The 3D quadrupole ion trap mass spectrometer as a complete chemical laboratory for fundamental gas-phase studies of metal mediated chemistry

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Received (in Cambridge, UK) 17th November 2005, Accepted 22nd December 2005
First published as an Advance Article on the web 30th January 2006
DOI: 10.1039/b516348j

Electrospray ionization provides a "treasure trove" of metal containing ions whose fundamental reactivity can be studied *via* collision induced dissociation and ion–molecule reactions using the multistage mass spectrometry capabilities of the quadrupole ion trap mass spectrometer. Examples of metal mediated chemistry relevant to catalysis, C–C bond coupling, bioinorganic and supramolecular chemistry are highlighted.

1 Why study the gas phase ion chemistry of metal containing species?

Many important reactions are mediated by metal containing species, but understanding condensed phase reactivity in detail can be complicated by:

(a) The presence of solvent molecules and counter ions.

(b) The fact that many metallic species adopt oligomeric forms that exist in complex equilibria.

(c) The fact that many important catalytic reactions involve heterogeneous catalysts.

As a consequence, the relationship between structure and reactivity is often poorly understood.

Mass spectrometry (MS) offers an opportunity to examine the fundamental reactivity of metal containing ions in a pristine gas-phase environment,[1] where the ability to manipulate ions allows researchers to examine the role of solvent molecules[2] and counter ions, to control charge state and to examine the reactivity of cluster ions as a function of size.[3] While the careful theoretical treatment of metal containing systems, especially transition-metal systems,[4a] remains a challenge, such studies are a perfect adjunct to MS experiments, as the structures and energies of key species on the potential energy surfaces of reactions can be explored.[4b]

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2 The 3D quadrupole ion trap mass spectrometer as a *"complete gas-phase chemical laboratory"*

The use of mass spectrometers to examine gas-phase inorganic chemistry has a rich history, spanning back to the discovery of the H_3^+ ion by the founding father of mass spectrometry, J. J. Thompson in 1915.[5] All mass spectrometers consist of: (i) an ionization source; (ii) a mass analyzer; (iii) a detector; (iv) a data recorder/processor.[6] There are many potential combinations of ionization source and mass analyzer that can be used for fundamental studies.[7] The most widely used mass spectrometers in metal ion studies over the past few decades have been: ion cyclotron resonance (ICR) mass spectrometers (including their Fourier transform variants),[8] guided ion beams,[9] triple quadrupole mass spectrometers,[10] flowing afterglow reactors[11] and sector instruments, especially those with high pressure sources[12]). Since previous reviews have described the use of these types of mass spectrometers in gas-phase metal studies, in this account, I largely describe the results of a number of recent studies on metal mediated reactions carried out using quadrupole ion trap mass spectrometry.

The relatively recent marriage[13] of two Nobel prize winning technologies (electrospray ionization (ESI) and quadrupole ion traps) has resulted in a powerful and versatile instrument for gas-phase ion chemistry studies (Fig. 1). ESI, developed by

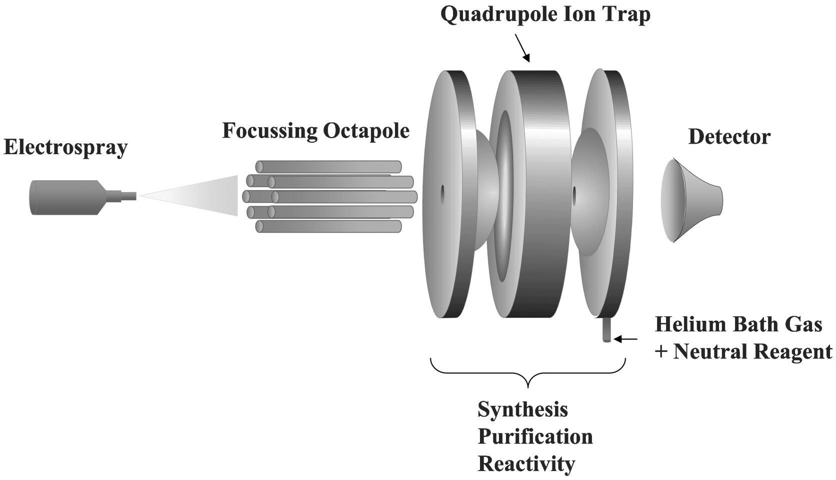


Fig. 1 Simplified schematic diagram of the ESI-QIT mass spectrometer. Ions generated *via* ESI are transferred to the QIT *via* the use of octapole ion guides. The QIT is then treated as a gas-phase reactor in which ions can be synthesized (*e.g. via* CID), purified *via* mass selection and then subjected to reactivity studies using either CID or ion–molecule reactions.[25,35b] Neutral reagents are introduced *via* the helium bath gas at a known concentration, allowing rate measurements by varying the reaction time. Ion–molecule reactions occur at room temperature.[25]

John Fenn (2002 Nobel Prize in Chemistry[14]) is a "soft" ionization technique, in which ions are transferred from solution into the gas phase. It is broadly applicable to any molecule that can form a charged species.[15] Of particular importance for metal ion studies is that ligated metal containing species in oxidation states commonly encountered in the condensed phase can now be studied in the gas phase.[16] This contrasts with many of the early gas-phase studies on bare atomic metal singly charged cations in which the metal was in the +1 oxidation state.[17] The QIT, invented by Wolfgang Paul (1989 Nobel Prize in Physics[18]), is a versatile mass analyzer[19] which offers multistage mass spectrometry (MS^n) capabilities[20] and the ability to examine structure and reactivity *via*: (i) low energy collision induced dissociation (CID), which is essentially a slowly "heating" process which utilizes the helium bath gas as a collision gas;[21] ion–molecule reactions;[22] ion–ion reactions;[23] gas-phase spectroscopy.[24]

Although numerous QITs with ESI capabilities have been sold, only a small number of research groups around the world have modified their instruments to allow gas-phase ion–molecule reactions to be examined. An important finding by Gronert has been that ions in such instruments are thermalized by the helium bath gas and are thus essentially at room temperature.[25] Both kinetic and thermodynamic data for ion–molecule reactions can be determined using these instruments,[25] and crude estimates for the energetics associated with CID processes can be determined using threshold CID measurements.[26] Thus the combination of ESI, which provides a "treasure trove" of interesting ions, and the MS^n capabilities of the QIT provides a powerful "complete gas-phase chemical laboratory"[27,28] in which ions can be manipulated and studied in a sequence of reactions. For example, novel metal-containing ions can be synthesized *via* CID, then purified *via* mass selection and then subjected to reactivity studies (*e.g.* CID or ion–molecule reactions). As a consequence of these instrumental capabilities, a diverse range of chemistry has been examined using the QIT, including the reactions of organic ions,[22] bimolecular and unimolecular reactions of biomolecules[29] and molecular recognition.[30] This account mainly focuses on work carried out on metal containing ions generated *via* ESI using a QIT in the author's laboratory. A number of other groups actively use QIT with various forms of ionization to examine metal containing systems,[31] but these studies are not discussed in detail here.

3 Metal mediated chemistry of relevance to organic chemistry

The synthetic organic chemist is interested in building molecules from small, readily available precursors. Two key classes of reactions that are at the heart of any organic synthesis are: (i) functional group transformations and (ii) the assembly of carbon frameworks from smaller components using C–C bond coupling. Both classes of reactions are often mediated by metals species, either in stoichiometric or catalytic amounts.[32] The following sections describe recent examples of these two key classes of reactions that occur in the *gas phase*.

3.1 Functional group transformations mediated by metal catalysts

There have been numerous gas-phase studies on metal mediated C–H, C–C[33] and other[17] bond activation. Here the focus is on how metal ions influence the oxidation of alcohols and the selective decomposition of acetic acid.

