

ESI-MS Study on First-Generation Ruthenium Olefin Metathesis Catalysts in Solution: Direct Detection of the Catalytically Active 14-Electron Ruthenium Intermediate

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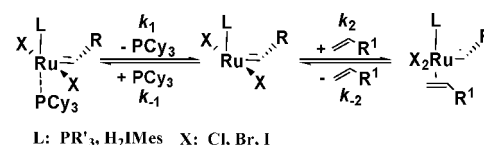
Electrospray ionization mass spectrometry (ESI-MS) and subsequent MS/MS analyses were used to study two first-generation ruthenium catalysts, **1** and **2**, in solution. *In situ* exchange of neutral tricyclohexylphosphine in **1** and **2** by cationic phosphine **3** allowed directly to detect and to characterize mass spectrometrically the catalytically active 14-electron ruthenium intermediates present in equilibrium in solution. Moreover, the catalytic activity of these species was directly demonstrated by gas phase reaction with ethylene to give the 14-electron methylene ruthenium species. It could be confirmed that all monomolecular steps in the catalytic cycle of ring-closing metathesis of diallyl compounds **5**, **6**, and **7** following olefin coordination are fast, and no intermediate can be accumulated to become detectable by ESI-MS. 18-Electron ruthenium species containing three phosphine ligands were shown to be present at low concentration in the solution of catalyst **1** or **2** in presence of 1.2 equiv of phosphine **3**. Finally, benzylidene trialkylphosphane **13** (in the presence of **3**) and phosphonium cation **11** were easily detected as degradation products of catalyst **1** and phosphonium cation **12** as a degradation product of catalyst **2**.

Introduction

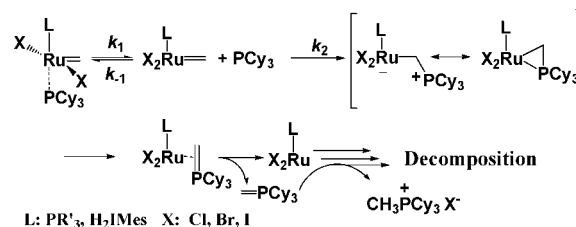
Ruthenium carbene-based olefin metathesis is a powerful method for the formation of carbon–carbon double bonds in organic and polymer syntheses.^{1,2} Grubbs showed by detailed mechanistic studies that initiation proceeds by dissociative substitution of a phosphine ligand with an olefinic substrate.³ The 14-electron ruthenium intermediates formed have been shown to be the catalytically active species by kinetic studies. Grubbs had to make two important assumptions in determining by kinetic measurements the ratio k_{-1}/k_2 (Scheme 1). First, the olefin coordination is essentially irreversible ($k_2 \gg k_{-2}$), and all of the steps following olefin coordination (particularly metal-lacyclobutane formation) are fast.³

The key to catalyst efficiency is the ratio of the rate of olefin metathesis relative to that of catalyst decomposition. Two different mechanisms of decomposition have been discussed.⁴ Ruthenium alkylidene complexes have been shown to decompose via dissociation of a phosphine to give the same 14-electron ruthenium intermediates as discussed above, followed by coupling of two monophosphine species to give an alkene by dimerization of the alkylidene fragment of the complex.^{4a}

Scheme 1. Initiation of Metathesis Reaction: Phosphine Dissociation and Alkene Coordination³



Scheme 2. Decomposition of Ruthenium Methylidene Complexes: Phosphine Dissociation and Attack Mechanism^{4c}



Recently, Grubbs studied the decomposition of ruthenium methylidene complexes, and the experimental results indicated that phosphine dissociation and nucleophilic attack of phosphine on the methylidene carbon (Scheme 2) is more reasonable than an internal phosphine attack mechanism.^{4c} The neutral methylene tricyclohexylphosphine is formed, which should react with H⁺ to generate methyltricyclohexylphosphonium salt.

Obviously, the same 14-electron ruthenium species is the catalytically active intermediate of metathesis reaction as well as the intermediate prone to degradation, thus deactivating the catalyst. However, this important 14-electron ruthenium species has not been detected directly in solution by any spectroscopic method.^{3b} The recent developments of mass spectrometric ionization methods at atmospheric pressure (API) like electrospray ionization (ESI) enable the investigation of liquid solutions by mass spectrometry and open up access to the direct investigation of chemical reactions in solution via mass spec-

