

## Structure and Reactivity of “Unusual” N-Heterocyclic Carbene (NHC) Palladium Complexes Synthesized from Imidazolium Salts

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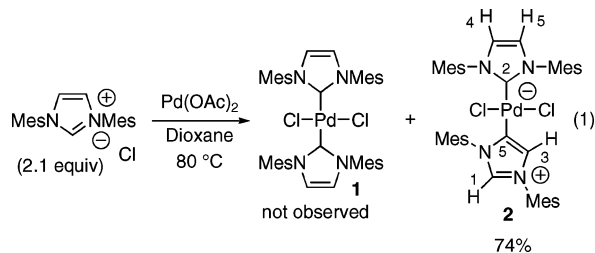
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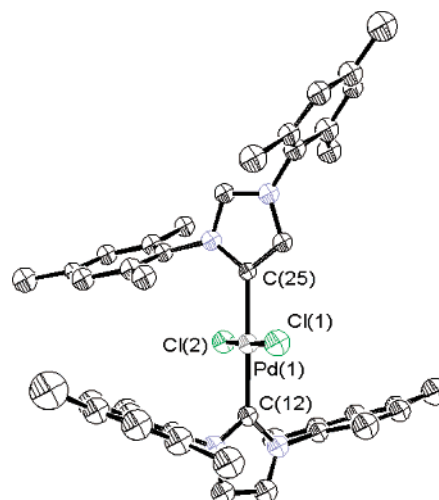
Recently, a number of new transition metal-catalyzed processes have been developed and optimized through high-throughput and combinatorial methods.<sup>1</sup> Such strategies are particularly efficient for the screening of a large number of transition metal–ligand combinations under various sets of reaction conditions. However, under these in situ conditions, the exact nature of the catalytic species is not always precisely known. Indeed, the assumption of a normal mode of binding between ligand and transition metal is most often assumed and may be misleading.

During the course of our studies focusing on ligands suitable to induce enantioselectivity in transition metal-catalyzed processes,<sup>2</sup> we became interested in testing N-heterocyclic carbene (NHC)–metal complexes. A number of simple NHC palladium-based complexes have recently emerged as effective catalysts for a variety of cross-coupling reactions.<sup>3</sup> Our study of the exact structure of various palladium NHC species reveals that the metalation site on the imidazolium salt is strongly influenced by the presence of base. We now report the synthesis and structure of novel palladium complexes bearing NHC ligands in “normal” and “abnormal” binding motifs. The binding mode of the NHC to Pd is shown to substantially affect the catalytic behavior of the palladium complexes.

It has been reported that palladium (II)–NHC complexes could be easily prepared from palladium (II) acetate and the corresponding imidazolium salts.<sup>4</sup> Metal binding at the C(2) position is usually observed, and complexes bearing two NHCs can potentially exist as trans or cis isomers, depending on the steric hindrance of the nitrogen substituent R. We first attempted to synthesize the palladium complex **1** derived from 2 equiv of *N,N'*-bis(2,4,6-trimethylphenyl)imidazolium chloride (IMes·HCl) (**1**) and 1 equiv of palladium (II) acetate under the standard reaction conditions (dioxane, 80 °C, 6 h). The reaction proceeded smoothly leading to the isolation of a single palladium-containing product.



The NMR data suggested an unusual coordination mode for the NHC ligands, as indicated by 11 proton and 22 carbon signals. In addition to the singlet at 6.85 ppm for H(4) and H(5) of a presumably C(2)-bound IMes ligand, the <sup>1</sup>H NMR spectrum



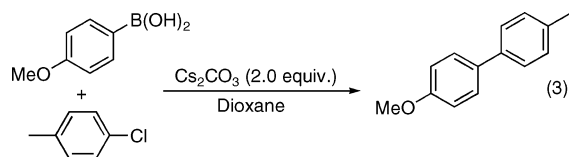
**Figure 1.** ORTEP diagram of palladium complex **2**. Selected bond lengths (Å) and angles (deg): Pd(1)–C(12), 2.019(13); Pd(1)–C(25), 2.021(11); Pd(1)–Cl(1), 2.289(4); Pd(1)–Cl(2), 2.302(4); C(12)–Pd(1)–C(25), 179.4(5); C(12)–Pd(1)–Cl(1), 93.3(4); C(25)–Pd(1)–Cl(1), 87.3(3); C(12)–Pd(1)–Cl(2), 88.6(4); C(25)–Pd(1)–Cl(2), 90.9(3); Cl(1)–Pd(1)–Cl(2), 177.23(18).

displayed two doublets at 6.57 and 7.47 ppm ( $J = 1.7$  Hz) corresponding to H(3) and the carbene H(1) of a possibly C(5)-bound IMes ligand. Furthermore, the <sup>13</sup>C NMR spectrum showed two carbon signals at 175.9 and 150.7 ppm that we assigned to C(2) and C(5) bound to the palladium center. Two carbon signals for C(4) and C(5), and for C(3), at respectively 122.8 and 125.5 ppm were also observed. On the basis of the NMR data, we proposed the reaction product to have the structure **2** (eq 1). To unambiguously establish this structure, single crystals were grown by slow diffusion of hexanes into a saturated solution of **2** in acetone. The single-crystal X-ray analysis provided the ORTEP diagram shown in Figure 1. The ORTEP reveals that the palladium is C(2) bound to one NHC ligand (the normal binding mode), whereas the second ligand is attached through the C(5) carbon of the second imidazolium. Both Pd–C distances are equivalent (2.019 and 2.021 Å) and are consistent with Pd–C single bonds. The ORTEP shows a square-planar coordination around the palladium center, with the two chlorine atoms bound to the palladium. Here again, no distortion in the Pd–Cl distances is observed (2.289 and 2.302 Å). Complex **2**, isolated in good yields (74%), is a rare example of C(5) coordination of an IMes ligand and constitutes the first example of an organometallic complex containing one C(2) NHC ligand and one C(5)-bound imidazolium ligand.<sup>5–7</sup>

