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Coulombic shielding during ion cyclotron excitation in FT-ICR mass spectrometry

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ABSTRACT

Fourier transform ion cyclotron resonance (FT-ICR) mass spectrometry relies upon linearity between the ion cyclotron excitation and the observed response. However, nonlinearities result from non-ideal applied electric and magnetic fields and Coulombic interactions. Here, we report nonlinear response at low excitation electric field magnitude due to Coulombic shielding. The measured ICR signal magnitude exhibits an excitation voltage threshold that increases monotonically with the number of shielding ions (i.e., unexcited ions). If shielding ions are not present, ICR signal magnitude versus excitation voltage is linear (e.g., for quadrupole-isolated ions of nearly a single m/z). Finally, we show that shielding results in a reduced cyclotron radius at low excitation voltage, resulting in an increased rate of transient decay; thereby exacerbating response nonlinearity and excitation threshold for long data acquisition period.

1. Introduction

Fourier transform ion cyclotron resonance (FT-ICR) signal detection requires coherent, large amplitude cyclotron motion that is conveniently induced by a resonant, oscillating excitation electric field. For an ion at rest at the center of the ICR cell subjected to oscillating peak-to-peak voltage V_{p-p} for a period T_{excite} at magnetic field strength B_0, with two infinitely extended conductive plates separated by d meters, post-excitation radius r (Eq. (1)) is [1]:

$$r = \frac{V_{p-p} T_{excite}}{2dB_0} \quad (1)$$

Eq. (1) implies linearity (ideal behavior) between peak-to-peak excitation voltage amplitude and signal magnitude (which is linearly proportional to cyclotron radius). However, an experimental ICR signal is typically not linear throughout the full cell radius range, particularly at low and high excitation amplitude. Such nonlinearity can arise from combination of nonideal magnetic and trapping electric fields, Coulombic interactions (space charge), and collisions with neutrals [2–4]. Here, we show that Coulombic shielding (Debye shielding) during ion cyclotron excitation produces nonlinearity by cancellation of the excitation electric field required for power absorption and concomitant growth in ion cyclotron radius.

Under the influence of an external electric field, an ensemble of charged particles redistributes in a manner that attenuates the propagation of the field within the collection [5–8]. This process is called Coulombic (or Debye) shielding and occurs to an extent that depends on charge density and electric field strength. If the charge density is high enough and/or the electric field strength low enough, the distance over which the external field penetrates into the ensemble (the Debye length) may be small relative to the dimension of the ensemble and the interior volume is effectively shielded from the influence of the external field. Studies have shown that Coulomb shielding can aid electrostatic trapping upon entrance of an ion cloud into a magnetic field [9]. Attempts to characterize abnormal relative peak height of ions close in mass at low excitation amplitude as an effect of space charge have been made [10], and there have been several analyses of Coulomb shift and broadening of FT-ICR signals [11–17], but, up to now, shielding during ion cyclotron excitation has not been considered. An excellent review of non-neutral plasmas with a focus in FT-ICR has been published by Peurrung et al. [6].

In this work, we show that an ion cloud comprising ions of a single m/z exhibits linear response to ion cyclotron excitation throughout a large range of excitation electric field ampli-

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tude:duration product. Further, the presence of ions of other m/z results in a nulling of the excitation electric field within the cloud at low voltage. As a result, a threshold appears, below which no ICR signal is observed, independent of excitation period. The threshold electric field magnitude increases monotonically with the number of shielding (i.e., non-resonant) ions in the cloud. Finally, shielding reduces the post-excitation ion cyclotron radius and increases time-domain signal decay damping, further reducing FT-ICR mass spectral signal magnitude. The impact of Coulombic shielding on FT-ICR experiments is discussed.

2. Materials and methods

2.1. Sample preparation

ESI tuning mix was purchased from Agilent Technologies (Wilmington, DE) and diluted 3:20 in 49:49:2 (by volume) methanol:water:acetic acid. Solvents were purchased from Sigma–Aldrich. The two components of interest were hexakis (2,2-difluoroethoxy) phosphazene (621.19 g/mol) and hexakis (2,2,3,3-tetrafluoropropoxy) phosphazene (921.01 g/mol). Substance P (1347.63 g/mol) was purchased from Sigma–Aldrich (St. Louis, MO) and used without further purification. A 1.0 μM solution of the peptide was prepared in 49:49:2 methanol:water:acetic acid. Direct infusion microelectrospray ionization was performed at a flow rate of 1.0 μL/min.