3.1.1 Oxidation of alcohols by transition-metal oxides and peroxides. The oxidation of primary alcohols to aldehydes and secondary alcohols to ketones represents one of the key functional group transformations that is a cornerstone of the production of bulk commodity chemicals as well as key intermediates in the fine chemical industry.[34] For example, the significant demand for formaldehyde-based resins in particleboard wood products makes formaldehyde one of the top 25 chemicals produced in industrial countries. Most production of formaldehyde involves the use of a molybdenum(VI) trioxide-based catalyst or a metallic silver catalyst. As a consequence, the partial oxidation of methanol over molybdenum(VI) oxide based catalysts has been the subject of many studies employing a range of techniques. Essentially the process involves three key steps.

(i) Gaseous methanol undergoes dissociative adsorption on the surface of the solid-state catalyst to yield surface methoxomolybdenum(VI) centers. Water may be desorbed from the catalyst in this step.

(ii) The activated methoxo ligands are oxidized and eliminated as formaldehyde, resulting in the reduction of the catalyst and the creation of an oxygen vacancy. This step is rate determining and elevated temperatures are required.

(iii) Oxidation of the bulk catalyst by dioxygen completes the cycle.

The fact that this process involves heterogeneous catalysis has meant that a detailed *molecular* understanding of the elementary reactions has been elusive. We have shown that multistage mass spectrometry experiments in a quadrupole ion trap, combined with isotope labelling studies, kinetic measurements and energy resolved CID can be used to generate detailed insights into the gas-phase oxidation of alcohols by group VI metal–oxo anions.[35] We have uncovered gas-phase catalytic cycles for the oxidation of alcohols *via* an anionic dimolybdate center (Fig. 2), which bear some similarities to the industrial process.

The oxidation of primary and secondary alcohols to aldehydes involves two gas-phase catalytic cycles (cycles 1 and 2 in Fig. 2), mediated by a binuclear dimolybdate center $[Mo_2O_6(OCH_3)]^-$, acting as the catalyst. The first cycle proceeds *via* three steps: (1) reaction of $[Mo_2O_6(OH)]^-$ with alcohol R_2HCOH and elimination of water to form $[Mo_2O_6(OCHR_2)]^-$; (2) oxidation of the alkoxo ligand and its elimination as aldehyde in the rate-determining step; and (3) regeneration of the catalyst *via* oxidation by nitromethane. Step (2) does not occur at room temperature and requires the use of collisional activation to proceed. The second cycle is similar, but differs in the order of reaction with alcohol and nitromethane. The nature of each of these reactions was probed by kinetic measurements and by variation of the substrate alcohols (structure and isotope labelling). The role of the binuclear molybdenum center was assessed by examination of the relative reactivities of the mononuclear $[MetalO_3(OH)]^-$ and binuclear $[Metal_2O_6(OH)]^-$ ions (Metal = Cr, Mo, W). The molybdenum and tungsten binuclear centers $[Metal_2O_6(OH)]^-$ (Metal = Mo, W) were reactive towards alcohol, but the chromium center $[Cr_2O_6(OH)]^-$ was not. This is consistent with the expected order of basicity of the hydroxo ligand in these species. The chromium and molybdenum centers $[Metal_2O_6(OCHR_2)]^-$ (Metal = Cr, Mo) oxidized the alkoxo ligand to aldehyde, while the tungsten center $[W_2O_6(OCHR_2)]^-$ did not, instead preferring the non-redox elimination of alkene. This is consistent with the expected order of oxidizing power of the anions. Each of the mononuclear anions $[MetalO_3(OH)]^-$ (Metal = Cr, Mo, W) was inert to reaction with methanol, highlighting the importance of the second MoO_3 unit in these catalytic cycles. Thus only the dimolybdate center has the proper balance of reactivity that allows it to participate in *each* of the three steps of the two catalytic cycles, to yield the overall process shown in eqn (6).

$$CH_3OH + CH_3NO_2 \rightarrow H_2CO + H_2O + CH_3NO \qquad (6)$$

The three reactions of these cycles are similar to the three essential steps proposed to occur in the industrial oxidation of gaseous methanol to formaldehyde (eqn (7)) at 300–400 °C over solid state catalysts based upon molybdenum(VI) trioxide. Indeed there are several remarkable common features, including: similar kinetic isotope effects for the rate determining second step are observed in both the gas phase (1.9 ± 0.4) and industrial processes (in the range of 1.7–2.2); molybdenum catalysts are favoured over tungsten, which tend to give products arising from non-redox processes.

$$CH_3OH + 1/2\ O_2 \rightarrow H_2CO + H_2O \qquad (7)$$

The electrospray process can be used to “synthesize” new inorganic species that can then be “purified” using mass selection. For example, in a follow up study we showed that mixing two different mononuclear group VI metal–oxo species produces a mixed binuclear species.[35c] By taking advantage of the different exchange rates of $H_2{}^{18}O$ with the mononuclear species, it is even possible to regioselectively label the oxo groups within the mixed binuclear species (eqn (8)). This allows the site of reactivity in these systems to be uniquely identified. For example, CID if the heterodimer

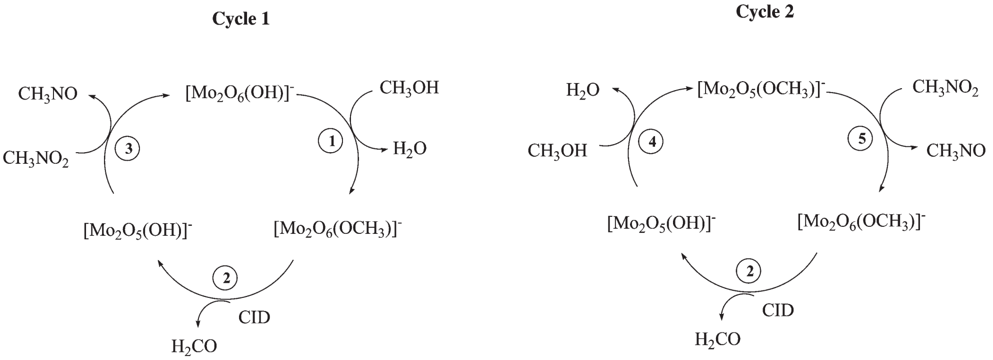


Fig. 2 Gas phase catalytic cycles for the oxidation of methanol to formaldehyde. Reaction (2) links $[Mo_2O_6(OCH_3)]^-$ and $[Mo_2O_5(OH)]^-$ and appears in both cycles. Cycles 1 and 2 differ in the sequence of reaction with CH_3NO_2 and CH_3OH.[35b]

tetrabutylammonium ion pair, $\{Bu_4N^+[MetalMetal'O_7]^{2-}\}^-$, results in an S_N2 reaction in which one of the oxygen atoms is butylated to give the $[MetalMetal'O_6(OBu)]^-$ product ion (eqn (9)). By using a combination of ^{18}O labeling together with studying the subsequent reactivity of the butylated product ion, it is possible to establish the site of alkylation. This is illustrated in Scheme 1 for the mixed chromium–molybdate system. Collisional activation of $[CrMoO_6(OBu)]^-$ generated from $\{Bu_4N^+[CrMoO_7]^{2-}\}^-$ (CrO_t, 92 atom% ^{18}O; MoO_t, 8 atom% ^{18}O) resulted in a major mass loss of 72 Da (^{16}O-butanal), consistent with the source of butanal being a terminal butoxo ligand at the molybdenum site (Path (a1) of Scheme 1). Separate ion–molecule ligand switching reactions with CF_3CH_2OH support the location of the site of butylation (Path (a2) of Scheme 1). Similar results were found for the mixed chromium–tungstate system, in which the site of butylation was the tungsten terminal oxo position. These results can be rationalized by alkylation occurring at the terminal oxo atoms of the less electronegative center (Mo or W), that are expected to be more nucleophilic.

