Mass Analysis with Islands of Stability with Linear Quadrupoles Incorporating Higher Order Multipole Fields

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Mass analysis with islands of stability has been investigated with three linear quadrupole mass filters: two with 4% added hexapole fields constructed with equal diameter (quadrupole 4A) and unequal diameter (quadrupole 4B) rods, and a conventional round-rod quadrupole that has apparently been slightly damaged. Islands are formed by applying auxiliary quadrupole excitation. With the Mathieu parameter, $a < 0$, mass analysis with both quadrupoles with hexapole fields operated normally, i.e., without islands, gives only low resolution. A factor of 10 or more increase in resolution is possible with the use of stability islands. With $a > 0$, when quadrupole 4A is operated normally, peak shapes similar to that of a conventional quadrupole can be obtained at resolutions higher than 850. At lower resolutions, peaks are split. When quadrupole 4B is operated without islands, resolution up to 2000 is possible, but there are low mass tails and structure is formed on the peaks. With mass analysis with an island of stability, both quadrupoles 4A and 4B show peaks free of structure and without tails. Ion transmission is also improved with some operating conditions. With the conventional round-rod quadrupole, mass analysis with islands of stability increases the limiting resolution from 2500 to 4360. At a resolution of 2500, the transmission is increased by about two orders of magnitude. These results show that the use of islands of stability improves mass analysis with quadrupoles with distorted fields, and may, in the future, allow use of quadrupoles constructed with at least some lower mechanical tolerances. (J Am Soc Mass Spectrom 2010, 21, 393–402) © 2010 American Society for Mass Spectrometry

Linear quadrupoles can be operated as either radio frequency (rf) only ion guides for ion transport, mass filters [1–4] or ion traps [5]. As with 3D Paul traps [6], adding higher order multipole fields, either DC [7] or rf [8], to a linear quadrupole can improve MS/MS fragmentation efficiency. In some instruments, a quadrupole operated as a linear ion trap (such as Q3 in a triple quadrupole mass spectrometer) must also be capable of mass analysis [9].

In general, the potential of a linear quadrupole with field distortions can be written as [10]

$$V(x, y, t) = \operatorname{Re} \left[\sum_{N=0}^{\infty} A_N \left(\frac{x + iy}{r_0} \right)^N \right] \varphi(t) \quad (1)$$

where x and y are Cartesian coordinates, r_0 represents the distance from the central axis to an electrode for an ideal quadrupole and otherwise is a normalization factor, $\operatorname{Re}[f(x + iy)]$ is the real part of the complex function $f(x + iy)$, $i^2 = -1$, A_N is the dimensionless amplitude of a multipole ($2N$ -pole), and $\varphi(t)$ is a time-dependent voltage applied to the electrodes. An ideal linear quadrupole has $A_2 = 1$ and all other multipoles

zero. A practical linear quadrupole usually has $A_2 \approx 1$, and other higher order multipole amplitudes in the range 10^{-5} to 10^{-3} [2–4]. Methods of adding an octopole field of 2% to 4% [11], i.e., $A_4/A_2 = 0.02 - 0.04$, and a hexapole field [12] of up to 12% ($A_3/A_2 \leq 0.12$) to linear quadrupoles constructed from round rods have been described. (Hexapole and octopole fields are the next two higher multipoles after the quadrupole in the expansion of eq 1.) A hexapole field is added by rotating the two y rods towards an x rod through a small angle θ . The amplitude of the hexapole, A_3 , is approximately proportional to θ . This method also adds other higher multipoles, including an octopole field [12].

Addition of these field distortions might be expected to cause conventional mass analysis, done by scanning the applied direct current (DC) and radio frequency (rf) voltages so that ions cross the tip of the first stability diagram [1], to deteriorate. Nevertheless, mass analysis with quadrupoles with added octopole [13] or hexapole [14] fields has been found to be possible in some cases, provided the positive DC is applied to the x rods so that the Mathieu parameter a , (eq 5 below) is positive for positive ions.

For mass analysis, linear quadrupoles can also be operated with islands of stability [4, 15–20]. Islands of stability, separated by bands of instability, are formed in a stability region when auxiliary quadrupole excita-

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tion with a properly chosen frequency and amplitude is added to the quadrupole. Islands can also be formed by amplitude modulation of the main rf voltage, the DC voltage, or both the rf and the DC voltages [19]. Tips of the stability islands are potential candidates for mass analysis.

