

13

A Tour Guide to Mass Spectrometric Studies of Hydrogenation Mechanisms

Corbin K. Ralph, Robin J. Hamilton, and Steven H. Bergens

13.1

Introduction

The ability of electrospray ionization (ESI) to generate intact complex organometallic ions in the gas phase has revolutionized the application of mass spectrometry (MS) to the study of reactions catalyzed by organometallic compounds [1]. To date, the catalytic reactions studied using ESI-MS include oxy transfer reactions with manganese-oxo-salen complexes [2], Ziegler-Natta polymerizations of alkenes [3], alkene metathesis using ruthenium-alkylidene catalysts [4], C–H activation by iridium complexes [5], Suzuki couplings [6], nickel-catalyzed coupling reactions [7], chiral catalysts for allylations [8], and catalytic hydrogenations [9]. The objectives of these studies have ranged from understanding elementary reactions between substrates and coordinatively unsaturated catalytic intermediates in the gas phase, to rapid screening of one-pot, complex catalyst mixtures for activity towards various reactions. Although MS studies of alkene hydrogenations have been carried out using other ionization techniques [10], for example to characterize product isotopomers or organometallic species present in solution, the focus of this chapter will be on ESI-MS studies.

The reported ESI-MS studies of catalytic reactions can roughly be divided into two categories: 1) characterization of species present in catalytically active solutions; and 2) application of tandem ESI-MS systems to study the chemistry of complex organometallic ions in the gas phase [1]. It is the study of reactivity of ions in the gas phase that has provided the most mechanistic information about catalytic hydrogenations using MS. A paramount concern which attends such studies from a solution-phase chemist's point of view is the relevance of gas-phase ion chemistry to a reaction of interest carried out in solution under a given set of conditions (temperature, pressure, concentrations, solvent, etc.). A number of factors come into play when making such comparisons. Ionic species in the gas phase can induce polarizations in neutral reagent molecules, for example, causing an electrostatic attraction between the reactants, and thereby resulting in substantially larger Arrhenius frequency factors and different activa-

tion energies in the gas phase than in solution [3a, 4a, 11]. Further, the concentrations and contact times between reagents are smaller in the gas phase than in solution. Also, a large component of activation energies for reactions carried out in solution can involve solvent effects [12]. Various steps in reactions catalyzed by transition-metal complexes in solution involve changes in coordination number, and thereby are accompanied by coordination or dissociation of solvent molecules. These and other factors are involved when comparing the reactivity of organometallic ions in solution to the gas phase, and no rigorous mechanistic theories or studies currently exist that specifically address these concerns [13]. The approach adopted for the present chapter is to provide a tour guide-level description and an understanding of the methods used to carry out such experiments. The studies of catalytic hydrogenation are then discussed in some detail, with the discussions being accompanied by relevant information and perspective from the other reactions and systems studied by ESI-MS. The objective of this tour guide is to provide chemists studying catalytic hydrogenations with sufficient perspective and information to determine if ESI-MS can provide experimental data relevant to a catalytic hydrogenation of interest. As with all tour guides, more detailed and insightful information can be obtained from the locals. Therefore, the interested hydrogenation tourist is encouraged to “step off the bus”, to study the source literature in more detail, and perhaps to contact the researchers involved to discuss a reaction of interest.

13.2

A General Description of ESI-MS

Perhaps of high interest to the hydrogenation chemist are the pertinent details of how gas-phase ions of organometallic catalysts are prepared. Of specific interest are the types of fragmentation events that can occur during the preparation of the gas phase ions, and what forms coordinatively unsaturated organometallic ions adopt in the gas phase.

ESI was first developed for MS by Fenn et al. in the mid-1980s [14]. ESI is the mildest method to generate ions in the gas phase from species dissolved in solution. Species with high molecular masses, such as synthetic polymers, DNA fragments, and proteins can be transferred to the gas phase without fragmentation. ESI has been applied to a wide variety of organometallic species [11]. The application of ESI has allowed the production of various organometallic ions in the gas phase with control over the number of solvent molecules associated with the ion, and control over gas-phase ligand dissociation reactions that generate coordinatively unsaturated ions for study [15]. Of note, however, is that ESI does not, in the strictest sense, generate charged molecules. Rather, it separates the charged species from each other, and from the neutral species in solution. In fact, ESI cannot easily be applied to neutral molecules unless they have, for example, basic groups that can associate with charged species also present in solution (e.g., protons or sodium ions). An interesting illustration of the ability of ESI-MS to detect

and separate minute amounts of charged species in solution is the study by Chen et al. of a mixture containing a variety of neutral alkene metathesis catalyst precursors with the general formula $[\text{RuCl}_2(\text{alkylidene})(\text{diphosphane})]$ [4c]. When dissolved in solution, these neutral catalyst precursors are in equilibrium with small amounts of the cationic catalysts, $[\text{RuCl}(\text{alkylidene})(\text{diphosphane})]^+$, formed by chloride dissociation. The application of ESI-MS to these mixtures allowed the detection of trace amounts of cationic catalysts, which could also be separated in the gas phase on the basis of their m/z ratio. The separated catalysts were then individually screened for activity towards the ring-opening olefin metathesis of norbornene in the gas phase. It was found that the cationic catalysts with the highest activities towards norbornene in the gas phase also had the highest activities in solution.