2.2. Instrumentation

A custom-built FT-ICR mass spectrometer equipped with a passively shielded 9.4 T superconducting horizontal solenoid magnet (Oxford Instruments) was used for all experiments [18]. Ions generated by the electrospray source are accumulated in an external linear octople ion trap with either helium or nitrogen gas for accumulation period between 0.1 and 10 s. A quadrupole was used to select ions within a given m/z range prior to accumulation in the octopole trap (a process henceforth referred to as quadrupole isolation). Time-domain data was acquired for 43.8 ms for the ESI tuning mix experiments and 285.3 ms for Substance P and zero-filled once before Fourier transformation. Cyclotron excitation was produced by frequency-sweep (2.9–255 V_{p-p} from m/z 2000 to 200 at 50 Hz/μs or 25 Hz/μs) or single frequency (2.9–255 V_{p-p} for 0.00045 or 0.00090s). No apodization was used.

3. Results and discussion

3.1. Signal magnitude linearity with respect to excitation amplitude

Control experiments confirm linear dependence of FT-ICR signal magnitude on excitation voltage for an ion cloud composed of ions of a single m/z (Fig. 1). The isolated ions are hexakis (1H, 1H, 3H-tetrafluoropropoxy) phosphazene (m/z 922), a heavily fluorinated compound with relatively low abundance of heavy isotopes. Frequency-sweep excitation (2.88–82.58 V_{p-p}, 50 Hz/μs) was followed by a short (5.48 ms) detection period to minimize nonlinearity caused by ion radius-dependent transient decay. The dependence of FT-ICR mass spectral peak height on excitation voltage amplitude is highly linear (Fig. 1, $r^2 > 0.998$), as is the dependence of peak height on ion accumulation period (Fig. 2). Thus, the number of accumulated ions varies linearly with accumulation period. Linearity as a function of V_{p-p} is independent of sweep rate and is equally linear for single frequency rather than frequency-sweep excitation (data not shown).

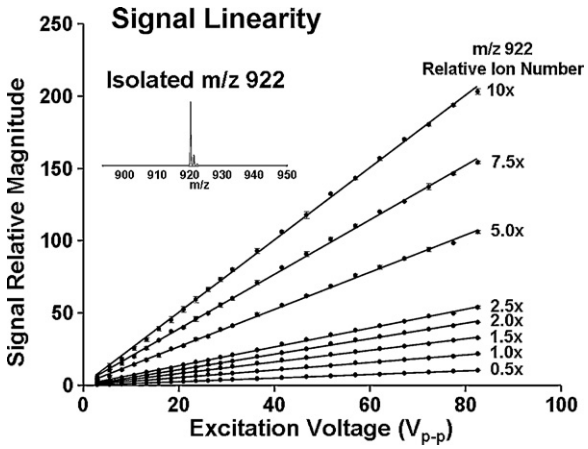

Fig. 1. FT-ICR MS relative peak height for isolated ions of m/z 922 (HP mix), following frequency-sweep excitation, as a function of excitation voltage amplitude. Data for all figures were taken in triplicate (error bars are typically smaller than the plotted data point width).

3.2. Coulombic shielding during resonant ion excitation

Evidence for Coulombic shielding is provided by Fig. 3. Two successive quadrupole isolations were performed before accumulation in an external octople and subsequent transfer to the ICR cell. The number of ions of m/z 922 was held constant (2 s accumulation period), and the number of shielding (i.e., unexcited) ions, hexakis (2,2-difluoroethoxy) phosphazene (m/z 622) was varied (0.0, 2.5, 5.0 and 10.0 s accumulation period). In the absence of shielding ions, the FT-ICR MS peak height for ions of m/z 922 varies linearly with excitation amplitude starting at zero excitation amplitude. In contrast, no ICR signal for ions of m/z 922 is observed below a minimum excitation amplitude threshold (>40 V_{p-p}) in the presence of a significant number of shielding ions of m/z 622, and that threshold voltage amplitude increases with the number of shielding ions (red, green and blue data in Fig. 3). A similar threshold is also observed with single-frequency excitation (data not shown).

Fig. 4 shows that the excitation voltage threshold for the onset of ICR signal as well as the ICR signal, measured shortly after ions reach their post-excitation radius, as a function of above-threshold excitation voltage are both independent of time-domain ICR data acquisition period from 2.74 to 43.8 ms. (A single 43.8 ms acquisition data set was truncated to yield data for shorter acquisition periods, and vertical scaling is such that undamped time-domain

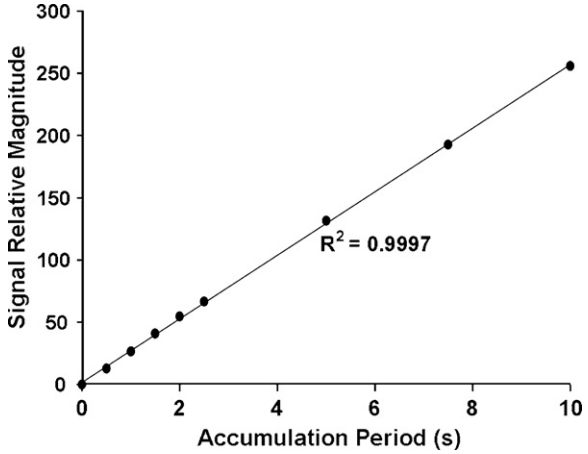

Fig. 2. FT-ICR MS relative peak height for isolated ions of m/z 922 (HP mix), following frequency-sweep excitation, as a function of ion external accumulation period.