Previously, mass analysis with islands has been used to correct for minor field distortions. Miseki [15] described the use of islands to correct for manufacturing tolerances and errors and showed it can be used to remove tails on peaks. Kononkov et al. [16], showed that use of islands can remove tails on peaks, but with “a high precision quadrupole.” Baranov et al. [17] also showed that the use of islands removes peak tails to improve abundance sensitivity, but with a commercial quadrupole designed to have minimal field distortions. Glebova and Kononkov [18] modeled the use of islands for “quadrupoles that have weak-field distortions.” They compared mass analysis with an ideal quadrupole field to mass analysis with the field of a quadrupole constructed with round rods instead of hyperbolic rods. The round rod set had multipole amplitudes, $A_2 = 1.00176$, $A_6 = 1.00 \times 10^{-3}$, and $A_{12} = 2.44 \times 10^{-3}$. They too showed that use of islands removes tails on the low mass side of the peak. For the same round-rod quadrupole, Kononkov et al. [19] showed that not only did the use of islands remove peak tails, but also the number of rf cycles required to reach a resolution of 400 was decreased from ~150 without islands to 75. In all these papers, islands were used to correct for minor field distortions, with $A_N/A_2 \approx 10^{-3}$.

We have found that the use of islands of stability can in some cases overcome the much greater field distortions of quadrupoles that have added octopole or hexapole fields. Computer simulations [20] and then experiments [21] showed that with quadrupoles with an added octopole field of 2%–4%, use of an island allows mass analysis when the positive DC is applied to the y rods. Without use of an island, only low-resolution and transmission are possible. Zhao et al. showed that with quadrupoles that have added hexapole fields of 4%–12%, use of a stability island greatly improves peak shape, resolution and, in some cases, transmission [22]. With added hexapole fields of 8% and 12%, the islands used were very narrow, and only a limited range of resolution could be explored. With quadrupoles with 4% added hexapole fields, islands similar to those of a conventional quadrupole can be formed, and the resolution can be adjusted over a considerable range by adjusting the slope of the scan line.

In this work, we report more detailed experimental investigations of mass analysis using islands of stability with three linear quadrupoles. Two of these quadrupoles have 4% added hexapole fields. The first, quadrupole 4A, has equal diameter rods. The second, quadrupole 4B, has x rods greater in diameter than the y rods to remove an octopole field. The third quadrupole is a conventional design with round rods, but apparently has been slightly damaged. With quadrupoles 4A and

4B with the positive resolving DC applied to the y rods, so that the Mathieu parameter $a < 0$, conventional operation gives only low-resolution mass spectra. It is possible to increase the resolution by a factor of 10 or more with the use of islands. With the DC reversed, so that $a > 0$, when quadrupole 4A is operated normally, i.e., without islands, peak shapes similar to that of a conventional quadrupole can be obtained at resolutions higher than 850, but peaks tail slightly on the high mass side. At resolutions lower than 850, split peaks are observed. When quadrupole 4B is operated without islands, although resolution up to 2000 is possible, low mass tails are observed at higher resolution and structure is formed on the peaks at intermediate resolution. When quadrupoles 4A and 4B are operated with mass analysis using an island of stability, peaks free of structure and without tails are formed, and, with some operating conditions, the transmission is increased. For the conventional round-rod quadrupole, mass analysis with islands increases the limiting resolution from 2500 to 4360. At a resolution of 2500, the transmission is increased by about two orders of magnitude. The experimental results show that the use of islands of stability improves mass analysis with quadrupoles with distorted fields, and may, in future, allow use of quadrupoles constructed with at least some lower mechanical tolerances.

Methods

Islands of Stability Theory

With auxiliary quadrupole excitation, the time-dependent voltage applied to a quadrupole is

$$\varphi(t) = U - V_{rf}\cos(\Omega t - \phi_0) - V'\cos(\omega_{ex}t) \quad (2)$$

where U is a DC potential applied to the electrodes, V_{rf} , Ω , and ϕ_0 are the amplitude, angular frequency, and initial phase of the main rf voltage, V' is the amplitude of the quadrupole excitation voltage with angular frequency ω_{ex} , and t is time. The equations of ion motion for the x and y directions for an ion of mass m can be written as

$$\frac{d^2x}{d\xi^2} + (a - 2q\cos[2(\xi - \xi_0)] - 2q'\cos(2\nu\xi)) \left(x + \frac{r_0^2}{2} \frac{\partial}{\partial x} \text{Re} \left[\sum_{n \neq 2} \frac{A_n}{A_2} \left(\frac{x + iy}{r_0} \right)^n \right] \right) = 0 \quad (3)$$

