ORGANIC LETTERS

2003
Vol. 5, No. 24
4635−4638

Borylation of Aryldiazonium Ions with N-Heterocyclic Carbene–Palladium Catalysts Formed without Added Base

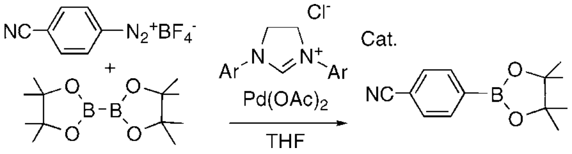
**Yudao Ma,[†] Chun Song, Wei Jiang,[†] Guoping Xue, John F. Cannon,
Xiaomei Wang,[†] and Merritt B. Andrus***

*Brigham Young University, Department of Chemistry and Biochemistry, C100 BNSN,
Provo, Utah 84602, and Chemistry College of Shandong University,
Shanda Road #100, Jinan, Shandong, 250100, P. R. China*

mbandrus@chemdept.byu.edu

Received September 24, 2003

ABSTRACT



A highly efficient catalytic borylation process with aryldiazonium ions was developed using a carbene–palladium catalyst formed in situ to give arylpinacolatoborane products. An X-ray structure for the N-heterocyclic carbene–palladium complex, used as the catalyst formed from bis(2,6-diisopropylphenyl)-4,5-dihydroimidazolium chloride, was obtained without added base.

Catalyzed reactions with N-heterocyclic carbene (NHC)−palladium complexes have become the subject of intense interest due to their enhanced reactivity and stability.[1] Successful transformations now include Heck,[2] Suzuki−Miyaura,[3] Hiyama,[4] and Kumada[5] couplings together with hydrogenation reactions.[2] In addition, NHC ligands hold great promise for catalyzing asymmetric transformations, but to date, this effort remains largely undeveloped.[6] A new class of bis-cyclophane NHC ligands was recently shown to catalyze arylborane additions to enones with high selectivity.[7] We have reported base-free conditions with NHC catalysts for efficient Heck and Suzuki couplings using reactive aryldiazonium ions,[8] as part of an effort to develop milder, low-temperature conditions for these transformations. 4,5-Dehydroimidazolium carbene−palladium complexes are now reported for borylation of aryldiazonium ions at room temperature without added base. X-ray structures are reported for the palladium(II) iodide−H_2IPr (*N*,*N*-bis-2,6-diisopropyl-4,5-dihydroimidazolium carbene) complex and, for the first time, the palladium(II) chloride complex formed in the absence of base. This unambiguous structure determination suggests an alternative mode for base-free carbene formation.

Imidazolium carbene ligands provide enhanced stability and reactivity compared to phosphines through strong σ-bond donation to the metal, together with attenuated back-bonding via N-lone pair donation.[1a] This combination of electronic effects renders the metal more electron rich, allowing for a

---

[†] Chemistry College of Shandong University.

(1) (a) Herrmann, W. A. *Angew. Chem., Int. Ed.* **2002**, *41*, 1290−1309. (b) Herrmann, W. A.; Kocher, C. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2162−2187.

(2) (a) Herrmann, W. A.; Elison, M.; Fischer, J.; Kocher, C.; Artus, G. R. J. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2371−2373. (b) Yang, C.; Lee, H. M.; Nolan, S. P. *Org. Lett.* **2001**, *3*, 1511−1514.

(3) (a) Zhang, C.; Huang, J.; Trudell, M. L.; Nolan, S. P. *J. Org. Chem.* **1999**, *64*, 3804−3806. (b) Fürstner, A.; Leitner, A. *Synlett* **2001**, 290−292. (c) Grasa, G. A.; Hillier, A. C.; Nolan, S. P. *Org. Lett.* **2001**, *3*, 1077−1080.

(4) Lee, H. M.; Nolan, S. P. *Org. Lett.* **2000**, *2*, 2053−2056.

(5) (a) Huang, J.; Nolan, S. P. *J. Am. Chem. Soc.* **1999**, *121*, 9889−9890. (b) Bölm, V. P. W.; Weskamp, T.; Gstöttmayr, C. W. K.; Herrman, W. A. *Angew. Chem., Int. Ed.* **2000**, *39*, 1602−1604.

