Reaction Mechanisms

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Insights into the Decomposition of Olefin Metathesis Precatalysts**

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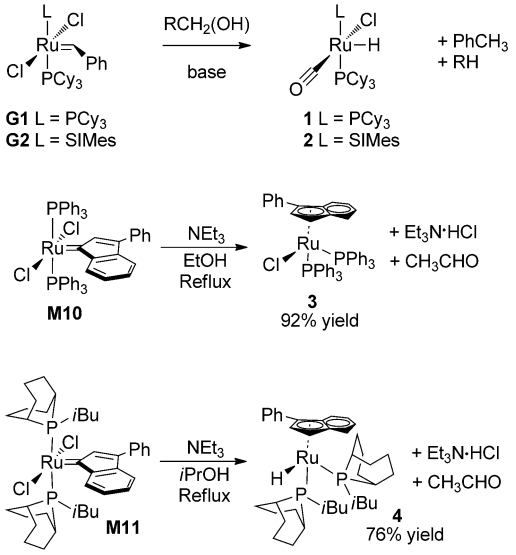
Abstract: *The decomposition of a series of benzylidene, methylidene, and 3-phenylindenylidene complexes has been probed in alcohol solution in the presence of base. Tricyclohexylphosphane-containing precatalysts are shown to yield [RuCl(H)(H_2)(PCy_3)$_2$] in isopropyl alcohol solutions, while 3-phenylindenylidene complexes lead to η^5-(3-phenyl)indenyl products. The potential-energy surfaces for the formation of the latter species have been probed using density functional theory studies.*

Stability and activity are two key requirements for robust and efficient catalysts. While these two properties are often inversely proportional, a thorough understanding of both is important. To develop catalysts with increased performance it is crucial to understand possible decomposition pathways, not only during catalysis but also during catalyst synthesis and handling. In addition, the characterization and investigation of decomposition products can lead to new understanding in organometallic chemistry.

Olefin metathesis has been the key step in many elegant syntheses of complex molecules,[1] and therefore (pre-)catalysts are routinely exposed to a plethora of functional groups. Previous work by numerous researchers has been conducted to explore the stability of metathesis precatalysts towards various reagents and conditions. Notably, when the Grubbs-type precatalysts **G1** and **G2** are heated in the presence of primary alcohols, the hydridocarbonyl complexes **1** and **2**, respectively, are formed (Scheme 1).[2] These complexes have been implicated in deleterious isomerization processes during metathesis reactions.[3] Recently, our efforts have been focused on understanding the stability of metathesis complexes, especially the versatile synthon [$RuCl_2$((3-phenyl)indenylidene)(PPh_3)$_2$] (**M10**), which is used for the synthesis of first-, second-, and third-generation metathesis precatalysts.[4] When **M10** was heated in alcohol solution, the new species [RuCl(η^5-(3-phenyl)indenyl)(PPh_3)$_2$] (**3**) was formed, wherein the indenylidene ligand coordinated in an η^5-fashion (Scheme 1).[5] This complex, and its cationic derivative,[6] have since been shown to be highly active in a number of transformations.[5–7] More recently, we have shown that this indenylidene-to-η^5-indenyl rearrangement is not limited to **M10**, but that it also occurs for the related complex [$RuCl_2$(3-phenylindenylidene)(*i*Bu-Phoban)$_2$] (**M11**), thus yielding the hydride species [Ru(H)-(η^5-(3-phenyl)indenyl)(*i*Bu-Phoban)$_2$] (**4**; Scheme 1; *i*Bu-Phoban = 9-isobutyl-9-phosphabicyclo[3.3.1]nonane).[8]



Scheme 1. Decomposition of **G1**, **G2**, **M10**, and **M11** in an alcohol solution. SIMes = 1,3-bis(2,4,6-trimethylphenyl)-4,5-dihydroimidazol-2-ylidene.