$$\frac{d^2y}{d\xi^2} + (a - 2q\cos[2(\xi - \xi_0)] - 2q'\cos(2\nu\xi)) \left(-y + \frac{r_0^2}{2} \frac{\partial}{\partial y} \text{Re} \left[\sum_{n \neq 2} \frac{A_n}{A_2} \left(\frac{x + iy}{r_0} \right)^n \right] \right) = 0 \quad (4)$$

where the dimensionless parameters are defined as

$$\begin{aligned}\xi &= \frac{\Omega t}{2}; \quad \xi_0 = \frac{\phi_0}{2} \\ a &= \frac{8zeU A_2}{m\Omega^2 r_0^2}; \quad q = \frac{4zeV_{rf} A_2}{m\Omega^2 r_0^2} \\ \nu &= \frac{\omega_{ex}}{\Omega}; \quad q' = \frac{4zeV' A_2}{m\Omega^2 r_0^2} = q \frac{V'}{V_{rf}}\end{aligned}\quad (5)$$

where z is the number of charges on the ion and e is the electron charge. Note q' is a measure of the quadrupole excitation strength. For a quadrupole with added higher order multipoles, the excitation field contains multipoles other than the quadrupole term. This is reflected in the summation terms in eqs 3 and 4.

When the ratio of the quadrupole excitation frequency to the main rf frequency is chosen to be

$$\nu = \frac{\omega_{ex}}{\Omega} = \frac{Q}{P} \quad (6)$$

where Q and P are integers with no common divisors except for 1, the common period of the main rf voltage and quadrupole excitation voltage is $\xi = P\pi$. For the special case of an ideal quadrupole ($A_2 = 1$ and all other multipole amplitudes zero), eqs 3 and 4 become Hill equations [23–25] because the coefficients are periodic in ξ . To determine the stability of the solutions of eqs 3 and 4 the matrix method is particularly advantageous. Details of the matrix method applied to the solutions of Hill equation can be found in [23], and applications to rf quadrupoles are in [24].

When $\nu = Q/P$, the unstable points form bands of instability along iso- β lines for the x and y directions. As a result, the first stability region in the (a, q) plane splits into islands of stability. The maximum possible number of unstable bands in each of the x and y directions is $P - 1$. The number of bands observed is usually less. The width of each band depends on the excitation

voltage and frequency. With the addition of nonlinear multipole fields to a quadrupole field, the matrix method is no longer strictly applicable to the calculation of stability, because eqs 3 and 4 have nonlinear terms and are no longer Hill equations. For example, theory and experiments show that with quadrupole excitation in linear quadrupoles with added octopole fields, the x and y frequencies differ slightly, so the island boundaries will not exactly match those calculated for a pure quadrupole field [26]. However, it has been found by simulations [20] and experiments [16, 17, 21] that the overall trend of island formation is still the same for quadrupoles incorporating weak higher order multipoles.

Operation with Islands of Stability

The positions of the stability islands and the widths of the unstable bands separating the stability islands are determined by the excitation frequency (ν) and strength (q'). The tips of stability islands can be used for mass analysis provided the scan line crosses only one island. The slope of a scan line is defined as

$$\lambda = \frac{a}{2q} = \frac{U}{V_{rf}} \quad (7)$$

Experimentally, for a given quadrupole excitation frequency, the excitation amplitude V' and the scan line slope λ are varied until a scan line can be found to cross the tip of one stability island only.

Figure 1 shows stability islands calculated with $P = 20$ and $P = 30$ ($\nu = 1/20$ and $\nu = 1/30$). Fringing fields were not included in the calculations. Nevertheless the island positions are likely realistic. Experimental measurements of the q values of island tips of a quadrupole with a 2.0% added octopole field are in good agreement with calculations that do not include the fringe fields [21]. With increasing P , the left-most stable bands

Figure 1. The first stability region without quadrupole excitation of an ideal quadrupole, shown by the solid triangle, and the stability islands formed with (a) $\nu = 1/20$, $q' = 0.006$; (b) $\nu = 1/30$, $q' = 0.003$. The uppermost four islands that might be used for mass analysis are labeled A, B, C, and D. The very narrow strip at the left cannot be used for mass analysis and therefore is not named.

become very narrow strips as shown by the dotted lines in Figure 1. The transmission in these narrow islands is very low so that the uppermost islands formed inside the stability boundary can be used for mass analysis, such as the island crossed by the scan lines $\lambda = 0.165$ in Figure 1a and $\lambda = 0.166$ in Figure 1b. The islands are named A, B, C, and D, as illustrated in Figure 1a. Because these islands use different excitation conditions, ν and q' , they cannot be compared directly to the islands with the same labels, used by others [16]. Scans over extended mass ranges require increasing the excitation amplitude proportional to mass, to keep q' constant [16]. In this work, because we scan a very limited mass range, the excitation amplitude was not changed with mass.

