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Ion-Ion Interactions in Charge Detection Mass Spectrometry

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Abstract

Charge detection mass spectrometry (CDMS) is a single-particle technique where the masses of individual ions are determined by simultaneously measuring their mass-to-charge ratio (m/z) and charge. Ions are usually trapped inside an electrostatic linear ion trap (ELIT) where they oscillate back and forth through a detection cylinder, generating a periodic signal that is analyzed by fast Fourier transforms. The oscillation frequency is related to the ion's m/z , and the magnitude is related to the ion's charge. In early work, multiple ion trapping events were discarded because there was a question about whether ion-ion interactions affected the results. Here, we report trajectory calculations performed to assess the influence of ion-ion interactions when multiple highly charged ions are simultaneously trapped in an ELIT. Ion-ion interactions cause trajectory and energy fluctuations that lead to variations in the oscillation frequencies that in turn degrade the precision and accuracy of the m/z measurements. The peak shapes acquire substantial high and low m/z tails, and the average m/z shifts to a higher value as the number of trapped ions increases. The effects of the ion-ion interactions are proportional to the product of the charges and the square root of the number of trapped ions and depend on the ions' m/z distribution. For the ELIT design examined here, ion-ion interactions limit the m/z resolving power to several hundred for a typical homogeneous ion population.

Graphical Abstract

Keywords

Ion-ion interactions; Charge detection mass spectrometry; CDMS; Electrostatic linear ion trap; ELIT

Introduction

Electrospray has made it possible to place very large ions into the gas phase [1]. However, their analysis by mass spectrometry has been hindered by heterogeneity which makes it

increasingly difficult to resolve charge states in the m/z spectrum as the mass increases [2, 3]. This limitation restricts the upper mass limit to well below a megadalton, except for a few cases where special care was taken to reduce heterogeneity [4, 5]. This shortcoming inspired the development of novel instrumentation capable of directly measuring the mass of individual ions [6]. One such technique is charge detection mass spectrometry (CDMS) [7–10]. Here, ions are directed through a conducting cylinder; each ion induces a charge on the cylinder as it passes through, and the induced charge is detected by a charge-sensitive amplifier. The flight time through the cylinder yields the m/z , and the amplitude of the signal provides the charge. The product of these two quantities is the mass. The main drawback with single-pass CDMS measurements is the large uncertainties in both the charge and m/z measurements which often lead to a single-digit mass resolving power [6]. On the plus side, single-pass CDMS measurements are relatively fast (10^2 – 10^3 ions/s). In recent work, Antoine and coworkers have used single-pass CDMS to measure the masses of a number of heterogeneous samples including amyloid fibrils, synthetic polymers, and nanoparticles [11–13].

One solution to the resolution problem is to place the detection cylinder in an electrostatic linear ion trap (ELIT) so that ions oscillate back and forth through the detection cylinder many times. In early work, Benner reported a theoretical charge uncertainty of 2.3 e (elementary charges) [14]. A number of recent technical developments, including the use of fast Fourier transforms (FFTs) to analyze the time domain signals, have reduced the root mean square deviation (RMSD) to below 0.2 e [15–21]. With an RMSD of 0.2 e, it is possible to assign the charge state with almost perfect accuracy [18, 22]. The mass resolving power is then determined by the uncertainty in the m/z measurement. Recent efforts have focused on optimizing the ELIT design to increase the m/z resolving power [20].

In our early work, trapping events containing more than one ion were discarded. We found that when multiple ions were trapped, one or more of the ions had a reduced trapping time. We thought that this was probably due to ion-ion interactions influencing the trajectories of the ions. Because changes in the trajectories could affect the oscillation frequency and hence the m/z measurements, we discard the multiple ion trapping events [17]. Restricting the measurements to single ions increases the time required to collect a CDMS spectrum. This time could be reduced if the multiple ion trapping events were analyzed as well. To investigate this issue, we modified our real-time analysis code [21] so that multiple ion trapping events could be analyzed and the results compared to those for single ion trapping, and we initiated a series of trajectory calculations aimed at providing more detailed insight into the ion trajectories in an ELIT and the effects of ion-ion interactions on CDMS measurements.

