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Pincer Complex-Catalyzed Redox Coupling of Alkenes with Iodonium Salts via Presumed Palladium(IV) Intermediates

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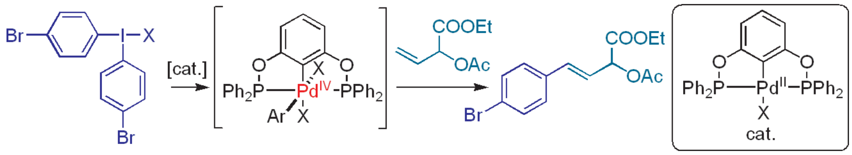
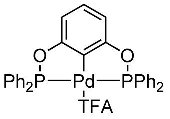
ABSTRACT

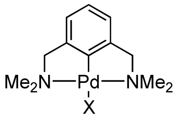


Palladium pincer complexes directly catalyze the redox coupling reactions of functionalized alkenes and iodonium salts. The catalytic process, which is suitable for mild catalytic functionalization of allylic acetates and electron-rich alkenes, probably occurs through Pd(IV) intermediates. Due to the strong metal−ligand interactions, the oxidation of phosphine and amine ligands of the pincer complexes can be avoided in the presented reactions.

Current development of catalytic procedures via palladium(IV) intermediates represents one of the most important recent innovations in transition metal catalysis.[1,2] The most attractive features[2] of this approach involve increased reactivity of the reductive elimination in Pd(IV) intermediates, increased chemoselectivity for the oxidative addition to Pd(II) catalytic precursors, and the avoidance of unstable Pd(0) intermediates.



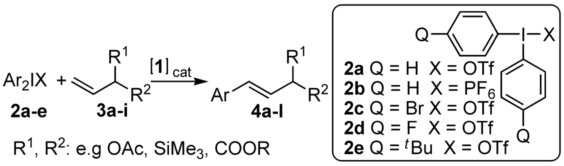
1a



1b X = OBz **1c** X = OAc

$Pd(OAc)_2$

1d



(1)

Although many excellent applications via proposed/observed Pd(IV) intermediates have been reported,[1,2] some problems have remained unresolved. Many ligand systems, such as phosphines, employed in Pd(0)/Pd(II) processes are easily oxidized under the reaction conditions used for generating Pd(IV) intermediates, for example when iodonium salts[1a,3a] are used as reagents. Besides, phosphines with π-acceptor character deactivate oxidation of Pd(II) to Pd(IV) species.

Therefore, catalytic transformations, aimed to proceed through Pd(IV) intermediates, are usually restricted to the use of simple palladium salts (such as acetates or chlorides) as catalyst sources. This generates two major problems for design of new processes via Pd(IV) intermediates: (i)

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(1) (a) Canty, A. J.; Rodemann, T.; Ryan, J. H. *Advances in Organometallic Chemistry*; Elsevier: New York, 2008; *Vol. 55*, p 279. (b) Canty, A. J. *Acc. Chem. Res.* **1992**, *25*, 83. (c) Deprez, N. R.; Sanford, M. S. *Inorg. Chem.* **2007**, *46*, 1924.

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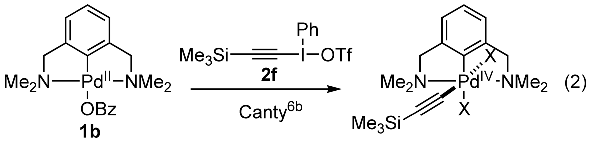
application of chiral ligands with phosphines (or other easily oxidizable species with high lying lone-pair orbitals), which may dissociate from palladium under the catalytic process, is strongly limited; and (ii) immobilization of palladium catalysts requiring firm multidentate ligation is encumbered by the easy oxidation of the applied ligand. To solve these issues in Pd(II)/Pd(IV) chemistry, the application of pincer complex (such as **1a−c**, eq 1) catalysts[4] offers a highly attractive approach. Although similar ideas emerged over a decade ago,[4a,b,5a−c] there has been an intensive debate on the possibilities of generating Pd(IV) intermediates, when pincer complexes are employed as direct catalysts. Several studies[5a−c] indicate that aryl iodides are probably not sufficiently reactive to maintain a Pd(II)/Pd(IV) catalytic cycle based on pincer complexes.