(6) For recent efforts, see: (a) Perry, M. C.; Cui, X.; Powell, M. T.; Hou, D. R.; Reibenspies, J. H.; Burgess, K. *J. Am. Chem. Soc.* **2003**, *125*, 113−124. (b) Glorius, F.; Altenhoff, G.; Goddard, R.; Lehmann, C. *Chem. Commun.* **2002**, 2704−2705.

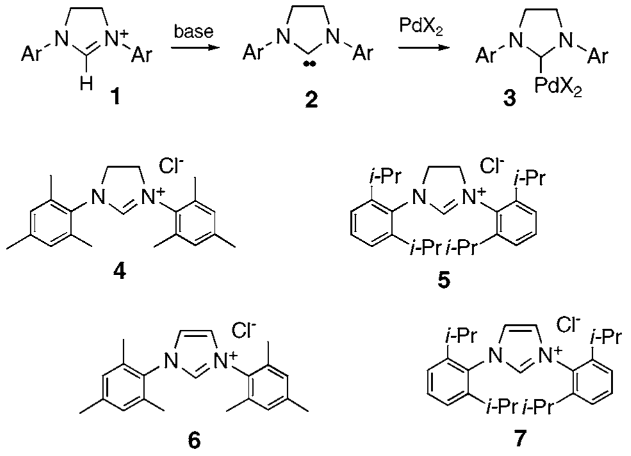
(7) Ma,Y.; Song, C.; Ma, C.; Sun, Z.; Chai, Q.; Andrus, M. B. *Angew. Chem., Int. Ed.* **2003**, *42*, in press.

(8) (a) Andrus, M. B.; Song, C. *Org. Lett.* **2001**, *3*, 3761−3764. (b) Andrus, M. B.; Song, C.; Zhang, J. *Org. Lett.* **2002**, *4*, 2079−2082.

10.1021/ol035857q CCC: \$25.00

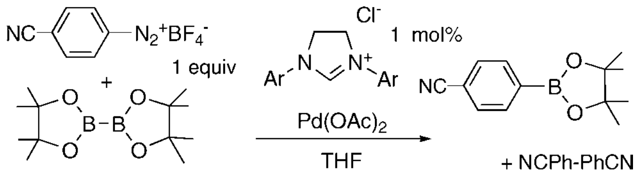
more favorable oxidative addition step. Typical NHC complexes, formed by treatment of an imidazolium salt **1** with base, give the free carbene **2** (Scheme 1). Free carbenes of this type, depending on the size of the nitrogen substituent, have been shown to be stable in solution and in crystalline form.[9] Treatment with a metal gives the carbene complex, many of which are air stable and can be chromatographed. Alternatively, the NHC−Pd complex can be formed in situ without added base from the imidazolium precursor. The imidazolium NHC precursors employed in this study include the nonaromatic *N*,*N*-bis-mesityl-4,5-dihydroimidazolium chloride **4** (H_2IMes), *N*,*N*-bis-2,6-diisopropylphenyl-4,5-dihydrochloride **5** (H_2IPr) and the corresponding aromatic analogues **6** (IMes•HCl) and **7** (IPr•HCl).

Scheme 1



Borylation of aryldiazonium tetrafluoroborates with bis(pinacolato)diborane, both used as 1 equiv, was optimized using the various NHC ligand complexes formed in situ without added base (Table 1). Ligand **4** gave only moderate yields of product (entries 1 and 2). Imidazolium **5** used with palladium acetate in THF proved optimal giving borylated product after only 2 h at room temperature in 79% isolated yield (entry 3). Importantly, the product in this case was obtained without the formation of biaryl side product, a drawback commonly encountered with this process. Higher temperature led to formation of significant amounts of biaryl coupling. The aromatic imidazolium ligands **6** and **7** were inferior giving lower yields together with more biaryl formation at elevated temperature (entries 6 and 8).[14] Leaving out the ligand (entry 8) produced even more biaryl formation at 65 °C. At room temperature without added ligand, a low yield of product, 21%, was obtained after a 24 h reaction period. When base was used in the absence of ligand at elevated temperature, again the yield was low (entry 10). With K_2CO_3 and ligand **5**, a significant amount of biaryl product was again seen (entry 11). Catalyst, $Pd(OAc)_2$ and **5**, at 0.5 mol % gave a 69% yield. Use of 0.1 mol % lowered the yield to 58%. Catalyst used at 0.01 mol % gave 58% product after 6 h at room temperature. Palladium/**5** 1:2, at 1 mol %, also gave a 79% yield after 2 h, while a 1:3 ratio of palladium/ligand gave a slightly lower 77% yield. Changing the counterion to BF_4^- in place of chloride had little effect in this case, lowering the yield to 77% (entry 12). Use of dioxane, DMF, or methanol as solvent in place of THF gave large amounts of biaryl formation (entry 13).

