C–H Activation

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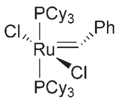
Double C–H Activation of an N-Heterocyclic Carbene Ligand in a Ruthenium Olefin Metathesis Catalyst**

*Soon Hyeok Hong, Anatoly Chlenov, Michael W. Day, and Robert H. Grubbs**

N-heterocyclic carbene (NHC) ligands have been widely used for transition-metal catalysts in a role analogous to that of phosphines and other neutral two-electron donors because of their distinctive high σ basicity and low π acidity.[1] However, it has been demonstrated that NHCs occasionally participate in unanticipated side reactions, such as activation of C–C and C–H bonds,[2,3] and sometimes enter into abnormal binding modes.[4] Decomposition reactions are detrimental to catalyst function, and understanding them is, therefore, of fundamental importance to the design of stable transition-metal catalysts that contain NHC ligands.[5] Herein we report the double C–H bond activation of an NHC in an olefin metathesis catalyst.



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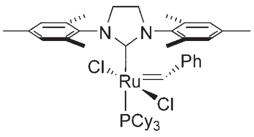

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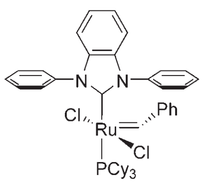

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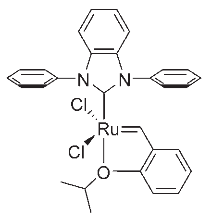

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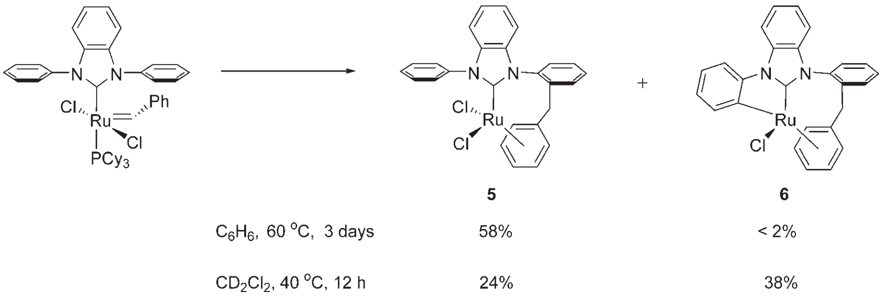
NHC-based olefin metathesis catalyst **4** shows high activity in ring-closing metathesis (RCM) reactions to form tetrasubstituted olefins.[6] Although catalyst **3**, a phosphine-analogue of **4**, is also active in the RCM reactions,[7] it has been found to decompose much faster, having a shorter half-life than both catalysts **1** (Cy = cyclohexyl) and **2** (30 min for **3** versus 8 days for **1** and ca. 38 days for **2** at 55 °C in 0.023 M C_6D_6 solution).[8,9] Although it is well documented that NHC-based ruthenium olefin metathesis catalysts are generally more stable than bis(phosphine)-based catalysts,[8,9] complex **3** is even much less stable than **1**. This abnormal instability of **3** led us to study the structural feature of the *N*,*N'*-diphenylbenzimidazol-2-ylidene (biph) ligand that led to the decomposition of **3**.

When complex **3** was heated in benzene at 60 °C under inert conditions, the decomposition product **5** precipitated in a yield of 58 % after three days (Scheme 1). Complex **6** was also observed in trace amounts (< 2 %). Interestingly, complex **6** was the major decomposition product along with **5** after 12 h in CD_2Cl_2 at 40 °C (Scheme 1).



Scheme 1. Thermal decomposition of complex **3**.