Experimentally, we have used two methods to change the mass resolution. The first is to adjust the scan line slope near the tip of an island. The second is to adjust the quadrupole excitation frequency and amplitude to make narrow islands. In this second case the width of the island determines the mass resolution.

Experimental

Apparatus

Experiments were performed with a single quadrupole mass spectrometer system described previously [13, 21]. Ions generated by electrospray pass through an aperture in a curtain plate, a curtain gas, an orifice (0.125 mm in diameter), and enter a quadrupole ion guide (Q0, 4.6 mTorr) where they are collisionally cooled to energy spreads of a few eV, then pass through an entrance lens (3.0 mm aperture diameter) and enter a differentially pumped mass analyzing quadrupole (Q1, 1.2×10^{-5} Torr). The mass analyzing quadrupole Q1 can be either a conventional quadrupole or one of two quadrupoles with added hexapole fields. Ions leaving Q1 pass through a mesh-covered exit lens and a second exit lens. Both exit lenses have 9 mm diameter apertures. A channel electron multiplier is used for ion counting.

The quadrupole power supply (SCIEX API III; Concord, ON, Canada) is operated at 1.0 MHz. Auxiliary quadrupole excitation, generated by a function generator (DS345; Stanford Research Systems, Sunnyvale, CA, USA) is added to the main rf voltage with a circuit described previously [21], which allows both the DC and rf voltages from the quadrupole power supply to be applied to the quadrupole electrodes. For all the measurements here, the positive DC was applied to the x rods, unless otherwise stated. The quadrupole excitation and the main rf quadrupole power supply are not phase locked.

Typical voltage settings are sprayer +4.3 kV, curtain plate +500 V, orifice 160 V, Q0 DC offset +110 V, inter-quadrupole lens Q0/Q1 +92 V, Q1 DC offset 107 V, first exit lens –30 V, and second exit lens –150 V. The transmissions given are $100\times$ the ion count rate at a given m/z , because one hundred scans were summed

to give a spectrum. Resolution is defined as $R_{1/2} = (m/z)/\Delta(m/z)_{1/2}$, where $\Delta(m/z)_{1/2}$ is taken as the full width at half maximum of a peak. With reserpine ions, the resolutions given are calculated at $m/z = 609$. A scan step size of 0.1 Th was used to obtain the mass spectra presented here, unless otherwise stated.

Quadrupoles

Linear quadrupole rod sets with 4% added hexapole fields with $r_0 = 4.5$ mm were constructed by rotating the two y rods of a quadrupole towards an x rod through an angle, θ , of 2.56° . Rod set 4A has equal diameter rods. Rod set 4B has the x rods greater in diameter than the y rods to remove an added octopole field [12]. The diameters of the electrodes, and the amplitudes of multipoles up to A_{10} for these quadrupoles, calculated in a coordinate system centered at the field center [12], are listed in Table 1. The third quadrupole is a conventional round rod quadrupole with $r_0 = 4.17$ mm and a rod radius $R = 1.125r_0$. All the quadrupoles have a length of 200 mm.

Reagents

Reserpine (50 μ M), (Sigma, St. Louis, MO, USA), was prepared in 50% methanol/50% deionized water/0.3% acetic acid. Methanol, acetonitrile, and acetic acid were from Fisher Scientific (Nepean, ON, Canada). Glacial acetic acid was from Aldrich (Oakville, ON, Canada). UHP-grade nitrogen, used as the curtain gas, was from Praxair (Vancouver, BC, Canada).