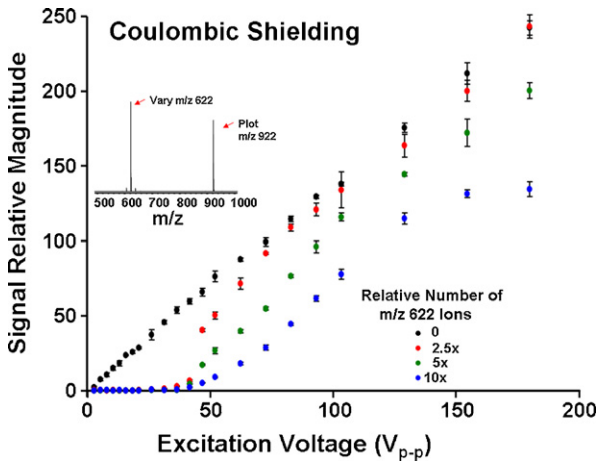

Fig. 3. FT-ICR MS relative peak height for ions of m/z 922 (HP mix) as a function of the relative number of nonresonant m/z 622 ions. Note the minimum voltage threshold required to generate a detectable signal for ions of m/z 922 in the presence of substantial numbers m/z 622 ions.

signals of different length have the same frequency-domain peak height value.)

3.3. Coulomb shielding and transient decay

Diminution of transient duration is a secondary effect of Coulomb shielding. To characterize that effect, plots of Substance P FT-ICR MS monoisotopic doubly-charged ion ($[M+2H]^{2+}$, $m/z \sim 674.38$) peak height as a function of excitation voltage for different time-domain data acquisition periods are shown in Fig. 5. (As for Fig. 4, the data acquisition period was varied by truncating the same 285 ms time-domain data by factors of 1, 4, 16, and 64.) Fig. 4 shows the effect of Coulomb shielding *during* excitation, and those effects do not change the observed ICR signal during a relatively short data acquisition period (up to 44 ms). However, Fig. 5 shows additional diminution of ICR signal with increasing data acquisition period, because Coulomb-shielded ions lose spatial coherence faster (i.e., shorter time-domain signal decay) than unshielded ions during detection, thus further reducing the FT-ICR signal as seen for the colored data points relative to the black points in Fig. 5. The faster decay rate for ions subject to shielding may result from reduced post-excitation cyclotron radius and increased ion–ion interactions, as well as a larger distribution of post-excitation radii caused by inhomogeneous shielding.

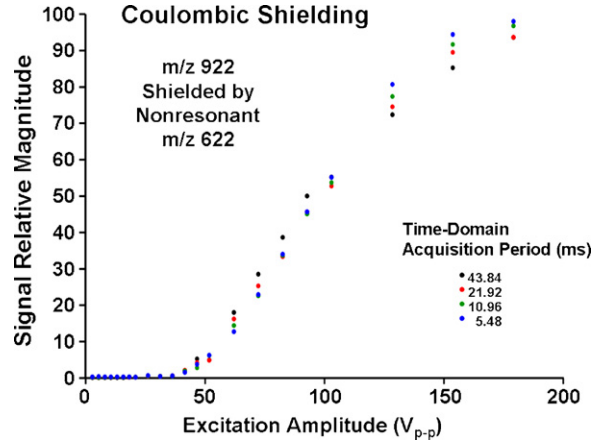

Fig. 4. FT-ICR MS relative peak height for ions of m/z 922 versus excitation voltage for a fixed number of shielding ions (10 s external accumulation for ions of m/z 622) as a function of time-domain data acquisition period.

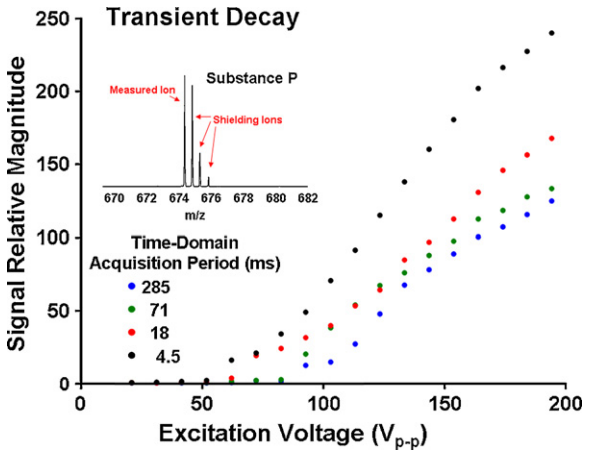

Fig. 5. FT-ICR MS relative peak height for Substance P doubly-charged monoisotopic ions vs. frequency-sweep excitation as a function of time-domain acquisition period.