During the course of this work, Williams and coworkers reported experimental studies where a large number of ions were simultaneously trapped in an ELIT and their signals analyzed by FFTs to determine the charges and m/z s of the individual ions [23]. They indicated that the trapping of multiple ions had no effect on the measurements. However, their studies were performed with an m/z resolving power < 50 so the effects of ion-ion interactions could easily be masked by the poor resolution (i.e., the effects would fall within the width of the already broad m/z peak and would not cause a noticeable degradation of the resolution). In

addition, they reported measurements for ions with a relatively low charge, a situation that minimizes the effects of ion-ion interactions.

Here, we report the results of trajectory calculations performed to investigate how ion-ion interactions affect m/z measurements in an ELIT. We find that ion-ion interactions cause energy fluctuations that degrade the precision and accuracy of the m/z measurements and limit the m/z resolving power to several hundred for a typical homogeneous sample. In addition to providing a high-resolution view of individual interactions, the trajectory calculations allow control over parameters that cannot be controlled in experiments, allowing a detailed picture of the effects of ion-ion interactions to emerge.

Methods

The ELIT used in these studies is the cylindrical trap design shown schematically in Figure 1. It has been described in detail elsewhere [20]. This trap was designed to have a duty cycle of 50% to optimize the charge measurement and reduce the dependence of the oscillation frequency on the ion energy (the duty cycle is the time spent in the detection cylinder during one oscillation divided by the total time for one oscillation). As shown in Figure 1, radial components of ion positions, velocities, and forces are in the xy -plane and the longitudinal components are along the z -axis. Ions are usually focused towards the center of the trap, so we discuss the ion entrance conditions in terms of the radial offset and angular divergence at the trap center. Consider a line parallel with the z -axis that passes through the ion at the trap center. The radial offset is the distance between the line and the center of the trap, and the angular divergence is the angle between the line and the ion's trajectory.

To perform trajectory calculations, it is necessary to know the components of the electric fields in the trap at the locations of all ions. Since these cannot be described analytically, a model of the ELIT was constructed in SIMION 8.1 (Scientific Instrument Services, Inc.) and the Laplace equation was solved with a refinement convergence objective of 1 μV to calculate an electric field array. Because the ELIT is cylindrically symmetric, the radial electric field from the trap end caps always points towards or away from the trap longitudinal axis. The three-dimensional electric field array can thus be reduced to a two-dimensional plane by using only a radial slice. The fields for each ion were then calculated by bilinear interpolation between grid points from the electric field array. Once the magnitude of the radial force was calculated, its x - and y -components were reconstituted by trigonometric relationships, bringing the simulation back into three dimensions. Note that this approach is not only faster, but more accurate than using a three-dimensional electric field array with a three-dimensional interpolation.

A custom Fortran program was written to simulate ion trajectories in three-dimensional Cartesian space using the Beeman algorithm, a variant of the Velocity Verlet algorithm [24]. The Beeman algorithm was chosen for this application because of its low energy error. The total energy of the system of ions in the trap is expected to be conserved throughout the simulation. The Coulomb force between ions was calculated in three dimensions and added to the force from the trap electric field. Any number of ions can be simulated by superimposing the component forces that each ion exerts on all other ions. Trajectories were

initialized with a 1-ns time step. As two ions approach and the Coulomb potential increases, the time step was decreased to minimize the energy error and prevent ions from skipping over each other while in close proximity. The time step was reduced by an order of magnitude when the Coulomb potential between any two ions in the trap exceeded 0.05 eV, reduced by another order of magnitude when the pair potential exceeded 0.5 eV, and by another order of magnitude at 5.0 eV, and so on. This ensured that the time step was significantly shorter than the timescale of the interaction so that both energy and momentum were conserved. It was not necessary to make the time step a function of the ELIT potential because ions travel more slowly in the end caps where the potentials are changing most rapidly. Trajectories were initiated at the center of the trap. For multiple ions, the trajectories were initialized with a random time delay at the beginning of the trapping event to simulate a continuous beam entering the trap.