Results and Discussion

Quadrupoles with 4% Added Hexapole Fields

Conventional mass analysis with quadrupoles 4A and 4B is possible [14, 22], provided that the positive DC is applied to the x rods, so that the Mathieu parameter $a > 0$. Quadrupole 4A gives peak shapes similar to

Table 1. The dimensionless amplitudes of the multipoles for quadrupoles with 4% added hexapole fields, $R_y/r_0 = 1.1487$, $r_0 = 4.5$ mm

	4A	4B
A_3/A_2	0.04	0.04
R_x/R_y	1	1.014
θ	2.56	2.56
A_0	–0.000219	0.001193
A_1	0.000000	0.000000
A_2	1.003482	1.004006
A_3	0.039715	0.039730
A_4	0.001467	0.000084
A_5	–0.007116	–0.007227
A_6	–0.000998	–0.001530
A_7	–0.001213	–0.001249
A_8	–0.000077	–0.000121
A_9	0.000060	0.000071
A_{10}	–0.002416	–0.002419

those of a conventional round-rod quadrupole at resolutions from about 850 to 1800. At resolutions lower than 850, peak splitting is observed. With quadrupole 4B, resolution up to 2000 is possible, but there is a low mass tail at higher resolution and peak structure at intermediate resolution.

High Excitation Frequencies

Stability islands can be formed with different excitation frequencies. Both high ($\nu \approx 1$) and low excitation frequencies ($\nu \leq 1/10$) were investigated. With $\nu = 9/10$, there can be a maximum of nine unstable bands

along the iso- β lines for motion in each of the x and y directions [25].

The left column of Figure 2, i.e., Figure 2a–d, show peak shapes obtained with quadrupole 4A with conventional mass analysis (no island) and with operation with islands of stability. Figure 2a shows the peak shape with $R_{1/2} = 1720$, obtained with conventional operation. This is close to the highest resolution obtained with this rod set. There is minor tailing on the high mass sides of the peaks. Figure 2b–d show peak shapes with the same quadrupole with mass analysis with islands of stability formed with three different excitation frequencies. These peaks have resolutions, $R_{1/2} = 2140$, 2140, and

Figure 2. Mass spectra of protonated reserpine ions with quadrupoles 4A (left column) and 4B (right column). Quadrupole 4A: (a) conventional mass analysis, transmission 1.51×10^5 ; (b) operation at the upper tip of island A, $\nu = 9/10$, $q' \approx 0.028$, transmission 1.29×10^5 ; (c) upper tip of island A, $\nu = 19/20$; $q' \approx 0.018$, transmission 4.11×10^4 ; (d) upper tip of island B, $\nu = 21/20$, $q' \approx 0.013$, transmission 4.10×10^4 . Quadrupole 4B: (e) conventional mass analysis, transmission 1.20×10^4 ; (f) upper tip of island A, $\nu = 9/10$, $q' \approx 0.030$, transmission 3.19×10^5 ; (g) upper tip of island A, $\nu = 19/20$, $q' \approx 0.021$, transmission 1.92×10^4 ; (h) upper tip of island B, $\nu = 21/20$, $q' \approx 0.010$, transmission 3.80×10^4 .

1920, respectively, all higher than that obtained with conventional mass analysis, **Figure 2a**.

With excitation frequencies of $\nu = 19/20$ as in **Figure 2c** and $\nu = 21/20$ as in **Figure 2d**, the tails on the high mass side are removed and consequently the isotopic peaks are baseline resolved. The transmission with $\nu = 9/10$ in **Figure 2b** is comparable to that with conventional mass analysis with this rod set. With excitation frequencies of $\nu = 19/20$ and $\nu = 21/20$, the transmission is reduced by a factor of ca. $\times 4$. This is likely a result of the smaller stability islands under these excitation frequencies, as discussed below for low-frequency excitation.

The right column of **Figure 2**, i.e., **Figure 2e–h**, show peak shapes obtained with quadrupole 4B with conventional mass analysis and with mass analysis with operation in islands of stability. The pairs of figures in each row of **Figure 2** were obtained with the same operating conditions. The minor difference in the excitation amplitudes for the two spectra of each pair is the result of their being taken 2 years apart. **Figure 2e** shows the peak shape with a resolution of $R_{1/2} = 1560$ obtained with conventional mass analysis. There are unacceptable tails on the low mass sides of the peaks. These tails were not seen in computer simulations of peak shapes with this quadrupole [12]. With mass analysis with islands of stability **Figure 2f, g, and h**, the resolution is increased to $R_{1/2} = 1820, 2450$, and 2350 , respectively. Transmissions are increased by factors of ca. (f) 26 (g) 1.6, and (h) 3.2 compared with that obtained with conventional operation (**Figure 2e**). With mass analysis in islands of stability, in all cases the tails on the lower mass sides are removed. For excitation frequencies (g) $\nu = 19/20$ and (h) $\nu = 21/20$, the isotopic peaks are baseline resolved.