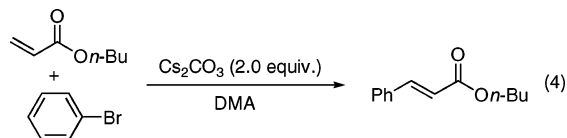
Surprisingly, when a mixture of cesium carbonate, palladium (II) acetate, and IMes·HCl was stirred at 80 °C in dioxane, the formation of **2** was not observed, and the normal C(2) complex **1**

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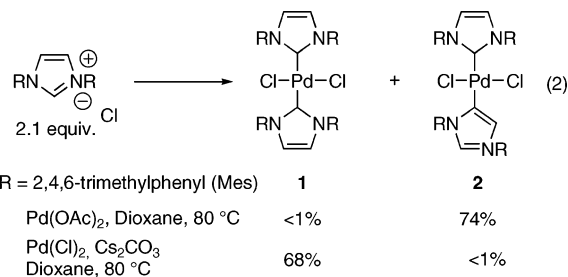
**Table 1.** Palladium-Catalyzed Suzuki–Miyaura Reactions

entry	catalyst (2 mol %)	temp (°C)	yield (%)
1	complex <b>1</b>	80	<5
2	complex <b>2</b>	80	44
3	IMes·HCl, Pd(OAc) <sub>2</sub> (2:1)	80	76
4	IMes·HCl, Pd(OAc) <sub>2</sub> (1:1)	80	28

**Table 2.** Palladium-Catalyzed Heck Reactions

entry	catalyst (2 mol %)	temp (°C)	yield (%)
1	complex <b>1</b>	120	<5
2	complex <b>2</b>	120	77
3	IMes·HCl, Pd(OAc) <sub>2</sub> (2:1)	120	66
4	IMes·HCl, Pd(OAc) <sub>2</sub> (1:1)	120	56

was formed together with (IMes)<sub>2</sub>Pd(OAc)<sub>2</sub>.<sup>8</sup> Complex **1** was also isolated in 68% from palladium (II) chloride, cesium carbonate, and 2 equiv of IMes·HCl (eq 2). The structure of complex **1** was also unambiguously established by single-crystal X-ray analysis (see Supporting Information). Attempts to convert complex **2** into the C(2) isomer **1** in the presence of a base were unsuccessful.<sup>9</sup>



The reactivity of **1** and **2** was studied and compared with the in situ-formed catalyst (from Pd(OAc)<sub>2</sub> (1 equiv) and IMes·HCl (2 equiv)) for the Suzuki–Miyaura (Table 1) and Heck reactions (Table 2).

Complex **1** proved to be an inactive catalyst for both coupling reactions, while complex **2** led to the desired product. In Suzuki–Miyaura reactions, complex **2** was not as efficient as the in situ-formed catalyst.<sup>10</sup> In sharp contrast, the highest isolated yield for the Heck coupling reaction was obtained with **2**.

In conclusion, these findings highlight the importance of the procedure used for the generation of a catalytically active species in cross-coupling reactions. It appears that the catalytically active species precursor in cross-coupling reactions is not complex **1** in both Suzuki and Heck coupling reactions. Although complex **2**

showed a difference in reactivity when compared to the in situ-generated catalyst, it was found to be a more suitable precursor for Suzuki and Heck coupling reactions. Work aimed at unveiling the nature of catalytically active species in in situ-generated NHC–Pd systems is ongoing.

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**Supporting Information Available:** Characterization data for new compounds and experimental procedures (CIF/PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>

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- (7) The related unusual C(2)–C(5) complex was also obtained with *N,N*-bis(2,6-diisopropylphenyl)imidazolium chloride (IPr·HCl).
- (8) The normal C(2) complex **1** and (IMes)<sub>2</sub>Pd(OAc)<sub>2</sub> were obtained as an inseparable mixture.
- (9) The mechanism for the formation of complex **2** has not been unambiguously established. However, there are some indications that it proceeds via the formation of a palladium–carbene complex that undergoes a C–H insertion into the C(5)–H bond of the second imidazolium salt. For instance, the use of weaker base, such as dimethylaniline, led mainly to formation of complex **2**. Conversely, complex **2** could not be obtained from palladium chloride, which suggests that palladium acetate acted as a base for the formation of the carbene ligand. We thank a reviewer for useful comments and suggestions regarding the mechanism for the formation of **2**.
- (10) It should be noted that in Suzuki–Miyaura cross-coupling reactions, well-defined complexes bearing only one NHC are better catalysts than those bearing two. See ref 3f.

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