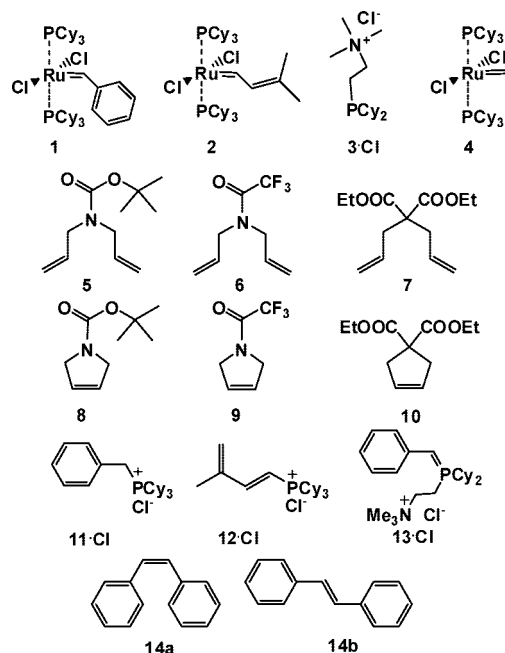
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Scheme 3. Ruthenium Catalysts, Charge-Labeled Phosphine Ligand, Substrates, Products of Ring-Closing Metathesis Reaction, and Degradation Products


trometry.⁵ In principle, they make possible the detection and the study not only of reaction substrates and products but even of short-lived reaction intermediates as they are present in solution, providing new insights into the mechanism of the reactions studied.⁶ Chen et al. used ESI-MS to generate 14-electron ruthenium species in the gas phase and demonstrated their metathesis catalytic activity in ion/molecule reactions with alkenes.⁷

Herein, we studied two first-generation ruthenium catalysts, **1** and **2**, in solution by ESI-MS and ESI tandem mass spectrometry (ESI-MS/MS) using the charge-labeled phosphine **3** · Cl with the aim to detect and characterize the catalytically active 14-electron intermediates directly from solution, to show their catalytic activity as well as their degradation. Furthermore, we studied ruthenium catalyst **4**, investigating ring-closing metathesis of dienes **5**–**7** to give products **8**–**10**, focusing on the detection of intermediates in the catalytic cycle (Scheme 3).

Results

We studied the first-generation catalyst **1** in CH₂Cl₂ solution by ESI-MS and observed clearly the corresponding radical cation **1**^{•+} at *m/z* 822 formed by electrochemical oxidation of substrate **1** at the ESI spray tip (Figure 1a).⁸ We also observed some

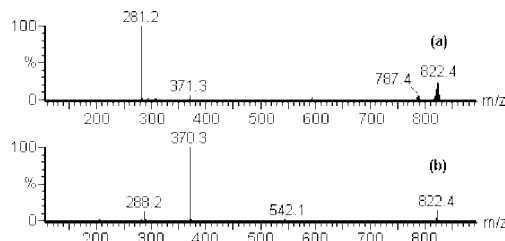


Figure 1. (a) ESI mass spectrum of ruthenium catalyst **1** in CH₂Cl₂; (b) ESI-MS/MS spectrum for CID of molecular ion **1**^{•+} at *m/z* 822.

heterolysis of complex **1** to produce by loss of Cl[−] the cation (PCy₃)₂ClRu=CHPh⁺ at *m/z* 787. Interestingly, the base peak of the ESI spectrum is the ion Cy₃PH⁺ at *m/z* 281. Mass spectrometric formation of this ion, i.e., by in-source CID, could be excluded because the ESI-MS/MS spectrum for CID of the ion of *m/z* 822 (radical cation **1**^{•+}) shows the peak at *m/z* 281 only with very low intensity (Figure 1b). Thus, the free ligand Cy₃P, most likely formed by dissociation of **1** (Scheme 1), can be detected clearly from solution phase as a protonated molecule. Unfortunately, the corresponding 14-electron Ru species formed by dissociation could not be detected unambiguously. We obtained only a rather poor ESI-MS/MS spectrum for CID of the ion at *m/z* 542.⁹ Remarkably, at *m/z* 371 the benzyltricyclohexylphosphonium cation **11** was observed with low intensity. We followed the ESI spectrum of the solution of **1** over 8 h and found that the abundance of the ion at *m/z* 371 increased continually and became finally the base peak, giving clear evidence that **11** was formed by reaction in solution. Additionally, we could detect *cis*- and *trans*-stilbene **14** in the solution of **1** by GC-MS after eight days' reaction time. Comparable results have been obtained studying catalyst **2**.⁹

