

Direct observation of ion evaporation from a triply charged nanodroplet†

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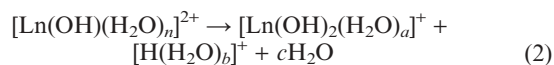
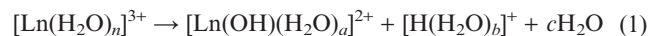
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Triply charged, highly solvated metal ions of the form $[\text{Ln}(\text{H}_2\text{O})_n]^{3+}$ can be generated using a commercial mass spectrometer, and CID studies on these highly charged metal-solvent clusters allow for the direct observation of a process best described as ion evaporation.

Ion-centered water clusters are easy to generate using electrospray, atmospheric pressure chemical ionization, or thermospray, so much so that protonated water clusters are routinely used as calibration standards in mass spectrometry with peaks observed for $[\text{H}(\text{H}_2\text{O})_n]^+$ every 18 m/z all the way out to over 2000 m/z (*i.e.* $n > 100$).¹ The modified “cold-flooding” conditions required to produce protonated water clusters in an electrospray ionization (ESI) source involve high flow rates ($\sim 50 \mu\text{L min}^{-1}$), cool source and desolvation gas temperatures and high cone voltages. The highly solvated ions thus generated are essentially nanodroplets whose desolvation is not yet complete by the time they pass out of the source. We report here our studies of nanodroplet-solvated lanthanide ions, and their relevance as intermediates in the electrospray process.

Lanthanide(III) ions solvated by diacetone alcohol,² acetonitrile,³ various sugars,⁴ dimethyl sulfoxide and hexamethylphosphoramide⁵ are sufficiently stable in the gas phase to be detected by ESI-MS. But despite the fact that the Ln^{3+} ions are stable in aqueous solution, aquo complexes of lanthanide(III) ions are only observed as charge-reduced 2+ and 1+ species when investigated by ESI-MS under conventional conditions. The appearance of these ions is best explained by the following charge-reduction reactions:



Despite intensive efforts^{6–11} aimed at observing solvated metal trications in the gas phase, to our knowledge only one prior observation of stable Ln^{3+} -water clusters has been made, in which a custom-made ESI source incorporating a resistively heated copper block coupled to an FTICR-MS with cooled ion cell was used to generate highly hydrated tricationic lanthanide ions, $[\text{Ln}(\text{H}_2\text{O})_n]^{3+}$, in the gas phase.¹² While exploring the formation of

various ionic solvent droplets on an unmodified Q-TOF instrument, we found that simply infusing dilute aqueous solutions of lanthanum(III) chlorides using cold-flooding conditions provided easy access to the same series of $[\text{Ln}(\text{H}_2\text{O})_n]^{3+}$ droplets without the need for custom instrumentation.† Given easy access to these highly charged metal-centered nanodroplets, we chose metals spanning the lanthanide series (La^{3+} , Tb^{3+} and Lu^{3+}) for more detailed study. The resulting spectra are dominated by abundant $[\text{H}(\text{H}_2\text{O})_n]^+$ clusters, but they also contain extensive series of peaks separated by 6 m/z that are attributed to $[\text{Ln}(\text{H}_2\text{O})_n]^{3+}$ (Fig. 1).

Singly and doubly charged metal ions have minimum solvation numbers (n_{min}) below which the ions are unstable in the gas phase, and numerous studies have determined values for n_{min} between 1–7 for a variety of doubly charged ions of the form $[\text{M}(\text{H}_2\text{O})_n]^{2+}$.^{13–16} The $[\text{Ln}(\text{H}_2\text{O})_n]^{3+}$ ions are not stable (*i.e.* are absent from spectra) below n_{min} values of 15–18. These values differ within the series of lanthanides in a predictable way: Lu^{3+} is the smallest lanthanide at $r = 112$ pm, and its higher charge density means that it requires more water molecules (18) to stabilize its +3 charge than either Tb^{3+} ($r = 118$ pm, $n_{\text{min}} = 17$) or La^{3+} ($r = 130$ pm, $n_{\text{min}} = 15$).