$$[Cr^{16}O_3(^{16}OH)]^- + [Mo^{18}O_3(^{18}OH)]^- \rightarrow [^{16}O_3Cr^{16/18}OMo^{18}O_3]^{2-} + {}^{16/18}OH_2 \quad (8)$$

$$\{Bu_4N^+[MetalMetal'O_7]^{2-}\}^- \rightarrow [MetalMetal'O_6(OBu)]^- + NBu_3 \quad (9)$$

Considerable attention has focussed on the use of transition-metal catalysts in combination with hydrogen peroxide as an oxidant for the oxidation of organic substrates.[36] Noyori and co-workers have described a peroxo–tungstate system capable of catalysing the oxidation of alcohols, olefins and sulfides. Given that we showed that oxo tungstate anions were poor oxidants,[35b] we became interested in comparing the oxidizing effects of oxo *vs.* peroxo ligands in the gas phase oxidation of alkoxo ligands in bis(peroxo) $[MetalO(O_2)_2(OR)]^-$ and trisoxo $[MetalO_3(OR)]^-$ anions (Metal = Cr, Mo, W).[37] The molybdate and tungstate anions $[MetalO(O_2)_2(OR)]^-$ underwent parallel elimination of aldehyde (ketone) and dioxygen while the equivalent chromate underwent loss of dioxygen only. The peroxo ligands were the source of oxidizing equivalents in both reactions. For each alkoxo ligand, the total yield of aldehyde for the tungstate system (eqn (10)) exceeded that for the molybdate system. Collisional activation of $[MetalO_3(OMe)]^-$ led to clean elimination of formaldehyde with the metal center supplying the oxidizing equivalents. For larger alkoxo ligands, only the chromate center eliminated aldehyde, while the molybdate and tungstate (eqn (11)) centers underwent clean loss of alkene. Threshold activation voltages indicated that the peroxo ligands of $[WO(O_2)_2(OMe)]^-$ are more oxidizing than the tungstate center of $[WO_3(OMe)]^-$. Deuterium and ^{18}O isotope tracing experiments were consistent with a formal hydride transfer mechanism operating for oxidation of alkoxo ligand in each system.

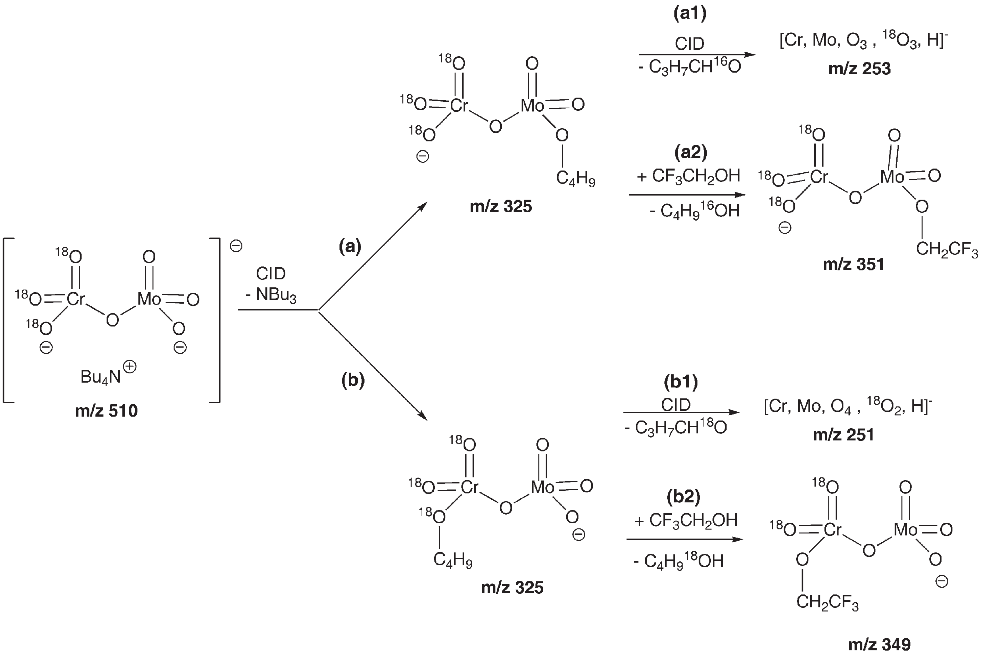
$$[WO(O_2)_2(OCH_2CH_3)]^- \rightarrow [WO_3(OH)]^- + CH_3CHO \quad (10)$$

$$[WO_3(OCH_2CH_3)]^- \rightarrow [WO_3(OH)]^- + CH_2{=}CH_2 \quad (11)$$

A similar change in selectivity for oxo *vs.* peroxo ligands has been reported for related mononuclear vanadium systems.[38] Thus CID of the oxo anion results in the non-redox loss of the alkene (eqn (12)), while the peroxo system undergoes oxidative cleavage *via* loss of the ketone (eqn (13)).

$$[VO_2(OCH(CH_3)_2)_2]^- \rightarrow [VO_2(OCH(CH_3)_2)(OH)]^- + CH_3CH{=}CH_2 \quad (12)$$

$$[VO(O_2)(OCH(CH_3)_2)_2]^- \rightarrow [VO_2(OCH(CH_3)_2)(OH)]^- + (CH_3)_2C{=}O \quad (13)$$



Scheme 1

3.1.2 Controlling the selective decomposition of acetic acid using metal catalysts. The thermal decomposition of acetic acid has been widely studied and in the absence of catalyst, two competing sets of products are formed: (i) ketene and water; (ii) methane and carbon dioxide.[39] The former products are formed about twice as much as the latter. Given the use of ketene as a feedstock for the production of acetic anhydride and the synthetic importance of ketenes in general, there has been interest in devising catalysts to lower the activation energy and improve the selectivity for ketene formation.[40] We have recently used multistage mass spectrometry experiments to show that two different types of metal catalysts can favour the selective decomposition of acetic acid *via*: (i) a ketene channel (Fig. 3(a))[41a] or (ii) a decarboxylation channel (Fig. 3(b)).[41b] Both catalytic cycles proceed *via* two-step processes, and using the multistage trapping capabilities of the ion trap instrument, it was possible to establish both cycles as being truly catalytic by carrying out the reactions on the same population of starting ions. Each cycle is now described in further detail.

The dehydration of acetic acid to ketene (eqn (18)) is catalysed by group VI mononuclear $[Mo_3(OH)]^-$ and binuclear $[Metal_2O_6(OH)]^-$ oxo-anions (Metal = Mo, W). In contrast to the three-step oxidation of methanol (Fig. 2), the catalytic dehydration of acetic acid (Fig. 3(a)) is less sensitive towards the structure of the catalyst, working for both molybdenum and tungsten mononuclear and binuclear anions. Both catalytic cycles share a similar first metathesis step in which the OH ligand is switched for either an alkoxy ligand (reaction (1) in Fig. 2) or a carboxylato ligand (reaction (14) in Fig. 3(a)). The second step is the rate determining step (reaction (15) in Fig. 3(a)) as it requires activation (under CID conditions) to induce dehydration to reform the oxo-anion catalyst. Interestingly, there are a number of similarities to this catalytic process and previous reports on the preparation of ketenes *via* catalytic dehydration of carboxylic acids over silica, metal or metal oxide surfaces. These reactions were also proposed to involve two-step processes: (i) interaction of the carboxylic acid with a surface hydroxyl site to form a surface carboxylate with elimination of water; (ii) decomposition at high temperature to induce ketene loss with regeneration of the surface hydroxyl site.

