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Authors

Su, Bo

Bunescu, Ala

Qiu, Yehao

et al.

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Palladium-catalyzed oxidation of β -C(sp³)-H bond of primary alkylamines through a rare four-membered palladacycle intermediate

Bo Sua^a, Yehao Qiu^a, Ala Bunescu^a, Stephan J. Zuend^b, Martin Ernst^c, and John F. Hartwig^{a*}

a. Department of Chemistry, University of California, Berkeley, Berkeley, California 94720, United States

b. BASF Corp., 46820 Fremont Boulevard, Fremont, California 94538, United States

c. BASF SE, Carl-Bosch-Straße 38, 67056 Ludwigshafen, Germany

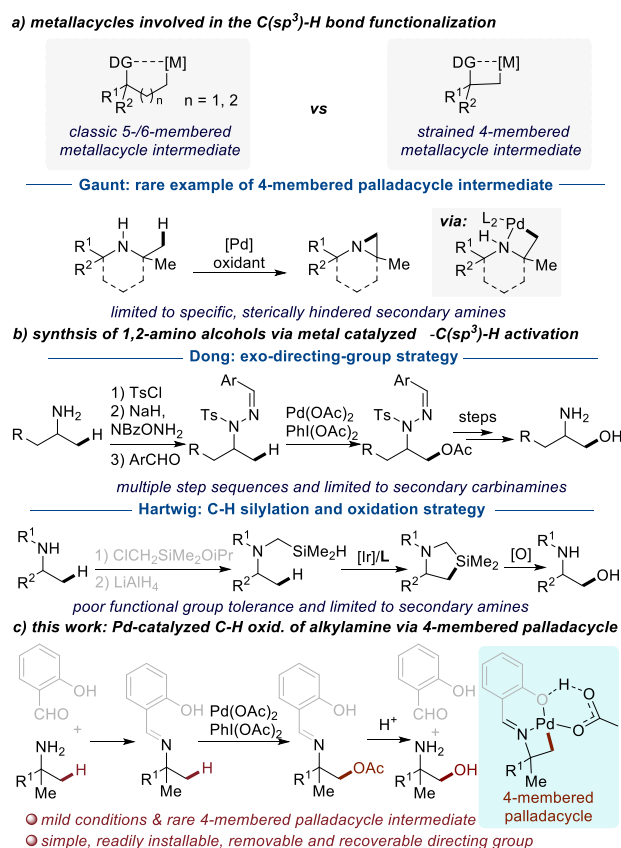
ABSTRACT: Site-selective functionalizations of C-H bonds are often achieved with a directing group that leads to five- or six-membered metallacyclic intermediates. Analogous reactions that occur through four-membered metallacycles are rare. We report a challenging palladium-catalyzed oxidation of primary C-H bonds β to nitrogen in an imine of an aliphatic amine, a process that occurs through a four-membered palladacycle intermediate. The success of the reaction relies on the identification, by a study on H/D exchange, of a simple directing group (salicylaldehyde) capable of inducing the formation of this small ring. To gain insight into the mechanism of this unusual oxidation reaction, a series of mechanistic experiments and DFT calculations were conducted. The experimental studies showed that cleavage of the C-H bond is rate-limiting, and formation of the strained four-membered palladacycle is thermodynamically uphill. DFT calculations corroborated these conclusions and suggested that the presence of an intramolecular hydrogen bond between the oxygen of the directing group and hydroxyl group of the ligating acetic acid that is crucial for stabilization of the palladacyclic intermediate.

Introduction

Aliphatic amines are important organic compounds that are widely found in natural products, pharmaceuticals, and agrochemicals.¹ Therefore, the development of synthetic methods that enable efficient synthesis or functionalization of aliphatic amines has been a longstanding goal.² The functionalization of C(sp³)-H bond in alkylamines³ and their derivatives^{4,3h,5} by transition-metal complexes has been pursued because it can transform ubiquitous inert C(sp³)-H bonds of these molecules to valuable functional groups that are usually inaccessible or difficult to be introduced by traditional methods.

