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Rhodium-mediated activation of an alkane-type C–H bond

Anneke Krüger, Antonia Neels and Martin Albrecht*†

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Abnormal C4-bonding of N-heterocyclic carbenes effectively modulates the electron density at rhodium and allows for the selective cleavage of an unactivated C(sp3)–H bond, whereas no such intramolecular C–H bond breaking is observed when the carbene binds normally through the C2 carbon.

The functionalization of unactivated C–H bonds, especially in alkanes, constitutes one of the most challenging areas of catalysis and has major implications in various areas such as in organic (retro)synthesis or in utilizing fossil fuel feedstocks with greater efficiency.1,2 The absence of electronically active substituents in alkane substrates renders the C(sp3)–H bond particularly inert. Functionalization of alkanes has been achieved under heterogeneous conditions, though the required high temperatures are economically unattractive and typically preclude selective product formation.3,4 In recent years, powerful homogeneous catalysts have been developed for the functionalization of methane5 based on Shilov chemistry,4 and of alkanes,6 some with remarkable selectivities.6e,7

Common to the most successful systems is the underlying mechanism, which involves oxidative addition of the C–H bond to an electron-rich transition center.7 Consequently, strong donor ligands tend to facilitate metal-mediated C–H bond activation. In search for strong donors, N-heterocyclic carbenes have emerged as a class of formally neutral ligands that are significantly more basic than the strongest trialkylphosphine donors, and indeed, modifications on Shilov’s system using NHC ligands have successfully been accomplished.8 More recently, abnormal variations of NHCs have shown to substantially enhance the ligand donor properties,9 thus representing an attractive scaffold for metal-catalyzed functionalization of unactivated bonds.10 Here, we report on the successful application of this strategy for rhodium-mediated intramolecular activation of an alkane-type C–H bond. Such bond activation requires the abnormal bonding of the NHC ligand and was not observed in analogous normally bound NHC complexes, thus providing further evidence for the unique impact of abnormal carbene ligands.11

The reaction of propylene-linked diimidazolium salts 1 and RhCl3 in the presence of NaOAc induced multiple C–H bond activation (Scheme 1).‡ After anion metathesis using KI and subsequent column chromatography (SiO2, CH2Cl2/acetone), the cyclometalated rhodium(III) complexes 3 comprising a facially C,C,C-tridentate coordinating ligand were obtained in good yields (3a 59%, 3b 71%). While C4 bonding of the NHC ligand has been expected from previous studies on methylene-linked dicarbene ligands,12 activation of the Calkyl–H bond in the propylene linker is unprecedented and remarkable, given the mild (MeCN, 80 °C) and aerobic reaction conditions.

A crystal structure of 3a confirmed the C–H bond activation (Figure 1, Table 1).‡ The two rhodium centers are crystallographically symmetry-related through a mirror plane and reside in a slightly distorted octahedral environment comprising the C,C,C-tridentate dicarbene ligand and three μ3-bridging iodide ligands. The Rh–Calkyl bond lengths are 1.968(17) Å and 1.957(17) Å and hence similar to the rhodium-carbene bond lengths in analogous bidentate NHC complexes (1.98 – 2.04 Å),12,13 yet they are significantly shorter than the Rh–Calkyl bond (2.066(12) Å).

The dimeric structure of the tridentate complex can easily be cleaved in solution with a coordinating solvent such as acetonitrile, thus quantitatively affording the monomeric complexes 2 (Scheme 1). This monomeric complex is also
surmised to be the initially formed product in the cyclometalation reaction prior to column chromatography. Evidence for the monomeric structure of 2 was provided by X-ray crystallography (Figure 1, Table 1). While most bond lengths and angles of 2a are similar to those of the dimeric complex 3a, the Rh–C<sub>alkyl</sub> bond length is slightly elongated (2.089(8) Å) and the carbene–rhodium–carbene bite angle decreased from 87.5(8)<sup>°</sup> in 3a to 83.3(3)<sup>°</sup>. These geometrical changes suggest some flexibility of the tridentate ligand.

Further confirmation of the formed rhodium-alkyl bond was obtained by NMR analyses. Microanalytically pure samples of 2 showed consistently two sets of signals (ca. 2.5:1 ratio). In the major species the resonances of the carbene residue were broad, while ligand broadening comprised predominantly the propylene signals in the minor species. For example, the rhodium-bound alkyl carbon in complex 2a appears in the <sup>13</sup>C NMR spectrum as a doublet at 33.7 ppm (δ<sub>HAC</sub> = 28 Hz; major species) and as a broad signal at δ<sub>C</sub> 39 (minor species). In contrast, the rhodium-bound carbene resonances were not resolved for the major species, yet they are distinguished as a well-resolved doublet at δ<sub>C</sub> 144.6 (δ<sub>HAC</sub> = 46 Hz) in the minor complex. Based on the expected higher trans effect of iodide as compared to MeCN, a mutual cis arrangement of the iodide and the alkyl ligands has been tentatively assigned to the major species, and a trans configuration (cf. X-ray of 2a) to the minor species. The nearly statistical distribution of the iodide ligand suggests a similar trans effect for the alkyl group and the abnormal carbene. In line with this model, the NMR spectrum of dimeric complex 3 reveals two sets of signals in approximate 1:2 ratio, attributed to isomers comprising the alkyl ligands in syn (cf. X-ray of 3a) and anti eclipsed conformation, respectively. All signals are well-resolved, consistent with a rigid dimeric structure.