We carried out a series of MS/MS experiments to explore the desolvation and fragmentation of these highly solvated $[\text{Ln}(\text{H}_2\text{O})_n]^{3+}$ clusters. The ions $[\text{La}(\text{H}_2\text{O})_{48}]^{3+}$, $[\text{Tb}(\text{H}_2\text{O})_{47}]^{3+}$, and $[\text{Lu}(\text{H}_2\text{O})_{48}]^{3+}$ were selected using a quadrupole mass analyser, and fragmented at increasing collision energy in an argon-filled collision cell under multiple-collision conditions. The product ion spectra were collected using a time-of-flight (TOF) mass analyser,

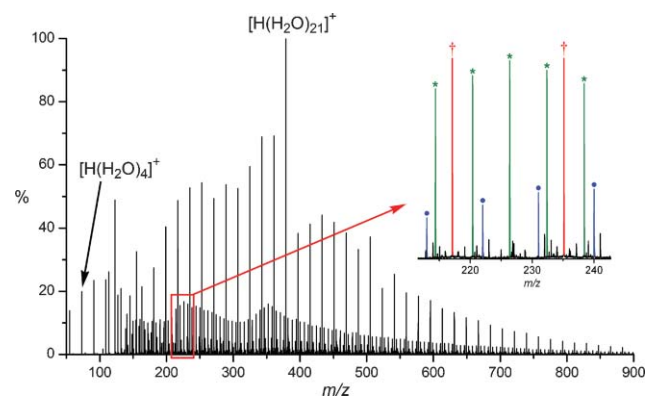


Fig. 1 Positive-ion ESI mass spectrum of an aqueous solution of LaCl_3 . The spectrum is dominated by water clusters (red †), in particular the “magic” cluster $[\text{H}(\text{H}_2\text{O})_{21}]^+$,^{18,19} but also present are $[\text{La}(\text{H}_2\text{O})_n]^{3+}$ (green *) and $[\text{La}(\text{OH})(\text{H}_2\text{O})_n]^{2+}$ water clusters (blue ●). The inset shows clearly the differences in m/z spacing for the 1+, 2+ and 3+ clusters (18, 9 and 6 m/z , respectively). The unremarkable intensity of the $[\text{H}(\text{H}_2\text{O})_4]^+$ cluster is indicated.

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† Electronic supplementary information (ESI) available: Experimental and computational details and EDESI-MS/MS of $[\text{Tb}(\text{H}_2\text{O})_{47}]^{3+}$ and $[\text{Lu}(\text{H}_2\text{O})_{48}]^{3+}$. See DOI: 10.1039/b711689f

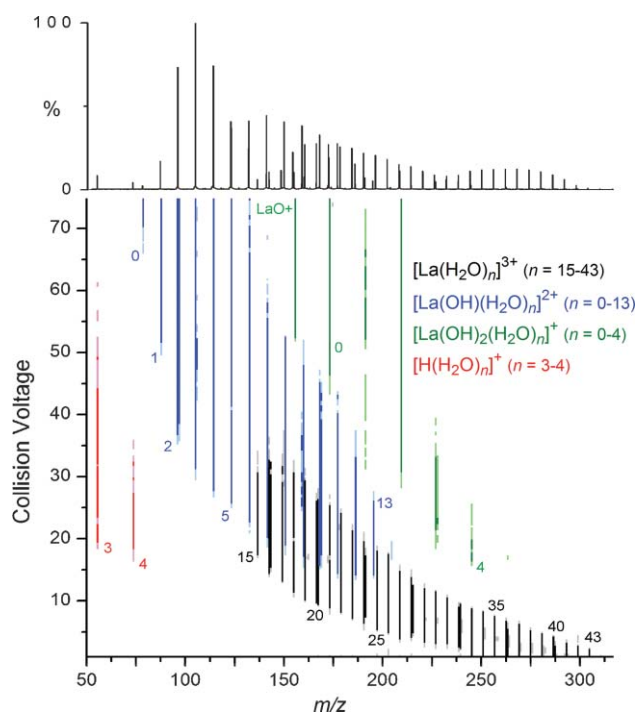


Fig. 2 Positive-ion EDESI-MS/MS of $[\text{La}(\text{H}_2\text{O})_{48}]^{3+}$. Fragmentation energy increases vertically in the contour map. The top mass spectrum is a summation of all 75 spectra used to generate the contour map.

and the data converted into a matrix and plotted as a contour map, thus generating an energy-dependent electrospray ionization MS/MS (EDESI-MS/MS).¹⁷ One of these maps is shown in Fig. 2 for $[\text{La}(\text{H}_2\text{O})_{48}]^{3+}$; the other two may be found in the ESI.†

The $[\text{La}(\text{H}_2\text{O})_n]^{3+}$ (black) clusters decompose exclusively through sequential solvent evaporation when the droplet is large and the collision voltage is low (<15 V). As desolvation progresses and charge density increases, the clusters reach a critical size ($n_{\text{crit}} = 17\text{--}28$) below which charge reduction (eqn (1)) competes with solvent loss. Both simple evaporation and the fragmentation of the $[\text{Ln}(\text{H}_2\text{O})_n]^{3+}$ clusters into $[\text{Ln}(\text{OH})(\text{H}_2\text{O})_n]^{2+}$ (blue) and $[\text{H}(\text{H}_2\text{O})_n]^+$ (red) clusters are readily apparent in the contour maps (Fig. 2 and ESI†). Before splitting into product droplets, the

like-charged $[\text{Ln}(\text{OH})]^{2+}$ and H^+ ions must momentarily exist inside the same water droplet (Fig. 3). The division of each 3+ cluster into 2+ and 1+ clusters occurs in a range ($17 < n < 28$) where both the 3+ ions and the 2+ ions maintain more than their minimum solvation shells (8–9 waters), and are both best described as rapidly shrinking charged droplets.