Low Excitation Frequencies

Low excitation frequencies, $\nu = 1/10, 3/40, 1/15, 1/20$, and $1/30$, (100 kHz, 75 kHz, 66.6 kHz, 50 kHz, 33.3 kHz, respectively), were investigated. Some of the spectra are shown in **Figure 3**. With these frequencies, peak tails are also eliminated and the isotopic peaks are baseline resolved. The left column of **Figure 3**, i.e., **Figure 3a–d**, show spectra obtained with quadrupole 4A. In comparison to spectra with conventional mass analysis with the same quadrupole (**Figure 2a**), the spectra obtained with islands with frequencies (a) $\nu = 1/10$, (b) $\nu = 1/15$, (c) $\nu = 1/20$, and (d) $\nu = 1/30$ all have peaks free of structure and tailing, and are baseline resolved. The resolutions are $R_{1/2} = 1740, 1940, 1960$, and 2580 at $\nu = 1/10, 1/15, 1/20$, and $1/30$, respectively. In addition, the transmission is changed by (a) $\times 2$, (b) $\times 1/7$, (c) $\times 1$, and (d) $\times 1.4$ compared with **Figure 2a**.

The right column of **Figure 3**, i.e., **Figure 3e–h**, shows mass spectra obtained with quadrupole 4B with mass analysis with islands of stability formed with the same low excitation frequencies used for quadrupole 4A. The pairs of figures in each row of **Figure 3** were obtained

with the same ν and q' . In comparison to spectra with conventional mass analysis with the same quadrupole (**Figure 2e**), all the spectra obtained with mass analysis in islands of stability for frequencies (e) $\nu = 1/10$, (f) $\nu = 1/15$, (g) $\nu = 1/20$, and (h) $\nu = 1/30$ are baseline resolved and the tails on the low mass sides are removed. Higher resolutions are obtained for $\nu = 1/20$ ($R_{1/2} = 2720$) and $\nu = 1/30$ ($R_{1/2} = 2950$). In addition, increases in transmission of 4(e) $\times 12$ 4(f) $\times 2.6$, 4(g) $\times 17$, and 4(h) $\times 14$ were observed in comparison with **Figure 2e**.

Rod set 4B also produced considerable structure on the peaks when operated conventionally at low to intermediate resolutions of 300 to 1200. It was found that when the island formed with $\nu = 1/10$, $q' \approx 0.012$ was used for mass analysis, all structure at low and intermediate resolution was removed, and the transmission increased by up to a factor of 10 (data not shown). There was slight tailing on the high mass sides of the peaks.

The mass spectra of **Figure 2** and **Figure 3** show that mass analysis with islands of stability removes peak structure and tails on peaks caused by the higher order multipoles added to the potential of quadrupoles 4A and 4B. Comparison of the results with high and low frequencies shows that low-frequency excitation tends to give higher resolution, especially when $\nu < 1/10$. To obtain a mass spectrum with the same or higher resolution, the required excitation strength q' is much lower with low-frequency excitation than with high-frequency excitation. For example with quadrupole 4B, with excitation at $\nu = 9/10$ (900 kHz), $q' \approx 0.030$ is needed for the spectrum in **Figure 2f** (resolution $R_{1/2} = 1820$, high mass tails), while for excitation at $\nu = 1/30$ (33.3 kHz), $q' \approx 0.003$ only is needed to obtain the spectrum in **Figure 3h** (resolution $R_{1/2} = 2950$, no tails).

Transmission Versus Resolution

With conventional mass analysis, quadrupoles 4A and 4B gave lower transmission over the range of achievable resolutions in comparison to a conventional quadrupole operated under the same conditions. As shown above, it is possible to improve peak shape, resolution, and, in some cases, transmission, when quadrupoles 4A and 4B are operated in islands of stability. When the size of an island is relatively large, e.g., those formed at an excitation frequency of $\nu = 9/10$, the overall transmission tends to be higher while the improvements in the peak shape and resolution are less than in the case of a smaller/narrower island formed at a low excitation frequency, e.g., $\nu = 1/30$. When a smaller/narrower island is used, however, only a limited range of resolution can be achieved by adjusting the slope of a scan line.