Notably, in the latter case, a much cleaner reaction occurred when a secondary alcohol was used. Seeking to have a more comprehensive understanding of the decomposition of

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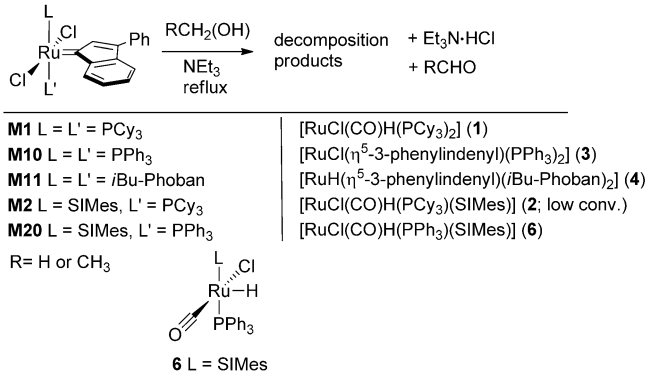
ruthenium indenylidene complexes, the stability of different first-generation species was evaluated in primary and secondary alcohols in the presence of a base. The two key questions were 1) whether indenylidene complexes behave differently from their benzylidene congeners and 2) whether the behavior of a complex might be predicted based on its chemical structure. To this end, a series of complexes were systematically explored in alcohol solutions in the presence of triethylamine. The methylidene $[RuCl_2(=CH_2)(PCy)_2]$ (**5**; see Scheme 4) was also studied, as it is commonly implicated as a fragile species in metathesis reactions. This compound was prepared using a modified version of the protocol from Fogg and co-workers,[9] where 1,7-octadiene was used in place of ethene, as the former undergoes rapid and complete metathesis[10] to yield ethene in situ (see the Supporting Information for details).

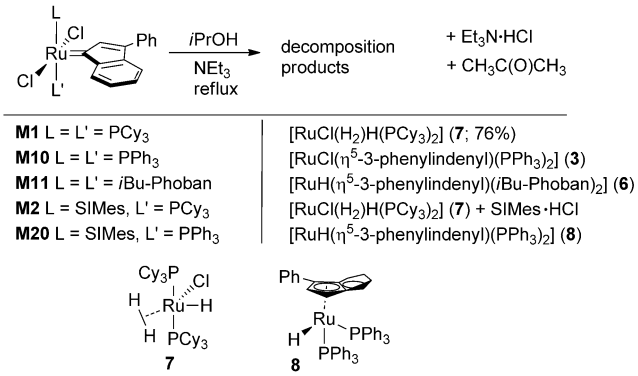
The products of each of the reactions in primary alcohols were investigated first (Scheme 2). As disclosed previously,[8] **M1** reacts in the same manner as **G1**, thus forming the hydridocarbonyl complex **1. M2** decomposed slowly to yield low quantities of **2**; this slow reaction is most likely



Scheme 2. Decomposition of indenylidene complexes in alcohol solution.

a consequence of its low initiation rate.[11] **M20** features a more labile phosphane, and decomposed more quickly to the corresponding hydridocarbonyl species **6**. The decomposition of **M11** yielded **4**.

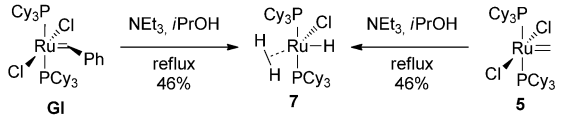
The same set of complexes was exposed to isopropyl alcohol, to investigate the reactivity differences in this solvent (Scheme 3). Only traces of hydridocarbonyl complexes were observed in these reactions, presumably because of either the need to cleave two carbon–carbon bonds to form a carbonyl ligand, or the presence of traces of primary alcohols in the solvent. Despite the previously reported lack of reactivity of **G1** in secondary alcohols,[2b] **M1** yielded $[RuCl(H)(H_2)(PCy_3)_2]$ (**7**). The analytically-pure product was isolated in 76% yield after work-up and the NMR data were consistent with previous reports.[12] The compound **7** is typically a decomposition product from hydrogenolysis reactions,[12a] but this is the first example where this complex is obtained without the direct use of dihydrogen, thus suggesting that alcoholysis and hydrogenolysis may proceed by similar pathways. Fogg and co-workers has shown that **7** can be advanced



Scheme 3. Decomposition of indenylidene complexes in isopropyl alcohol.

to **1** by methanolysis,[13] so **7** is a plausible potential intermediate in the primary-alcohol-mediated decomposition of metathesis catalysts.