The structures of **5**[10] and **6**[11] were elucidated by X-ray crystallography (Figures 1 and 2). The crystal structure of **5** showed that the benzylidene carbon atom of **3** had inserted into an *ortho* C–H bond of one of the *N*-phenyl rings of the biph ligand. Moreover, η^6 binding of the ruthenium center to the phenyl group of the benzylidene moiety was observed along with complete loss of the phosphine ligand. The protons of the η^6-bound phenyl group have characteristic upfield ^{1}H NMR chemical shifts at $\delta = 4.5$–6.0 ppm. Recently, Diver and co-workers reported that carbon monoxide promotes the insertion of benzylidene into an aromatic C–C bond of a mesityl group of the NHC ligand in complex **2** to produce a seven-membered ring.[12] Here, the benzylidene inserts into an *ortho* C–H bond of the phenyl group of the NHC ligand with

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[*] S. H. Hong, A. Chlenov, Prof. R. H. Grubbs
The Arnold and Mabel Beckman Laboratory of Chemical Synthesis
Division of Chemistry and Chemical Engineering
California Institute of Technology
Pasadena, CA 91125 (USA)
Fax: (+1) 626-564-9297
E-mail: rhg@caltech.edu

Dr. M. W. Day
Beckman Institute
X-ray Crystallography Laboratory
California Institute of Technology
Pasadena, CA 91125 (USA)

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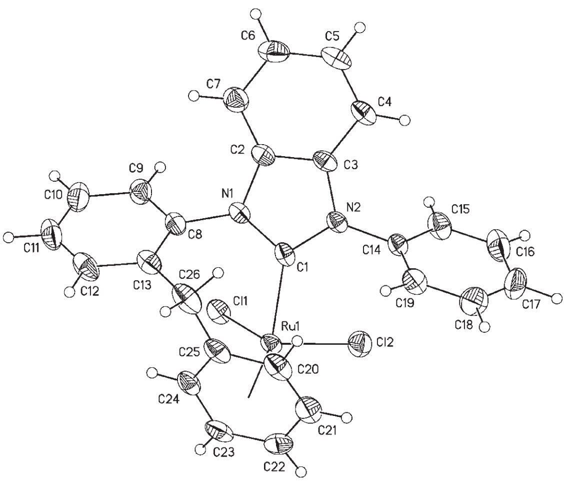


Figure 1. ORTEP drawing of **5**. Atoms are represented by ellipsoids at the 50% probability level. Hydrogen atoms have been omitted for clarity. Selected bond lengths [Å] and angles [°]: Ru-C1 2.042(2), Ru-Cl1 2.4108(5), Ru-Ph_{center} 1.69; C1-Ru-Ph_{center} 127.8, Cl1-Ru1-Ph_{center} 126.0, C1-Ru-Cl1 86.55(5), Cl1-Ru-Cl2 85.280(18).

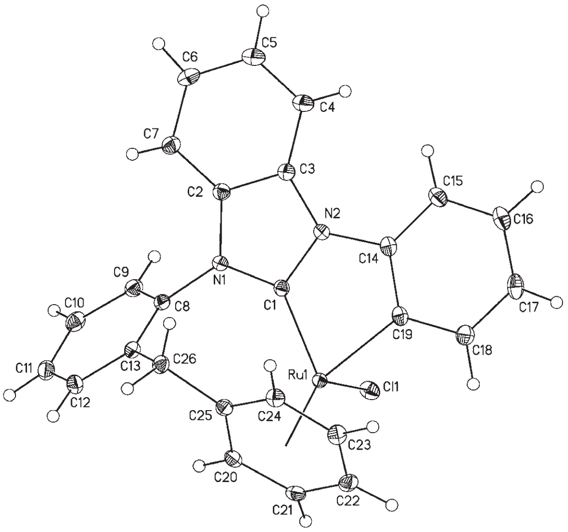
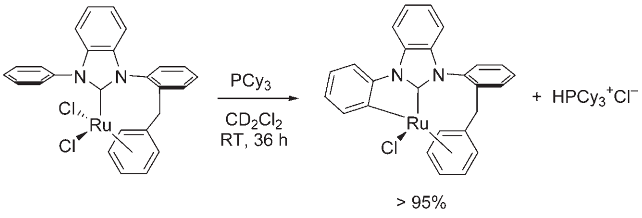


Figure 2. ORTEP drawing of complex **6**. Atoms are represented by ellipsoids at the 50% probability level. Hydrogen atoms have been omitted for clarity. Selected bond lengths [Å] and angles [°]: Ru-C1 2.0142(17), Ru-Cl1 2.4212(4), Ru-Ph_{center} 1.730, Ru-C19 2.0693(17); C1-Ru-Ph_{center} 129.9, C19-Ru-Ph_{center} 129.7, Cl1-Ru1-Ph_{center} 126.1, C1-Ru-Cl1 92.29(5), C19-Ru-Cl1 86.04(5).

concomitant η^6 coordination to the ruthenium atom and loss of the tricyclohexylphosphine (PCy_3) ligand.