Table 1. Effect of Ligand and Conditions for Aryl Borylation



entry	ligand	Ar	*T*, °C	time, h	yield,[a] %	bi-Ar, %
1	**4**	mesityl	23	2	57	
2	**4**		65	1	50	28
3	**5**	2,6-di-*i*-PrPh	23	2	79	
4	**5**		65	1	68	17
5	**6**	4,5-dehydro-bis-mesityl	23	2	31	
6	**6**		65	1	10	31
7	**7**	4,5-dehydro-bis(2,6-di-*i*-PrPh)	23	2	45	
8	(none)		65	1	41	38
9			23	24	21	23
10			65	12	37[b]	trace
11	**5**	2,6-di-*i*-PrPh	23	2	68[b]	24
12	**5**		23	2	77[c]	
13	**5**		23	2	53[d]	28[a]

[a] Yields are for isolated, chromatographed materials. [b] Reaction was performed with added K_2CO_3 (1 equiv). [c] Imidazolium anion was BF_4^- in place of Cl^-. [d] Reaction was performed in methanol as solvent.

Borylation couplings involving tetraalkoxydiboron derivatives including bis(pinacolato)diborane with aryl halides have been reported previously using $Pd_2(dba)_3$ or $PdCl_2(PPh_3)_2$ with added base at elevated temperatures.[10] Use of excess (3−4 equiv) aryldiazonium ions has been reported recently to couple with bis(pinacolato)diborane using $PdCl_2(dppf)_2$ at 3 mol % in methanol at reflux.[11] IMes•HCl **6** has also been employed recently with palladium acetate and added potassium acetate as base to couple aryl chlorides in THF at reflux.[12] The more active aryldiazonium ions used as 1 equiv are now shown to couple with high yield at room temperature without added base.

---

(9) Arduengo, A. J. *Acc. Chem. Res.* **1999**, *32*, 913−920.

(10) (a) Ishiyama, T.; Murata, M.; Miyaura, N. *J. Org. Chem.* **1995**, *60*, 7508−7510. (b) Takagi, J.; Takahashi, K.; Ishiyama, T.; Miyaura, N. *J. Am. Chem. Soc.* **2002**, *124*, 8001−8006.

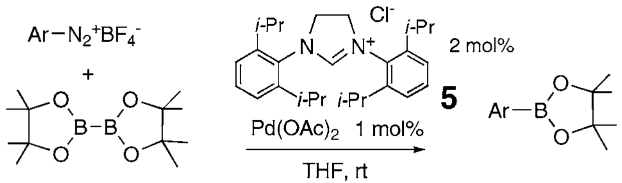
(11) Willis, D. M.; Strongin, R. M. *Tetrahedron Lett.* **2000**, *41*, 8683−8686.

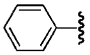
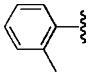
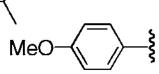
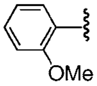
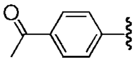
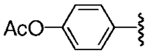
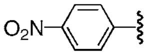
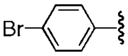
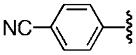
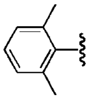
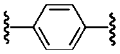
(12) Furstner, A.; Seidel, G. *Org. Lett.* **2002**, *4*, 541−543.