To improve the detection limit of the ruthenium species, we studied the phosphine exchange reaction of catalysts **1** and **2** with "charge-labeled" phosphine **3** · Cl, developed for water-soluble ruthenium catalysts by Grubbs et al.¹⁰ Chen used this ligand to generate in the gas phase 14-electron Ru species such as **1B** by in-source CID of the dication of the respective 16-electron Ru species obtained by ESI of **1C** · Cl (Scheme 4).^{7a,b} In the ESI process, the ruthenium complexes containing the cationic phosphine **3** are desolvated, enhancing the opportunity to detect the intermediates from solution even in very low concentration. Thus, we reacted 1.2 equiv of phosphine **3** · Cl with 1 equiv of catalyst **1**, both dissolved in CH₂Cl₂, in a microreactor directly coupled to the ESI source.⁶ Here the injection speed of both solutions was set at 5 μL/min, allowing the study of the solution after a reaction time of approximately 12 s. The ESI mass spectrum obtained shows exclusively phosphine-exchanged ruthenium complex ions (Figure 2). In addition to the signal of the 16-electron ruthenium species **1A** at *m/z* 826, being the base peak, and **1C** at *m/z* 865 (intensity 4.3%), the 14-electron species **1B** at *m/z* 546 could be detected with low intensity of about 0.3%, however most clearly and unambiguously. Furthermore, the 18-electron ruthenium complex ions **1D** at *m/z* 1145 and **1E** at *m/z* 1184 containing three phosphine ligands having intensities of 5.2% and 0.4%, respectively, could be observed (Scheme 4). Remarkably, these ions were detected preferentially as monocations, whereas

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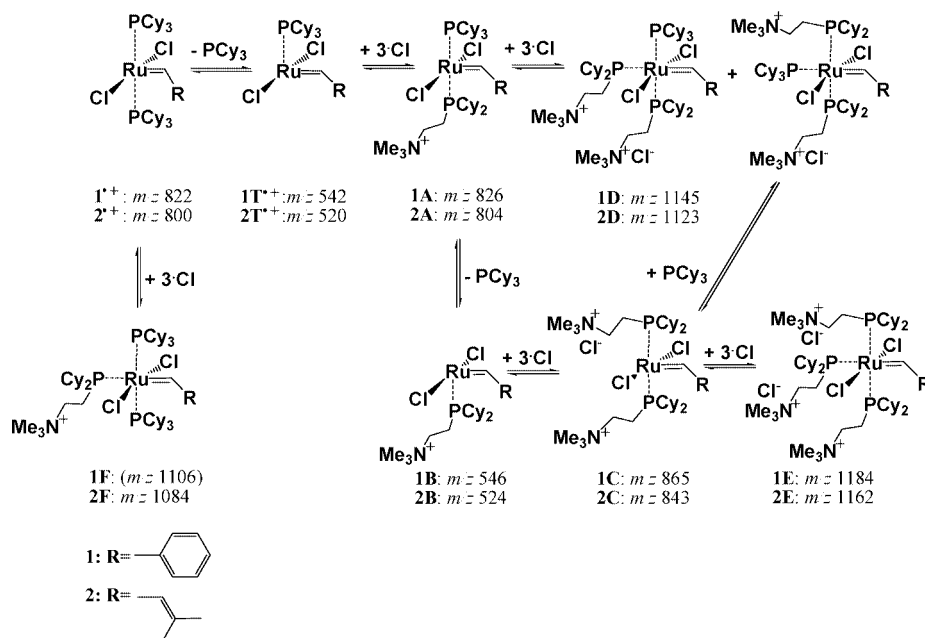
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Scheme 4. Phosphine Exchange Reactions of Ruthenium Complexes **1** and **2**, Respectively, with Phosphine **3** · Cl^a

^a The respective cations (without counterion) are given with *m/z* values of the ions, in parentheses, if the ions could not be detected in the ESI spectrum.

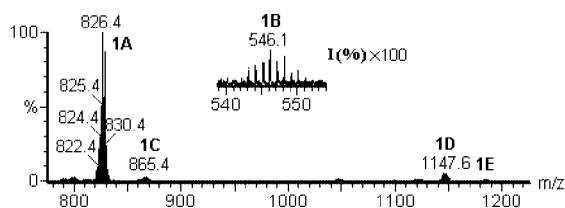


Figure 2. ESI mass spectrum of the online phosphine exchange reaction of catalyst **1** (1 equiv) with "charge-labeled" phosphine **3** · Cl (1.2 equiv) using a microreactor; reaction time is approximately 12 s.

dications could be observed with much lower intensity by ESI-MS/MS.⁹ All the complex ions **1A**–**1E** were characterized by their isotopic pattern and by CID.⁹ It could be possible that ion **1B** detected in the ESI spectrum could be formed by in-source CID of complex ion **1A** in the gas phase and would not be present in solution. This possibility could be excluded unambiguously by variation of the cone voltage below 30 eV, which revealed clearly that **1B** was not formed by in-source CID at our standard conditions of MS measurement.⁹ Thus, in combination with the detection of the free ligand Cy₃P as a protonated molecule in the ESI spectrum (see above) we can assume that ion **1B** was clearly present in the reaction solution and was transferred by the ESI process into the gas phase.