$$CH_3CO_2H \rightarrow CH_2CO + H_2O \quad (18)$$

The decarboxylation of acetic acid (eqn (19)) is catalysed by the organomagnesate anions $[CH_3MgL_2]^-$, (where L = Cl or CH_3CO_2) (Fig. 3(b)). The first step is another metathesis reaction, in which a CH_3 ligand is switched for a carboxylato ligand (reaction (16) in Fig. 3(b)). Once again, the second step is the rate determining step (reaction (17) in Fig. 3(b)) as it requires activation (under CID conditions) to induce decarboxylation of the magnesium acetate anion $[CH_3CO_2MgL_2]^-$, to reform the organometallic catalyst $[CH_3MgL_2]^-$. $[CH_3MgCl_2]^-$ is expected to be a better catalyst than $[CH_3MgO_2CCH_3]^-$. This is not only due to the fact that the activation energy for decarboxylation of $[CH_3CO_2MgO_2CCH_3]^-$ is higher, but this ion also suffers from a competing decomposition pathway *via* loss of an acetate anion (the range of competing fragmentation pathways for metal acetate ions is discussed further in Section 3.2).

$$CH_3CO_2H \rightarrow CH_4 + CO_2 \quad (19)$$

The decarboxylation of acetic acid catalysed by an organometallic intermediate appears to be a unique process. While there have been several reports on the use of copper(I) salts to catalyse the decomposition of carboxylic acids in the condensed phase, work by Darensbourg *et al.* suggests that the mechanism of these catalytic reactions are quite complex and may not involve an organometallic intermediate, but rather will involve electrophilic intermediates.[42]

3.2 Synthesis of organometallic ions and their mediation of C–C bond coupling reactions

Some of the most important C–C bond forming methods involve the use of metal species to mediate reactivity in a selective and controlled way.[43] While the reverse reaction, C–C bond activation has been widely studied in the gas phase,[33c] fewer studies have examined C–C bond coupling.[44–46] Two examples suffice to illustrate such processes. The first example used the MS^3 capabilities of multistage quadrupole mass spectrometry to demonstrate that coordinatively unsaturated iron carbonyl cations $Fe(CO)_x^+$ mediate the C–C coupling of allyl chloride.[45] Of all the cations, $Fe(CO)_4^+$ was the most reactive, ultimately yielding an ion of stoichiometry $[FeC_6H_{10}Cl_2]^+$. CID of this ion yielded a mixture of products (eqn (20a) and (20b)), which were suggested to arise from two different structures **1** (giving the products of eqn (20a)) and **2** (giving the products of eqn (20b)).

$$[FeC_6H_{10}Cl_2]^+ \rightarrow C_6H_{10}^+ + FeCl_2 \quad (20a)$$

$$\rightarrow [FeC_3H_5Cl]^+ + C_3H_5Cl \quad (20b)$$

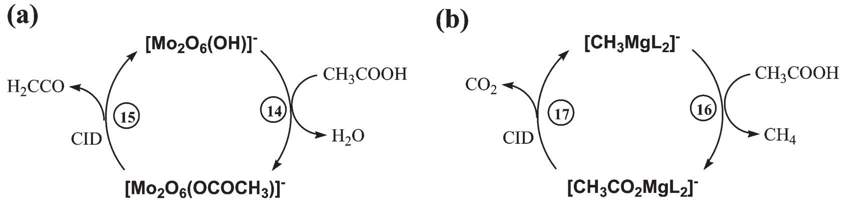


Fig. 3 Gas phase catalytic cycles for the metal mediated: (a) dehydration of acetic acid;[41a] (b) decarboxylation of acetic acid.[41b]

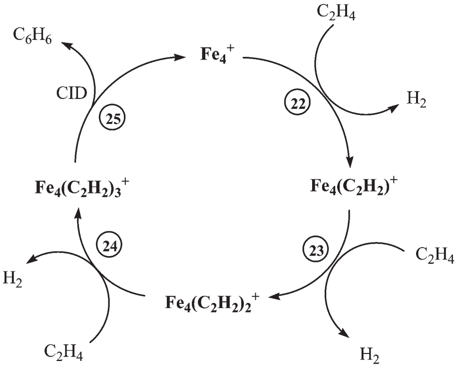
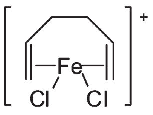


Fig. 4 Gas phase catalytic cycles for the metal mediated assembly of benzene.[46]



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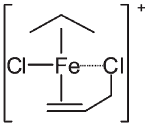

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The second example is a rare demonstration of a clear dependence on metal catalysts cluster size in the mediation of C–C bond coupling, and utilised the multistage mass spectrometry abilities of a FT-ICR mass spectrometer.[46] Fig. 4 illustrates how the Fe_4^+ cluster catalyses the dehydrogenation and assembly of three molecules of ethylene to form benzene (eqn (21)).[46a–e] In the first step, Fe_4^+ reacted with C_2H_4 by dehydrogenation to yield $Fe_4(C_2H_2)^+$ and H_2. Further stepwise reaction of ethylene with concomitant loss of H_2 then yielded an ion of stoichiometry $Fe_4(C_4,H_4)^+$ followed by the $Fe_4(C_6,H_6)^+$ ion. Collisional activation of $Fe_4(C_6,H_6)^+$ resulted in the loss of neutral 'C_6H_6', which was assigned as benzene. This regenerated Fe_4^+ and established a catalytic cycle for the dehydrogenation and assembly of three molecules of ethylene to benzene. $Fe_4(C_6,H_6)^+$ was proposed to be a mixture of $Fe_4(C_6H_6)^+$ and a second isomer that did not contain an intact benzene ligand. This was based on: (i) $Fe_4(C_6,H_6)^+$ undergoing partial ligand exchange only with labelled C_6D_6; and (ii) differences in the fragmentation of $Fe_4(C_6,H_6)^+$ and 'authentic' $Fe_4(C_6H_6)^+$ prepared from reaction of Fe_4^+ with C_6H_6.[46e] This implied that the collisional activation process used to detach benzene from $Fe_4(C_6,H_6)^+$ was also responsible for providing the energy required to assemble the benzene ligand for at least some component of the parent ion. The activity of Fe_n^+ clusters of differing stoichiometry was also examined.[46a,c] Smaller clusters (n = 2, 3) were completely unreactive, while Fe_5^+ was significantly less reactive than Fe_4^+, and larger clusters (n = 6–13) were also completely unreactive. These experiments highlighted an important size or electronic effect that rendered unique reactivity for the Fe_4^+ cluster in the catalytic cycle of Fig. 3 and illustrate the power of gas-phase experiments to examine the effect of cluster size on reactivity.

$$3\ C_2H_4 \rightarrow C_6H_6 + 3\ H_2 \qquad (21)$$

We have recently discovered ways of "synthesising" organometallate anions,[41b,47] and silver cluster cations[48] in the gas phase, which has allowed us to explore their reactivity including their role in C–C bond coupling. Decarboxylation of metal acetates appears to be a general way of synthesising organometallic "ate" species,[49] some of which are related to textbook organometallic species, used in organic synthesis (*e.g.* Grignard[50] and Gilman[51] reagents). These studies further highlight the powerful multistage mass spectrometry capabilities of the ion trap. For example, two stages of CID and one ion–molecule reaction event (a MS^4 experiment) are required to synthesise and study the reactions of $(CH_3)_2Metal^-$ (Metal = Cu and Ag) with methyl iodide in the gas phase, which are described in further detail in Section 3.2.2.

