

# Roles of Ligand and Oxidant in the Pd(II)-Catalyzed and Ligand-enabled C(sp<sup>3</sup>)-H Lactonization in Aliphatic Carboxylic Acid: The Mechanistic Studies

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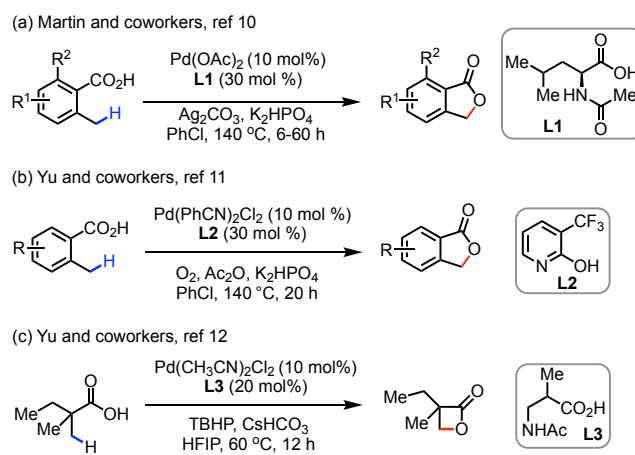
**ABSTRACT:** The mechanism of the Pd(II)-catalyzed, mono-*N*-protected amino acid (MPAA) ligand and TBHP oxidant mediated lactonization of  $\beta$ -C(sp<sup>3</sup>)-H bond in aliphatic carboxylic acid has been studied. We have shown that the combination of the TBHP oxidant and MPAA ligand is very critical: the reaction proceeds via the MPAA ligand mediated Pd(II)/Pd(IV) oxidation by TBHP and following C-O reductive elimination from the Pd(IV) intermediate. While the Pd(II)/Pd(IV) oxidation is a rate-limiting step, the C-H bond activation is the regioselectivity controlling step. MPAA ligand acts as not only auxiliary ligand to stabilize the catalytic active species, but also as a proton acceptor in the C-H bond deprotonation, and as a proton donor during the Pd(II)/Pd(IV) oxidation by TBHP. The use of the peroxide-based oxidant with the hydroxyl group is absolutely necessary as well: in the rate-limiting Pd(II)/Pd(IV) oxidation transition state, H-atom of OH group participates in the 1,2-hydrogen shift to facilitate the proton-shuttling between MPAA ligand and peroxide. Thus, lactonization of the C(sp<sup>3</sup>)-H bond in aliphatic carboxylic acid occurs via the Pd(II)/Pd(IV) catalytic cycle, unlike to the previously reported Pd(II)-catalyzed, pyridone ligand and O<sub>2</sub> oxidant assisted benzylic C-H lactonization in aromatic *o*-methyl benzoic acid, which occurs via the Pd(II)/Pd(0) catalytic cycle and an intramolecular S<sub>N</sub>2 nucleophilic substitution mechanism. Comparison of these findings for the C(sp<sup>3</sup>)-H bond lactonization in aliphatic and aromatic carboxylic acids enabled us to identify roles of catalyst, substrate, ligand, and oxidant.

**KeyWords:** C-H bond lactonization, Pd(II)-catalyst, ligand controlled, MPAA ligand, aliphatic carboxylic acid, DFT calculations

## INTRODUCTION

Transition metal-catalyzed selective C-H bond functionalization, i.e., conversion of “inert” C-H bonds to functional C-C and C-X (X = heteroatom) bonds, has emerged as a powerful synthetic strategy in late-stage functionalization.<sup>1-3</sup> Ongoing research in this field of the chemical science has demonstrated extreme complexity of this process and has emphasized critically importance of nature of the used catalyst, substrate, solvent, base, and oxidant. Despite of numerous advances, still the search for practical, green and sustainable C-H functionalization methodologies utilizing chemically and biologically accessible substrates, and inexpensive ligands and green oxidants is continuing.<sup>4</sup> It is anticipated that the discovery of the novel C-H functionalization strategies will enable syntheses of useful materials and synthons with critical C-X bonds which otherwise cannot be achieved in cost- and atom-economical ways in a large scale. In this context, catalytic C-H oxidation in the broadly accessible hydrocarbons is one of those highly active research directions, because of importance of lactones, and hydroxides in modern chemical and pharmaceutical industries.<sup>5-8</sup>

## Scheme 1. Pd(II)-Catalyzed C-H Lactonization with Aromatic *o*-Methyl Benzoic Acid (BA) and Aliphatic Carboxylic Acid (AA).