Cyclometallation is a crucial step in the functionalization of C-H bonds at specific sites by transition-metal catalysts.⁶ A wide range of directing groups have been developed to promote cyclometallation to form stable five- or six-membered metallacyclic intermediates (Figure 1a, top left). Such cyclometallation with alkylamines and their derivatives have led to the functionalization at C-H bonds γ - or δ - to the nitrogen atom.^{6c} In contrast, reactions that occur by C-H bond activation to form four-membered metallacycles are rare because formation of a strained-ring intermediate is kinetically and thermodynamically less favorable (Figure 1a, top right). Thus, functionalization of an alkylamine derivative at the C-H bond β to nitrogen is challenging,^{3a,3c-g,7,5l,8} and corresponding four-membered metallacycles are only known in specific cases.^{3a,3c} For example, Gaunt and coworkers reported a seminal palladium-catalyzed, β -C(sp³)-H activation of alkylamines directed by the amine nitrogen to form strained aziridine derivatives; however, the amines were limited to sterically hindered, secondary amines (Figure 1a, bottom).^{3a}

Scheme 1. Transition metal-catalyzed C-H functionalization of aliphatic amines

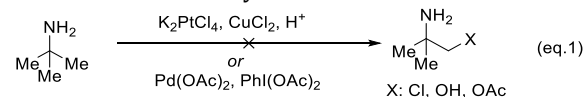


To achieve the functionalization of β -C(sp³)-H bonds in alkylamine derivatives, other more circuitous pathways have been developed, but none of these involve four-membered metallacyclic intermediates.^{51,8-9} For example, Dong and coworkers reported a palladium-catalyzed acetoxylation of β -C(sp³)-H bond of alkylamines to form 1,2-amino alcohol derivatives by converting the alkylamines to hydrazone derivatives, but this method is limited to secondary carbinamines, requires multiple steps to install the directing group on the nitrogen of the amine and requires additional steps to unveil the desired 1,2-amino alcohol products (Figure 1b).⁵¹ Our group recently developed an iridium-catalyzed intramolecular silylation of the β -C(sp³)-H bonds of secondary amines.⁸ In combination with oxidation of the C-Si bond, this reaction creates an alternative approach to form 1,2-amino alcohols, but preparation of the hydrosilane was required and the functional group tolerance of the synthesis of this silane with LiAlH₄ would limit application of this process. Thus, functionalizations that occur through four-membered metallacycles and direct oxidations of the β -C(sp³)-H bonds of alkylamine derivatives are needed.

Here, we report an imine-directed acetoxylation of the β -C(sp³)-H bonds of tertiary carbinamines under mild, neutral reaction conditions by the formation of a four-membered palladacyclic intermediate (Scheme 1c). The appropriate imine (from salicylaldehyde)^{5b,5g} was revealed by initial studies on H/D exchange, and this directing group is inexpensive, readily installed, removed and recovered. Mechanistic studies show C-H bond cleavage is rate-limiting, and formation of the strained four-membered palladacycle is thermodynamically uphill.

Results and Discussion

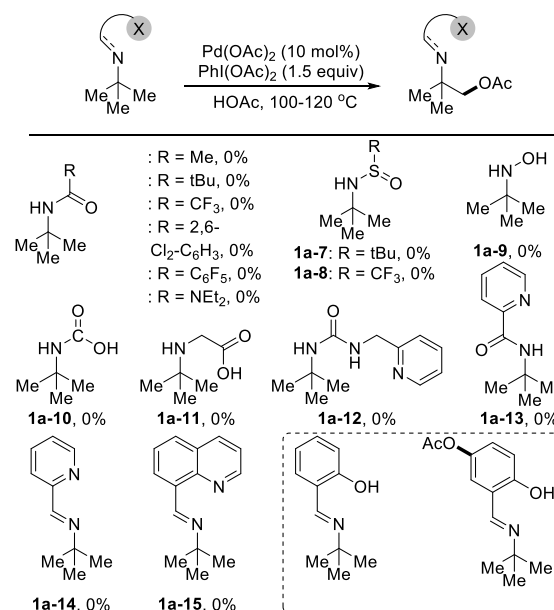
1. Preliminary studies on the undirected C-H oxidation of *tert*-butyl amine. *tert*-Butyl amine, the simplest tertiary carbinamine, was selected as the model substrate to investigate the β -C(sp³)-H oxidation of primary alkylamines because of the utility of the corresponding oxidation product, 2-amino-2-methylpropanol (AMP).¹⁰ Preliminary investigations focused on reported conditions for platinum- and palladium-catalyzed C(sp³)-H oxidation of free amines,^{11, 12} but no product derived from C-H bond functionalization was observed (eq. 1). The lack of reactivity of *tert*-butyl amine in the presence of the platinum catalyst in acid could be explained by the combination of steric hindrance and electron-poor property of the C-H bond of the protonated amine.¹¹ The lack of reactivity in the presence of the palladium catalyst under more neutral conditions can be attributed to coordination of *tert*-butyl amine, leading to deactivation of the catalyst.⁷