ESI operates in stages (Fig. 13.1) [1, 14]. A typical sequence is as follows. The organometallic ion is introduced as a salt dissolved in a sprayable solvent through a capillary into the electrospray chamber. Polar solvents such as dichloromethane, acetonitrile, and alcohols are easily sprayed, whilst nonpolar solvents can be sprayed as mixtures with polar solvents. The concentration of the organometallic complex typically ranges from 0.001 to 10 mM, which is similar to the concentration range used in homogeneous catalysts. The electrospray chamber often contains a nitrogen “bath” gas at or near atmospheric pressure when used to transfer organometallic ions to the gas phase. The capillary contains an electrode which is in contact with the sample solution. A large potential difference (typically 4–6 kV) is applied between this electrode and the walls of the chamber. The electric field is intensified at the tip of the capillary, causing ion separation and formation of charged droplets in the atmosphere of the chamber. The droplets contain an excess of either negative or positive ions, depending on whether the capillary tip is negative relative to the chamber walls, or positive. Solvent evaporation occurs as the charged droplets containing the ions are accelerated towards the chamber walls by the potential difference. Rapid solvent evaporation leads to a decrease in the droplet diameter. The droplet diameter decreases until the coulombic repulsions between the ions near the surface exceed the surface tension of the solvent. The droplet will then undergo fission into smaller droplets containing fewer ions than the parent, and/or expulsion of the ions from the surface of the droplet into the gas phase. This sequence repeats itself until all the ions in the gas phase are free from solvent. In practice, desolvation occurs over several stages of the process (*vide infra*). The charged ions or solvated ions are driven by a pressure differential through a heated capillary (held typically at temperatures ranging from 150 to 200 °C) into the first vacuum chamber that is typically maintained at 0.5–1 Torr. The ions are essentially pulled through the capillary by the viscous drag forces of the nitrogen gas escaping into the first vacuum chamber to emerge as a supersonic stream. The outlet of the capillary is sheathed in a metal tube, and a potential is applied between this tube and a skimmer at the other end of the chamber. This “skimmer-” or “tube potential” accelerates the ions in the expanding stream towards the skimmer. The skimmer potential typically ranges from 35 to 100 V. The first