Ions with a mass of 5 MDa and a charge of 200 e were used in most of the simulations. For some simulations, masses or charges close to these nominal values were used. Specific details are provided below. For calculations performed for a distribution of ion entrance conditions the energy, radial position and angular distributions were all assumed to be Gaussian. The energy distribution was centered at 130 eV per charge (eV/z) with a full width at half maximum (FWHM) of 0.1 eV/z. A beam entering the trap was focused towards the center of the trap by the entrance end cap while it was held in transmission mode. This produced a 0.15-mm FWHM beam width and an angular divergence of 0.1° FWHM. Note that the width of the energy distribution and the ion entrance conditions used here were selected to simulate conditions that yield a high-resolution m/z measurement. High-resolution CDMS measurements with an ELIT require a well-focused ion beam and a well-defined ion energy. A resolving power of around 10^3 has recently been achieved with the cylindrical trap employed here. We use the high-resolution conditions in the trajectory calculations because our main interest is in determining the effect of ion-ion interactions on the m/z resolving power and at low m/z resolving power the effects could be masked. A few simulations were performed using low-resolution entrance conditions (see below).

For each complete oscillation in the trap, the ions pass through the detector tube twice. Thus, the signal frequency is twice the ion oscillation frequency. In what follows, all oscillation frequencies are given in terms of the signal frequency.

Results and Discussion

Trajectories for Single Ions Trapped in an ELIT

Analysis of the trajectory calculations for single trapped ions revealed two limiting types of trajectory; examples are given in Figure 2. Ions in planar trajectories (Figure 2a) oscillate back and forth along the length of the trap with their trajectories constrained to a single line in the xy-plane that intersects the z-axis, though not necessarily at the center of the trap. On the other hand, ions in cylindrical trajectories (Figure 2b) revolve around the z-axis as they oscillate along the trap. The radial offset and angular divergence with which an ion enters the trap determines whether ions fall into planar or cylindrical trajectories. A beam with a well-defined focal point anywhere along the z-axis (no radial offset at the focal point) or a collimated beam (no angular divergence) both lead to planar trapping trajectories. This

occurs because the electric field of the end caps provide a restoring force that reverses the ion motion in the z-direction while also directing the ion towards the z-axis. If the velocity of an ion in the xy-plane of the trap is parallel or antiparallel with the restoring force in the xy-plane, then the ion motion is in the same direction as the force, resulting in a planar trajectory that passes through the z-axis. On the other hand, if a significant component of the ion's velocity in the xy-plane is perpendicular to the restoring force vector, then that velocity is in a direction that is not acted on by the restoring force. When that ion turns around in the z-direction in an end cap, it also rotates in the xy-plane. This rotation causes the ion to orbit around the z-axis, creating a cylindrical trajectory with a hollow center. Ions entering the trap with a combination of radial offset and angular divergence that points the xy-plane velocity away from the restoring end cap force attain cylindrical trajectories. The size of the plane or cylinder is proportional to the radial offset of the ion as it enters the ELIT. For cylindrical trajectories, the entrance angle also scales with the offset position.

Factors That Influence the Strength of Ion-Ion Interactions

Figure 3 shows a plot of the kinetic energies versus time for a typical trajectory where two ions were simultaneously trapped. In this example, the initial kinetic energies were 130.00 eV/z and 130.03 eV/z. Ion-ion interactions cause the ions to exchange kinetic energy. While both ions experience increases and decreases in their kinetic energies, the overall result is that the kinetic energies appear to diffuse apart. By the end of the 100-ms trajectory, the energy difference between the trajectories is close to 4 eV/z. Energy and trajectory fluctuations during a trapping event are undesirable because they decrease the certainty with which the frequency can be determined, compromising the precision of the m/z measurement.

The extent to which a Coulomb interaction affects the motion of a pair of ions can be expressed as a scattering angle, χ , in the center-of-mass reference frame [25]:

$$\chi = 2 \tan^{-1} \left(\frac{q_1 q_2}{4\pi\epsilon_0 b \mu v_r^2} \right) \quad (1)$$

where q_1 and q_2 are the ion charges, ϵ_0 is the permittivity of free space, b is the impact parameter, μ is the reduced mass, and v_r is the relative velocity. Inspection of Eq. (1) reveals that for a constant relative velocity, the scattering angle for large impact parameter collisions is proportional to the product of the charges.