2. Identification of a suitable directing group. Further studies involving directing groups^{6c} on nitrogen led to functionalization of the β -C-H bond, but the reactions required substantial investigation. A series of auxiliary groups were installed on the nitrogen of *tert*-butyl amine to form the corresponding amine derivatives **1a-1** to **1a-16** (Table 1). Under commonly employed conditions for the acetoxylation of C(sp³)-H bonds (10 mol% Pd(OAc)₂, 1.2 equiv of PhI(OAc)₂,

in AcOH at 100-120 °C),^{4b,4c,13} none of the reactions of **1a-1** to **1a-15** gave any detectable product from acetoxylation; the reaction with **1a-16** gave the product from acetoxylation at the C(sp²)-H bond para to the hydroxyl group of the imine to form **2a-16** in 82% yield without evidence for reaction at the C(sp³)-H bond.

Table 1. Pd-catalyzed C-H acetoxylation of amine derivatives



We considered two possible origins of the lack of reactivity of amine derivatives **1a-1** to **1a-15** and lack of reactivity of **1a-16** at the alkyl C-H bond based on the typical mechanism for palladium-catalyzed directed C-H oxidation (Figure 1).^{5g} First, cleavage of the C(sp³)-H bond might not occur because the barrier to formation of a four-membered palladacycle **B** is too high. Second, C(sp³)-H cleavage could occur, but the transition state energy for subsequent oxidation of the Pd(II) intermediate **B** to the Pd(IV) intermediate **C** is too high, either because oxidation of the palladacycle is slow or formation of the palladacycle **C** is endothermic.

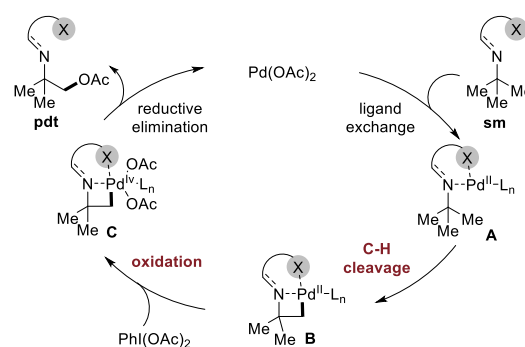


Figure 1. Proposed catalytic cycle for the β -C-H functionalization

To distinguish between these possibilities, a set of H/D-exchange experiments was conducted (Scheme 2). The combination of *tert*-butyl amine derivatives **1a-1** to **1a-16**, Pd(OAc)₂ (10 mol%), and AcOD (2.0 equiv) were heated in CHCl₃ at 80 °C for 12 h. No detectable incorporation of deuterium into **1a-1** to **1a-15** was observed by ²H NMR spectroscopy, showing that cleavage of the C-H bond in

these substrates does not occur. In contrast, H/D exchange with **1a-16** occurred at the C(sp³)-H bonds; 9.3% of the hydrogen atoms in the *tert*-butyl group of **1a-16** were deuteriated, indicating that the C(sp³)-H bond activation occurred with the imine derived from salicaldehyde. These data indicate that cleavage of the C(sp³)-H bond in **1a-16** occurs under more neutral conditions without activation of the aryl C-H bond that underwent oxidation in neat acetic acid.

Scheme 2. H/D exchange experiments

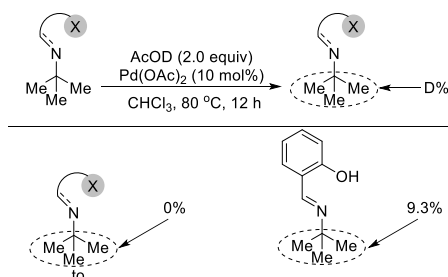


Table 2. Evaluation of the conditions for the acetoxylation of compound 1a

entry	additive	solvent	2a %	mono:di
1	NaOAc (1.5 equiv)	CHCl ₃	48%	2.2:1
2	NaOAc (1.5 equiv)	<i>m</i> -xylene	34%	8:1
3	NaOAc (1.5 equiv)	benzene	51%	4:1
4	NaOAc (1.5 equiv)	toluene	34%	10:1
5	NaOAc (1.5 equiv)	THF	7%	>20:1
6	NaOAc (1.5 equiv)	dioxane	14%	>20:1
7	NaOAc (1.5 equiv)	EA	28%	8:1
8	NaOAc (1.5 equiv)	MeCN	25%	7:1
9	NaOAc (1.5 equiv)	DMF	4%	>20:1
10	NaOAc (1.5 equiv)	DMPU	0%	---
11	Na ₂ HPO ₄ (1.5 equiv)	benzene	48%	3.8:1
12	KH ₂ PO ₄ (1.5 equiv)	benzene	49%	4:1
13	PhSO ₃ Na (1.5 equiv)	benzene	51%	4:1
14	---	benzene	48%	4:1
15	N-Boc-Ala (10 mol%)	benzene	58%	4:1