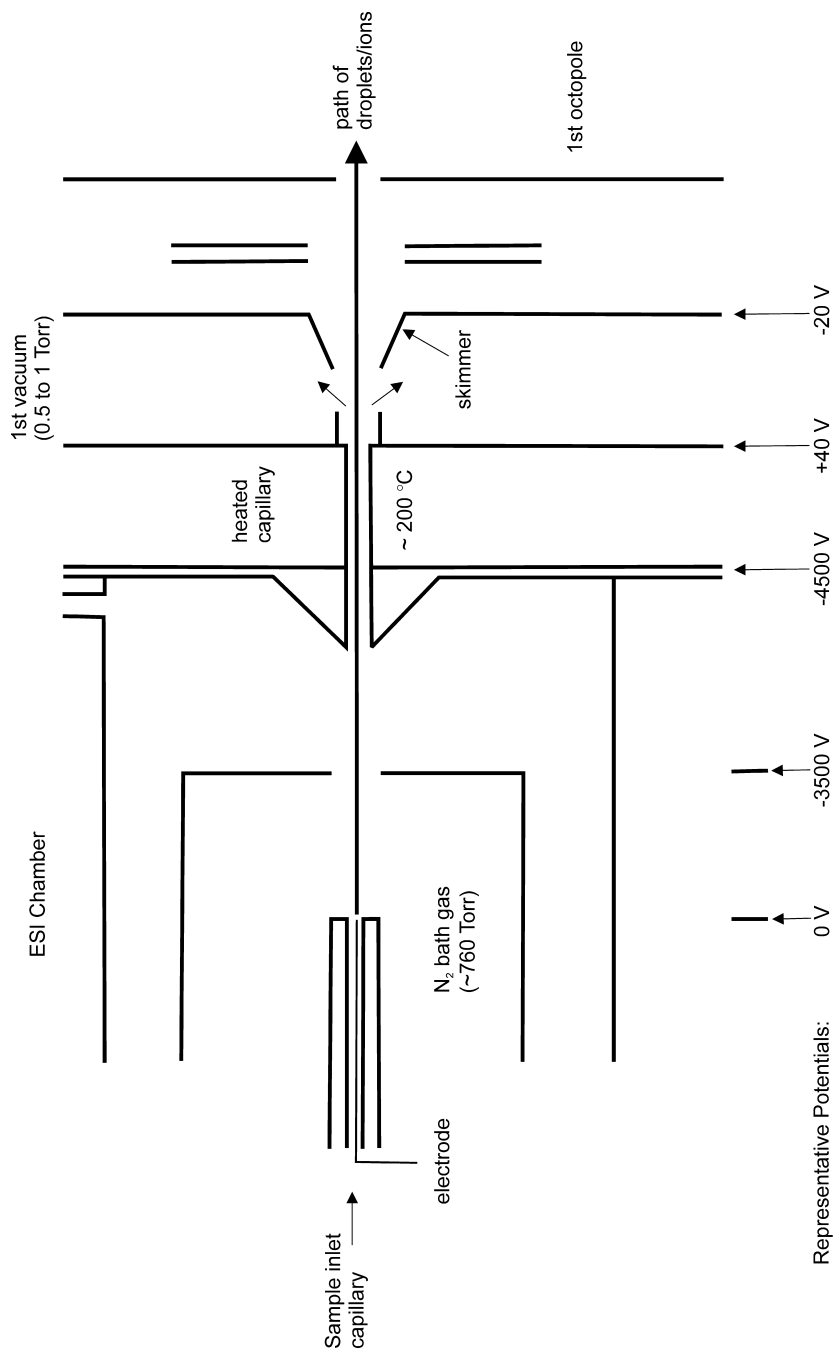


Fig. 13.1 A schematic simplification of typical events that occur during the formation of gas-phase ions by electrospray ionization. The diagram is loosely based upon those found elsewhere [1 b, c, 12].

pumping chamber typically serves three functions. First, it completes desolvation of the ions. Second, it imparts translational kinetic energy to the ions via the skimmer potential before the ions pass into the next chamber (either an octopole or quadrupole). Third, collisions occur between the background gas in the chamber and the ions as they are accelerated towards the skimmer. The energy of these collisions is in part controlled by the magnitude of the skimmer potential. At higher voltages, the collisions with the remaining background gas can induce ligand dissociation from the parent organometallic ion. The skimmer potential is thereby used as an adjustable parameter to control the translational kinetic energy of the ions before they pass into the next chamber, and if desired, to control collision-induced dissociation (CID) of ligands from the parent organometallic ions before they leave the skimmer chamber.

A point of interest at this stop in our tour is that fragmentation of organometallic ions in ESI-MS often proceeds via ligand dissociation (e.g., phosphane loss) to generate coordinatively unsaturated organometallic ions [1–9]. One of the strengths of this technique is that such unsaturated ions are typically proposed as reactive intermediates in catalytic reactions carried out in solution (*vide infra*), allowing ESI-tandem-MS systems to study directly the gas-phase reactivity of such species.

For the published ESI-MS mechanistic hydrogenation studies, the ions pass through the skimmer into the first octopole [9]. The longitudinal kinetic energy of the ions entering the first octopole is determined in part by the skimmer potential. The octopole serves several functions. The first is as an ion guide in which any neutral molecules remaining in the ion stream are removed by vacuum. A radiofrequency is applied to the poles that functions, in effect, to contain the ions in the region near the radial center of the octopole without imparting significant kinetic energy upon them as they move longitudinally through the unit. The second function of the octopole is to act as a gas-phase reactor. The octopole is typically held at moderate temperatures (e.g., 70 °C) and it contains a neutral inert or reagent gas at pressures up to ~0.1 Torr. The organometallic ions interact with the neutral gas molecules as they move through the octopole via collisions and/or reactions. One experimental concern is to keep the energy distribution of the gas molecules as near as possible to thermal equilibrium inside the octopole. The process is called “thermalization”, and it occurs via collisions between the ions that have been accelerated by the skimmer potential and the neutral gas present in the octopole. One incentive for establishing and maintaining thermal equilibrium among the ions in the octopoles is that the system then better represents ions in solution. Another incentive is that Maxwell-Boltzmann statistics can then be applied to model the distribution of vibrational, rotational, and kinetic energies among the molecules in the gas phase. Models have been developed that incorporate Maxwell-Boltzmann statistics as well as certain experimental parameters (e.g., temperature, pressure, and longitudinal velocity) [1 b, c]. These models provide information such as the number of collisions between an ion and the neutral gas molecules as it travels through the octopole, or information about the kinetic energies of the collisions, or in

some cases, bond dissociation energies can be obtained through CID studies. Reaction probabilities can be obtained by comparing product yields to the number of calculated collisions between an organometallic ion and the reagent gas in the octopole. Apart from thermalization, collisions between the ions and the background gas can induce either CID (at high skimmer potentials) or reactions with reagent gases such as hydrogen [1 b, c, 16].