To understand how the alkylidene might affect decomposition, **G1** and **5** (the catalyst resting state) were heated with triethylamine in isopropyl alcohol (Scheme 4). In both cases, **7** was obtained, thus suggesting that this pathway is general to bis(tricyclohexylphosphane) complexes. Notably, methylidene, benzylidene, and (3-phenyl)indenylidene complexes bear different degrees of alkylidene substitution, yet yield the same product.



Scheme 4. Decomposition of **G1** and **4** in isopropyl alcohol.

Clearly, the nature of the phosphine ligand appears to play a role in determining the reactivity. Triphenylphosphine and tricyclohexylphosphine are quite different in terms of both steric and electronic properties (cone angles of 145°and 170°, and TEPs of 2068.9 cm^{-1} and 2056.4 cm^{-1}, respectively), when studied on model $[Ni(CO)_3(PR_3)]$ complexes.[14] However, in **M10** and **M1** they show similar steric bulk, having average percent buried volumes (% V_{bur})[15] of 26.5% (**M10**; Ru-P = 2.39 Å) and 27.6% (**M1**; Ru-P = 2.42 Å).[16] Single crystals of **M11** were grown from CH_2Cl_2/pentanes and analyzed by X-ray crystal diffraction (Figure 1). The % V_{bur} was found to be 27.4%, which is similar to PCy_3. The electronic properties of *i*Bu-Phoban were measured from IR spectroscopy of $[IrCl(CO)_2(iBu\text{-}Phoban)]$[17] (see the Supporting Information). The average of the carbonyl stretching frequencies was 2029 cm^{-1}, which compares to 2028 cm^{-1} for PCy_3 and 2044 cm^{-1} for PPh_3. Insofar as can be measured using these common metrics, *i*Bu-Phoban possesses similar steric and electronic properties to PCy_3.

We therefore turned to theoretical studies (at the M06L\TZP\\BP86\SVP level of theory) to explore the important issue of how structure influences the decomposition

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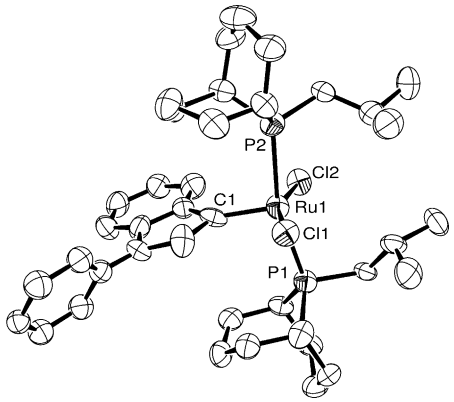

Figure 1. X-ray crystal structure of **M11**. Thermal ellipsoids are shown at 50% probability, and hydrogen atoms are excluded for clarity.

pathway.[19] The full pathway for **M10** to **3** (PPh_3) has been modeled previously.[5] This pathway was therefore modeled for **M1** (PCy_3) and **M11** (*i*Bu-Phoban; Figure 2). The potential-energy surfaces (PESs) for the rearrangement of precatalysts **M10**, **M1**, and **M11**, generically indicated as **A** in the following calculations, to yield complexes of the form [RuCl-(η^5-(3-phenyl)indenyl)(PR_3)$_2$], generically indicated as **H** in the following calculations, are presented in Figure 2 (energies are normalized to **A** plus NEt_3 and methanol). Before starting the discussion we remark that in the case of the PPh_3 complex, the final product **H** corresponds to the experimentally observed product **3**.

Endergonic dissociation of the phosphine ligand from **A** yields the 16-electron species **B**, which can undergo reaction with methanol (**C**) and subsequent base-promoted loss of HCl (**D**, **E**). Recoordination of (**F**) is followed by elimination of formaldehyde (**G**). The barrier **FG**‡ (pictured in Figure 3) is the highest identified for each complex. Rearrangement of **G** furnishes the chloride complex **H**, which corresponds to **3** in the case of PPh_3.