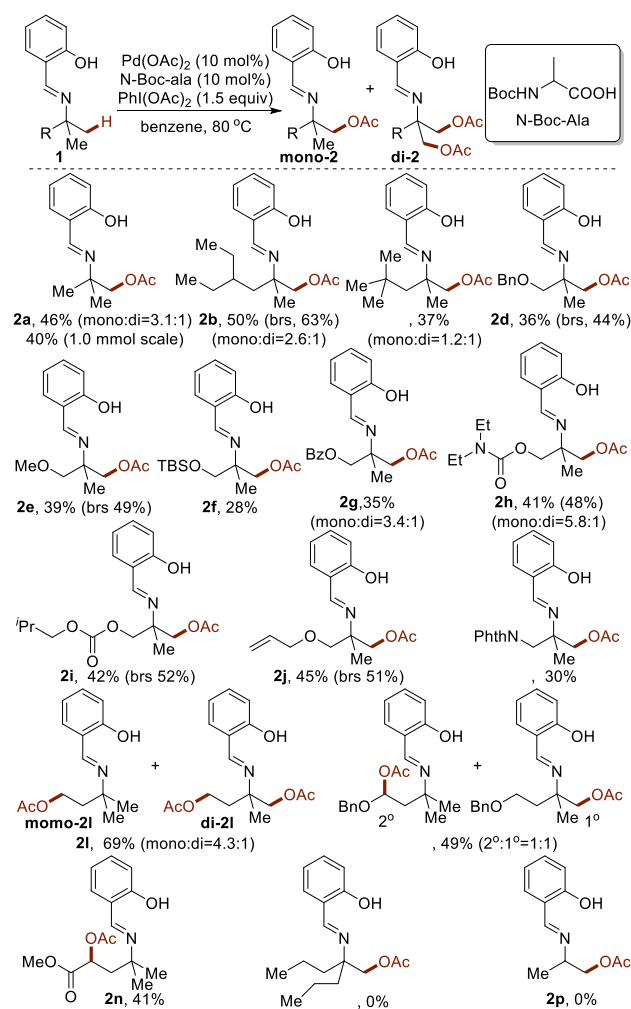
Conditions: reaction was conducted with **1a** (0.1 mmol), and the yields and ratio of **mono-2a** vs **di-2a** were determined by GC with dodacane as the internal standard

3. Development of the β-C(sp³)-H bond acetoxylation.

Having shown that the C(sp³)-H bond of the salicaldimine **1a-16** (hereafter abbreviated as **1a**) undergoes cleavage, we considered that solvent and acidity could influence the selectivity for functionalization of the sp² versus sp³ C-H bonds (compare results in Table 1 and Scheme 2) and enable oxidation of the Pd-C bond of palladacycle **B**. Indeed, in the absence of acetic acid in nonpolar solvents, the product from acetoxylation of the C(sp³)-H bond was obtained (Table 2). Among the reactions conducted in nonpolar solvents, the reaction in benzene gave a 4:1 mixture of acetoxylation products **mono-2a** and **di-2a** in a combined

51% yield (entry 3). Reactions conducted with a series of added bases showed that weak bases had little effect on the yield (entries 3, 11-14). Reactions with some of the ligands¹⁴ currently used for palladium-catalyzed oxidation showed that the reaction with *N*-(*tert*-butoxycarbonyl)-L-alanine (*N*-Boc-Ala) occurred in a slightly higher 58% yield than that without ligand (51%) (entry 15, see supporting information for more details).

Table 3. Scope of the β-acetoxylation of amine derivatives.