The respective experiment with catalyst **2** gave after the same reaction time of 12 s a mass spectrum showing only some minor phosphine exchange and, remarkably, the 18-electron ruthenium complex **2F** at *m/z* 1084, being the primary adduct of the reaction of catalyst **1** with phosphine **3** · Cl (Figure 3a, Scheme 4). However, the base peak of the spectrum is still the signal of radical cation **2⁺** at *m/z* 800. After 5 min reaction time, the signals of **2⁺** and of **2F** disappeared, and the signal of the 16-electron ruthenium complex ion **2A** at *m/z* 804 was the base peak. Only phosphine-exchanged cations could be observed, and all the ions described for **1** could be detected for **2** as well and, most importantly, also the reactive 14-electron species **2B** at *m/z* 524 having an intensity of 0.2% (Figure 3b).

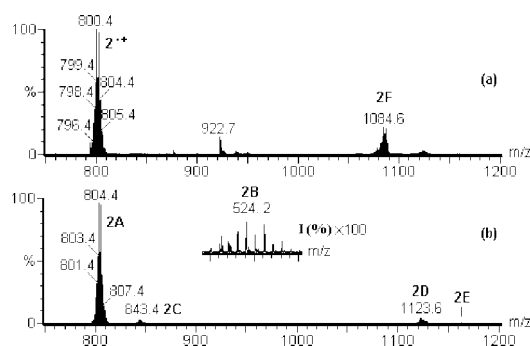
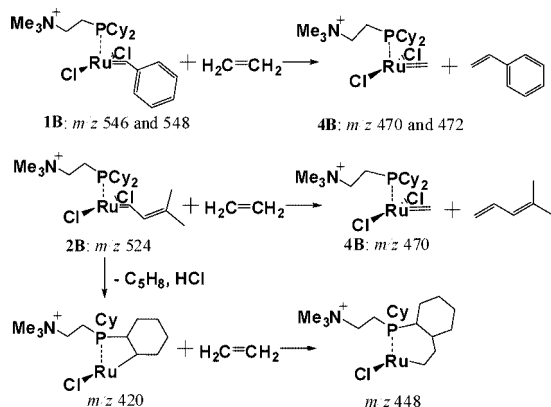


Figure 3. ESI mass spectra of phosphine exchange reaction of catalyst **2** (1 equiv) with "charge-labeled" phosphine **3** · Cl (1.2 equiv) at reaction times of (a) 12 s; (b) 5 min.

It could be thought that the 18-electron species **1D**, **1E** and **2D**–**2F**, respectively, containing three phosphine ligands, may be formed in the gas phase in the ESI source by ion/molecule reaction of the 16-electron species **1**, **1A**, **1C** and **2**, **2A**, **2C**, respectively, with phosphine **3**. We performed a dual-spray experiment with a solution of ruthenium catalysts **1** and **2**, respectively, in the main capillary and phosphine **3** · Cl in the transverse capillary, both dissolved in CH₂Cl₂. This experiment, using two independent electrosprays, enables the transfer of two reactants simultaneously and continuously to the gas phase in the ESI source.¹¹ In our experiment, we could not observe any signal of the primary 18-electron species **1F** and **2F**, respectively, giving evidence that the 18-electron species (Figures 2, 3) were formed in solution and not in the gas phase. Interestingly, in addition to the benzyltricyclohexylphosphonium cation **11** at *m/z* 371, the cationic benzylidene trialkylphosphorane **13** containing phosphine **3** could be detected with low intensity at *m/z* 374 in the solution of the phosphine exchange reaction of **1** with **3**.

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Scheme 5. Gas Phase Reactions of the Ions 1B and 2B, Respectively, with Ethylene


Being able to detect unambiguously the 14-electron Ru species from solution, we wanted to probe directly that it is indeed the catalytically active species and performed in the collision cell of the Q-TOF the gas phase reaction of the monoisotopic ion **1B** using the isotopologue of m/z 546 and of m/z 548, respectively (selected in the quadrupole), with ethylene and carried out mass analysis of the product ions using the TOF analyzer.^{6f} Under low-energy collisions (1.1–2.0 V) in the collision cell, the mass-selected and relatively cold cation **1B** (quenched by low-energy collisions with the neutral C_2H_4) reacted with C_2H_4 , yielding the cationic metathesis product ion **4B** at m/z 470 and 472, respectively (Scheme 5, Figure 4). The intensity of ion **4B** is 5.3% of the parent ion **1B**. Remarkably, when performing the analogous experiment using the same reaction conditions with cation **2B** at m/z 524, the intensity of **4B** at m/z 470 was only 0.8% (Figure 5a). These results indicate that the catalytic activity of **1B** is higher than of **2B**. Interestingly, Figure 6a shows the additional fragments at m/z 284, 420, and 448. Comparison with the ESI-MS/MS spectrum for CID of the ion at m/z 524 reveals that the ions at m/z 284, clearly phosphine ligand **3**, and at m/z 420 are fragment ions,⁹ whereas m/z 448 must be formed by gas phase reaction of the ion at m/z 420 with ethylene. This was experimentally verified. The ion at m/z 420 was independently generated by in-source CID of the ion **2B** at a high voltage of 100 eV and selected in the quadrupole. Gas phase reaction of this ion with ethylene in the collision cell as described above yielded exclusively the ion at m/z 448 (Figure 5c).