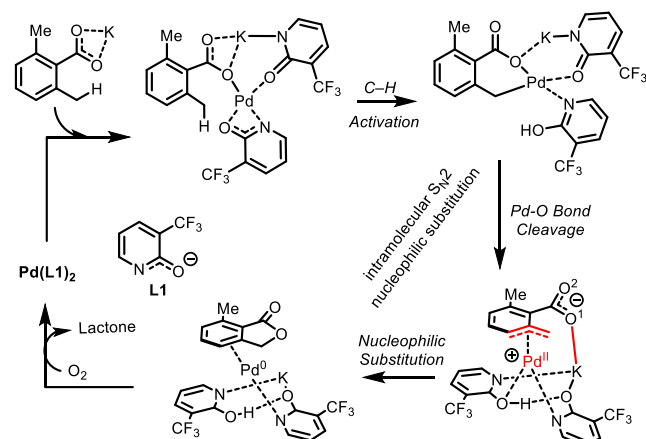


In the literature, several C-H lactonization processes were reported. For example, Chang and coworkers have developed a platinum(II)-catalyzed benzylic C-H lactonization with CuCl<sub>2</sub>

as the oxidant.<sup>9</sup> Martin and coworkers have reported a palladium-catalyzed C(sp<sup>3</sup>)-H lactonization with mono-*N*-protected  $\beta$ -amino acid MPAA ligand and stoichiometric silver(I) as the oxidant (**Scheme 1a**).<sup>10</sup> Yu and coworkers have discovered a palladium(II)-catalyzed C(sp<sup>3</sup>)-H lactonization of 2,6-dimethyl benzoic acids (BA) using molecular oxygen as an oxidant (**Scheme 1b**).<sup>11</sup> In this study, the authors used pyridone as a ligand, PhCl as a solvent, and K<sub>2</sub>HPO<sub>4</sub> as a base.

However, for lactonization of  $\beta$ -C(sp<sup>3</sup>)-H bond of aliphatic carboxylic acid (AA) by the Pd(II)-catalyst, the authors have to use MPAA as a ligand, TBHP as an oxidant, HFIP as a solvent, and CsHCO<sub>3</sub> as a base (**Scheme 1c**).<sup>12</sup> Just recently, Yu group have demonstrated that the use of a bidentate pyridine/pyridone ligand in combination with the Pd(II) pre-catalyst enables the C-H bond hydroxylation by the external oxygen molecule.<sup>13</sup>

**Scheme 2. Previously Proposed Mechanism of the Pd(II)-Catalyzed and Pyridone Ligand Assisted C(sp<sup>3</sup>)-H Lactonization in 2,6-Dimethyl Benzoic Acid (BA).**



Despite the broader application of these synthetic protocols in the late-stage functionalization,<sup>14</sup> we anticipate that elucidation the mechanisms of the C-H bond oxidation (by internal oxidant, like C-H lactonization in carboxylic acids, or external oxidant, like C-H hydroxylation in heterocyclic carboxylic acids by O<sub>2</sub> molecule), as well as the roles of the utilized catalyst, substrate, ligand, base, and oxidant undoubtedly will broaden scope of these synthetic protocols and enable discovery of more efficient, environmentally benign, and highly practical novel C-H oxidation reactions. Based on these anticipations, recently, we have studied the mechanism and controlling factors of the Pd(II)-catalyzed and pyridone ligand assisted C(sp<sup>3</sup>)-H lactonization in 2,6-dimethyl benzoic acid (**Scheme 1b**, below referred as the reaction rBA).<sup>15</sup> Briefly, we found that (see **Scheme 2**):