(13) A flat, μ^2-bridged chloride, Pd−NHC X-ray complex formed from the free, base-generated unsaturated carbene **6** is known: (a) Viciu, M. S.; Kissling, R. M.; Stevens, E. D.; Nolan, S. P. *Org. Lett.* **2002**, *4*, 2229−2231. For an attempt at the dimeric X-ray structure, see ref 8a. For a hindered 2:1 NHC−Pd complex formed with base, see: (b) Gstottmayr, C. W. K.; Bohm, V. P. W.; Herdtweck, E.; Grosche, M.; Herrmann, W. R. *Angew. Chem., Int. Ed.* **2002**, *41*, 1363−1365.

(14) Dible, B. R.; Sigman, M. S. *J. Am. Chem. Soc.* **2003**, *125*, 872−873.

Table 2. Palladium−Carbene-Catalyzed Aryl Borylation

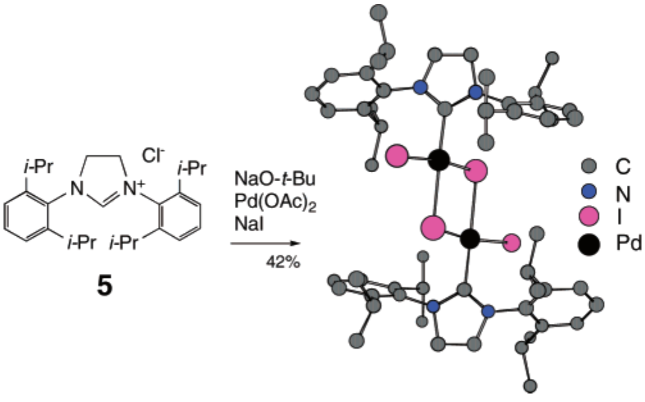


$Ar-N_2^+$	time, h	yield, %
	1.5	87
	1.5	92
	1.5	90
	1	85
	1	81
	1.5	87
	2	80
	1	88
	1.5	95
	2	79
	2	63
	1.5	71

The optimized reaction conditions with palladium acetate and imidazolium **5** as catalyst in THF at room temperature were applied to a variety of aryldiazonium tetrafluoroborate substrates (Table 2). Electron-rich and -deficient aryldiazonium ions all gave excellent yields of borylated products again used at 1:1 stoichiometry with bis(pinacolato)borane. All yields reported are for isolated, chromatographically pure products. Reactions with the phenyl- and tolyldiazonium ions were complete in 1.5 h with high yields. The anisyl substrates reacted within 1 h, but with slightly lower yields. Acetyl- and nitrobenzenediazonium ions also gave high yields. *P*-Bromophenyl reacted with the highest yield at 95%. This product has the added potential of further cross-coupling reactions through either the pinacolborane or the bromide. Ortho-substituted substrates, including the very hindered 2,6-dimethylphenyldiazonium ion, all gave good to excellent yields. The 1,4-bis-diazonium ion also gave a good yield of the bis(pinacolato)diborane product under these conditions.

Additional studies were pursued to explore the nature of the NHC-palladium catalyst controlling the process. Dark red crystals were obtained from the reaction of H_2IPr **5** with sodium *tert*-butoxide, NaI, and palladium(II) acetate to give a dimeric palladium(II) iodide NHC complex (Scheme 2).

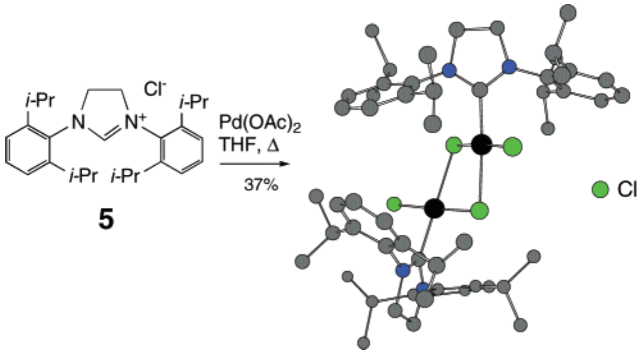
Scheme 2



The structure adopts a flat, four-membered ring μ^2-bridged arrangement with square-planar palladium where the halides are twisted out of plane relative to the heterocycle nitrogens. This planar arrangement has been observed in an X-ray structure of the aromatic NHC complex formed with IMes **6** and added base.[13] A related nickel halide dimer formed using **7** has also been reported recently.[14]