Droplet evolution in ESI is thought to proceed through either Coulomb fission (also known as the “charged residue mechanism”, CRM)²⁰ or *via* the ion evaporation mechanism (Iribarne and Thomson’s IEM: “...clusters composed of a few molecules plus a single charge evaporate from the surface of a charged drop”).²¹ Recent indirect evidence seems to support the IEM under most conditions.²² This experimental setup has essentially moved the last stages of ESI—the evaporation and fragmentation of highly solvated and highly charged ion-solvent clusters—away from the source and into the collision cell. To the best of our knowledge, our experiments represent the first time fully solvated ions have been observed evaporating from the surface of a droplet, despite the fact that this very occurrence is frequently implicated in discussions of the mechanism(s) by which ions are produced in the ESI process.²³

The nanodroplets generated in these experiments possess water molecules in excess of that required to fully solvate both the $[\text{Ln}(\text{OH})]^{2+}$ and $[\text{H}]^+$ ions, and as such, the way in which the water molecules are partitioned between the product ions is of special interest. The proton departs with no more than four water molecules (see red clusters in Fig. 2),²⁴ an ion best formulated as the Eigen cation $[\text{H}_3\text{O}(\text{H}_2\text{O})_3]^+$.²⁵ Significantly, the $[\text{Ln}(\text{OH})(\text{H}_2\text{O})_n]^{2+}$ product ion has more water molecules associated with it than needed for a full coordination sphere, whereas $[\text{H}_3\text{O}(\text{H}_2\text{O})_3]^+$ does not. As such, regarding the fragmentation event as one in which a solvated ion evaporates from the surface of a nanodroplet is a suitable description of the observed process. A more rigorous evaluation of the same process can be performed by comparing the calculated charge densities of the product ions that appear at a given collision energy, and of representative $[\text{Ln}(\text{H}_2\text{O})_n]^{3+}$ precursors whose abundance is diminishing at the same point (Table 1).

The charge density of the $[\text{H}_3\text{O}(\text{H}_2\text{O})_3]^+$ ion is 50–100% higher than that of either the precursor 3+ ions or the product 2+ ions. Ion evaporation involves a droplet undergoing a significant decrease in charge but a small decrease in mass; here, the event

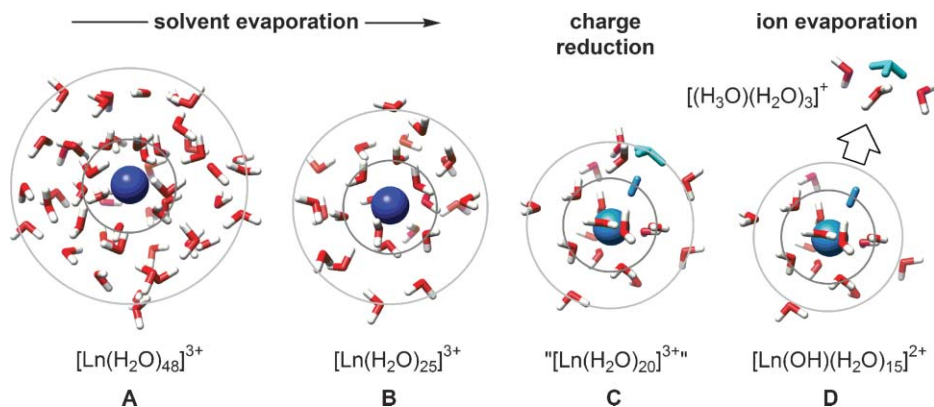


Fig. 3 Cartoon depiction of the solvent/ion evaporation process. **A**: the mass-selected water cluster. **B**: solvent evaporation through CID removes water from the droplet. **C**: the instant following charge reduction; both $[\text{La}(\text{OH})(\text{H}_2\text{O})_n]^{2+}$ and $[\text{H}(\text{H}_2\text{O})_n]^+$ simultaneously exist within the droplet. **D**: the $[\text{H}_3\text{O}(\text{H}_2\text{O})_3]^+$ ion evaporates from the surface of the droplet. The dark grey circles are the same size in each case and approximate the size of the inner coordination sphere; the pale grey circles inscribe the outer solvation sphere.