Interestingly, much can be gained from the inspection of the free-energy differences between **A** and **H**, and from the **FG**‡ barrier. For **M10**, where **3** is obtained, **H** is favored by 15 kcal mol^{-1}. For **M1** and **M11**, **H** is unfavorable by 10.8 and 5.5 kcal mol^{-1}, respectively. Notably, **H** is not recovered from the reaction of **M11**, but the hydride species is recovered. Prolonged heating of **3** in alcohol in the presence of a base is known to yield the hydride complex **8**. At this point, the remarkable difference in stability of **M10**, **M1**, and **M11** is clearly related to the height of the **FG**‡ barrier and to the stability of **H** relative to **A**. Considering that in **H** the two phosphine ligands are placed *cis* to each other, whereas in the **A** they are *trans*, we wondered if the height of the **FG**‡ barrier and the stability of **H** and **A** could be related to increased steric clashes between the phosphine ligands as they move from *trans* to *cis*, since the **FG**‡ barrier is lower and **H** is more stable than **A** for the smaller PPh_3 relative to the bulkier PCy_3 (Figure 3). To this end, we evaluated the energy difference between **A** and **H** using the smaller PMe_3. To our delight, in this case we calculated the **FG**‡ barrier to be only 20.2 kcal mol^{-1}, and that **H** is more stable than **A** by 26.5 kcal mol^{-1}. This result highlights which factor is key to the observed decomposition, and provides a way to predict the stability of new complexes, with respect to this decomposition pathway.

To complete the study, we modeled the reaction of the chloride complexes **H** to yield the hydride species **M** (Figure 4; normalized to **H** plus NEt_3 and methanol). The relative energies of **H** and **M** for **M1**, show that **M** lies 12.7 kcal mol^{-1} above **H**, which is already 10.8 kcal mol^{-1} above **M1** (i.e. 23.5 kcal mol^{-1} in total).

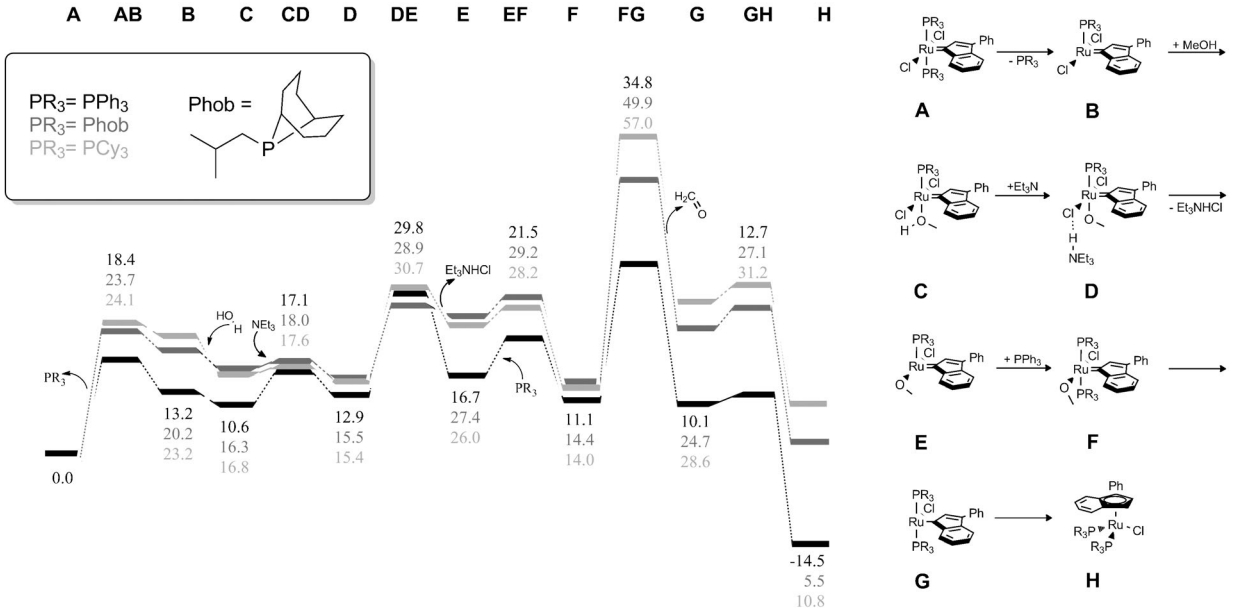

Figure 2. Potential-energy surfaces for the rearrangement of ruthenium indenylidene complexes to yield η^5-complexes. Energies are free energies in solvent, in kcal mol^{-1}.