The most significant energy shifts occur when ions come in close proximity to each other for extended periods of time. This can happen if two ions with similar frequencies oscillate in phase with each other for several cycles in the trap. During that time there is a relatively high probability that their trajectories intersect and cause a deflection to occur. Interactions that give rise to large deflection angles may result in the loss of one or more of the involved ions if their trajectories become no longer trappable. On the other hand, interactions that result in smaller deflections are observed as a shift in the kinetic energies and oscillation frequencies and the involved ions generally remain trapped for the full trapping period. An example of this behavior is provided by the results in Figure 3.

A Closer Look at One Energy Shifting Encounter

A more detailed view of the behavior in one energy shifting encounter (the one at 93.12 ms in Figure 3) is shown in Figure 4. Figure 4a shows a view of the trajectories looking down the trap axis, before and after the energy shifting encounter. Initially, the two ions are oscillating in planar trajectories with similar radial directions. The ion trajectories come into longitudinal phase with each other and undergo a deflection that perturbs the trajectories, energies, and oscillation frequencies. After the encounter, both trajectories have shifted to new radial directions. Figure 4b shows a plot of the distance between the ions against time. The distance oscillates until the ions get close enough for a significant perturbation of their trajectories to occur.

Figure 4c shows a plot of the oscillation frequencies against time around the encounter. The frequency points are spaced out because the frequencies are determined from the time it takes for each ion to complete one oscillation cycle in the trap. Finally, Figure 4d shows how the energy changes during the encounter. Note that the fractional changes in the oscillation frequencies are much smaller than the fractional changes in the kinetic energies because the trap used here was designed to reduce the kinetic energy dependence of the oscillation frequency [20]. The nature of the trajectory also influences the oscillation frequency, but no effort was made to reduce the dependence of the oscillation frequency on the trajectory during the design of this trap. Much larger frequency shifts are expected in the cone trap design used in our earlier work because the frequency is much more strongly dependent on the energy [15].

The shift in the energy at 93.12 ms in Figure 4d occurs at the closest encounter in Figure 4b. In this case, the encounter occurs in the detection cylinder and the distance of closest approach is around 0.0252 mm. There is another close encounter a little earlier, at 92.77 ms. However, there is no sign of this encounter in the ion energies in Figure 4d (though there is evidence when the vertical scale is expanded). The distance of closest approach for the 92.77 ms encounter was 0.0982 mm, which is around four times farther away than the closer encounter at 93.12 ms. However, the encounter distance is only part of the explanation for why there is not a significant impact on the energies at 92.77 ms: the relative velocities are also substantially different. The 93.12 ms encounter occurs in the detection cylinder; the relative velocity is small, and the encounter relatively long lived. The 92.77 ms encounter occurs in the end cap close to the turnaround point. The ions have lost most of their kinetic energy, so the small difference in their kinetic energies in the detector tube now leads to a much larger relative velocity and a much shorter encounter. The close encounters at 93.45 ms and 93.65 ms in Figure 4b are similar to the one at 92.77 ms and occur in one of the end caps close to the point where the ions are turning around.

Effect of the m/z Difference on the Average Frequency Deviation

The number of times that two ions oscillate in phase with each other depends on the difference between their frequencies and the trapping duration. The frequency difference also affects the amount of time the ions spend in close proximity to each other, so there is expected to be an interplay between the duration of a close interaction and the number of times an interaction occurs. As the frequency separation between two ions increases, the

ions encounter each other more often but spend less time near each other during each encounter. To investigate the effect of the initial frequency difference on the frequency stability, we performed a series of trajectory calculations where one ion was given an m/z of 25,000 Da and the other ion was given larger m/z values to produce a range of frequency differences. The larger m/z values were obtained by keeping the charge at 200 e and increasing the mass. Trajectories were calculated for 100 ms, and then, the frequency deviations were determined from the difference between the frequency of an ion at the end of the trapping event and its initial frequency. The average deviation was then obtained by averaging over 2500 trapping events at each initial frequency difference. The average energy deviations were obtained in a similar way.