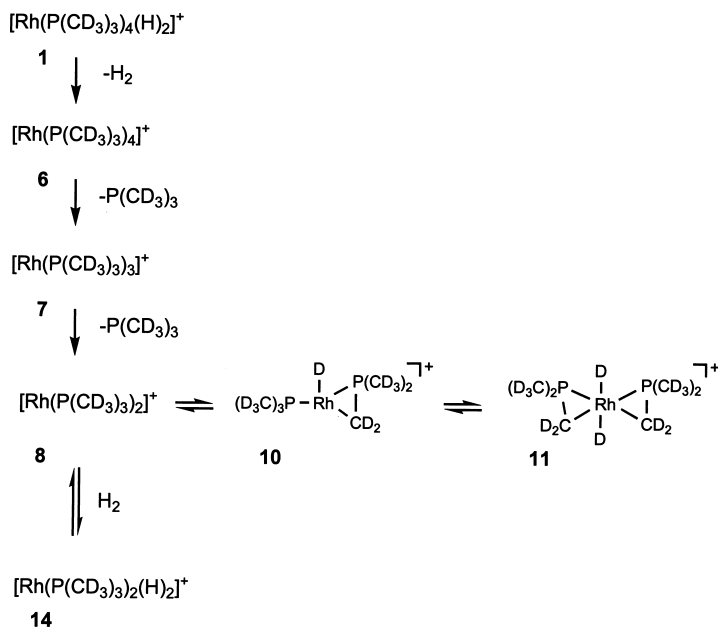
The resulting mixture of organometallic ions leaves the octopole and is then separated on the basis of m/z using the first quadrupole, typically at 10^{-6} Torr. The quadrupole allows ions of only one m/z ratio to pass through. The separated organometallic ions are characterized as much as possible by subsequent CID and gas-phase reactivity studies, and by isotopic labeling (*vide infra*). After leaving the first quadrupole, the separated organometallic ions are then driven into a second octopole containing a neutral or reagent gas *via* another potential difference. The magnitude of this potential difference determines the kinetic energy of the organometallic ions entering the second octopole. The product ions leaving the second octopole (or gas-phase reactor) are analyzed with a second quadrupole and detector. The experimental strategy typically applied to mechanistic studies with ESI-MS is thereby to vary the operating parameters of the ESI, the first octopole, and quadrupole to generate an organometallic ion of interest. The ion of interest is fragmented or reacted with a reagent molecule in the second octopole, and the products characterized in the last quadrupole and detector. It is the gas-phase reactions of the organometallic ions in the octopoles that are used to model the solution chemistry of the reaction. A point of interest at this part of our tour is that one-pot catalyst mixtures have been screened with ESI-MS systems by separating out the ions using the first octopole-quadrupole and then studying their individual gas-phase reactivity in the second octopole [1 c, 4 c, 8].

13.3 Mechanistic Hydrogenation Studies

Although a number of reactions catalyzed by organometallic complexes have been studied using ESI-MS (*vide supra*), the number of reports detailing ESI-MS mechanistic studies of alkene hydrogenation is small [9]. The first was carried out by Chen et al. using cationic rhodium(I)-phosphine complexes as catalyst systems. A number of cationic Rh(I) precursors were sprayed, including $[\text{Rh}(\text{P}(\text{CD}_3)_3)_4(\text{H})_2]^+$ (1), $[\text{Rh}(\text{P}(\text{CH}_3)_3)_3(\text{nbd})]^+$ (2, nbd = norbornadiene), $[\text{Rh}(\text{PPh}_3)_2(\text{nbd})]^+$ (3), $[\text{Rh}((S, S)\text{-chiraphos})(\text{nbd})]^+$ (4, (S, S)-chiraphos = (2S, 3S)-(-)-bis(diphenylphosphino)butane), and $[\text{Rh}((R)\text{-BINAP})(\text{MeOH})_2]^+$ (5, BINAP = 2,2'-bis(diphenylphosphino)-1,1'-binaphthyl). As discussed in the previous section, the tube lens potential was adjusted to control successively the amount of desolvation to produce gas phase ions of the parent rhodium compound, or to induce ligand and/or hydrogen loss by CID. The mixture of ions leaving the first octopole were separated by the first quadrupole, and then studied by CID or reactions with reagent gases in the second octopole.

Spraying dichloromethane solutions of **1** and using N₂ gas in the first octopole allowed mass selection at the first quadrupole of either [Rh(P(CD₃)₃)₄]⁺ (**6**), from loss of hydrogen from **1**; [Rh(P(CD₃)₃)₃]⁺ (**7**), from subsequent loss of P(CD₃)₃; and [Rh(P(CD₃)₃)₂]⁺ (**8**), from further loss of P(CD₃)₃ (Scheme 13.1). Compound **8** is a gas-phase mimic of catalyst species that have been observed in solution such as *trans*-[Rh(PPh₃)₂(MeOH)₂]⁺ (**9**), that contain extremely labile solvento ligands, and that are proposed to be catalytic intermediates in hydrogenations of alkenes using cationic rhodium-(PR₃)₂ complexes as catalysts [17]. One immediate difference between **9** in methanol solvent, and **8** in the gas phase is the absence of coordinating solvent molecules, making **8** an extremely reactive, coordinatively-unsaturated species. This difference is not unique to this system and warrants further discussion here. Most fundamental steps of catalytic cycles such as oxidative additions, reductive eliminations, and insertions involve changes in the ligands coordinating and changes in coordination number, and are thereby influenced by solvent molecules that act as ligands. The empirical observation can be made that organometallic ions in the gas phase tend to relieve coordination unsaturation by intramolecular bonding or activation. For example, gas-phase reactivity, CID, and deuterium-labeling experiments indicate that the formally 12-electron species **8** exists in equilibrium with the mono- and di-C–D activated species **10** and **11** (Scheme 13.1).