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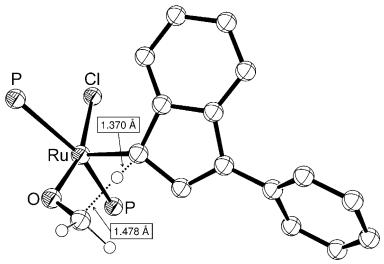

Figure 3. DFT-derived transition state **FG** for **M1** (selected distances in Å, cyclohexyl moieties are omitted for the sake of clarity).

The reaction of **3** to form **8** is considerably uphill, even though the formation of **3** from **M10** is energetically very favorable. The difference in energy between **M10** and **8** is 18.3 kcal mol^{-1}. For **M11**, while the formation of **H** is slightly uphill, the subsequent reaction to form the hydride species **4** is slightly favored (by 0.4 kcal mol^{-1}). In addition, the barriers on the chloride to hydride pathway are all much smaller than the largest barrier on the indenylidene to chloride pathway in Figure 2 (**FG**$^{+}$ is 35.5 kcal mol^{-1} higher in energy than **F**). We therefore believe that these DFT calculations are in full agreement with the observed behavior of the indenylidene species. These DFT calculations may well hold predictive value for future studies, to assess the decomposition behavior of new generations of ruthenium indenylidene metathesis precatalysts.

In conclusion, we have probed the decomposition of first- and second-generation metathesis catalysts in the presence of alcohols, thus revealing the formation of [RuCl(H)(H_2)-(PCy_3)$_2$] (**7**) in the case of PCy_3-containing complexes. While simple measures of the steric and electronic properties of the phosphine ligands were unable to rationalize the different behavior of the complexes examined, DFT calculations to probe the effect of structure on this rearrangement reaction revealed that the primary decomposition mechanism is in fact predictable using theoretical methods. We believe this information will be of significant utility and interest to researchers preparing new generations of metathesis precatalysts, and to chemists applying alkene metathesis transformations in their laboratories.

Experimental Section

Typical decomposition experiment: In the glovebox (under an Ar atmosphere), the ruthenium complex (typically ca. 100 mg) was weighed into a screw-cap vial. Dry, oxygen-free alcohol (2 mL) was added, followed by a stirrer bar, and the vial was closed, sealed with tape, and removed from the glovebox. At the bench, triethylamine (ca. 0.5 mL) was added by syringe, and the vial was heated at reflux temperature overnight. The vial was returned to the glovebox and the reaction mixture was worked up. Full experimental details and characterization data can be found in the Supporting Information.

DFT calculations**:** All calculations were performed with the Gaussian09 package at the BP86 GGA level using the SDD ECP on Ru and the SVP basis set on all main group atoms. The reported energies have been obtained by single-point calculations at the M06 L MGGA and BP86 level of theory with the TZVP basis set on main group atoms and an additional diffuse function on Cl and O. Solvent effects, MeOH, were included with the PCM model. Full computational details and *xyz* coordinates, absolute energies, and three-dimensional view of all computed species can be found in the Supporting Information.

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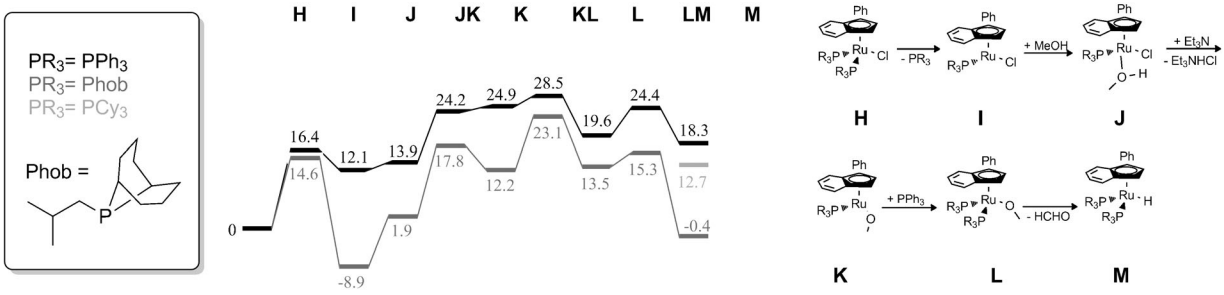

Figure 4. Potential-energy surfaces for the onward reaction of the chloride complexes **H** to yield hydride species **M**. Energies are free energies, in kcal mol^{-1}.

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