In fact, CID of metal acetate ions can proceed *via* a number of different pathways including:[52,53] decarboxylation (eqn (26a));[54] acetate anion loss (eqn (26b)); oxidation of the acetate anion with concomitant reduction of the metal (eqn (26c)); loss of ketene (eqn (26d)) and loss of water (eqn (26e)).

$$[CH_3CO_2Metal(L)_n]^- \rightarrow [CH_3Metal(L)_n]^- + CO_2 \qquad (26a)$$

$$\rightarrow CH_3CO_2^- + [Metal(L)_n] \qquad (26b)$$

$$\rightarrow [Metal(L)_n]^- + CH_3CO_2 \qquad (26c)$$

$$\rightarrow [HOMetal(L)_n]^- + CH_2CO \qquad (26d)$$

$$\rightarrow [HCCOMetal\ L)_n]^- + H_2O \qquad (26e)$$

Which of these reactions is favoured will depend on the type of metal, the auxiliary ligand, L, as well as the oxidation state of the metal. While we have not done a comprehensive survey of main group and transition-metal acetates with a range of auxiliary ligands, some trends have emerged from our studies on alkali and alkaline earth metals,[41b,47c] group VI oxometallate anions[41a] and copper and silver species.[47a,b]

(i) Alkali earth acetate ions $[Metal(O_2CCH_3)_2]^-$ (where Metal = lithium, sodium, potassium, rubidium and caesium; L = CH_3CO_2; n = 1) all fragment *via* loss of the acetate anion (eqn (26b)),[47c] with virtually no formation of the organometallate. In contrast, the alkaline earth acetate ions (Metal = magnesium, calcium, strontium, and barium; L = CH_3CO_2; n = 2) not only fragment *via* loss of the acetate anion (eqn (26b)), but also all fragment to form the organometallates (eqn (26a)).[47c]

(ii) Oxometallate anions favour the ketene loss channel as discussed above, with the selectivity being best for Mo and W.[41a]

(iii) Decarboxylation (eqn (26a)) readily proceeds for the Cu(I) ion $[(CH_3CO_2)_2Cu]^-$, but the redox reaction (eqn (26c)) occurs for the Cu(II) ion $[(CH_3CO_2)_3Cu]^-$.[47b]

3.2.1 Role of the ligand and metal in the reactions of organoalkaline earths.

Metathesis reactions of organometallics (eqn (27)) are of fundamental interest, and offer opportunities to seek correlations between the strengths of carbon–metal bonds and those of other species (such as the carbon–hydrogen bonds in the parent hydrocarbons).[55] In a number of instances, the ill-defined structural nature of the reactive species can hamper such studies. A classic case is the organoalkaline earths, which form complex solvent dependant aggregates.

Indeed this was the motivation for Lambert and von Rague Schleyer's theoretical studies on the trends in the reaction energetics of organoalkalis with a range of substrates (acids), AH (eqn (27), where: R = CH_3; Metal = Li, Na, K, Rb, Cs; x = 0; AH = H_2, H_2O, H_3N, HF and CpH).[55b] They found that the substrate has a profound effect on the reaction energetics. In the case of AH = H_2, the reaction energies are nearly independent of the metal, consistent with the trends in ionicity (and hence stabilities) of R–Metal compared to H–Metal. In contrast, the reaction energetics of R–Metal with the π donating ligands H_2O, H_3N, HF and CpH exhibit a non-monotonous behaviour. At the highest level of theory, they found the following order for the reaction with water of ΔH (in kJ mol^{-1}): CH_3Cs (175.3) > CH_3Li (164.8) > CH_3K (162.8) ≈ CH_3Rb (162.3) > CH_3Na (130.5).

$$\mathrm{RMetal(L)}_x + \mathrm{AH} \rightarrow \mathrm{AMetal(L)}_x + \mathrm{RH} \qquad (27)$$

The ability to synthesise organoalkaline earths $[CH_3MetalL_2]^-$ and study their ion–molecule reactions provided us with a unique opportunity to study reactions directly related to eqn (27) to thus to see how reactivity is controlled by: the auxiliary ligand;[41b] the nature of the metal;[47c] the substrate.[41b] In our first study on the organomagnesates $[CH_3MgL_2]^-$ (L = Cl and = O_2CCH_3) we examined the influence of the auxiliary ligand and the substrate on reactivity.[41b] We found that these $[CH_3MgL_2]^-$ ions exhibit some of the reactivity of Grignard reagents, reacting with neutral species containing an acidic proton (AH) *via* addition with concomitant elimination of methane to form $[AMgL_2]^-$ ions (eqn (28)), in direct analogy to eqn (27). Kinetic measurements, combined with DFT calculations, provided clear evidence for an influence of the auxiliary ligand on reactivity of the organomagnesates $[CH_3MgL_2]^-$. Thus $[CH_3Mg(O_2CCH_3)_2]^-$ exhibited reduced reactivity towards water. The DFT calculations suggest that this may arise from the bidentate binding mode of acetate, which induces overcrowding of the Mg coordination sphere. Interestingly there is a report in the literature on the enhanced selectivity (*i.e.* reduced reactivity) of solution phase Grignard reagents processing carboxylate ligands instead of the traditional halides.[56]

$$[\mathrm{CH_3MetalL_2}]^- + \mathrm{AH} \rightarrow [\mathrm{AMetalL_2}]^- + \mathrm{CH_4} \qquad (28)$$

The substrate also plays a key role on the reactivity of the $[CH_3MgL_2]^-$ ions. This is dramatically illustrated for the reaction of aldehydes containing enolisable protons, which reacted *via* enolisation, rather than *via* the Grignard reaction (eqn (29)). This is consistent with DFT calculations on the competition between enolisation and the Grignard reaction for $[CH_3MgCl_2]^-$ ions reacting with acetaldehyde, which suggest that while the latter has a smaller barrier, it is entropically disfavoured.

$$[\mathrm{CH_3MgL_2}]^- + \mathrm{RCHO} \rightarrow [\mathrm{RC(CH_3)OMgL_2}]^- \qquad (29)$$

Interestingly, our study provides an additional example on the role of the substrate in the reactions of $[CH_3MgL_2]^-$ (eqn (28)). Thus while acetaldehyde is much more acidic than water (by over 100 kJ mol^{-1}), it reacts much less readily with $[CH_3MgCl_2]^-$. This illustrates a dramatic impact of metal coordination on the effective acidity of the reagent, further confirmed by the DFT calculated energetics, which suggest both a kinetic barrier as well as a thermodynamic effect (the overall enthalpy changes of the water and acetaldehyde reactions are essentially the same). A similar change in stabilisation of the acetaldehyde enolate and phenolate anions upon binding to alkali metals has been demonstrated by Kremer and von Rague Schleyer.[55c] Finally, as noted above, when acetic acid is the substrate, the $[CH_3MgL_2]^-$ ions complete a catalytic cycle for the decarboxylation of acetic acid (Fig. 3(b)).

Given that the acetate ligand appears to tame the reactivity of organomagnesates, in our next study we used this ligand to probe the reactivity of other organoalkaline metallates.[47c] Each of these organometallates $[CH_3Metal(O_2CCH_3)_2]^-$ react with background water in the QIT *via* addition with concomitant elimination of methane to form the metal hydroxide $[HOMetal(O_2CCH_3)_2]^-$ ions (eqn (28)), with a relative reactivity order of: $[CH_3Ba(O_2CCH_3)_2]^-$ ≈ $[CH_3Sr(O_2CCH_3)_2]^-$ > $[CH_3Ca(O_2CCH_3)_2]^-$ > $[CH_3Mg(O_2CCH_3)_2]^-$. The DFT predicted reaction exothermicities for these reactions generally supported the reaction trends observed experimentally, with $[CH_3Mg(O_2CCH_3)_2]^-$ being the least reactive. Once again, there are similarities with Schleyer's study, in which a non-monotonous behaviour was found for the thermodynamics for eqn (27), when R = CH_3 and AH = H_2O.[55b]