In complex **6**, the ruthenium center has further inserted into another *ortho* C–H bond of the other *N*-phenyl ring of the biph ligand to give a new Ru–C bond (2.0693(17) Å) and formation of a five-membered metallacycle. This type of C–H or C–C bond activation of the *ortho*-methyl groups of H_2IMes (H_2IMes = 1,3-dimesityl-4,5-dihydroimidazol-2-ylidene) and IMes (IMes = 1,3-dimesitylimidazol-2-ylidene) ligands has been previously observed in some ruthenium olefin metathesis catalysts[9,13] and other ruthenium complexes.[2] The formation of this five-membered metallacycle cause the planes of the phenyl groups of the biph ligand to become approximately perpendicular to each other.

Based on their structural similarity, **5** would appear to be the precursor to **6**. This would explain the increased production of **6** in CD_2Cl_2, as **5** is more soluble in CD_2Cl_2 than in C_6D_6. Contrary to this hypothesis, heating a solution of **5** in CD_2Cl_2 for over a week at 40 °C did not yield **6**, as **5** is thermally stable. However, when 1.2 equivalents of tricyclohexylphosphine (PCy_3) was added to a solution of complex **5** in CD_2Cl_2, **5** quantitatively transformed into **6** at room temperature after three days (Scheme 2). PCy_3 likely acts as a base to receive the HCl eliminated from **5** to generate $HPCy_3^+Cl^-$, which is observable by ^1H and ^{31}P NMR spectroscopy as well as HRMS.[14]



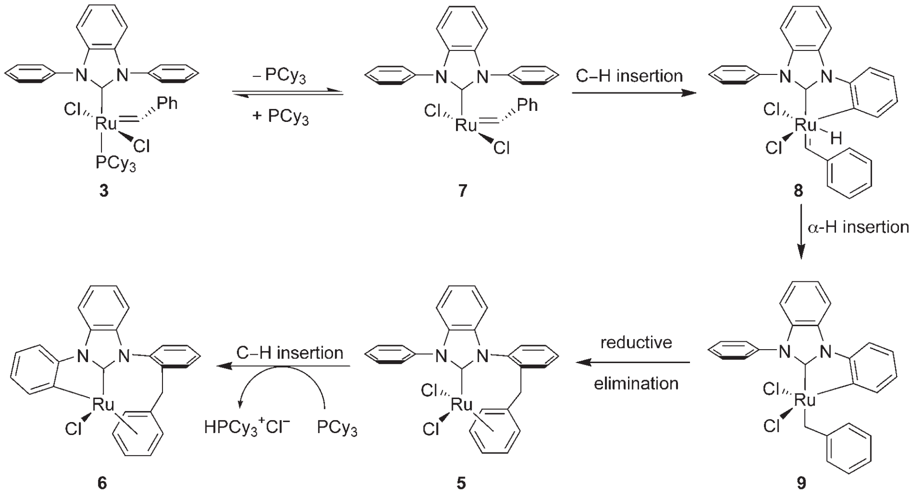
Scheme 2. PCy_3-assisted C–H insertion.

One plausible mechanism for the decomposition of **3** is presented in Scheme 3. Following phosphine dissociation, which is the initiation step in ruthenium-catalyzed olefin metathesis,[15] ruthenium hydride complex **8** may be formed by the oxidative addition of an *ortho* C–H bond of an *N*-phenyl group of biph to the ruthenium center. The resulting hydride then inserts at the α-carbon atom of the benzylidene ligand to generate complex **9**. Formation of **5** could then occur by reductive elimination between the metalated phenyl carbon atom of biph and the α-carbon atom of benzylidene. Finally, C–H insertion together with the PCy_3-mediated elimination of HCl could generate complex **6**. Intermediate complexes **7**–**9** are only postulated and have not been observed by spectroscopic methods, most probably because of their short lifetimes.