(a) This lactonization reaction engages the Pd(II)/Pd(0) catalytic cycle and proceeds through a stepwise intramolecular S<sub>N</sub>2 nucleophilic substitution mechanism. The used molecular oxygen during the reaction oxidizes the resulted Pd(0) species and re-generates the Pd(II)-catalyst;

(b) The generated  $\eta^3$ -( $\pi$ -benzylic)-Pd and potassium-O(carboxylate) interactions (in red, **Scheme 2**), in course of the reaction, are critical for the success of this reaction;

(c) Consistent with the previously reported case,<sup>16</sup> the used pyridone ligand is not only an auxiliary ligand for generation of the catalytic active species Pd(pyridone)<sub>2</sub>, but it also serves as the deprotonating reagent in the C-H bond activation via the concerted metalation-deprotonation (CMD) transition state;

(d) The C-H bond activation is reversible, and the C-O bond formation is a rate-determining step.

Herein, we extend our previous joint computational and experimental efforts<sup>15</sup> and are aimed to establish the mechanism of the  $\beta$ -C(sp<sup>3</sup>)-H bond lactonization in aliphatic carboxylic acid, previously reported by Yu and coworkers.<sup>12</sup> We are aiming to identify reasons why the use of MPAA ligand and TBHP oxidant (below, this reaction is referred as a rAA) was critically important for success of this reaction. We hypothesize that comparison of the obtained fundamental knowledge for this reaction with those for the previously reported<sup>15</sup> Pd(II)-catalyzed and pyridone ligand assisted C(sp<sup>3</sup>)-H lactonization in BA will shed light on roles of ligand, oxidant, and base in the Pd(II)-catalyzed and ligand enabled C-H bond lactonization in both aromatic and aliphatic carboxylic acid substrates.

## RESULTS AND DISCUSSION

### I. Nature of substrate and catalytic active species under the used experimental conditions.

We initiate our discussion by identifying the true nature of substrate and active catalyst in the reported reaction conditions (see **Scheme 1c**). Calculations show that the reaction of the used aliphatic carboxylic acid with the base is exergonic (see the Supporting Information, SI), and leads to the cesium-carboxylate salt (**1**, Figure 1). Therefore, in the presented computational studies, we adopted the cesium-carboxylate (**1**) as a substrate.

Previously, we have demonstrated that in the presence of MPAA ligand, pre-catalyst Pd(II)X<sub>2</sub> (where X = AcO or Cl) converts to the catalytic active species of either XPd(II)(MPAA) or Pd(II)(MPAA)<sub>2</sub>.<sup>17-22</sup> Consistently, the presented DFT calculations in this paper show that the formation of Pd(CH<sub>3</sub>CN)<sub>2</sub>(MPAA) (**2**, Figure 1) upon reaction of pre-catalyst Pd(CH<sub>3</sub>CN)<sub>2</sub>Cl<sub>2</sub>, MPAA ligand, and CsHCO<sub>3</sub> base, is exergonic by 10.9 kcal/mol (here, and below, we discuss only the calculated Gibbs free energies, unless otherwise stated, while enthalpy values of the presented structures are also given in figures. See SIs for more details). Therefore, herein we adopt mononuclear Pd(CH<sub>3</sub>CN)<sub>2</sub>(MPAA), **2**, as the catalytic active species under the utilized experimental conditions. It should be noted that in **2**, MPAA is a di-anionic  $\kappa^2$ -(*N,O*) ligand that binds to palladium with one of its carboxylic oxygens and amide nitrogen (after the deprotonation of amide N-center), which is consistent with the previous studies.<sup>17-22</sup>