We studied the ring-closing metathesis reaction (RCM) of diallyl compounds **5–7** with catalysts **1** and **2**, respectively, in the presence of phosphine **3** · Cl using a microreactor directly coupled to the mass spectrometer.

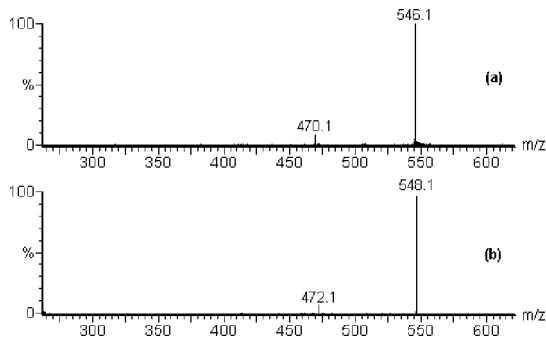


Figure 4. Mass spectra of the gas phase reactions of isotopologues of ion **1B** at (a) m/z 546 and (b) m/z 548 with ethylene to give isotopologues of ion **4B** at (a) m/z 470 and (b) m/z 472.

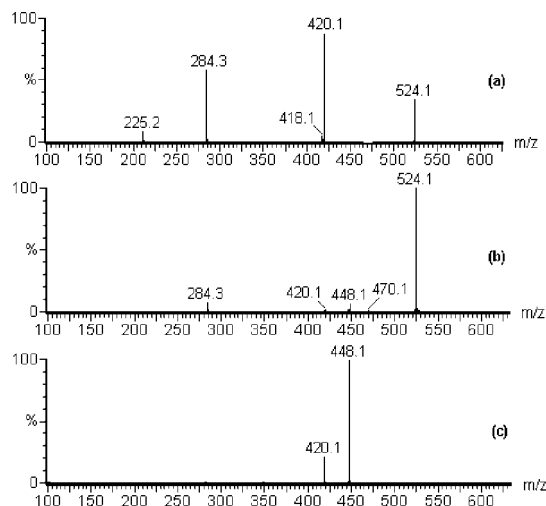


Figure 5. (a) ESI-MS/MS spectrum for CID of the ion **2B** at m/z 524; (b) gas phase reaction of the ion **2B** at m/z 524 with ethylene to give the ion **4B** at m/z 470 and ions at m/z 448, 420, and 284; (c) gas phase reaction of fragment ion at m/z 420, generated by in-source CID and selected in the quadrupole, with ethylene to give a product ion at m/z 448.

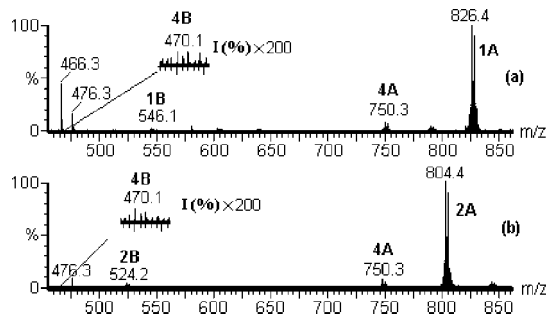


Figure 6. ESI mass spectra of the reacting solution of diene **5** (10 equiv) in the presence of phosphine **3** · Cl (1.2 equiv) after a reaction time of 6 s with catalyst (1 equiv) (a) **1** and (b) **2**.

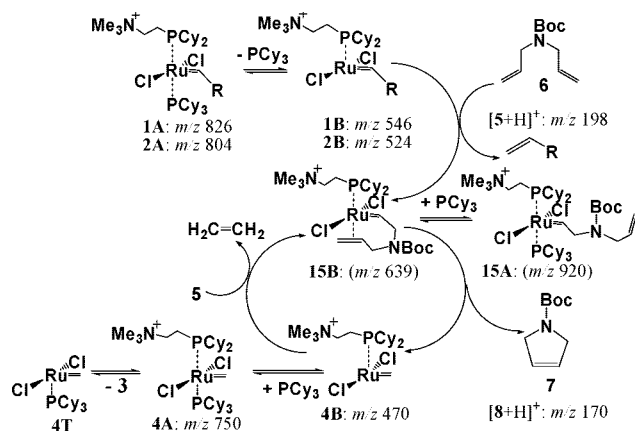
A solution of 1 equiv of catalyst **1** together with 1.2 equiv of **3** · Cl and a solution of 10 equiv of diene **5**, both in CH_2Cl_2 , were mixed in a microreactor by using two syringes, and the reaction solution was continuously fed into the ESI source. Here the injection rate of both solutions was set to 10 $\mu L/min$. These conditions allowed the study of the solution after a reaction time of 6 s.⁶