To illustrate the general trend of transmission versus resolution of quadrupoles 4A and 4B when operated with islands, in comparison to conventional mass analysis, a compromise between the size of an island and the attainable resolutions has to be made. We choose an

Figure 3. Mass spectra of protonated reserpine ions with quadrupoles 4A (left column) and 4B (right column) obtained with mass analysis with islands of stability operated at the uppermost island. Quadrupole 4A: (a) $\nu = 1/10$, $q' \approx 0.011$, transmission 3.06×10^5 ; (b) $\nu = 1/15$, $q' \approx 0.008$, transmission 2.26×10^4 ; (c) $\nu = 1/20$, $q' \approx 0.006$, transmission 1.34×10^5 ; (d) $\nu = 1/30$, $q' \approx 0.003$, transmission 1.05×10^5 . Quadrupole 4B: (e) $\nu = 1/10$, $q' \approx 0.011$, transmission 1.43×10^5 ; (f) $\nu = 1/15$, $q' \approx 0.008$, transmission 3.11×10^4 ; (g) excitation $\nu = 1/20$, $q' \approx 0.009$, transmission 1.98×10^5 ; (h) $\nu = 1/30$, $q' \approx 0.003$, transmission 1.68×10^5 .

excitation frequency of $\nu = 1/10$ and excitation strength of $q' \approx 0.012$. With these conditions, Figure 4 shows the ion transmission versus resolution for a conventional quadrupole with conventional mass analysis, and quadrupoles 4A (in Figure 4(a)) and 4B (in Figure 4(b)) operated at the upper and lower tips of island A, and the upper tip of island B. With conventional mass analysis and mass analysis using the stability island with $\nu = 1/10$ and $q' \approx 0.012$, the transmission of these quadrupoles with added hexapole fields is lower than that of a conventional quadrupole. For instance, at a resolution of 1000, the transmission at the upper tip of island B of quadrupole 4B is 7 times lower than that of

a conventional quadrupole. The transmissions of both quadrupoles 4A and 4B operated with islands are comparable to those without islands. This result, and the experimental observation of increased transmission under some conditions with mass analysis using islands of stability, suggests the use of islands is not the reason for the lower transmission, at least with these operating conditions.

The effect of stability island size on the ion transmission was also investigated. Experimentally, it is observed that for a given quadrupole at a fixed excitation frequency, the island size decreases with increasing excitation strength. We also observe that as the size of

Figure 4. Transmission versus resolution for a conventional quadrupole and quadrupoles with added 4% hexapole fields (a) 4A (b) 4B. Curve 1, the conventional quadrupole operated without stability islands. Curve 2, open triangles, quadrupoles 4A or 4B operated without islands. Curves 3, 4, 5, solid symbols, quadrupole 4A or 4B operated at the upper and lower tips of island A and upper tip of island B, as labeled. The islands are formed with $\nu = 1/10$ (100 kHz) and $q' \approx 0.012$. The resolution was changed by varying the slopes of the scan lines.

an island decreases, the transmission decreases. When a scan line crosses the widest part of an island, the transmission is highest. For example, for quadrupole 4A at an excitation frequency of $\nu = 1/10$, the highest transmission in island A is reduced from 3.09×10^7 (corresponding to $R_{1/2} = 150$) to 2.05×10^6 (corresponding to $R_{1/2} = 300$) when the excitation strength is changed from $q' \approx 0.011$ to $q' \approx 0.018$. Note for each of these two excitation amplitudes, the slope of the scan line is chosen to give the highest ion transmission in each case. These slopes differ. This result is consistent with the computer simulations of island formation with an ideal quadrupole field, reported in [18].

Quadrupoles with a 4% Added Hexapole Field with $a < 0$

With the positive resolving DC applied to the two shifted y -rods, so that the Mathieu parameter $a < 0$, conventional mass analysis with quadrupoles 4A and 4B gives only low-resolution. As shown in Figure 5a, the mass spectrum of quadrupole 4A has a resolution of about 80; while in Figure 5c, the mass spectrum of quadrupole 4B has a resolution of 84. Attempts to increase the resolution by increasing the slope of the scan line resulted only in losses of signal, with no increases in resolution. In both cases the stability boundaries are not well defined. This is reflected in the existence of small broad peaks on both the high and low mass sides adjacent to the main peaks. For both quadrupoles, mass analysis with islands of stability can greatly improve the resolution. Figure 5b shows a mass spectrum obtained with quadrupole 4A operated at the upper tip of island A. The islands are formed with $\nu = 1/20$ and $q' \approx 0.012$. The resolution is $R_{1/2} = 1180$, about 15 times higher than that of the mass spectrum in Figure 5a, while the transmission in Figure 5b is only marginally lower than Figure 5a. Figure 5d shows a mass spectrum obtained with quadrupole 4B operated at the upper tip of island A, formed with $\nu =$

$1/20$ and $q' \approx 0.009$. The resolution is about $R_{1/2} = 840$, 10 times greater than with conventional analysis (Figure 5c). However, in this case the transmission is six times lower than that with conventional operation, Figure 5c. Thus, with rod sets 4A and 4B, when $a < 0$, the use of an island of stability helps to overcome the adverse effects of the added multipole fields, as was seen with a quadrupole with an added octopole field [20, 21].