As another example, studies of the catalytic activity of the gas-phase ions [Ru-Cl(alkylidene)(diphosphane)]⁺ toward ring-opening olefin metathesis of norbornene show that an alkene group in the growing polymer chain reaches back to oc-

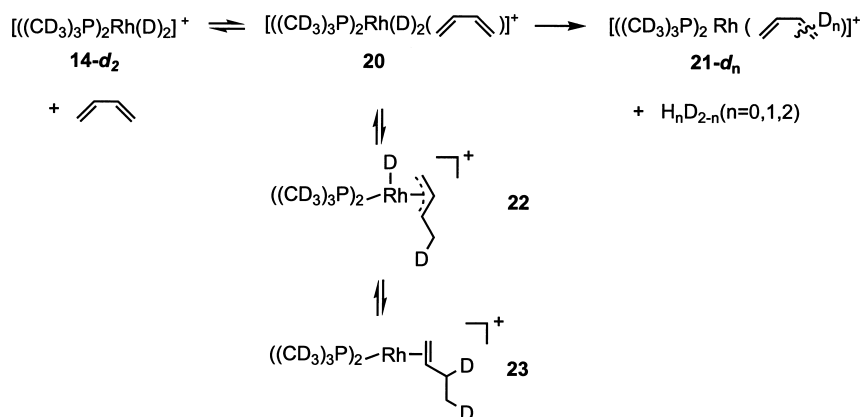


Scheme 13.1

cupy a vacant coordination site on ruthenium [4d]. In some cases, this tendency towards intramolecular bonding or activation has led to new discoveries that have borne true in the corresponding solution-phase chemistry. For example, an ESI-MS study of the gas-phase chemistry of the unsaturated, formally 16-electron cation $[(\eta^5\text{-C}_5\text{Me}_5)\text{Ir}(\text{CH}_3)(\text{P}(\text{CH}_3)_3)]^+$ (**12**) showed that it undergoes C–H activation down a P–CH₃ group, followed by elimination of methane to generate $[(\eta^5\text{-C}_5\text{Me}_5)\text{Ir}(\text{CH}_3)(\eta^2\text{-CH}_2\text{P}(\text{CH}_3)_2)]^+$ (**13**) [5]. Further study in the gas phase showed that **13** is substantially more active towards intermolecular C–H activation than **12**. Subsequent solution-phase chemistry by another group confirmed that $[(\eta^5\text{-C}_5\text{Me}_5)\text{Ir}(\text{CH}_3)(\eta^2\text{-CH}_2\text{P}(\text{CH}_3)_2)(\text{OTf})]$ (**13'**, OTf = triflate, a weakly coordinating anion) is substantially more active towards intermolecular C–H activation in solution than is $[(\text{C}_5\text{Me}_5)\text{Ir}(\text{CH}_3)(\text{P}(\text{CH}_3)_3)(\text{OTf})]$ (**12'**) [18].

Organometallic ions that undergo reversible intramolecular activation or bonding are more likely to provide gas-phase analogues to reactions of catalytic intermediates in solution containing labile solvento ligands. Returning to hydrogenation for an example, the mass-selected compound **8**, which likely exists as a mixture with **10** and **11**, reacts with H₂ gas in the second octopole to give the dihydride $[\text{Rh}(\text{P}(\text{CD}_3)_3)_2(\text{H})_2]^+$ (**14**) (see Scheme 13.1). The reaction can be reversed without H–D exchange with the CD₃ groups, showing that it was **8**, not **10** or **11**, that reacted with the H₂ gas. The reversible activation of the methyl groups to form **10** and **11** thereby functions partially to relieve the coordination unsaturation of **8**, as do the methanol solvento ligands in solutions of **9**. In this sense, reaction of **8** with H₂ gas to generate the dihydride **14** provides a gas-phase analogue to the known oxidative addition of H₂ to **9** in methanol solution to generate *trans*- $[\text{Rh}(\text{H})_2(\text{PPh}_3)_2(\text{MeOH})_2]^+$ (**15**) [17b].