Figure 5a shows a plot of the average frequency deviation against the m/z difference. The upper scale in Figure 5a shows the average initial frequency differences that correspond to the m/z differences. Variations in the energy, radial offset, and angular divergence have a small effect on the oscillation frequencies. Thus, when both ions have identical m/z s, their longitudinal phases are set at the beginning of the trajectory and remain almost constant for the entire 100-ms trapping event. As the frequency difference increases, the ions are more likely to come into phase with each other so the average frequency deviation rises rapidly until an initial difference of 20 Hz is reached (see Figure 5a). At 20 Hz, the ions are guaranteed to come into phase at least once over the 100-ms trapping event. For larger frequency differences, the ions come into phase more than once. On the other hand, as the initial frequency difference increases, the relative velocity between the ions also increases and so the perturbation caused by one encounter becomes smaller (see Eq. (1)). As can be seen in Figure 5a, for initial frequency differences of more than 20 Hz, the average frequency deviation gradually increases, peaks at a frequency difference of around 120 Hz, and then gradually decreases. We attribute this behavior to a balance between the increase in number of times the ions come into phase as the frequency difference increases and the decrease in the perturbation as the relative velocity increases. At large frequency differences, the decrease in the perturbation as the relative velocity increases becomes dominant and the average frequency deviation declines.

The combination of a low relative velocity and in-phase oscillations yields the worst frequency stability for the ELIT employed here at around 120 Hz which corresponds to an m/z difference of around 600 Da. An m/z difference of this magnitude can easily occur for samples typically measured by CDMS. For initial frequency differences above 120 Hz (m/z differences greater than 600 Da), the frequency deviation gradually decreases as the relative velocity of the ions increases. Figure 5b shows a plot of the average frequency deviation against the average energy deviation, showing a linear relationship between these two quantities.

Trajectory Calculations for More Than Two Identical Ions

Increasing the number of trapped ions beyond the two considered above is expected to increase the frequency instability. With a few ions in the trap, the vast majority of close encounters are still two body events, so the number of close encounters should be proportional to the number of ions in the trap minus one. To investigate the dependence on

the number of ions, we first performed a series of 100 ms simulations with one to eight identical ions in the trap (i.e., the ions all had the same m/z of 25,000 Da and the same charge of 200 e). The average frequency was determined for each ion by averaging over the 100 ms trajectories. The average frequencies were then converted into m/z values using the equation [15]:

$$m/z = \frac{C}{f^2} \quad (2)$$

where f is the oscillation frequency and C is a constant that depends on the ion energy and trap dimensions. The m/z values were then binned to give m/z distributions which are shown in Figure 6a. When a single ion is trapped (black line in Figure 6a), the width of the m/z peak is entirely due to the energy distribution, the distribution of radial offsets, and the angular distribution of the ions at the beginning of the trajectory. The peak shape is Gaussian. Changes in the m/z peaks when multiple ions are trapped result from ion-ion interactions. When two ions are trapped, substantial tails form to both high and low m/z . This results because the relative velocity difference between the ions is small (they all have the same m/z), and so the probability that the two ions interact is mainly determined by their proximity at the beginning of the trajectory. For ions that do undergo a close encounter, the perturbation to their trajectories is relatively large because their relative velocity is small. On the other hand, with only two ions in the trap, many of them do not undergo a close encounter and so their trajectories are not significantly affected. As the number of trapped ions increases (see Figure 6a), the fraction that undergo close encounters increases, and the peak shape becomes more Gaussian. As the results in the figure show, with eight ions in the trap, the m/z peak width is seriously degraded by ion-ion interactions.

Figure 6b shows a plot of the m/z peak width against the number of ions in the trap. The black points show the m/z peak width determined from the root mean square deviation multiplied by 2.355, and the red points were obtained from the FWHM of the peaks in Figure 6a. For a Gaussian distribution, these two methods yield the same result. They converge as the number of trapped ions increases but diverge at intermediate values where the ions in the low and high m/z tails cause the RMSD to increase rapidly while the FWHM is less strongly affected.