Mass analysis with $a < 0$ and islands of stability formed with other excitation frequencies, $\nu = 9/10$, $19/20$, $21/20$, $1/10$, $1/15$, $3/40$, and $1/30$, was also investigated. Although the resolution in each case was increased, compared with the resolution with conventional analysis, none gave resolution or transmission higher than those seen in Figure 5b and d.

Conventional Round Rod Quadrupole

The conventional quadrupole used here has a limiting resolution of about 2500. The quadrupole apparently has been slightly damaged. A curve of transmission versus resolution for a quadrupole with the same construction is shown in [13]. The transmission decreases only about a factor of 10 between $R_{1/2} = 1000$ and $R_{1/2} = 4000$ and the limiting resolution is greater than 5000. With the quadrupole here, at a resolution of $R_{1/2} = 1000$, the transmission is about 1/17 of that at resolutions less than about 200; at $R_{1/2} = 2000$, the transmission is about 1/100 of that at low resolutions. The effects of mass analysis with an island of stability were investigated for this quadrupole. The results are shown in Figure 6. The use of a stability island greatly improves the transmission at resolutions above 500, as evidenced by curves 2, 3, and 4 in Figure 6. With $\nu = 9/10$ and $q' \approx 0.004$ (curve 4), the transmission remains constant up to at least $R_{1/2} \approx 1000$. At $R_{1/2} = 2000$ the transmission is still more than half of that at $R_{1/2} = 200$. Resolutions $R_{1/2} > 3000$ were also possible. At $R_{1/2} =$

Figure 5. Mass spectra of protonated reserpine ions with quadrupoles 4A (left column) and 4B (right column) obtained with conventional mass analysis and with mass analysis with islands of stability operated at the upper tip of island A. The positive resolving DC is applied to the y -rods so that the Mathieu parameter $a < 0$. Quadrupole 4A: (a) conventional mass analysis, transmission 5.02×10^4 ; the scan step size is 0.5 Th; (b) $\nu = 1/20$, $q' \approx 0.012$, transmission 4.09×10^4 . Quadrupole 4B: (c) conventional mass analysis, transmission 1.31×10^5 ; the scan step size is 0.5 Th; (d) $\nu = 1/20$, $q' \approx 0.009$, transmission 2.21×10^4 .

2500, mass analysis in islands of stability increased the transmission by up to two orders of magnitude in comparison with that obtained without islands.

With other excitation conditions, $\nu = 1/10$ and $q' \approx 0.011$, a mass spectrum with a resolution of $R_{1/2} = 4360$

was obtained, indicating that the limiting resolution can be increased by using an island of stability. At this resolution, the transmission is about 1/220 of that at low resolutions, about the same as that obtained by mass analysis without stability with the same quadrupole at its limiting resolution of 2500. In addition to the improvements in transmission, mass analysis in islands of stability with this quadrupole gives sharper peaks at the baseline in contrast to the mild tails of the peaks obtained with the same quadrupole with conventional mass analysis without stability islands, consistent with [16].

Summary

Mass analysis using islands of stability was investigated for linear quadrupoles with 4% added hexapole fields constructed from equal and unequal diameter rods. With $a > 0$, both high and low-frequency excitation produce stability islands in which improved resolution, peak shape, and transmission are possible. Resolutions up to 3000 were obtained. With $a < 0$, an increase of a factor of 10 or more in resolution is possible with mass analysis using islands of stability. A conventional quadrupole also showed improved performance when operated with islands of stability. Apparently the stability boundaries formed by quadrupole excitation are more suited to mass analysis than the conventional boundaries when quadrupoles have distorted fields. The use

Figure 6. Transmission versus resolution for a conventional quadrupole. Curve 1, mass analysis without stability islands; Curves 2, 3, and 4, mass analysis at the upper tip of island A formed with $\nu = 1/10$ and $q' \approx 0.007$, for line 2, $\nu = 1/15$ and $q' \approx 0.003$, for line 3 and, $\nu = 9/10$ and $q' \approx 0.004$, for line 4. The resolution was changed by varying the slopes of the scan lines.

of islands of stability generally provides an improved method of mass analysis for quadrupoles with field distortions. In the future, this may allow the use of quadrupoles with at least some lower mechanical tolerances and, hence, lower cost.

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