Intramolecular bonding or activation to alleviate coordination unsaturation in the gas phase does fail, at times, to mimic the behavior of labile solvento complexes in solution. For example, the gas-phase ion $[\text{Rh}(\text{PPh}_3)_2]^+$ (**16**), which is the solvent-free, direct analogue of **9**, failed to add H₂ or D₂ in the second octopole. The authors attributed this lack of analogous reactivity for **16** in the gas phase to the proposed formation of an intramolecular η^6 -arene complex with one of the phosphines. The formation of such an 18-electron arene complex is presumably irreversible on the timescale that the ion resides in the second octopole. Consistent with this behavior, the gas-phase ions $[\text{Rh}((S, S)\text{-chiraphos})]^+$ (**17**) and $[\text{Rh}((R)\text{-BINAP})]^+$ (**18**) also failed to react with H₂ in the second octopole. Worthy of mention, however, is that the analogues of complexes **17** and **18** in methanol solution react reversibly, but only to a small extent with hydrogen to generate traces of $[\text{Rh}(\text{diphosphane})(\text{H})_2(\text{MeOH})_2]^+$ [19]. One therefore cannot rule out, on the bases of the data in the literature, that the gas-phase ions **17** and **18** did not mimic the behavior of their solvento analogues in methanol solution. The authors also reported that **17** reacts, at very low collision energies, with methyl acrylate to generate the adduct $[\text{Rh}((S, S)\text{-chiraphos})(\text{methyl acrylate})]^+$ (**19**). Although the authors did not pursue this avenue further, formation of the adduct **19** does provide an analogue to the known reactions between $[\text{Rh}((S, S)\text{-chiraphos})(\text{CH}_3\text{OH})_2]^+$ and $[\text{Rh}((R)\text{-BINAP})(\text{MeOH})_2]^+$ and various



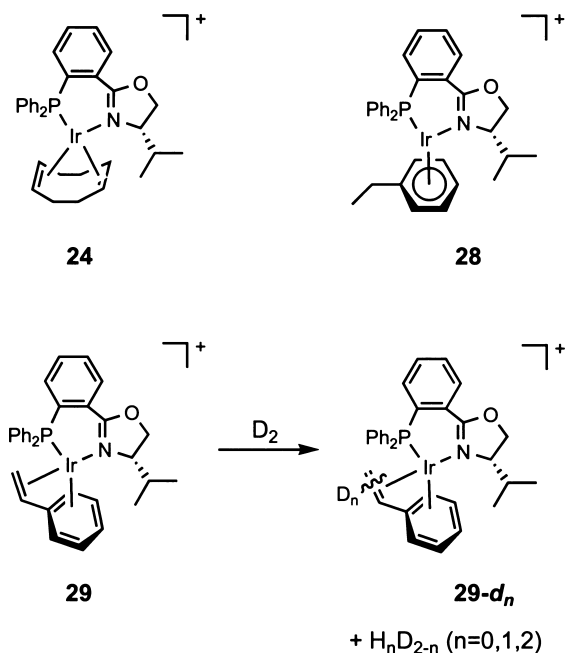
Scheme 13.2

unsaturated organic carbonyl compounds to form adducts similar to **19** in methanol solution [19].

Further studies using butadiene and isotopic labeling established the reaction pathway shown in Scheme 13.2. Complex **14-d₂** was shown to react with butadiene to generate the observed diene adduct **20**. Compound **20** then reacted further to lose H_nD_{2-n} (n=0, 1, 2) and generate the observed butadiene compound **21-d_n** (n=0, 1, 2). The observation of H–D exchange between the deuterides and butadiene-hydrogen atoms in **20** is evidence for the reversible formation of the allyl-deuteride **22** and perhaps for the butene complex **23** (both not observed). This pathway thereby provides a gas-phase analogue for the following plausible sequence of steps in a catalytic alkene hydrogenation: oxidative addition of H₂, alkene coordination, and alkene-hydride insertion. In support of this sequence in the gas phase, reaction of [Rh(P(CD₃)₃)₂]⁺ (**8**) with 1-butene leads to the butadiene-dihydride isotopomer of **20**, presumably via the protio isotopomers of **22** and **23**.

Noyori et al. recently used ESI-MS to characterize species present in catalytically active solutions during the hydrogenation of aryl-alkyl ketones using their base-free catalyst precursors *trans*-[Ru((*R*)-tol-BINAP)((*R*, *R*)-dpen)(H)(η¹-BH₄)] (tol-BINAP = 2,2'-bis(ditolylphosphino)-1,1'-binaphthyl; dpen = 1,2-diphenylethylenediamine) in 2-propanol [9b]. Based upon ESI-MS observations, deuterium-labeling studies, kinetics, NMR observations, and other results, the authors proposed that the cationic dihydrogen complex *trans*-[Ru((*R*)-tol-BINAP)((*R*, *R*)-dpen)(H)(η²-H₂)]⁺ is an intermediate in hydrogenations carried out in the absence of base.

The mechanism for hydrogenation of styrene using the iridium-phosphanyloxazoline compound [(PHOX)Ir(COD)]⁺ (**24**, Scheme 13.3) as catalyst precursor has also been studied using ESI-MS [9c]. Catalytically active solutions were prepared by reacting the catalyst precursor and substrate dissolved in methylene chloride with hydrogen gas until all the cyclooctadiene-containing iridium species were consumed. To minimize loss of H₂ during spraying, the mixture was forced into the spray chamber using the pressure of hydrogen in the reactor (6 bar H₂). Three