3.4. Excitation frequency sweep direction

Coulomb shielding depends strongly on excitation frequency-sweep ("chirp") direction. Consider ions of two m/z values and highly unequal abundance. If the higher-abundance ions are excited first, then they will not be affected by the low-abundance unexcited ions. However, if the smaller population is excited first, it will be subject to shielding from the unexcited larger population. For the general case of ions of multiple m/z values and abundances, the observed extent of shielding effects will vary with frequency-sweep direction and ion relative abundance. For the data in Fig. 5, the excitation frequency was swept from high to low, so that the monoisotopic ions were excited first and are thus Coulomb shielded by (not yet excited) ions containing 1–3 ^{13}C atoms.

4. Conclusions

To this point, we have considered Coulomb shielding by ions of one m/z on ions of one or a few other m/z. In FT-ICR analysis, ions of up to thousands of different m/z and widely different abundances are present simultaneously. The present results demonstrate that shielding and the increased rate of ion cloud dephasing that accompany reduced cyclotron radius can result in significant loss of signal magnitude. Further, high-resolution ion isolation requires a longer-duration ICR excitation waveform. As the required frequency-domain resolution increases, the time-domain duration of the isolation waveform must increase and its voltage amplitude must decrease: for the constant sweep rate typically used in chirp or SWIFT experiments, the required voltage scales inversely with the square root of the duration of the isolation waveform [1]. The present results show that the voltage amplitude cannot be arbitrarily small, so that the ultimate ion isolation resolving power will be limited by the number of ions to be injected into the ICR cell. Future work will probe the effect of such shielding in more complex samples at voltages more typical of routine FT-ICR analysis.

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References

[1] A.G. Marshall, C.L. Hendrickson, G.S. Jackson, Mass Spectrom. Rev. 17 (1998) 1.
[2] A.J. Peurrung, R.T. Kouzes, Phys. Rev. E 49 (1994) 4362.
[3] E.F. Gordon, D.C. Muddiman, J. Mass Spectrom. 36 (2001) 195.
[4] S. Guan, G.-Z. Li, A.G. Marshall, Int. J. Mass Spectrom. Ion Proc. 167/168 (1997) 185.
[5] F.F. Chen, Introduction to Plasma Physics and Contolled Fusion. Plasma Physics, vol. 1, Plenum Press, New York, 1984.
[6] A.J. Peurrung, R.T. Kouzes, S.E. Barlow, Int. J. Mass Spectrom. Ion Proc. 157/158 (1996) 39.
[7] C. Roberson, C. Driscoll, Nonneutral Plasma Physics, American Institute of Physics, New York, 1988.
[8] R.C. Davidson, Physics of Nonneutral Plasmas, Addison Wesley, Redwood City, 1990.
[9] S.C. Beu, C.L. Hendrickson, V.H. Vartanian, D.A. Laude Jr., Int. J. Mass Spectrom. Ion Proc. 113 (1992) 59.
[10] G.T. Uechi, R.C. Dunbar, J. Am. Soc. Mass Spectrom. 3 (1992) 734.
[11] T.-C.L. Wang, A.G. Marshall, Int. J. Mass Spectrom. Ion Proc. 68 (1986) 287.
[12] S.-P. Chen, M.B. Comisarow, Rapid Commun. Mass Spectrom. 5 (1991) 450.
[13] S.-P. Chen, M.B. Comisarow, Rapid Commun. Mass Spectrom. 6 (1992) 1.
[14] M.V. Gorshkov, A.G. Marshall, E.N. Nikolaev, J. Am. Soc. Mass Spectrom. 4 (1993) 855.
[15] C.L. Hendrickson, S.C. Beu, D.A. Laude Jr., J. Am. Soc. Mass Spectrom. 4 (1993) 909.
[16] A.J. Puerrung, R.T. Kouzes, Int. J. Mass Spectrom. Ion Proc. 145 (1995) 139.
[17] D.W. Mitchell, R.D. Smith, Phys. Rev. E 52 (1995) 4366.
[18] K. Håkansson, M.J. Chalmers, J.P. Quinn, M.A. McFarland, C.L. Hendrickson, A.G. Marshall, Anal. Chem. 13 (2003) 3256.