The ESI mass spectra of the reacting solutions are shown in Figure 6. In addition to the catalyst ions **1A** and **1B**, the cationized 16-electron Ru methylidene intermediate **4A** at m/z 750 and the respective 14-electron species **4B** at m/z 470 were detected. The catalytic cycle of the reaction is shown in Scheme 6.^{12,13} Remarkably, the expected intermediates **15A** at m/z 920 and **15B** at m/z 639, respectively, could not be detected. We tried also to detect further intermediates in the catalytic cycle such as the alkene π -complex and the metallacyclobutane. No evidence could be found for these intermediates. The analogous reaction using catalyst **2** showed comparable results as well as the respective reactions of dienes **6** and **7**.⁹ However, we detected clearly phosphonium ion $CH_3Cy_3P^+$ at m/z 295 in the RCM reaction solution.⁹

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Scheme 6. Ring-Closing Metathesis Reactions with 1A and 2A, Respectively, in the Presence of Phosphine 3 · Cl with Diene 5^a



^a The respective cations (without counterion) are given with m/z values of the ions, in parentheses, if the ions could not be detected in the ESI spectrum.

Discussion

On the basis of the above results, we can confirm some important aspects of the mechanism of the ruthenium-catalyzed olefin metathesis derived by Grubbs and others. Already the simple ESI mass spectra of Ru complexes **1** and **2** dissolved in CH_2Cl_2 give clear evidence for dissociation of **1** and **2**, respectively, to give tricyclohexylphosphine and the corresponding 14-electron Ru species. The signal of the phosphine is present in the spectrum with high intensity as a protonated molecule (Figure 1). The 14-electron Ru species could not be detected unambiguously.⁹ Obviously, the expected concentration will be quite low as well as the sensitivity of detection of the radical cation formed by oxidation at the ESI tip.⁸ However, the 14-electron species of **1** and **2** could be detected directly from solution using the exchange of the neutral tricyclohexylphosphine by cationic phosphine **3**, giving the charge-labeled species **1B** and **2B**, respectively (Figures 2, 3). This observation gives independent evidence that the four-coordinated intermediates **1B** and **2B** are formed by dissociation of the precatalysts **1** and **2**, respectively. Thus, there are two independent experimental results for dissociation of **1** and **2** in solution. The equilibrium lies far toward the 16-electron species in these systems (Scheme 4). Only a small amount of species **1B** of about 0.3% and **2B** of about 0.2% relative to the 16-electron complexes **1A** and **2A** occurs in solution. The rate of dissociation of **1** and **2** is different, as can be derived from Figures 2 and 3. Exchange of tricyclohexylphosphine of **1** with phosphine **3** · Cl was observed after a reaction time of approximately 12 s, whereas **2** showed after 12 s just the start of the exchange reaction and needed for comparable exchange with **1** about 300 s. Thus the rate of phosphine exchange of **1** is found to be, at room temperature, faster than of **2**, which is in accordance with kinetic measurements of Grubbs,³ giving additional experimental evidence that **1B** and **2B** are derived from solution and are not formed by some reaction during the electrospray.

It is most remarkable that we observed in the ESI mass spectra of **1** or **2** in the presence of phosphine **3** in addition to the signals of the 16-electron ruthenium complex **A**, being the base peak, and the 14-electron intermediate **B** also the signals of 18-electron species **D**, **E**, and **F**, having three phosphine moieties coordinated to ruthenium with low intensity (Figures 2, 3; Scheme

4). These species are present in solution in low concentration, obviously too low to be detected by NMR spectroscopy.^{3b} Olefin coordination to form an 18-electron intermediate (or transition state) followed by dissociation of phosphine was discussed in the associative pathway of the ligand exchange of phosphine with olefinic substrate in metathesis reactions.^{3c} The formation of these complexes in the equilibrium could open, in addition to the dissociative pathway (Scheme 1), an associative pathway for the phosphine exchange in solution (Scheme 4), which should give, if any, only a minor contribution because the rate of exchange would become dependent on the concentration of phosphine. Grubbs, however, showed by kinetic studies that the rate of phosphine self-exchange is not dependent on the concentration of phosphine, giving evidence for dissociation as the rate-determining step (Scheme 1).^{3b} Obviously, the relevance of these 18-electron species in solution seems to be low. It may be mentioned that Chen et al. detected the dication in the ESI spectrum of **1C** · Cl.^{7a,b} We detected dications only with very low intensities and observed preferentially monocations in the ion-pairing complexes, such as species **C** or **D**, as well as species **E**.⁹ Ion pairing is a common aspect in ESI-MS.¹³