Scheme 13.3

species were observed at low tube potentials: one with a m/z ratio corresponding to the sum of $[(\text{PHOX})\text{Ir}]^+$, styrene, and H_2 (**25**); the second with a m/z ratio corresponding to the sum of $[(\text{PHOX})\text{Ir}]^+$, styrene, and $2 \times \text{H}_2$ (**26**); and the third with a m/z ratio corresponding to the sum of $[(\text{PHOX})\text{Ir}]^+$ and styrene (**27**). Further, the gas-phase reaction of $[(\text{PHOX})\text{Ir}(\text{H}_2)_2]^+$ and ethylbenzene formed a mixture from which a species $[(\text{PHOX})\text{Ir}(\text{ethylbenzene})]^+$ (**28**) was separated in the gas phase by its m/z ratio at the first quadrupole. Although precise structural determinations are not possible with MS data, the authors quite reasonably proposed that **28** is an 18-electron compound with ethylbenzene acting as η^6 -arene ligand (Scheme 13.3). Based upon this proposal, it is possible that **25**, the species isolated from the active catalytic solution, and **28** are the same compound.

The ion **28** loses H_2 by CID with argon to form $[(\text{PHOX})\text{Ir}(\text{styrene})]^+$ (**29**). Compound **29** then undergoes H–D exchange with D_2 gas to form the mixture of isotopomers **29**, **29-d₁**, and **29-d₂** (Scheme 13.3). When combined, these observations show that the oxidative addition of H_2 to **29** is followed by alkene hydride insertion, and that both these steps occur rapidly and reversibly in the gas phase. These results thereby provide gas-phase analogues for catalytic elementary steps that are proposed to occur in solution. Support for this proposed sequence of steps was obtained from a solution-phase catalytic deuteration of styrene. Analysis showed no deuterium incorporation in the unreacted styrene at various conversions, and clean formation of dideuterio ethylbenzene as sole product.

Based upon their data and upon results in the literature, the authors concluded that hydrogenations using **24** or related species as catalyst precursor proceed in solution by mechanisms involving iridium(I)/(III) formal oxidation states. During the course of their discussions, the authors made the interesting observation that the rate of gas-phase collisions between the thermalized iridium organometallic ions and D_2 under their experimental conditions in the octopole were similar to the rate of diffusion-controlled encounters between iridium species and D_2 in solution.

13.4 Conclusions

ESI represents a powerful method by which to transfer organometallic ions from catalytically active solutions into the gas phase. ESI-MS systems allow the characterization of the gas-phase ions using CID, reactivity, and isotope-labeling studies. The application of ESI-tandem-MS systems allows gas-phase preparations and isolation of desired organometallic ions in the first ESI-octopole-quadrupole, followed by characterization or reactivity studies in the second octopole-quadrupole.

ESI-MS study of gas-phase chemistry is a relative young area of interest in organometallic chemistry. ESI-MS mechanistic investigations have shown that organometallic reactions occurring as part of catalytic reactions in solution – including oxidative additions, insertions, metathesis, and eliminations – also occur in the gas phase. The extent to which such gas-phase analogues are relevant to reactions that occur in solution has not, to date, been addressed by a rigorous theoretical and experimental investigation. However, we end this tour by pointing out that a number of examples now exist where the gas-phase organometallic reactivity has been shown experimentally to be relevant to solution-phase catalytic reactions. In some cases, the gas-phase organometallic reactions have provided successful new leads to solution-phase studies. We predict that with careful gas-phase experimentation, combined with confirmation by experiments carried out in solution, ESI-MS studies will continue to discover and explore hydrogenation systems for which the gas-phase organometallic chemistry is relevant to the analogous reactions carried out in solution. Finally, there are a number of hydrogenations catalyzed by cationic catalyst systems that have not yet been studied using ESI-MS [20]. Further, hydrogenations using non-ionic catalyst systems can, in principle, be modified for ESI-MS studies by substituting neutral for ionic groups in the ancillary ligands. Recent advances in the use of ESI-tandem-MS systems to evaluate chiral catalysts for enantioselective allylations can perhaps also be modified for enantioselective catalytic hydrogenations [8].

Acknowledgments

The production of this chapter was supported by the University of Alberta. The authors are very grateful to Professor Paul Kebarle for many useful discussions, and for his kind patience.

Abbreviations

CID collision-induced dissociation
 ESI electrospray ionization
 MS mass spectrometry