Having identified the nature of substrate (**1**) and active catalyst (**2**), we expect the next step of the reaction to be the substrate coordination to the Pd(II)-center of **2**. This process occurs via the exchange of two [CH<sub>3</sub>CN] ligands by substrate **1**, and leads to the substrate-bound complex, **3**: overall reaction (**1**) + (**2**) → (**3**) + 2[CH<sub>3</sub>CN] is exergonic by 3.5 kcal/mol (see Figure 1). Similar to the previously reported Pd(II)-catalyzed C-H

activation in 2-benzhydrylpyridine, mediated by the [(cyclohexyloxy)carbonyl]-L-leucine ligand,<sup>17-22</sup> the C<sup>1</sup>-H<sup>1</sup> bond activation of AA in intermediate **3** occurs via the concerted metalation-deprotonation (CMD) transition state **4-ts**, where the carbonyl oxygen (O<sup>1</sup>) of the *N*-acetyl group of MPAA ligand acts as a proton acceptor. In transition state **4-ts**, the activated C<sup>1</sup>-H<sup>1</sup> bond is 1.38 Å, and formed Pd-C<sup>1</sup> and H<sup>1</sup>-O<sup>1</sup> bonds are 2.22 and 1.37 Å, respectively. Overcoming of 11.2 kcal/mol activation free energy barrier at transition state **4-ts** leads to formation of palladacycle **5**. Overall, the C(sp<sup>3</sup>)-H bond activation in complex **3**, i.e., reaction **3** → **4-ts** → **5** is exergonic by 6.9 kcal/mol.

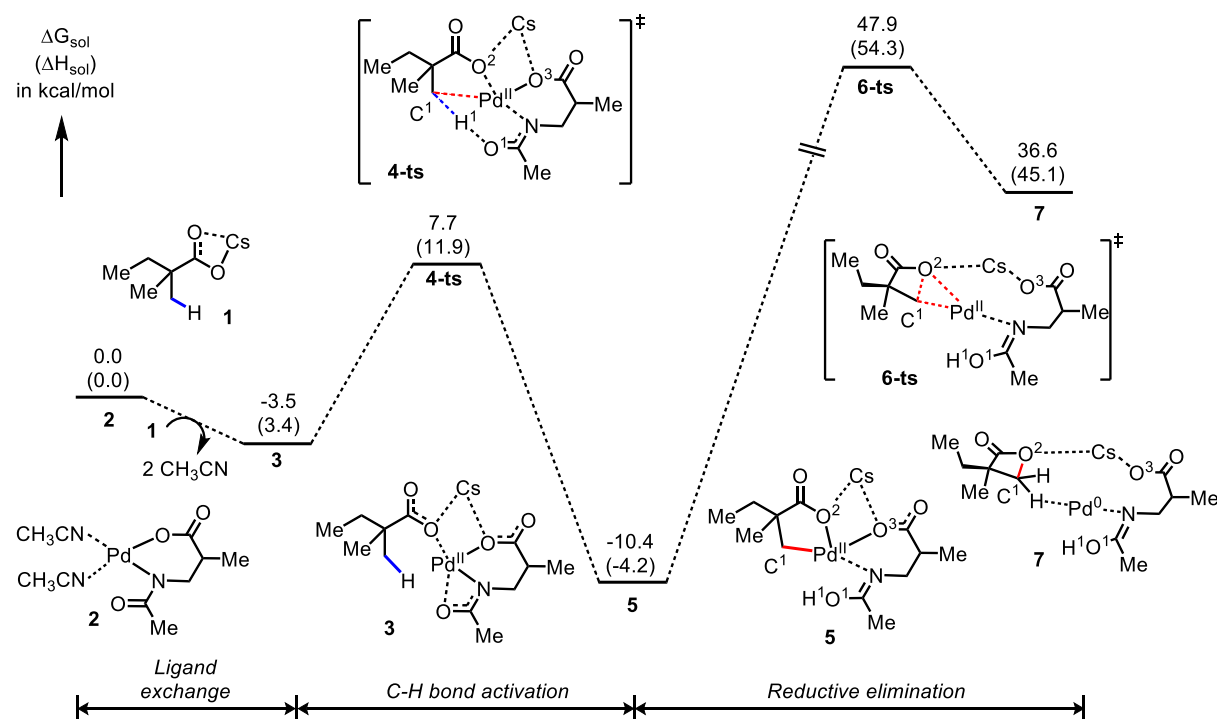
The performed kinetic isotope effect (i.e. KIE) calculations for the C-H activation indicate that the C-H activation cannot a rate-controlling step: the calculated KIE 1.00.