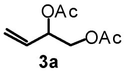
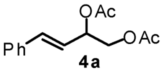
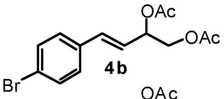
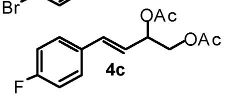
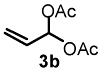
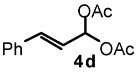
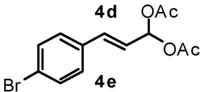
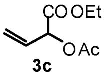
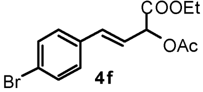
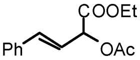
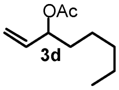
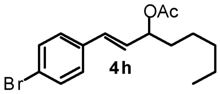
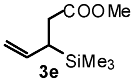
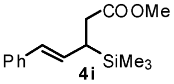
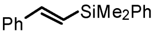
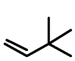
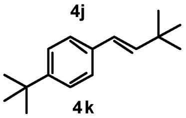
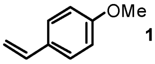
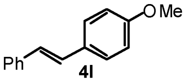
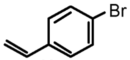
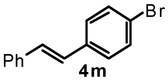
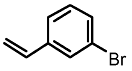
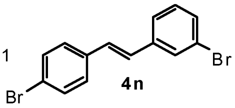
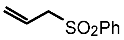
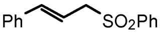


(2)

Interestingly, however, van Koten[6a] and Canty[6b] have shown that NCN complexes, such as **1b**, undergo stoichiometric oxidative addition with iodonium salts[3] affording Pd(IV) pincer complexes (eq 2). We have now found that palladium pincer complexes **1a**,**b** can be employed as highly active catalysts in Heck-type redox[7] reactions of easily available[3b] aryl-iodonium salts **2a−e** with functionalized alkenes (**3a−k**) in the presence of $NaHCO_3$ in THF/CH_3CN (eq 1, Table 1).

The ^{31}P NMR spectrum of the crude reaction mixture (see Supporting Information) indicated that the pincer structure of **1a** remained intact after full conversion of the substrates. A further confirmation that the pincer complex is the direct catalyst of the reaction[5a−c] arises from the negative mercury-drop test.[5d] When the reaction (entry 1) was conducted in the presence of 150 equiv (per Pd) of elemental Hg, catalyst poisoning was not observed, and the isolated yield was identical to the yield of the corresponding process conducted

Table 1. Pd-Catalyzed Coupling of Alkenes with Iodonium Salts[a]

entry	substrate	cat.	Ar_2IX	solv.[b]	t[h]	product	yield[%][c]
1	 **3a**	**1a**	**2a**	A	14	 **4a**	94/93[d]
2	**3a**	**1a**	**2b**	A	14	**4a**	94
3	**3a**	**1d**	**2b**	B	20	**4a**	98/90[d]
4	**3a**	**1a**	**2c**	B	21	 **4b**	91
5	**3a**	**1a**	**2d**	A	16	 **4c**	99
6	 **3b**	**1a**	**2a**	B	20	 **4d**	91
7	**3b**	**1d**	**2a**	B	22	**4d**	99
8	**3b**	**1a**	**2c**	B	14	 **4e**	89
9	 **3c**	**1a**	**2c**	B	21	 **4f**	83
10	**3c**	**1a**	**2b**	B	19	 **4g**	92
11	**3c**	**1d**	**2b**	B	22	**4g**	92
12	 **3d**	**1a**	**2c**	B	21	 **4h**	90
13[e]	 **3e**	**1a**	**2b**	A	19	 **4i**	82
14	 **3f**	**1b**	**2a**	A	14	 **4j**	89
15	 **3g**	**1a**	**2e**	A	14	 **4k**	74
16	 **3h**	**1b**	**2a**	A	16	 **4l**	89
17	 **3i**	**1a**	**2a**	A	18	 **4m**	99
18	**3i**	**1b**	**2a**	A	17	**4m**	95
19	 **3j**	**1a**	**2c**	B	21	 **4n**	89
20	**3j**	**1d**	**2c**	B	15	**4n**	98
21[f]	 **3k**	**1a**	**2b**	B	22	 **4o**	77
22	**3k**	**1d**	**2b**	B	22	**4o**	99

[a] Unless otherwise stated, **3** (0.3 mmol), **2** (0.2 mmol), $NaHCO_3$ (0.2 mmol), and catalyst **1a**,**b**,**d** (5 mol %) were dissolved in THF (A) or CH_3CN (B) (0.3 mL) and stirred at 50 °C. [b] Solvent. [c] Isolated yield. [d] Isolated yield in the presence of 150 equiv of Hg. [e] 0.4 mmol of **3e** was used. [f] Performed at 65 °C.

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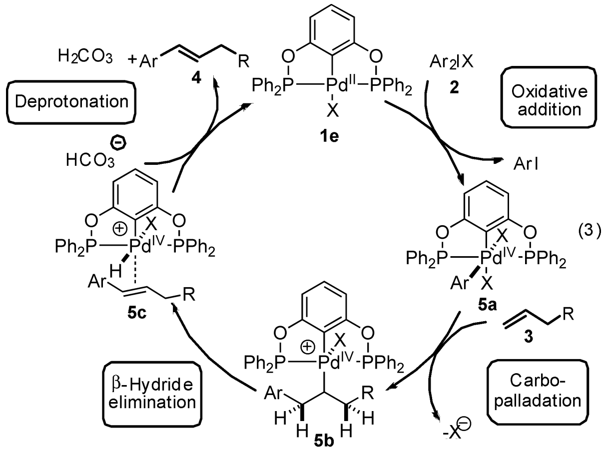
without Hg (entry 1). Mercury itself did not show any catalytic effect in the process. It is well established[5a−c] that addition of Hg instantly terminates Heck reactions, when PCP complexes (such as **1a**) are not the *direct* catalysts but *dispensers* of active Pd(0) species.