References

- Reviews: (a) R. Colton, A. D'Agostino, J.C. Traeger, *Mass Spectrom. Rev.* **1995**, *14*, 79; (b) D.A. Plattner, *Int. J. Mass. Spec.* **2001**, *207*, 125; (c) P. Chen, *Angew. Chem. Int. Ed.* **2003**, *42*, 2832.
- (a) D. Feichtinger, D.A. Plattner, *Angew. Chem. Int. Ed.* **1997**, *36*, 1718; (b) D.A. Plattner, D. Feichtinger, J. El-Bahraoui, O. Wiest, *Int. J. Mass. Spec.* **2000**, *195/196*, 351; (c) D. Feichtinger, D.A. Plattner, *J. Chem. Soc., Perkin Trans. 2* **2000**, 1023; (d) D. Feichtinger, D.A. Plattner, *Chem. Eur. J.* **2001**, *7*, 591.
- (a) D. Feichtinger, D.A. Plattner, P. Chen, *J. Am. Chem. Soc.* **1998**, *120*, 7125; (b) C. Hinderling, P. Chen, *Int. J. Mass. Spec.* **2000**, *195/196*, 377.
- (a) C. Hinderling, C. Adlhart, P. Chen, *Angew. Chem. Int. Ed.* **1998**, *37*, 2685; (b) C. Adlhart, C. Hinderling, H. Baumann, P. Chen, *J. Am. Chem. Soc.* **2000**, *122*, 8204; (c) C. Adlhart, P. Chen, *Helv. Chim. Acta* **2000**, *83*, 2192; (d) M.A.O. Volland, C. Adlhart, C.A. Kiener, P. Chen, P. Hofmann, *Chem. Eur. J.* **2001**, *7*, 4621.
- (a) C. Hinderling, D.A. Plattner, P. Chen, *Angew. Chem. Int. Ed.* **1997**, *36*, 243; (b) C. Hinderling, D. Feichtinger, D.A. Plattner, P. Chen, *J. Am. Chem. Soc.* **1997**, *119*, 10793.
- O. Aliprantis, J.W. Canary, *J. Am. Chem. Soc.* **1994**, *116*, 6985.
- S.R. Wilson, Y. Wu, *Organometallics* **1993**, *12*, 1478.
- C. Markert, A. Pfaltz, *Angew. Chem. Int. Ed.* **2004**, *43*, 2498.
- (a) Y.-M. Kim, P. Chen, *Int. J. Mass. Spec.* **1998**, *185/186/187*, 871; (b) C.A. Sandoval, T. Ohkuma, K. Muniz, R. Noyori, *J. Am. Chem. Soc.* **2003**, *125*, 13490; (c) R. Dietiker, P. Chen, *Angew. Chem. Int. Ed.* **2004**, *43*, 5513.
- Examples: (a) J.R. Morandi, H.B. Jensen, *J. Org. Chem.* **1969**, *34*, 1889; (b) M. Castiglioni, R. Giordano, E. Sappa, *J. Organomet. Chem.* **1995**, *491*, 111; (c) X.-Y. Wang, Z.-Y. Hou, W.-M. Lu, F. Chen, X.-M. Zheng, *J. Chromatogr. A* **1999**, *855*, 341.
- For example, see: (a) W.E. Farneth, J.I. Brauman, *J. Am. Chem. Soc.* **1976**, *98*, 7891; (b) T.B. McMahon, T. Heinis, G. Nicol, J.K. Hovey, P. Kebarle, *J. Am. Chem. Soc.* **1988**, *110*, 7591.
- R.B. Jordan, *Reaction Mechanisms of Inorganic and Organometallic Systems*, 2nd edn. Oxford University Press, New York, **1998**.
- See [1b, c] and references cited therein for discussions of these factors.
- (a) M. Yamashita, J.B. Fenn, *J. Phys. Chem.* **1984**, *88*, 4451; (b) C.M. Whitehouse, R.N. Dreyer, M. Yamashita, J.B. Fenn, *Anal. Chem.* **1985**, *57*, 675.
- The first example, V. Katta, S.K. Chowdhury, B.T. Chait, *J. Am. Chem. Soc.* **1990**, *112*, 5348.
- Y.-M. Kim, P. Chen, *Int. J. Mass. Spec.* **2000**, *202*, 1.

- 17 (a) R. R. Schrock, J. A. Osborn, *J. Am. Chem. Soc.* **1976**, *98*, 2134; (b) J. Halpern, D. P. Riley, A. S. C. Chan, J. J. Pluth, *J. Am. Chem. Soc.* **1977**, *99*, 8055; (c) J. M. Brown, P. A. Chaloner, P. N. Nicholson, *J. Chem. Soc., Chem. Comm.* **1978**, 646.
- 18 H. F. Luecke, R. G. Bergman, *J. Am. Chem. Soc.* **1997**, *119*, 11538.
- 19 For examples, see: (a) J. M. Brown, P. A. Chaloner, *J. Chem. Soc., Chem. Commun.* **1978**, 321; (b) A. S. C. Chan, J. Halpern, *J. Am. Chem. Soc.* **1980**, *102*, 838;
- (c) A. S. C. Chan, J. J. Pluth, J. Halpern, *J. Am. Chem. Soc.* **1980**, *102*, 5952; J. Halpern, *Science* **1982**, *217*, 401; (d) A. Miyashita, H. Takaya, T. Souchi, R. Noyori, *Tetrahedron* **1984**, *40*, 1245; reference [15 b]; and references cited therein.
- 20 For examples, see: (a) J. A. Wiles, S. H. Bergens, *Organometallics* **1999**, *18*, 3709; (b) D. A. Dobbs, K. P. M. Vanhessche, E. Brazi, V. Rautenstrauch, J.-V. Lenoir, J.-P. Genêt, J. Wiles, S. H. Bergens, *Angew. Chem. Int. Ed.* **2000**, *39*, 1992.