It is accepted generally that the 14-electron intermediates **B** and **T** are the catalytically active species (Scheme 4).³ We reacted ethylene with intermediate **1B**, which was extracted from the liquid phase into the gas phase, and could observe the formation of the metathesis product **4B** (Figure 4). No intermediates such as a π -complex and metallacyclobutane could be detected. Similar results were reported by Chen, who performed an analogous experiment with 1-butene.^{7a,b} The respective reaction of **2B** showed also the formation of **4B**, though the extent of reaction seems to be much lower. Interestingly, a CID product was formed at m/z 420, being able to react with one molecule of ethylene (Figure 5). Obviously, the fragment at m/z 420 formed by CID from intermediate **1B** contains a Ru–C σ -bond that is able to insert one ethylene. The reaction product could be alternatively an ethylene–ruthenium π -complex. Because of the fact that we have not been able to observe in our studies any alkene–Ru π -complex, we can assume that ethylene was inserted into a Ru–C-bond, as shown in Scheme 5.

We studied some standard ring-closing metathesis reactions by using the microreactor technique. We focused on the detection of intermediates in the catalytic cycle (Scheme 6). It seems to be most remarkable that we could detect methylene ruthenium intermediate **4** only as **4A** (16 electrons), which has already been detected by NMR studies,¹⁴ and **4B** (14 electrons); however we could not detect intermediate **15**, neither as **15A** nor as **15B**. As in the gas phase (see above), no π -complexes as well as metallacyclobutane intermediates could be detected. Thus, as was assumed by Grubbs from kinetic studies,³ all monomolecular steps in the catalytic cycle following olefin coordination are fast and no intermediate will be accumulated to become detectable, even carbene complex **15**.

Grubbs showed that the 14-electron intermediate **4T** is also the intermediate of degradation of the catalyst, giving methylenetricyclohexylphosphine, which is transformed to the methylphosphonium salt (Scheme 2).^{4c} In contrast, substituted ruthenium carbenes were found to decompose by dimerization of the organic fragment of the complex.^{4a} Thus, as expected, *cis*- and *trans*-stilbene **14** were formed in the solution of complex **1** after some time as the product of degradation. We could easily detect in the ESI mass spectra from the reaction

(14) (a) Grubbs, R. H.; Miller, S. J.; Fu, G. C. *Acc. Chem. Res.* **1995**, 28, 446. (b) Kirkland, T. A.; Grubbs, R. H. *J. Org. Chem.* **1997**, 62, 7310.

solutions of the ring-closing metathesis reactions of dienes **5**–**7** the methylphosphonium cation $\text{CH}_3\text{P}^+\text{Cy}_3$ at m/z 295 as a degradation product of methylene ruthenium complex **4**.^{4c} Most surprisingly, we observed in the ESI mass spectra of **1** and **2** the phosphonium ions **11** at m/z 371 and **12** at m/z 347, respectively, giving evidence that degradation of these ruthenium complexes occurs at least partially similar to that accepted for **4** (Scheme 2).^{4b,4c} Moreover, in the presence of phosphine **3**, the charge-labeled benzylidenetrialkylphosphine **13** at m/z 374 was detected, giving clear evidence of the primary product of the phosphine attack decomposition pathway.^{4c} Unfortunately, no evidence of the corresponding ruthenium-containing degradation products could be obtained, in agreement with the results reported.⁴

Conclusion

In conclusion, it has been shown that reactions of first-generation ruthenium olefin metathesis catalysts in solution can be studied successfully by ESI-MS. It was possible to detect and characterize 14-electron ruthenium intermediates directly from solution. Moreover, the catalytic activity of these species was directly demonstrated by gas phase reaction with ethylene. It could be shown that all monomolecular steps in the catalytic cycle of ring-closing metathesis following the olefin coordination are fast and no intermediate will be accumulated to become detectable. 18-Electron ruthenium species containing three phosphine ligands were shown to be present in solution in low relative concentration. Finally, alkylidene trialkylphosphane and phosphonium salts were easily detected as degradation products of first-generation catalysts.

Experimental Section

The mass spectrometric measurements were performed on the Micromass Premier quadrupole-time-of-flight (Q-ToF) instrument (Waters, Manchester) equipped with a ESI ion source containing a stainless steel metal spray capillary (127 μm inner diameter, 229 μm outer diameter, 181 mm in length). The capillary voltage of 3.5 kV, source and desolvation temperatures of 50 °C, and cone voltage of 20 eV were applied as standard ESI operation conditions. The collision-induced dissociation (CID, argon collision gas with flow of 0.2 mL/min) was performed in the collision cell region; the collision energy was set to 2–30 eV for different ion species.

MS continuous-flow experiments were performed using two syringes containing solutions of the different reactants, mixing them before entering into the ionization source. For this, a microreactor (Techlab, Peek mixing tee) was directly connected to the ESI spray capillary. The reaction occurred in the metal spray capillary of the ion source, and different reaction times were achieved by varying the flow rate in the syringe pumps.