3.2.2 Dimethylcuprate *vs.* dimethylargentate. While Gilman reagents, "R_2CuLi", have proved to be useful in a range of C–C bond coupling reactions,[51] including reactions with alkyl halides, the mechanistic aspects[57] of their reactions remain obscure due to two main reasons: (i) the nature of the reactive species can be uncertain; (ii) there can be more than one pathway due to the potential involvement of Cu(III) intermediates. Several theoretical studies have suggested that these reactions occur *via* copper clusters.[57] This seems to be supported by a report that the simplest model system, the dimethyl cuprate ion $(CH_3)_2Cu^-$, is unreactive towards simple electrophiles such as 1-dodecanyl bromide in the condensed phase.[58] Thus we embarked on a combined experimental and theoretical study to examine the reactivity of the dimethyl cuprate ion $(CH_3)_2Cu^-$, and its silver congener with one of the simplest, most reactive alkyl halides, CH_3I. We found that while the dimethylcuprate ion (M = Cu) reacts with CH_3I *via* C–C bond cross coupling (eqn (30)) at a modest rate (corresponding to a reaction efficiency of 3 out of every 100 collisions), its silver congener is unreactive. Deuterium labelling studies were carried out to evaluate the kinetic isotope effects for the reaction. Comparing the rate constants for the reaction of $(CH_3)_2Cu^-$ with CH_3I and CD_3I, revealed that breaking the C–I bond involves an inverse isotope effect (k_H/k_D = 0.88 ± 0.40). An inverse β-deuterium isotope effect (k_H/k_D = 0.82 ± 0.05) for the Cu–C bond was determined from a comparison of the ion abundances (integrated peak areas) of CH_3CuI^- and CD_3CuI^- in the reaction of

$CD_3CuCH_3^-$ with CH_3I. That two isotope effects are operating in the cross coupling reaction is further confirmed by the combined isotope effect of $k_H/k_D = 0.66 \pm 0.05$ determined from a comparison of the ion abundances of CH_3CuI^- and CD_3CuI^- in the reactions of $CD_3CuCH_3^-$ with CD_3I.

$$[(CH_3)_2Cu]^- + CH_3I \rightarrow [CH_3CuI]^- + CH_3CH_3 \quad (30a)$$

$$\rightarrow I^- + CH_3Cu + CH_3CH_3 \quad (30b)$$

The experimental results are consistent with MP2/6-31++G** (with ECPs for the metal) *ab initio* calculations on two different mechanisms (Scheme 2) for cross coupling of $(CH_3)_2Metal^-$ (where Metal = Cu and Ag) with CH_3I. Path A involves a "side on" S_N2 reaction, while Path B involves the formation of a "T shaped" transition state. The *ab initio* calculations reveal that the latter pathway has the lower barrier, with an energy below that of the separated reactants. In contrast, the transition state energies for both pathways for the silver congener are above the energy separated reactants. This is consistent with the experimental observation that $(CH_3)_2Cu^-$ reacts with CH_3I but $(CH_3)_2Ag^-$ does not. Subsequent theoretical studies by Nakamura[59] have further addressed the fundamental question: Why are organo copper compounds superior to their silver and gold counterparts? They studied the energetics associated with two steps: (i) attack of the ate complex $(CH_3)_2Metal^-$ (where Metal = Cu, Ag and Au) onto an electrophile, E^+: (ii) decomposition of the $R_2MetalE$ intermediate. Copper is favoured in both steps since: (i) Cu has higher lying d-orbitals that directly participate in the nucleophilic reaction; (ii) the Cu(III) intermediate is less stable and thus is more susceptible to decomposition *via* reductive elimination.

3.2.3 The Ag_4H^+ cluster ion as a model for C–C bond coupling on silver surfaces and silver nanoparticles? The use of metal surfaces[60] and nanoparticles[61] to mediate C–C bond coupling is an active area of research. Allyl halides (C_3H_5X) react with a range of metal surfaces in different ways that depend on both the metal as well as the halide.[62] Silver surfaces appear to be the most effective at mediating carbon–carbon bond coupling of allyl halides to give 1,5-hexadiene. Two distinct pathways have been observed:[62] (i) dissociative adsorption of C_3H_5X to give surface bound allyls, which then undergo coupling; (ii) a coupling reaction between C_3H_5X and a surface bound allyl group. Surface defects play a significant role in the selectivity of 1,5-hexadiene formation, which increases from 20% to greater than 60% when chlorine atoms are preadsorbed on silver surfaces.[62] Also of interest are the largely forgotten results of Tamura and Kochi,[63] who synthesised silver nanoparticles over 30 years ago and showed that they reacted with allyl bromide to give 1,5-hexadiene and silver bromide (eqn (31)).

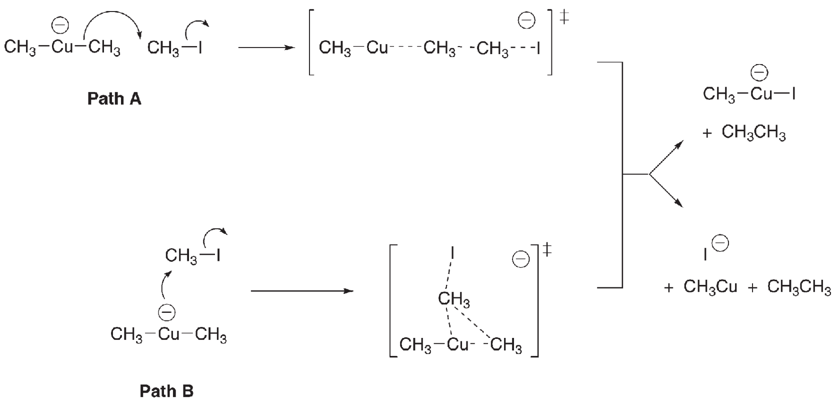
$$\begin{gathered}(Ag)_x + x\ CH_2{=}CHCH_2Br \rightarrow \\ (AgBr)_x + x/2\ CH_2{=}CH(CH_2)_2CH{=}CH_2\end{gathered} \quad (31)$$

We have recently shown that the Ag_4H^+ cluster can be "synthesised" *via* CID of silver-amino acid clusters and have examined its ion–molecule reactions with the allyl halides, $CH_2{=}CHCH_2X$ (X = Cl, Br and I).[48a] We found that Ag_4H^+ exhibits the highest selectivity for C–C bond coupling with allyl bromide, $CH_2{=}CHCH_2Br$. In the first step, allyl bromide reacts with Ag_4H^+ *via* a metathesis reaction to yield Ag_4Br^+ (eqn (32)), which subsequently reacts with a second molecule of allyl bromide to form the ion $Ag_4Br_2(C_3H_5)^+$ (eqn (33)). Reaction of $Ag_4Br_2(C_3H_5)^+$ with a third molecule of allyl bromide results in the formation of the silver organometallic ion $Ag(C_3H_5)_2^+$ in combination with the neutral cluster Ag_3Br_3 (eqn (34)). Overall these equations combine to give the C–C bond coupling reaction (eqn (35)). CID of $Ag(C_3H_5)_2^+$ results in the sole formation of Ag^+ (eqn (36)), providing support that C–C bond coupling had occurred. Furthermore, the identity of the C–C bond coupled C_6H_{10} product was shown to be 1,5-hexadiene *via* a comparison of the energy resolved CID spectrum of the $Ag(C_6H_{10})^+$ ion with a range of ions of "authentic" structures.

$$Ag_4H^+ + CH_2{=}CHCH_2Br \rightarrow Ag_4Br^+ + CH_2{=}CHCH_3 \quad (32)$$

$$Ag_4Br^+ + CH_2{=}CHCH_2Br \rightarrow Ag_4Br_2(C_3H_5)^+ \quad (33)$$

$$\begin{gathered}Ag_4Br_2(C_3H_5)^+ + CH_2{=}CHCH_2Br \rightarrow \\ Ag(C_3H_5)_2^+ + Ag_3Br_3\end{gathered} \quad (34)$$