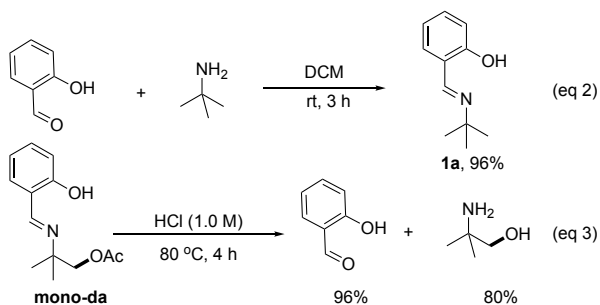


4. Scope of the β-C(sp³)-H bond acetoxylation.

The scope of the acetoxylation of amines under the developed conditions via imine **1a** is shown in Table 3. Reactions of imines from tertiary carbinamines containing a range of substitution patterns and functional groups on the amine afforded products from acetoxylation of the β-C(sp³)-H bonds in moderate yields. For example, acetoxylation of the β-C(sp³)-H bond of imines **1a-1c** bearing a series of alkyl substituents afforded the corresponding products (**2a-2c**). The ratio of mono-acetoxylation product to di-acetoxylation product was higher for the examples containing a smaller alkyl substituent. The acetoxylation also occurred in the presence of a variety of functional groups (**1d-1k**), including benzyl and alkyl ethers (**1d** and **1e**), a silyl ether (**1f**), an ester (**1g**), a carbamate (**1h**), a carbonate (**1i**), an alkene (**1j**), and an amide (**1k**). The yield from acetoxylation on a larger scale was similar to that on smaller scale (Table 3, substrate **1a**).

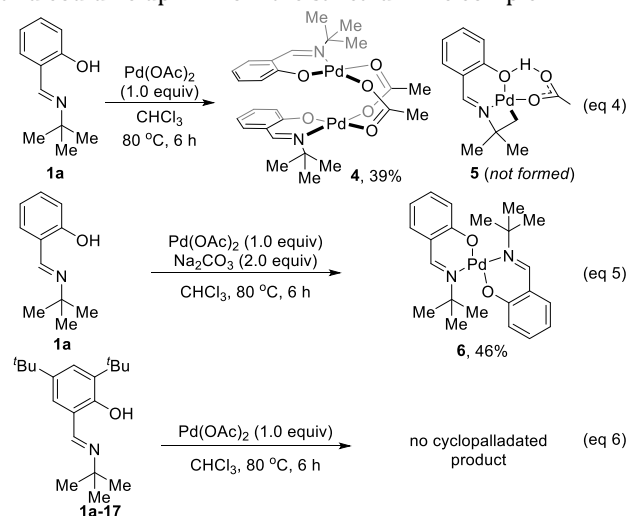
The regioselectivity and yield for the acetoxylation depended on the architecture of the alkyl group. Acetoxylation of **1l**, which contains both γ - and β -methyl C-H bonds, occurred predominantly at the γ -methyl C-H bonds through a more favorable five-membered palladacycle intermediate. The site of acetoxylation of **1m** and **1n**, which contain both secondary γ -C(sp³)-H bonds and unactivated primary β -C(sp³)-H bonds, depended on the nature of the substituents on the secondary carbon. Reaction of **1m** containing a benzyloxy substituent at the γ methylene position gave a 1:1 mixture of products from reaction at the primary β -C(sp³)-H bond and secondary γ -C(sp³)-H bond, while reaction with substrate **1n** containing an alkoxy carbonyl group at the γ methylene position gave the product from acetoxylation at the acidic secondary γ -C(sp³)-H bond exclusively.¹⁵ Imine **1o** containing a single β methyl group and imine **1p** derived from a secondary, rather than tertiary, carbinamine did not react.

5. Installation, removal and recovery of the directing group. Installation and removal of the directing group are efficient and operationally simple, and the directing group is recoverable. The imine **1a** was obtained almost quantitatively (96%) by condensation of *tert*-butyl amine with salicylaldehyde in DCM at room temperature (eq 2). To demonstrate the ability to remove and recover the directing group, **mono-2a** was subjected to a 1.0 M aqueous solution of HCl at 80 °C (eq 3). The salicylaldehyde was removed and recovered in 96% yield, based on the amount of **mono-2a**. After basification of the aqueous solution, followed by extraction by organic solvent (DCM), the free amino alcohol was obtained in 80% yield.



6. Mechanistic investigation. To determine whether cleavage of the C-H bond or oxidation of the Pd-C bond is rate-limiting and to gain insight into the thermodynamics for formation of the four-membered palladacycle, we conducted synthetic organometallic studies of cyclopalladated species. Reaction of imine **1a** with 1.0 equiv of Pd(OAc)₂ at 80 °C formed a dinuclear bis- μ -acetatopalladium complex **4** in 39% yield. No cyclopalladated complex **5** formed (eq 4). The same reaction in the presence of base (eg. Na₂CO₃) to promote the C-H bond cleavage formed the palladium complex **6** containing two deprotonated salicaldimines, but, again, no cyclopalladated species formed (eq 5). Stoichiometric reactions were also conducted with **1a-17** that contains a bulky *tert*-butyl substituent at the ortho position of the hydroxyl group on the aryl group, but the cyclopalladated species was again absent (entry 6). To potentially stabilize the four-membered palladium intermediate, external ligands, such as triphenyl phosphine and pyridine, were added to the reaction of **1a** with Pd(OAc)₂, but no palladacycle formed from cleavage of the C(sp³)-H bond. Consistent with these synthetic studies, no palladacyclic intermediate

was observed during the catalytic reactions (eq 4-6), as judged by analysis of the crude reaction mixture by ¹H NMR spectroscopy. This set of mechanistic suggest that the formation of the four-membered palladacycle is unfavorable and could lie uphill from the salicaldimine complex **4**.