The solvent CH_2Cl_2 was distilled from CaH_2 and saturated with argon prior to use. The catalysts **1** and **2**, phosphine **3** $\cdot$ Cl, and olefins **5**, **6**, and **7** were purchased from Aldrich (Steinheim, Germany) and used as received without further purification. All organometallic manipulations were carried out under argon and at room temperature.

General Procedure for the Online Microreactor ESI-MS Study of the Phosphine Exchange Reaction of Catalysts **1 and **2** with **3** $\cdot$ Cl.** A solution of 0.4 mg (5.5×10^{-5} M) of **1** in 10 mL of CH_2Cl_2 was prepared and mixed with a solution of 0.2 mg (6.3×10^{-5} M) of phosphine **3** $\cdot$ Cl in 10 mL of CH_2Cl_2 using two respective syringes feeding a mixing tee coupled directly to the

ESI-MS ion source. The injection speed of both solutions was set to 5 $\mu\text{L}/\text{min}$, allowing the study of the solution after a reaction time of approximately 12 s. The respective experiment was performed with catalyst **2** analogously.

Dual-Spray experiment.¹¹ The above given solution of **1** or **2**, respectively, was sprayed using the main capillary of the Q-ToF, and the solution of **3** was sprayed using the transverse capillary.

Off-Line Monitoring of the Phosphine Exchange Reaction of **1 or **2** with **3** $\cdot$ Cl.** A 0.4 mg (5.5×10^{-5} M) sample of **1** and 0.2 mg (6.3×10^{-5} M) of phosphine **3** $\cdot$ Cl, respectively, were dissolved in 10 mL of CH_2Cl_2 . Then 5 mL of both solutions were mixed. An aliquot was withdrawn from the reaction mixture after preset reaction times to follow the reaction progress. The respective experiment was performed with catalyst **2** analogously.

General Procedure for the Online Microreactor ESI-MS Study of the Ring-Closing Metathesis Reaction of diene **5, **6**, or **7** with Catalyst **1** or **2** in the Presence of Phosphine **3** $\cdot$ Cl.** An aliquot of a solution of 0.4 mg (5.5×10^{-5} M) of **1** or **2** and of 0.2 mg (6.3×10^{-5} M) of **3** $\cdot$ Cl in 10 mL of CH_2Cl_2 was mixed with an aliquot of a solution of 1 mg (5.1×10^{-4} M) of diene **5**, **6**, or **7**, respectively, in 10 mL of CH_2Cl_2 , by using two respective syringes feeding a mixing tee coupled directly to the ESI-MS ion source. The injection speed of both solutions was set to 10 $\mu\text{L}/\text{min}$, allowing the study of the solution after a reaction time of approximately 6 s.⁶

Gas Phase Metathesis Reactions of **1B and **2B**, Respectively, with Ethylene.** The collision cell of the Q-TOF was filled with highly pure ethylene (99.99%, Aldrich, Steinheim, Germany). The ethylene pressure was retained approximately at 6.0×10^{-3} mbar.^{6d} The monoisotopic ion of **1B** at m/z 546 or 548 and of **2B** at m/z 524 was selected in the first quadrupole to react with ethylene in the collision cell under low-energy collisions (1.1–2.0 eV), and the product ions were detected by the TOF analyzer. The fragment ion of **2B** at m/z 420 was generated by in-source CID of **2B** using a cone voltage of 100 eV.

GC-MS Detection of *cis*- and *trans*-1,2-Diphenylethylene. GC-MS (EI) spectra were recorded using a Hewlett-Packard HP5890 series II instrument with a DB-5 capillary column (30×0.25 mm $\times$ 0.25 μm , Agilent) and a Finnigan MAT-95 mass detector (Thermo) set to scan from 40 to 650 m/z at a rate of 1.5 scans/s. The oven temperature program was as follows: initial temperature 60 °C, ramp at 20 °C/min to 300 °C, hold for 15 min. Measurements were performed in split mode (split ratio 1:50) using helium as carrier gas (linear velocity 1 mL/min at 25 °C). GC-MS peak assignments: *cis*-1, 2-diphenylethylene at retention time 16.24 min, molecular peak (EI) at m/z 180; *trans*-1,2-diphenylethylene at retention time 19.17 min, molecular peak (EI) at m/z 180.¹⁵ The EI mass spectra of *cis*-1,2-diphenylethylene and *trans*-1,2-diphenylethylene are in agreement with the standard EI spectrum from SDBS (spectral database for organic compounds).

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Supporting Information Available: Detailed isotopic cluster distribution of all the Ru-containing species and ESI-MS/MS spectra for CID of all the protonated olefin reactants, Ru intermediates, and decomposition products of catalysts are given free of charge via the Internet at <http://pubs.acs.org>.

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