency was assumed to be zero. The electric potential was given by an eighth order polynomial that was fitted to the evalua-

tion of the separation-of-variables series solution of the trapping potential.

The ion cloud maximum radial extent is shown in Figure 1 and gives the largest ion cloud radius during the 50-ms integration time. The radial extent includes contributions from both the cyclotron and magnetron motions. The ion cloud radius was evaluated at every 1/1000th of the cyclotron period by using the first order approximate of the transfer map as deduced from $\partial \vec{X} / \partial \vec{X}_0$. The ion cloud radius was based on an electron beam diameter that was one tenth the trap size and an initial ion radial speed equal to the mean speed of a 300-K neutral of the same mass. Figure 1 shows calculated results for ions with relative z -mode amplitudes (A_z) of 0.1 to 0.9. The maximum radial extent was clipped at the maximum possible radius of the trap of 0.0127 m.

Parametric resonance is indicated for various mass-to-charge ratio ions that undergo an increase in the maximum radial extent (i.e., undergo cloud expansion). Any mechanism that transfers energy from the magnetron mode will increase the magnetron radius [21]. From inspection of the numerical calculations it appears that on resonance, energy is transferred from the magnetron mode to the cyclotron mode to increase the radii of both. No change in the z -mode energy has been detected so far. Curiously, there is no expansion indicated by the first order calculations at $A_z = 0.8$. The lack of first order expansion, however, does not necessarily imply there is no expansion at higher orders.

Experiments were done with an FTMS system consisting of a 2.54-cm, molybdenum cubic trap mounted between the poles of a Varian (Varian Associates, Walnut Creek, CA) V-3400 iron magnet with a V-FR250

Figure 1. Numerical calculation of ion cloud radius as a function of mass-to-charge ratio for ions of various relative z -mode amplitudes (A_z). Ions of different z -mode amplitudes will resonantly couple with the radial modes over different mass-to-charge ratio ranges. The dashed line is drawn at that mass-to-charge ratio value calculated from eq 3 when $n = 2$. The inset along the mass-to-charge ratio axis gives the experimental results obtained by the scaling technique (see Figure 2) and are superimposed for the reader's convenience.

Fieldial current regulator. The maximum field strength was 1.2 Tesla. Ion populations were from benzene at 2×10^{-8} torr (uncorrected from the ion gauge reading) ionized at 15 eV employing 300 nA of emission current followed by a 100-ms delay. Excitation was by a 0.35 V_{b-p} constant frequency radiofrequency pulse to each excitation plate. Detection was in the heterodyne mode using 4 k data points. The behavior of different high mass (target) ions at 7 Tesla was investigated with the benzene (model) ion by scaling the magnetic field strength and time parameters by eqs 6-8 [9].

Target mass:

$$\text{mass}_{\text{target}} = \frac{(B_{\text{target}})^2 \text{mass}_{\text{model}}}{B_{\text{model}}^2} = \frac{(7 \text{ Tesla})^2 78 \text{ u}}{B_{\text{model}}^2} \quad (6)$$

Excitation time:

$$\begin{aligned} \text{time}_{\text{model}} &= \text{time}_{\text{Benzene@1.2T}} \frac{B_{\text{model}}}{B_{\text{Benzene}}} \\ &= 700 \mu\text{sec} \frac{B_{\text{model}}}{1.2 \text{ Tesla}} \end{aligned} \quad (7)$$

Bandwidth:

$$\begin{aligned} \text{BW}_{\text{model}} &= \text{BW}_{\text{Benzene@1.2T}} \frac{1.2 \text{ Tesla}}{B_{\text{model}}} \\ &= 1000 \text{ Hz} \frac{1.2 \text{ Tesla}}{B_{\text{model}}} \end{aligned} \quad (8)$$

To model the mass-to-charge ratio range 25652 to 37324, the magnet strength was scaled from 0.386 to 0.320 Tesla, the excitation time from 225.2 to 186.7 μsec , and the bandwidth from 3.1 to 3.8 KHz, respectively.

The loss of ion-phase coherence and signal degradation associated with expanded ion clouds were observed in two experiments [22] and will be discussed in detail in a full-length article. In the first experiment high mass behavior was modeled for an ion of m/z 20000 at 7 T by using the benzene molecular ion at 0.437 T. There is increasing loss of signal as radial expansion progresses due to an increasing number of ion-neutral collisions occurring during an increasing time delay between ionization and excitation. In the second experiment overt expansion of methane molecular ion at 1.215 Tesla was achieved by application of a 1.16145 MHz 1.0 V_{b-p} radiofrequency burst on the dc bias of the trapping plates. There was no signal observed for small ion populations, which had generated large signals without the trap plate modulation, and a poor signal at a higher ion population could be significantly improved by a small increase in population. The effect of ion number on the signal mimics that observed for high mass ions [9].

The experimentally measured effects of the resonance on the spectral peak height of the benzene molecular ion when $n = 2$ are shown in Figure 2. The region of signal loss is 5000 mass-to-charge ratio units wide and centered at m/z 31000. This compares well

Figure 2. Experimental results of modeling high mass ion behavior with benzene for different ion numbers. Signal loss (determined by peak height) parallels the range for which numerical calculations (see Figure 1) predict orbit radius expansion. The shaded areas indicate plus and minus one standard deviation from the average of six measurements. Ionization times were: (○) 100 ms, (◇) 50 ms, (△) 25 ms, and (▽) 12.5 ms.

with the theoretical estimate of m/z 30545. The structure of the signal loss is relatively simple and parallels the mass-to-charge ratio range and location for which numerical calculation predicts that cloud expansion would occur. For this resonance, numerical calculations show the range of mass-to-charge ratio values at which the ion cloud expands is a function of the ion's z -mode amplitude (see Figure 1). These mass-to-charge ratio ranges fall over the same relatively narrow mass interval, thus predicting a simple band of signal loss with few complications in the features. Resonances when $n = 1$, centered at m/z 91500, and $n = 3$, centered at m/z 14500, were also experimentally observed, and they also correlate with theory.

We propose that traps more anharmonic than the cubic cell should produce stronger coupling between the z and radial modes. In these traps wider and stronger resonances are expected to occur. Accordingly, quadrupolar potential wells are the appropriate direction for the new trap designs that are needed for high mass work.

Acknowledgments

This research was supported by the National Science Foundation (grant nos. DIR-9017262 and CHE-9017250).

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