To test if a salicaldimine-ligated palladium is capable of forming a metallacycle by cleavage of a C(sp³)-H bond, we allowed Pd(OAc)₂ to react with substrate **1l** that could form a five-membered palladacycle under the same conditions as the reaction with **1a**. Indeed, the five-membered palladium complex **5'** formed in quantitative yield, as determined by ¹H NMR spectroscopy (eq 7). Although complex **5'** is stable in solution, it decomposed during attempts to purify by various methods. Thus, an external ligand (3,5-bis(trifluoromethyl)phenyl)phosphine was added to the crude reaction mixture of **5'** to form a more stable complex **7**, which was isolated by silica gel column chromatography in 86% yield. The structures of palladium complexes **4**, **6**, and **7** were confirmed by X-ray crystallography (Figure 2).

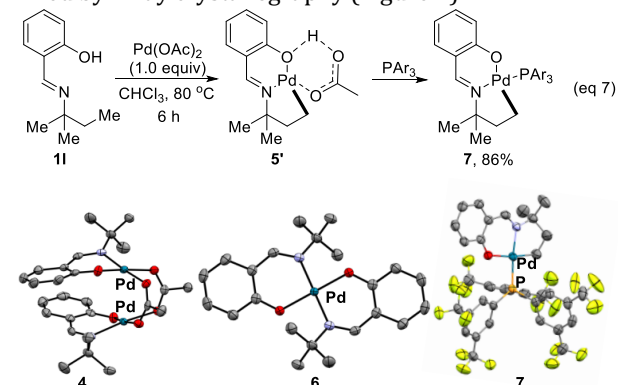
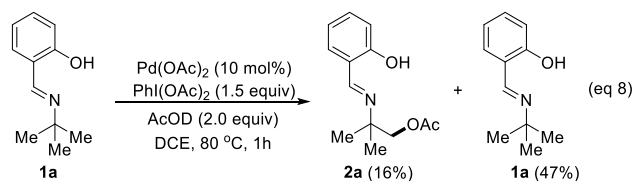


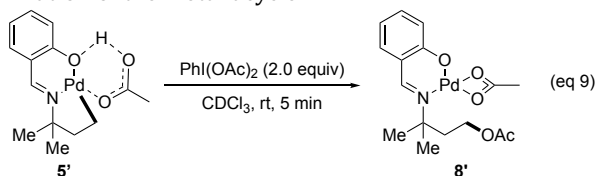
Figure 2. Solid-state structures of 4, 5, and 7 determined by single crystal X-ray diffractions.

To probe whether the β -C(sp³)-H bond was cleaved reversibly under the conditions of the acetoxylation, we ran the catalytic reaction of **1a** in the presence of 2.0 equiv of AcOD and 1.5 equiv of PhI(OAc)₂ to partial conversion. After 1 h at 80 °C (eq 8), ¹H NMR analysis of the crude reaction mixture showed that 47% of the starting material **1a** remained (16% of the acetoxylation product **2a** formed), and no deuterium had been incorporated into the unreacted **1a**, as determined by ²H NMR spectroscopy. These data indicate

that the C-H cleavage is irreversible and, therefore, that oxidation of the metallacyclic intermediate is more rapid than reversion to the acyclic precursor.



To gauge the rate of the oxidation of a palladacycle derived from the salicyldimines, we studied the oxidation of the five-membered metallacycle **5'** generated in solution (eq 9). The reaction of **5'** with 2 equiv of PhI(OAc)₂ occurred to completion at room temperature in less than 5 min to form the C acetoxyated complex in 46-50% yield. These data are consistent with rapid oxidation of the four-membered palladacycle at 80 °C that is required for irreversible formation of the metallacycle.