Scheme 2

$$\begin{gathered}\mathrm{Ag_4H^+ + 3\ CH_2{=}CHCH_2Br \rightarrow} \\ \mathrm{Ag(C_3H_5)_2^+ + Ag_3Br_3 + CH_2{=}CHCH_3}\end{gathered} \tag{35}$$

$$\mathrm{Ag(C_3H_5)_2^+ \rightarrow Ag^+ + (C_3H_5)_2} \tag{36}$$

4 Bioinorganic and supramolecular chemistry

4.1 Redox chemistry to generate radical cations of biomolecules

Electron transfer reactions are amongst the most important reactions in chemistry and biochemistry. Metal complexes undergo a range of fragmentation reactions in the gas phase, including electron transfer reactions in which oxidative ligand loss occurs with concomitant reduction of the metal centre (*e.g.* eqn (26c)). These redox reactions have a long history in inorganic mass spectrometry, having been discussed by Shannon in the first volume of this journal.[64] With the coupling of ESI to tandem mass spectrometers, there has been renewed interest in the gas-phase redox reactions of inorganic complexes. An emerging area is bioinorganic chemistry, where ternary metal complexes of biomolecules are used to generate radical cations of biomolecules. Radical cations of biomolecules are not readily formed directly *via* ESI, which tends to result in their protonated form (*i.e.* even electron ions) instead. While radical chemistry of peptides and amino acids coordinated to copper had been previously observed,[65] a major breakthrough was Siu's discovery that electrospray ionisation (ESI) of the ternary complex $[\mathrm{Cu^{II}(dien)(YGGFLR)}]^{2+}$ coupled with tandem mass spectrometry (MS/MS) could be used to form the gas-phase $\mathrm{YGGFLR}^{+\bullet}$. peptide radical cations.[66a]

Since then, several studies have examined the generality of the concept of using collision induced dissociation (CID) of ESI generated ternary metal complexes (eqn (37), where Metal = a transition-metal ion; L = an auxiliary ligand; M = the biomolecule analyte) to form radical cations of small biomolecules such as amino acids,[66b] peptides[66b–h] and the constituents of DNA.[67] These studies have focussed on the role of the auxiliary ligand in directing CID of peptide containing copper(II) complexes[66f–h] and determination of which peptides are amenable to this redox process.[66c] Siu notes that peptides lacking either aromatic or basic residues generally fail to form peptide radical cations, instead undergoing proton transfer reactions to form the protonated peptide.[66a,b] Recently however, this shortcoming has been circumvented by the use of either 12-crown-4 (1,4,7,10-tetraoxacyclododecane) or modified terpyridine as the auxiliary ligands, which promotes the formation of the radical cations for peptides which contain only aliphatic residues.[66g,h] A significant recent achievement has been the formation of protonated radical cations $[\mathrm{M + H}]^{2+\bullet}$.[66i] We have shown eqn (37) is indeed a general redox technique and that: (i) other biomolecule analytes such as nucleobases form radical cations;[67] (ii) that other ternary metal complexes involving transition-metal ions in the +3 oxidation with a dianionic auxiliary ligand (salen) can be used to yield radical cations of peptides.[68] These studies have also uncovered a rich fragmentation chemistry of long lived radical cations of peptides under low energy CID conditions, which can be initiated by either the charge site or the radical site.

$$\begin{gathered}[\mathrm{Metal}^{x+}(\mathrm{L})^{y-}(\mathrm{M})]^{(x-y)+} \rightarrow \\ [\mathrm{Metal}^{(x-1)+}(\mathrm{L})^{y-}]^{(x-y-1)+} + \mathrm{M}^{+}\end{gathered} \tag{37}$$

4.2 Metal ion induced assembly of supramolecular structures

The advent of electrospray ionization has given birth to the new area of gas-phase supramolecular chemistry. Recent studies have uncovered a host of new and interesting cluster ions involving biomolecules. Examples include the serine octamer[69a] and clusters of DNA constituents.[69b] Nucleobases are particularly suited to form a range of supramolecular structures with metal ions.[70] We have described detailed studies on the use of ESI, multistage mass spectrometry experiments involving both CID and ion–molecule reactions as well as DFT calculations aimed at examining the formation of oligomeric structures upon binding of silver to adenine, $[\mathrm{Ad}_x + \mathrm{Ag}_y - z\mathrm{H}]^{(y-z)+}$.[71] We employed the concept of "maps" as shown in Fig. 5 to suggest that the oligomeric ions are not simple "linear" polymers, but rather adopt more complex structures. Based on the known ability of adenine to from dimers, we suggested polymers of structure type **3**. The gas-phase ion–molecule and fragmentation reactions of the $[\mathrm{Ad}_x + \mathrm{Ag}_y - z\mathrm{H}]^{(y-z)+}$ complexes were found to be dependant on *x*, *y* and *z*, as illustrated for the dimer. Thus the doubly charged dimer reacts with butylamine *via* deprotonation (eqn (38)) and fragments to form the monomer (eqn (39)). In contrast, the singly charged dimer forms an adduct with butylamine

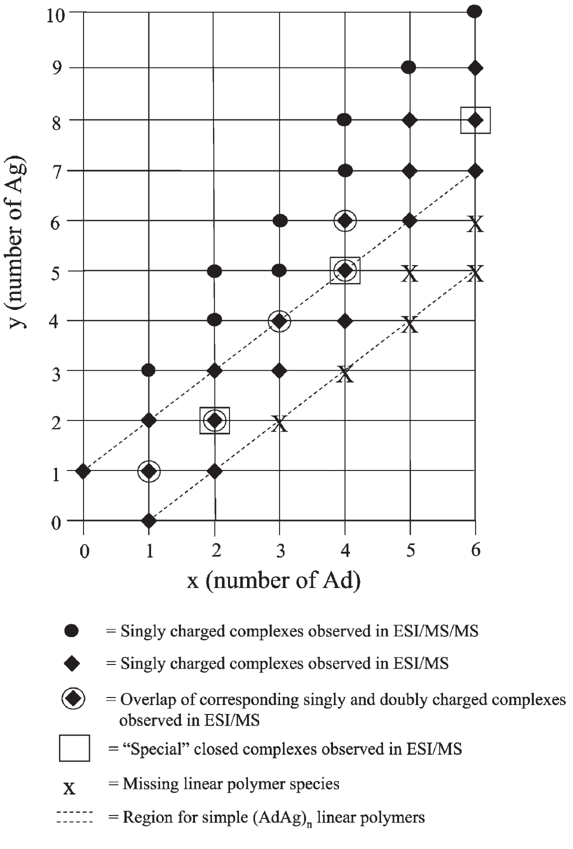


Fig. 5 Map of the results of gas-phase experiments on $[\mathrm{Ad}_x + \mathrm{Ag}_y - z\mathrm{H}]^{(y-z)+}$ complexes, which suggests more complex structures than simple "linear" polymers.