With a few ions in the trap, the vast majority of close encounters are two body events, so the number of close encounters is proportional to the number of ions in the trap minus one. Since the two possible outcomes of an interaction are an upward or downward frequency shift, the average frequency deviation is expected to be the square root of the number of possible interactions. (The frequency deviation is the difference between the oscillation frequency at the beginning and end of the 100-ms trajectory calculation.) Figure 6c shows a plot of the average frequency deviations against the number of trapped ions. The points are from the trajectory calculations, and the line shows the expected square root dependence. The agreement is not perfect. One factor that probably contributes to the deviation is the mutual repulsion between the ions which causes an increase in their radial separation. This separation slightly lowers the average frequency deviation from the ideal square root relationship.

To investigate the effect of the initial conditions on the ion-ion interactions, some simulations were performed for 1–5 identical 5 MDa ions with a charge of 200 e using low-resolution entrance conditions for the cylindrical trap (Gaussian energy distribution with a 0.60-eV/ z FWHM, Gaussian radial distribution with a 0.4-mm FWHM, and Gaussian angular distribution with a 0.78° FWHM). With the relaxed entrance conditions, the m/z peak widths for one trapped ion increased to around 74 Da. As the number of trapped ions increases, the peak widths from both the FWHM and 2.355 times the RMSD increase close to linearly (in contrast to the high-resolution entrance conditions shown in Figure 6b). The peak widths under low-resolution conditions increase by around 33% on going from one to five trapped ions.

While providing some insight into the consequences of trapping multiple ions, the approach adopted above is not particularly realistic because it is unlikely that a large number of ions with identical m/z values will be trapped simultaneously. In real life, a much more likely scenario is that the trapped ions have very similar masses but a distribution of charges due to the charge state envelope generated by electrospray. We model this situation by assuming that all ions have the same masses (5 MDa) but with a Gaussian charge distribution centered on 200 e and with a FWHM of 20 e. Charges were randomly assigned to the ions and then rounded to the nearest integer. This recipe leads to an m/z distribution containing a series of discrete peaks that follow a Gaussian envelope. For each ion, the average oscillation frequency was determined by averaging over the 100-ms trapping time. The average frequencies were converted to m/z values using Eq. (2) and then multiplied by their integer charges to give masses. The masses were then binned to give a mass distribution. Figure 7a shows mass distributions determined with one through eight ions in the trap. In all cases, the mass distributions include ions from 2500 trapping events. The mass distributions broaden as the number of trapped ions increases. The center of the peak also shifts slightly to higher mass as the number of ions increases. This shift is also evident in the m/z distribution shown in Figure 6a. It occurs because the ions tend to repel each other and their trajectories expand to occupy a larger volume in the trap, leading to slightly lower oscillation frequencies.

Figure 7b shows a plot of the mass peak width against the number of trapped ions. The black points show the mass peak width determined from 2.355 times the RMSD of each distribution. The red points show the peak width determined from the FWHM. For a Gaussian distribution, both approaches lead to the same result. This is close to true when single ions are trapped, but the values diverge sharply when two ions are trapped. With two ions, the measured mass distribution becomes highly non-Gaussian, with broad low intensity tails that extend to both high and low mass. As the number of trapped ions increases, the different methods of defining the peak width become more similar. However, even with eight ions, there are substantial differences and the mass distribution remains distinctly non-Gaussian.

Some simulations were performed to explore the increase in the mass peak widths that will occur for lower charged ions under low-resolution entrance conditions with the cylindrical trap. These simulations were performed for bovine serum albumin ions (69.293 kDa) with an average charge of 45 e and a Gaussian charge distribution with a 4-e FWHM. Ongoing from a single trapped ion to eight trapped ions, the peak widths increased by around 15%.

This result confirms expectations that under low-resolution conditions for ions with low charges, the degradation in the resolution is small when multiple ions are trapped.

Finally, simulations of fifty identical 5 MDa ions with charges of 200 e were performed to investigate whether they would self-bunch in a way similar to that reported by Zajfman and coworkers for a packet of singly charged ions trapped in an ELIT [26]. The 50 ions were simultaneously initiated at the center of the trap (i.e., the ions were dispersed in the x-y plane) under low-resolution conditions, and their evolution was monitored over 100 ms. Within the first 20 ms, the ion packet had dispersed, and it did not come back into phase during the remaining 80 ms. It is possible that the low ion density precludes self-bunching in this case.