7. DFT calculations of the catalytic acetoxylation. To gain insight into the thermodynamics for formation of a four-membered metallacycle, we performed DFT calculations on the catalytic acetoxylation process. These data are summarized in Figure 3. We determined the barrier and thermodynamics for cleavage of the β C-H bond of the bound salicyldimine by a concerted metallation deprotonation process involving the coordinated acetate in the monomeric complexes **9** and **9'** derived from the isolated dimeric complexes **4** and **4'**. Quasi-harmonic Gibbs free energies were calculated of the observed dimeric salicyldimine palladium complexes **4** and **4'**, the monomeric **9** and **9'** that would undergo C-H bond cleavage, the transition states for C-H activation by **9** and **9'** (**TS(9-10)** and **TS(9'-10')**) to form palladacycles **10** and **10'** containing a bound acetic acid, and palladacycles **5** and **5'**, which are isomers of **10** and **10'**, in which the carboxylic acid is engaged in an intramolecular hydrogen bond. These calculations showed that formation of the four-membered metallacycle is endergonic, but formation of the five-membered metallacycle is exergonic.

The free energy barriers for C-H activation within complexes **9** and **9'** to form the four-membered and five-membered palladacycles **10** and **10'** are 22.5 and 17.9 kcal/mol, respectively. The computed thermodynamics for the formation of the metallacycle depended strongly on the presence or absence of an intramolecular hydrogen bond involving the coordinated acetic acid. The computed energy of the four-membered palladacycle **5** containing the hydrogen bond is lower in energy than palladacycle **10** lacking the hydrogen bond by 13.8 kcal/mol. The computed difference in energy between the analogous structures **5'**

and **10'** containing the hydrogen bond is 14.2 kcal/mol. Thus, the formation of the four-membered palladacycle **5** is computed to be thermodynamically uphill of monomeric salicyldimine complex **9** by 1.3 kcal/mol and uphill of the isolated dimeric analog **4** by 10.6 kcal/mol, whereas formation of the five-membered palladacycle **5'** is computed to be downhill of monomeric **9'** by -8.8 kcal/mol and nearly thermoneutral with the dimeric complex **4'**. These results corroborate our experimental observation of the formation of five-membered palladacycle **5'** from **4'**, but detection of the formation of the four-membered palladacycle **5** only indirectly by H/D exchange.

DFT calculations on the remainder of the reaction pathway is included in Figure 3. Oxidation of both palladacycles **5** and **5'** by PhI(OAc)₂ was computed to be thermodynamically downhill by ~20 kcal/mol. The resulting Pd(IV) intermediates **11** and **11'** are computed to undergo nearly thermoneutral dissociation of HOAc to form complexes **12** and **12'**, which subsequently undergo reductive elimination to form acetoxyated products **8** and **8'** in which the functionalized salicyldimine remains bound to palladium. The free energy barriers for reductive elimination from intermediates **12** and **12'** were calculated to be 12.2 and 15.4 kcal/mol, respectively. A comparison of these barriers to the 22.5 and 17.9 kcal/mol barriers for C-H bond cleavage imply that C-H activation is irreversible and turnover-limiting for the catalytic acetoxylation process. This conclusion is consistent with the lack of incorporation of deuterium into the reactant under the conditions of the catalytic process.

Conclusion

In summary, we developed a palladium-catalyzed, directed β -C(sp³)-H acetoxylation of tertiary carbinamines, which likely proceeds through a rare four-membered palladacycle intermediate. Identification of the appropriate group on the nitrogen of the amine to enable C-H activation resulted from studies on the H/D exchange. The directing group is inexpensive, readily installed, removed, and recovered. Mechanistic studies revealed that the C(sp³)-H bond is cleaved irreversibly and is the rate-determining step of the reaction. DFT calculations were consistent with experimental results in which the four-membered palladacycle was not observed during the reaction but five-membered palladacycles formed readily. The DFT studies suggest that formation of the four-membered palladacycle is thermodynamically uphill, but the formation of the corresponding five-membered palladacycle is downhill. The combination of a directing group on nitrogen to facilitate formation of a four-membered metallacycle and oxidant that reacts rapidly with the unstable metallacycle enables this functionalization of the C-H bond of an amine to occur, and these principles should facilitate the discovery of additional reactions through such strained intermediates.