To demonstrate the synthetic potential of the Pd(II)/Pd(IV)-based transformation, we concentrated on the preparation of functionalized allylic acetates (**4a−h**) and aryl bromides. These functionalities (allylic acetate and/or aryl bromide) would easily undergo oxidative addition in a Pd(0)-catalyzed transformation but remained unchanged in the presented process. Unlike in standard[7] Pd(0)-catalyzed Heck reactions, alkenes with bulky electron-supplying groups (**3e−h**) react readily and with high yields (entries 13−16). Furthermore, diarylated byproducts were not detected.

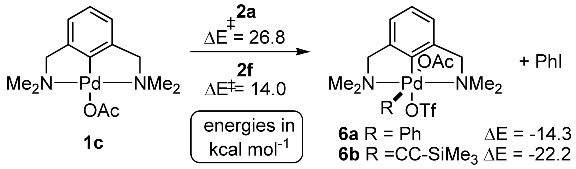
It was found that Pd(OAc)$_2$ **1d** also catalyzed the presented coupling reactions (entries 3, 7, 11, 20, and 22). Interestingly, the mercury-drop test[5d] with **1d** was also negative (entry 3), indicating that Pd(0) particles do not have a catalytic effect in the process. This suggests that the mechanism of the pincer complex and Pd(OAc)$_2$-catalyzed reactions is similar, i.e., does not involve formation of catalytically active Pd(0) species. As Pd(OAc)$_2$ readily catalyzed the coupling reactions of all types of substrates, such as allylic acetates (entries 3, 7, and 11), styrenes (entry 20), and even allyl sulfonate **3k** (entry 22), it can be regarded as an efficient, inexpensive catalyst for synthesis of functionalized allylic compounds and stilbene derivatives. However, application of pincer complexes has some important potential advantages. The trivalent phosphorus atom in **1a** remained unchanged under the coupling reaction due to the tight Pd−P coordination. However, when PPh$_3$ was added to the reaction catalyzed by Pd(OAc)$_2$ (entry 3) a complete oxidation of the phosphorus atom occurred. Furthermore, the above reactions performed by pincer complexes give important mechanistic insights as well. Pincer complexes are known[5a−c] to decompose, when the metal atom is reduced to Pd(0), while Pd(OAc)$_2$ would be fully regenerated after reduction of possibly occurring Pd(0) intermediates. Accordingly, our findings that decomposition of the pincer complex catalysts was *not* observed together with the negative Hg-poisoning tests (entries 1 and 3) show that Pd(0) species are unlikely to occur as catalytic intermediates indicating that the reactions with **1a−d** involve a Pd(II)/Pd(IV) redox cycle.

Thus, the catalytic cycle (eq 3) of the PCP complex catalyzed process is proposed to start with oxidative addition of **2** to catalyst **1e** affording Pd(IV) complex **5a**. The next step (**5a** → **5b**) is carbo-palladation followed by β-hydride elimination affording complex **5c**, which subsequently undergoes deprotonation by NaHCO$_3$ regenerating catalyst **1e**. The hydride probably enters *trans* to the X$^-$ ligand of **5b**, instead of *trans* to the Pd−C(aryl) bond, as the latter is destabilized by the *trans* influence of the hydride.



(3)

Our attempts to observe aryl−Pd(IV) complexes **5a** or **6a** remained fruitless. Preliminary DFT modeling studies show (eq 4) that oxidative addition of **1c** (OAc analogue of OBz complex **1b**) proceeds through a considerably higher (by 13 kcal/mol) activation barrier to iodonium salt **2a** than to **2f**[6b] (eq 2), while both reactions are highly exothermic. The relatively high barrier, requiring elevated reaction temperature, encumbers[6b] the observation of aryl−Pd(IV) complexes (e.g., **5a**, **6a**). Unfortunately, iodonium salt **2f** decomposed under the applied catalytic conditions, and therefore it could not be used as a substrate.



(4)

In summary, we have presented the first palladium pincer complex catalyzed redox reaction, in which the integrity of the complex is fully retained and the catalyst resists the Hg-poisoning test. This process is suitable for mild arylation of allylic acetates[7e] and electron-rich alkenes using easily available[3b] iodonium salts. The presented method opens new routes for application of PCP pincer complexes[8] and other palladacycles[4] as efficient catalysts in redox transformations. The main impact is expected for employment of Pd(II)/Pd(IV)-based redox systems in asymmetric catalysis[8c] and in immobilized/recyclable[4a−c] Pd catalysts.

Acknowledgment. This work was mainly supported by the Swedish Research Council (VR). Support from the Magn. Bergvalls Stiftelse is also acknowledged.

Supporting Information Available: Experimental procedures and spectroscopic data are provided. This material is available free of charge via the Internet at http://pubs.acs.org.

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