Table 1 Calculated precursor and product ion charge densities^a

Precursor ion	Charge density/Å ⁻³	Product ion	Charge density/Å ⁻³
[La(H ₂ O) ₁₈] ³⁺	0.00897	[La(OH)(H ₂ O) ₁₃] ²⁺	0.00768
[Tb(H ₂ O) ₁₈] ³⁺	0.00923	[Tb(OH)(H ₂ O) ₁₃] ²⁺	0.00789
[Lu(H ₂ O) ₂₀] ³⁺	0.00841	[Lu(OH)(H ₂ O) ₁₅] ²⁺	0.00695
		[H ₃ O(H ₂ O) ₃] ⁺	0.01360

^a See the ESI for details.

described by eqn (1) where $n = 18$, $a = 13$, $b = 4$ and $c = 0$ involves a 33.3% decrease in charge but only a 15.8% decrease in mass. Thus, by both consideration of solvation shells and a more quantitative consideration of charge densities, the observed fragmentation of Ln³⁺ nanodroplets constitutes the direct characterization of a solvated ion evaporating from a charged droplet consisting entirely of a volatile solvent. The experiments provide a snapshot of the point at which the “competing” mechanisms of ion evaporation and Coulomb fission are nearly indistinguishable in the evolution of a multiply-charged nanodroplet; however, the dramatically different charge densities of the two hydrated product ions strongly indicate that ion evaporation is a superior description for this system.

It is also interesting to consider how the [Ln(H₂O)_{*n*}]³⁺ ions were generated in the first place. Hydration of ions in the gas phase may occur through solvent condensation onto bare ions or by solvent evaporation from highly hydrated clusters.²⁶ Ln³⁺ ions are stable in aqueous solution and, as observed, in sufficiently large gas-phase water droplets. While we can't directly observe the initial formation of [Ln(H₂O)_{*n*}]³⁺ ions from much larger droplets containing multiple ions, our results shed some light on the process. The small ($n < 15$) [Ln(H₂O)_{*n*}]³⁺ clusters are unstable, and produce charge-reduced [Ln(OH)(H₂O)_{*n*}]²⁺ ions upon decomposition. If lanthanide-containing ions are evaporating from the droplet surface, they must have either (i) first undergone charge reduction, in which case we would expect the initial spectrum to be dominated by 2+ and 1+ charge-reduced ions or (ii) evaporate accompanied by at least 15–20 water molecules.

The use of cold-flooding conditions in ESI-MS has long been recognized as an appealing and facile method for generating charged nanodroplets in the gas phase. The bulk of studies using this technique have focused on singly charged droplets containing H⁺, OH⁻, and O₂⁻, and simple ammonium ions, many of which are valued for their “magic” stability.^{27–31} We have reported herein the extension of this methodology for simple generation of much sought-after triply charged metal–solvent droplets. The ability to observe these highly charged clusters has, in turn, allowed the direct observation of a step in the evolution of charged droplets that can best be described as ion evaporation.

Notes and references

† All experiments were run on an unmodified Micromass Q-ToF micro mass spectrometer in positive-ion mode with a capillary voltage of 2900 V and an ion energy of 1.0 V. In order to observe lanthanide clusters, 5 mM solutions of LnCl₃ were injected into the instrument with the cone voltage maximized (200 V) and the source and desolvation temperatures set to 60 °C and 20 °C respectively. For minimal [H(H₂O)_{*n*}]⁺ and maximum [Ln(H₂O)_{*n*}]³⁺ production, solvent flow rates ranged from 20 μL min⁻¹ to 50 μL min⁻¹ as the Ln³⁺ cluster intensities varied. The cone gas was turned off and the desolvation gas flow rate was 250 L h⁻¹ to optimize

[Ln(H₂O)_{*n*}]³⁺ formation. The experiments were largely insensitive to changes in the remaining instrumental parameters. EDESI experiments were carried out by performing MS/MS on a selected peak and increasing the collision voltage from 1 to 75 V in one-volt increments. Spectra were collected for 2 min at each collision voltage to obtain a reasonable ion count. Both high and low mass resolution were set to 15 for La and Lu species and 8 for Tb, to ensure only the ion of interest was passed through the quadrupole. Automation of the mass spectrometer software (MassLynx[®]) to carry out the EDESI experiments (ramping of the collision voltage) was achieved using the program Autohotkey (freely available from <http://www.autohotkey.com/>).

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