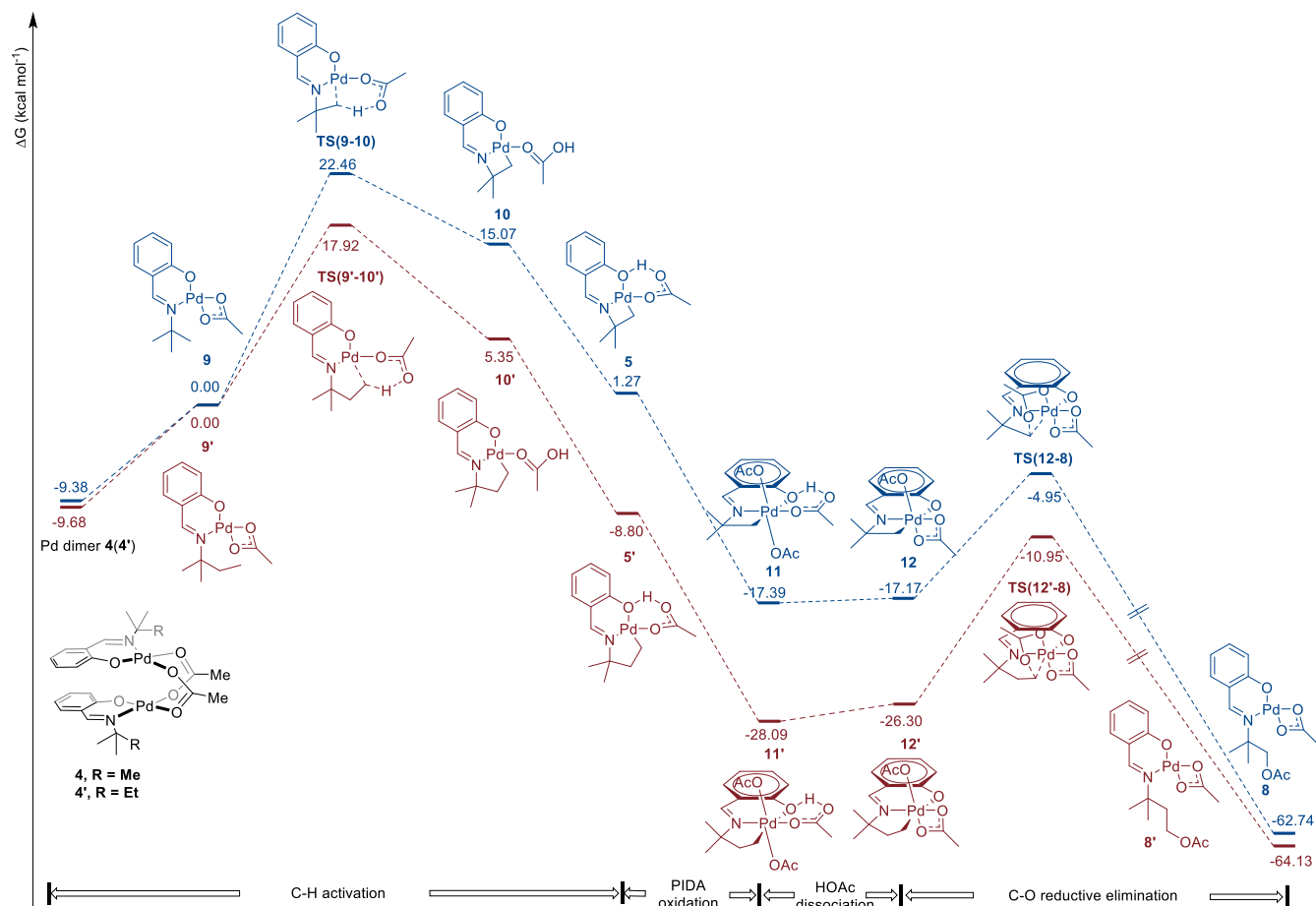


Figure 3. Quasi-harmonic Gibbs free energy ($T = 353.15$ K) profile of Pd-catalyzed α -acetoxylation of primary amines. Calculations were performed at the B3LYP-d3/LANL2DZ + 6-31G(d)/SMD(benzene)//M06-d3/SDD + 6-311+G(d,p)/SMD(benzene) level of theory.

ASSOCIATED CONTENT

Supporting Information.

"The supporting information is available free of charge via the Internet at <http://pubs.acs.org>."

Experimental procedures, characterization of new compounds, X-ray data, and computational details (PDF)

X-ray crystallographic data for compounds **4** (CIF)

X-ray crystallographic data for compounds **6** (CIF)

X-ray crystallographic data for compounds **7** (CIF)

AUTHOR INFORMATION

Corresponding Author

*jhartwig@berkeley.edu

ORCID

Bo Su: 0000-0002-1184-0828

Ala Bunescu: 0000-0002-3880-8182

John F. Hartwig: 0000-0002-4157-468X.

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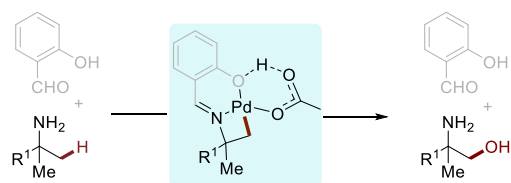
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