Obviously, the C–H bond activation process in the propylene linker of 1 benefits from a high degree of intramolecular preorganization. Related metal-mediated, intramolecular C<sub>alkyl</sub>–H bond cleavage has been demonstrated previously in highly constrained systems. In the case reported here, the ligand system would have the flexibility to twist out and to avoid any constrained situation that may promote C–H activation. For example, no C–H bond activation has been detected when normal C<sub>2</sub>-bonding dicarbene complexes were employed. Thus, reaction of RhCl<sub>3</sub> and the diimidazolium salt <sub>4</sub> under similar reaction conditions as used for 2 gave complex 5 in moderate 21% yield (Scheme 2).<sup>6</sup>

The dicarbene ligand in complex 5 is only bidentate with the propylene bridge folded away from the metal coordination sphere. This configuration is the common motif in propylene-linked dicarbene complexes. Alternatively, the definition of this ambiguity makes the thermodynamic stabilization of complex 2 more apparent. The thermodynamic stability of complex 2 along with the kinetic lability of the Rh–C<sub>alkyl</sub> bond indicates a potential of these complexes for heterolytic bond cleavage across the Rh–C<sub>alkyl</sub> bond. We therefore evaluated the activity of complex 2 in catalytic hydrogenations using cyclooctene as model substrate (Table 2, entries 1–4).

Scheme 3. Deuterium incorporation into 2a.

Apparent changes suggest some flexibility of the tridentate ligand. The definition of the difference in this ambiguity makes the thermodynamic stabilization of complex 2 more apparent. The thermodynamic stability of complex 2 along with the kinetic lability of the Rh–C<sub>alkyl</sub> bond indicates a potential of these complexes for heterolytic bond cleavage across the Rh–C<sub>alkyl</sub> bond. We therefore evaluated the activity of complex 2 in catalytic hydrogenations using cyclooctene as model substrate (Table 2, entries 1–4).

Scheme 2. Reagents and conditions: (i), RhCl<sub>3</sub>, NaOAc, MeCN reflux, then KBr.

Scheme 3. Deuterium incorporation into 2a.
Moderate activity of 2a was observed at elevated temperatures and pressures. However, the catalytic performance was markedly increased in catalytic runs using the dicaticonic complex 6, derived from AgBF₄-mediated abstraction of the iodides from 2 (entry 5). Possibly, the rise in activity originates from the enhanced availability of coordination sites for substrate binding at the metal center combined with the modulated electron density at rhodium in the dicaticonic species, which favors heterolytic H–H bond fission. Further studies towards the scope of the catalyst and its mode of action are currently in progress.

In conclusion, the activation of an electronically unactivated alkyl-type C–H bond has been achieved by coordinating two abnormally bound NHC ligands to a rhodium center. The bond activation occurs under remarkably mild conditions (80 °C, no precautions towards air or moisture). No such activation was observed in analogous complexes comprising normally, C2-bound NHC ligands, indicating that C4-bound abnormal carbenes entail an electronic configuration at the metal center that allows for the activation of C–H bonds that are difficult to activate otherwise. Current work in our laboratories is directed towards extending this concept for devising processes that allow for intermolecular C–H bond activation.

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Notes and references

Table 2. Rhodium-catalyzed hydrogenation of cyclooctene.a

<table>
<thead>
<tr>
<th>entry</th>
<th>Rh-cat</th>
<th>T °C</th>
<th>P bar</th>
<th>t/h</th>
<th>conversion</th>
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<tr>
<td>1</td>
<td>2a</td>
<td>60</td>
<td>60</td>
<td>5</td>
<td>43%</td>
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<tr>
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<td>2a</td>
<td>20</td>
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<td>24</td>
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</tr>
<tr>
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<td>2a</td>
<td>60</td>
<td>1</td>
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<tr>
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<tr>
<td>5</td>
<td>6</td>
<td>60</td>
<td>60</td>
<td>1</td>
<td>&gt;99%</td>
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a General conditions: 1 mmol substrate, 1 mol% catalyst, 5 mL of EtOH, except for entry 5 (minimal amount of CH₂Cl₂ was used to dissolve the rhodium complex), conversions determined by GC.

The residue was purified by column chromatography (SiO₂, CH₂Cl₂/acetone, 5:2), thus affording 3a as a light brown solid (380 mg, 59%). Notably, qualitatively similar results were obtained when salt metathesis was performed with KBr, yielding the bromide analogues of complexes 2 and 3.

Crystal data for 2a: C₉H₉N₃Rh, M = 726.24, orthorhombic, a = 13.7680(13), b = 13.7680(13), c = 15.0238(10) Å, V = 2733.24(24) Å³, T = 173(2) K, space group Pca₂₁, Z = 4, 1893 total reflections, 4629 unique (Rint = 0.0593), R1 = 0.0374, wR2 = 0.0846 for I > 2σ(I) for 3a: C₉H₉N₃Rh₂, M = 1347.44, orthorhombic, a = 15.0979(13), b = 20.8008(19) Å, V = 5059.18(18) Å³, T = 173(2) K, space group Pmn a, Z = 4, 36742 total reflections, 5201 unique (Rint = 0.01149), R1 = 0.0751, wR2 = 0.1913 for I > 2σ(I).

HR-MS (ESI): C₉H₉D₃I₃N₃[M–2MeCN]⁺ requires 519.0464, found 519.0466.

14 No coalescence of the signals was observed up to 70°C.

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Rhodium-mediated intramolecular activation of an electronically unactivated alkane-type C–H bond takes place when the metal center is coordinated by two abnormal carbene ligands, presumably as a direct consequence of the strong donor ability of this class of N-heterocyclic carbenes.