In conclusion, we have reported benzylidene insertion into an *ortho* C–H bond of the *N*-phenyl group of an NHC ligand in an olefin-metathesis catalyst **3**. Further C–H activation occurred with the assistance of the dissociated phosphine. These observations suggest that NHC ligands containing phenyl groups as opposed to mesityl groups produce ruthenium-based olefin metathesis catalysts that are more vulnerable to decomposition by C–H activation. New ligand design and synthesis of olefin metathesis catalysts are currently in progress to prevent this decomposition pathway, while maintaining activity for tetrasubstituted olefin synthesis.

Experimental Section

Procedure for a typical decomposition measurement: Complex **3**[6] (13.1 mg, 0.0161 mmol) and anthracene (ca. 1.0 mg, 0.00561 mmol) were weighed into a 1-dram vial in a nitrogen-filled glove box ($O_2 <$



Scheme 3. A plausible mechanism.

2.5 ppm). [D$_6$]Benzene or CD_2Cl_2 (0.700 mL) was used to transfer the sample to a screw-cap NMR tube. A screw-cap was used to seal the NMR tube, and this seal was reinforced with parafilm. The sample was placed into the spectrometer and allowed to equilibrate at the probe temperature for 10 min. Decomposition of the complex was following by monitoring the diminution of the benzylidene proton through collection of a time-delayed array of ^{1}H NMR spectra (referred to as a preacquisition delay (PAD) by Varian software). Conversions into **5** and **6** were measured by monitoring the characteristic ^{1}H signals of the η^6-bound phenyl group which appear in the region $\delta = 4.5$–6.0 ppm.

5: Complex **2** (50.0 mg, 0.0616 mmol) was dissolved in benzene (5.0 mL) in a sealed tube under Ar. The reaction mixture was heated to 60 °C. Precipitation of a red crystalline solid was observed after 2 h. After 72 h, the precipitate were filtered, washed with benzene, and dried under vacuum to afford **5** (19.0 mg, 0.0357 mmol, 58 %). ^{1}H NMR (300 MHz, CD_2Cl_2): $\delta = 7.06$–7.64 (m, 13 H), 5.88 (dd, $J = 6.0$, 5.7 Hz, 1 H), 5.80 (dd, $J = 6.6$, 5.4 Hz), 5.30 (d, $J = 5.4$ Hz, 1 H), 4.92 (dd, $J = 6.0$, 5.1 Hz), 4.64 (d, $J = 5.4$ Hz, 1 H), 3.93 (d, $J = 14.5$, 1 H), 3.40 ppm (d, $J = 14.5$ Hz, 1 H). ^{13}C{^{1}H} NMR (126 MHz, CD_2Cl_2): $\delta = 189.0$, 138.8, 137.8, 137.7, 136.5, 134.3, 131.7, 131.5, 131.1, 129.4, 129.3, 129.2, 129.0, 128.9, 127.3, 124.6, 124.4, 111.7, 111.6, 100.4, 97.7, 93.9, 86.1, 85.7, 81.7, 36.4 ppm. Elemental analysis calcd for $C_{26}H_{20}Cl_2N_2Ru\cdot 0.5(C_6H_6)$: C 60.95, H 4.06, N 4.90; found: C 61.15, H 4.26, N 4.92. HRMS analysis (FAB) m/z: calcd [M^+]: 532.0047, found: 532.0048.