Conclusions

Ion-ion interactions between multiple ions that are simultaneously trapped in an ELIT cause trajectory and ion energy variations that reduce the precision and accuracy of the m/z measurements. Ion-ion interactions result in non-Gaussian peak shapes with substantial high and low m/z tails. The average m/z shifts to higher values as the number of trapped ions increases. The degradation is expected to scale with the product of the charges on the ions and approximately with the square root of the number of trapped ions. It also depends on the ions' m/z distribution and on the design of the trap. In particular, how strongly the oscillation frequency depends on the ion energy and ion trajectories in the trap. The trap used here was designed to have oscillation frequencies that are considerably less dependent on the ion energy than in the conical trap used in our previous work [20]. It is likely that more improvements in trap design could further reduce the effects of ion-ion interactions on the accuracy and precision of the m/z measurements. High-resolution CDMS measurements with an ELIT require a well-focused ion beam and a well-defined ion energy. Unfortunately, these requirements promote ion-ion interactions that degrade the resolution. The effects of ion-ion interactions limit the m/z resolving power to several hundred for homogeneous samples with the cylindrical trap used here.

On the other hand, under very low-resolution conditions, the effects of ion-ion interactions will probably not be detectable, at least for a few ions. Thus, our results do not conflict with those of Williams and coworkers [23]. However, they do point to significant restrictions on when multiple ions can be analyzed in CDMS. In the future, it may be possible to design ELITs that minimize ion-ion interactions, so the multiple ion trapping and high-resolution m/z measurements are not mutually exclusive.

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Figure 1.
SIMION representation of the electrostatic linear ion trap used in the simulations with the x-, y-, and z-axes superimposed

Figure 2.

Examples of the two limiting forms of trajectories found for single trapped ions. **(a)** A planar trajectory that resulted for an ion that started with a radial offset of 0.75 mm in the y-direction and had an entrance angle of 0° . **(b)** A cylindrical trajectory that resulted for an ion that started with a radial offset of 0.75 mm in the y-direction and had an entrance angle of 1.2° in the x-direction. In both cases, the ions had a mass of 5 MDa, a charge of 200 e, and an initial kinetic energy of 130 eV/z

Figure 3.

Plot of the ion energy against time for two ions simultaneously trapped for 100 ms. The second ion trajectory was initialized 6 μ s after the first. In that time, the first ion had moved 4 mm from the center of the detection cylinder where the trajectories were initiated

Figure 4.

More detailed information about the ion-ion interaction that causes the energy jump in Figure 3 at around 93 ms. **(a)** Views of the trajectories in the xy-plane (i.e., looking down the axis of the trap) before (black lines) and after (red lines) the encounter that causes the energy shifts. **(b)** A plot of the distance between the two ions as a function of time. **(c)** The change in the oscillation frequency as a function of time. **(d)** The change in the ion energy

Figure 5.

Average frequency deviations for two ion trapping events. **(a)** The average frequency deviation as a function of the m/z difference for two ion trapping events. The upper scale is the average initial frequency differences that correspond to the m/z differences given in the lower scale. The points are the average from 2500 simulated trapping events. **(b)** The average frequency deviations and the average energy deviations are linearly related

Figure 6.

Results for trapping of multiple ions with the same m/z (25,000 Da) and charge (200 e). (a) Plots of the m/z distributions obtained for trapping of one to eight ions. (b) A plot of the m/z peak width versus the number of trapped ions. The red points are determined from the FWHM of the m/z distributions in (a). The black points are determined from 2.355 times the RMSD of the distribution. Both methods yield the same value for a Gaussian distribution. (c) A plot of the average frequency deviation from ion-ion interactions against the number of trapped ions

Figure 7.

Results for trapping of multiple ions with the same mass (5.00 MDa) and a Gaussian charge distribution centered on 200 e. (a) Plots of the mass distributions obtained for trapping of one to eight ions. (b) A plot of the mass peak width versus the number of trapped ions. The red points are determined from the FWHM of the mass distributions in (a). The black points are determined from 2.355 times the RMSD of the distribution. Both methods yield the same value for a Gaussian distribution