Previously, NHC−metal X-ray structures have not been obtained in the absence of added base from the *N*,*N*-bis-arylimidazolium salts **4**−**7**.[15] To establish its formation under these and comparable coupling conditions, we were pleased to find that chloride **5**, when treated with palladium(II) acetate 2:1 *without added base or halide* in THF, also produced suitable crystals for X-ray analysis (Scheme 3).[16]

Scheme 3



The orange palladium−NHC complex formed was chromatographed and obtained in 37% isolated yield based on the dimer formed. In contrast to the diiodide structure, this palladium−carbene μ^2-dimer is twisted out of plane adopting

---

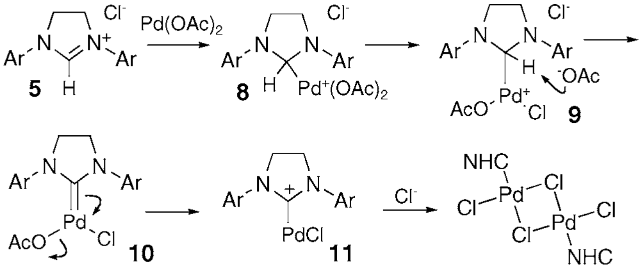
(15) X-ray structures of *N*,*N*-dimethylimidazolium·palladium NHC complexes formed without base have been reported: (a) Herrmann, W. A.; Elison, M.; Fischer, J.; Köcher, C.; Artus, G. R. J. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2371−2374. For a more recent example with a chelating bis-imidazolium NHC·Pd complex, see: (b) Clyne, D. S.; Jin, J.; Genest, E.; Gallucci, J. C.; RajanBabu, T. V. *Org. Lett.* **2000**. *2*, 1125−1128.

(16) Hydrogens are omitted for clarity. See the Supporting Information for full details.

a puckered, nonplanar, four-membered ring core where the chlorides now are not found in a plane.

To account for the formation of the NHC complex in the absence of base, an alternative mechanism is proposed (Scheme 4). Instead of a free carbene intermediate formed with strong base, palladium acetate adds directly to the imidazolium **5** (Ar = 2,6-diisopropylphenyl) C2 position to give adduct **8**. This adduct can undergo ligand exchange to give the chloropalladium acetate **9**.[17] Deprotonation by acetate at the activated C2 position then gives carbene complex **10**. Loss of acetate and transfer of the π-electrons from carbon to palladium gives **11**. Addition of chloride to palladium gives the dichloro-Pd NHC which dimerizes to give the observed structure. Oxidative insertion has also been proposed as an alternative for base-free conditions for an intermediate leading to metal–hydride NHC products with palladium(0) starting materials.[18]

Scheme 4



These conditions for active palladium carbene catalyst formation and its use in THF at room temperature for highly efficient borylation coupling should find other applications to related processes. The characterization of the palladium chloride complex unambiguously demonstrates that added base is not needed for carbene formation or catalyst turnover. An alternative mechanism for palladium–NHC formation for this case is proposed.

Acknowledgment. We are grateful for the support provided by Brigham Young University and the National Institutes of Health (GM57275). We also thank Bruce Jackson for MS analyses.

Supporting Information Available: Experimental procedures, characterization, and X-ray data. This material is available free of charge via the Internet at http://pubs.acs.org.

OL035857Q

---

[17] Triazolium ions have been shown to undergo nucleophilic addition with methoxide at the electrophilic carbon position: Enders, D.; Breuer, K.; Raabe, G.; Runsink, J.; Teles, J. H.; Melder, J. P.; Ebel, K.; Brode, S. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1021–1024.

[18] (a) McGuinness, D. S.; Cavell, K. J.; Yates, B. F.; Skelton, B. W.; White, A. H. *J. Am. Chem. Soc.* **2001**, *123*, 8317–8328. (b) Grundemann, S.; Albrecht, M.; Kovacevic, A.; Faller, J. W.; Crabtree, R. H. *J. Chem. Soc., Dalton Trans.* **2002**, 2163-2167. (c) Duin, M. A.; Clement, N. D.; Cavell, K. J.; Elsevier: C. J. *Chem. Commun.* **2003**, 400–401.