6: Complex **5** (19.0 mg, 0.0357 mmol) and tricyclohexylphosphine (10.0 mg, 0.0357 mmol) were dissolved in CD_2Cl_2 (1.0 mL) in a screw-capped NMR tube under Ar. The reaction was monitored by ^{1}H NMR spectroscopy. After 72 h, **5** was completely converted into **6**. Complete isolation of **6** from phosphine by-products was not facile because of the air-sensitivity of the compound. Yellow crystalline solids (3 mg, 0.006 mmol, 17 %) were obtained by slow diffusion of benzene into a CH_2Cl_2 solution. ^{1}H NMR (300 MHz, CD_2Cl_2): $\delta = 8.24$ (dd, $J = 7.5$, 1.2 Hz, 1 H), 8.09 (d, $J = 9$ Hz, 1 H), 7.77–7.82 (m, 2 H), 7.65–7.72 (m, 3 H), 7.41–7.47 (m, 2 H), 7.33 (td, $J = 7.5$ Hz, 1.2 Hz, 1 H), 7.05 (td, $J = 7.5$, 1.2 Hz, 1 H), 5.98 (td, $J = 5.4$, 1.2 Hz, 1 H), 5.90 (tt, $J = 5.4$, 0.9 Hz, 1 H), 5.85 (td, $J = 6.0$, 1.5 Hz, 1 H), 5.21 (d, $J = 6.3$ Hz, 1 H), 4.13 (d, $J = 15$ Hz, 1 H), 3.89 (d, $J = 5.7$ Hz, 1 H), 3.35 ppm (d, $J = 15$ Hz, 1 H). ^{13}C{^{1}H} NMR (126 MHz, CD_2Cl_2): $\delta =$ 202.3, 164.0, 147.3, 142.1, 137.0, 136.9, 134.1, 133.1, 131.9, 129.3, 129.1, 128.5, 124.5, 124.4, 123.4, 123.1, 113.5, 112.1, 111.7, 107.8, 102.6, 100.6, 86.6, 83.7, 69.0, 38.0 ppm. HRMS analysis (FAB) m/z: calcd [M^+]: 496.0280, found: 496.0260.

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[10] Crystal data for **5**: $C_{26}H_{20}Cl_2N_2Ru\cdot 2\,CH_2Cl_2$, $M_r = 702.26$, monoclinic, space group $P2_1/c$, $a = 9.5097(3)$, $b = 12.7335(4)$, $c = 24.0073(8)$ Å, $\beta = 99.6940(10)°$, $V = 2865.58(16$ Å^3, $Z = 4$, $\rho_{calcd} = 1.628$ g cm^{-3}, $\mu = 1.128$ mm^{-1}, Mo$_{K\alpha}$ (0.71073 Å), $T = 200(2)$ K, 51512 reflections collected ($2\theta_{max} = 79.32°$), 14127 independent ($R_{int} = 0.067$), $R1 = 0.0895$, $wR2 = 0.0798$, GOF = 1.415. Data were collected on a red-orange fragment (0.38 × 0.28 × 0.15 mm) using a Bruker SMART1000 and integrated with SAINT. The structure was solved by direct methods and refined by least-squares on F^2 ($1/\sigma^2(F_o^2)$ weights) using anisotropic displacement parameters for non-hydrogen atoms and no restraints whatsoever on hydrogen atoms.[16]

[11] Crystal data for **6**: $C_{26}H_{19}ClN_2Ru\cdot CH_2Cl_2$, $M_r = 580.88$, monoclinic, space group $P2_1/n$, $a = 13.8444(5)$, $b = 13.1657(5)$, $c = 14.0413(5)$ Å, $\beta = 117.6790(10)°$, $V = 2266.45(14$ Å^3, $Z = 4$, $\rho_{calcd} = 1.702$ g cm^{-3}, $\mu = 1.065$ mm^{-1}, Mo$_{K\alpha}$ (0.71073 Å), $T = 100(2)$ K, 45136 reflections collected ($2\theta_{max} = 85.42°$), 14581 independent ($R_{int} = 0.086$), $R1 = 0.0862$, $wR2 = 0.0803$, GOF = 1.026. Data were collected on a yellow blade (0.30 × 0.26 × 0.07 mm) using a Bruker SMART1000 and integrated with SAINT. The structure was solved by direct methods and refined

by least-squares on F^2 ($1/\sigma^2(F_o^2)$ weights) using anisotropic displacement parameters for non-hydrogen atoms and no restraints on hydrogen atoms, except solvent hydrogen atoms which were refined as riding atoms.[16]

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[16] CCDC-253554 (**5**) and CCDC-256301 (**6**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif. Structure factors are available from the authors via email:xray@caltech.edu.