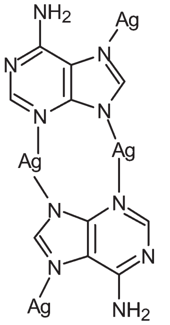
(eqn (40)) and fragments *via* loss of neutral adenine (eqn (41)). One of the aims of examining ion–molecule reactions of these $[Ad_x + Ag_y - zH]^{(y-z)+}$ complexes was to see if they could be used to "titrate" the vacant coordination sites. We found that while there is some correlation between the number of ligands which added and the predicted vacant Ag coordination sites, in some instances fully coordinated species still underwent ligand addition (*e.g.* eqn (40)). This might arise from the formation of hydrogen bonded adducts rather than the formation of a coordinated ligand. Vachet has also noted that caution needs to be adopted in using ion–molecule reactions to "titrate" vacant coordination sites on metals as the rates and thermodynamics for these processes can depend on the nature of the metal, its existing ligand sphere and the properties of the "titrating" ligand.[31a]

$$\begin{gathered}[Ad_2 + Ag_2]^{2+} + BuNH_2 \rightarrow \\ [Ad_2 + Ag_2 - H]^+ + BuNH_3^+\end{gathered} \tag{38}$$

$$[Ad_2 + Ag_2]^{2+} \rightarrow 2\,[Ad + Ag]^+ \tag{39}$$

$$\begin{gathered}[Ad_2 + Ag_2 - H]^+ + BuNH_2 \rightarrow \\ [Ad_2 + Ag_2 - H + BuNH_2]^+\end{gathered} \tag{40}$$

$$[Ad_2 + Ag_2 - H]^+ \rightarrow [Ad + Ag_2 - H]^+ + Ad \tag{41}$$



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More recently, we discovered that $[Pt(tpy)Cl]^+$ reacts with deoxyguanosine (dG) to yield a range of cluster of type $[Pt(tpy)(dG)_n]^{2+}$.[67] These clusters do not exhibit "magic" numbers, and thus they may involve the formation of guanine strips.[70b]

4.3 Models for enzyme sites

Gas phase studies have been carried out to model aspects of metallo enzymes, including carbonic anhydrase[72] and cytochrome P-450.[73] Using a combination of triple quadrupole mass spectrometry experiments and DFT calculations, two reports have appeared on the reactivity of mimics for the known structure of carbonic anhydrase, which consists of Zn^{2+} coordinated to three histidine residues and a water molecule in the active site. In the first, Peschke *et al* used imidazole (Im) to model histidine and examined the thermodynamics associated with ligand binding to Zn^{2+} as well as the deprotonation of a bound water ligand to zinc (eqn (42)) and the subsequent formation of the bicarbonate anion (eqn (43)).[72a]

$$Im_3Zn(OH_2)^{2+} \rightarrow Im_3Zn(OH)^+ + H^+ \tag{42}$$

$$Im_3Zn(OH)^+ + CO_2 + H_2O \rightarrow Im_3Zn(OH_2)^{2+} + HCO_2^- \tag{43}$$

Three main points emerged from this study regarding nature's choice of three histidine residues in the active site of the enzyme.

(i) Strongly bonding residues are essential to make the Zn^{2+} ion in the enzyme stable, relative to the aqueous environment (*i.e.* to prevent "leaching out");

(ii) Most strongly bonding ligands tend to raise the energy for eqn (42).

(iii) Strongly bonding ligands favourably lower the energetics associated with eqn (43).

Histidine emerged as the ligand of choice, as it is an excellent compromise between the two opposing effects for eqns (42) and (43).

In the second study, Schroeder *et al.* used ^{18}O labeling to examine the activation of CO_2 using simple ligated zinc hydroxide ions (eqn (44), where L = pyridine (Py) or imidazole (Im) and n = 0–3).[72b] The relative rates of this exchange reaction are dependent on the type and number of ligands. The bare zinc hydroxide is almost unreactive, while the ligated systems show a reactivity order of: $Im_2Zn(^{18}OH)^+ > PyZn(^{18}OH)^+ > Py_2Zn(^{18}OH)^+ > Im_2Zn(^{18}OH)^+ \gg L_3Zn(^{18}OH)^+$. Two opposing effects were suggested to explain these reactivity orders.

(i) Complexation of CO_2 is required in the first step. The energetics for this step become less favourable for increasing n.

(ii) The nucleophilicity of the OH ligand increases for increasing n.

Two imidazole ligands appear to be the best compromise between these two opposing effects.

$$L_nZn(^{18}OH)^+ + C^{16}O_2 \rightarrow L_nZn(^{16}OH)^+ + O^{18}C^{16}O \tag{44}$$

5 Future prospects

This account has given a brief overview of the wide range of metal ion studies possible using ion trap mass spectrometry. There are a number of new and exciting developments in mass spectrometry instrumentation, which may have an important impact on future gas-phase studies of metal containing ions. These include the design of instruments which allow oppositely charged species to react, such as electron capture dissociation (in which multiply charged cations are allowed to react with electrons[74]) and ion-ion reactions.[23] Solution phase chemists widely use other spectroscopic techniques, and emerging gas-phase methods include the coupling of various spectroscopic techniques with mass spectrometry. Photoelectron spectroscopy of metal containing anions has already provided a wealth of fundamental data.[75] The development of the free electron laser has proven to be a break though in the IR spectroscopy of ions, and several recent examples of metal ions have appeared.[76] There are also a number of examples of UV-Vis spectroscopy being used to gain insights into the electronic structure of metal containing species.[2b,33a] X-Ray crystallography remains the premier technique for structure determination of inorganic and organometallic systems. Remarkably, electron diffraction has also been attempted on gas-phase metal cluster ions,[77] and these studies appear to offer promising structural insights. For example, trapped ion electron diffraction technique has been used to show $(CsI)_nCs^+$ cluster structures (n = 30–39) exhibit contributions to diffraction from both rock salt (NaCl) and cesium chloride lattice (CsCl) bulk structures.[77a] More recently, studies have shown that the nature of the charge on the silver cluster can influence its structure.[77b,c] Thus analysis of electron diffraction data suggest that Ag_{55}^+ adopts an ideal Mackay icosahedron, whereas Ag_{55}^- is a weakly Jahn–Teller distorted icosahedron.[77c]

As noted in a previous review,[3a] there are opportunities for an interplay between mass spectrometry and the development of new materials. Apart from fundamental studies which offer insights into reactivity as a function of cluster size and the use of mass spectrometry as an analytical technique for nanoparticles, MS based techniques offer the possibility of preparing materials *via* deposition of mass selected ions onto surfaces.[78–80] There is still fundamental work to be done on the actual deposition process and how it effects the surface morphology. For example, recent studies on the deposition of mass-selected Ag_n^+ (n = 1–3) clusters onto rutile TiO_2 (110)(1 × 1) single crystal surfaces at room temperature revealed that the size of the gas-phase cluster dictated the final surface morphology, as revealed by scanning tunneling microscopy.[79] While Ag monomers and dimers are highly mobile on reaching the surface and sintered to form larger clusters, deposited trimers remained intact.

On a final note, MS based techniques are also playing a role in understanding solution phase catalytic processes[81] as well as providing ways of rapidly screening new catalysts.[82] For example, ESI/MS has been used to monitor the formation of metal intermediates of catalytic cycles.[81] Chen has developed a catalyst screening method that combines *in situ* synthesis of complexes with an assay by electrospray ionization tandem mass spectrometry.[82]

Acknowledgements

None of the work described in this account could have been carried out without the generous financial support of the Australian Research Council and the technical and intellectual contributions of a small, but dedicated and enthusiastic group of undergraduate and postgraduate students and research associates, whose names appear on the papers cited. I just want to single out three: Gavin Reid for carrying out the modification of the LCQ, preforming our first ion–molecule reaction studies and for providing a version of Fig. 1; Tom Waters for his careful development of kinetics and threshold measurements; and George Khairallah for "pushing the envelope" in the silver cluster work. I gratefully acknowledge the guidance and encouragement of a number of academic colleagues: Scott McLuckey for introducing me to the wonders of ion traps during a sabbatical nearly a decade ago, Scott Gronert for sharing his method for carrying out ion–molecule reactions in the LCQ and both Peter Armentrout and Michael Bruce for generous discussions and insights into metal ion chemistry. At Melbourne my inorganic colleagues and collaborators Tony Wedd and David McFadyen have been a constant source of advice. Finally, I have been inspired by a number of pioneers in inorganic mass spectrometry in Australia: John Bowie, Michael Bruce, Ian Dance and Gary Willett.

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