The calculated 11.2 kcal/mol free energy barrier of the reaction **3** → **4-ts** → **5** is smaller than 18.5 kcal/mol barrier, previously reported for the C(sp<sup>3</sup>)-H bond activation of BA by the Pd(II)-coordinated pyridone ligand.<sup>15</sup> Thus, the C(sp<sup>3</sup>)-H bond activation of AA by the MPAA ligand is more facile than the C(sp<sup>3</sup>)-H bond activation of BA by the pyridone ligand. In addition, the use of HFIP solvent may further facilitate the C(sp<sup>3</sup>)-H bond activation of AA through presumably Pd-O weak interaction or hydrogen bonding.<sup>23</sup> In order to better understand

roles of the ligand (MPAA vs pyridone) in the C-H bond activation in aliphatic and aromatic carboxylic acids (i.e., in the AA and BA), we have extended our study to the C-H bond activation in: (a) the aliphatic carboxylic acid with the Pd(II)-pyridone, and (b) the *o*-methyl benzoic carboxylic acid with the Pd(II)-MPAA. We find that the activation free energy barriers of these reactions are 11.2 and 15.4 kcal/mol, respectively (see SI for details). Comparison of the calculated activation barriers for these four reactions shows that the C-H bond activation in the AA and BA substrates, in general, is a facile process regardless of the nature of the used ligands (i.e., MPAA or pyridone).

## II. C-O bond formation

**II.1 Direct C-O reductive elimination.** From the generated palladacycle **5**, the lactonization process is expected to proceed via the C<sup>1</sup>-O<sup>2</sup> bond formation. As previously we have discussed,<sup>15</sup> the C-O bond formation from the Pd(II) and/or high-valent Pt and Pd-complexes is a complicated process.<sup>24-33</sup> Success of this process is not only dependent on the nature and oxidation state of the used transition metals, but also on the nature of the auxiliary ligands, oxidant, and base. For example, multiple experimental groups<sup>27-32</sup> have provided evidences that C-O bond formation in the Pd(IV) and Pt(IV)-complexes may proceed via either direct reductive elimination or/and stepwise S<sub>N</sub>2 nucleophilic substitution mechanisms.



**Figure 1.** Energy profile for the ligand exchange, C-H bond activation, and direct C-O reductive elimination steps for the β-C(sp<sup>3</sup>)-H lactonization with aliphatic carboxylic acid catalyzed by the MPAA-ligated Pd(II) complex.

However, in the literature, only rare mechanistic studies on the C-O bond formation from the Pd(II)-complexes were reported. In 2011, Hartwig and coworkers have reported the C(sp<sup>3</sup>)-O reductive elimination from the *bis*-phosphine-ligated

Pd(II)-aryloxide complexes, and have established an ionic mechanism including the dissociation of ArO<sup>-</sup>, followed by nucleophilic attack of ArO<sup>-</sup> anion on the cationic benzyl-palladium species.<sup>33</sup> In 2011, Martin and coworkers have proposed

a concerted reductive elimination mechanism for the Pd(II)-catalyzed C(sp<sup>3</sup>)-H lactonization with stoichiometric silver(I) oxidant,<sup>10</sup> however, they have not ruled out a stepwise mechanism including the dissociation of the carboxylate ligand and following C-O bond formation. Just recently, our group have proposed and validated a stepwise *intramolecular* S<sub>N</sub>2 nucleophilic substitution mechanism of the Pd(II)-catalyzed and pyridone ligand-enabled lactonization in *o*-methyl benzoic acid, which utilizes K<sub>2</sub>HPO<sub>4</sub> as a base, and O<sub>2</sub> as an oxidant.<sup>15</sup>

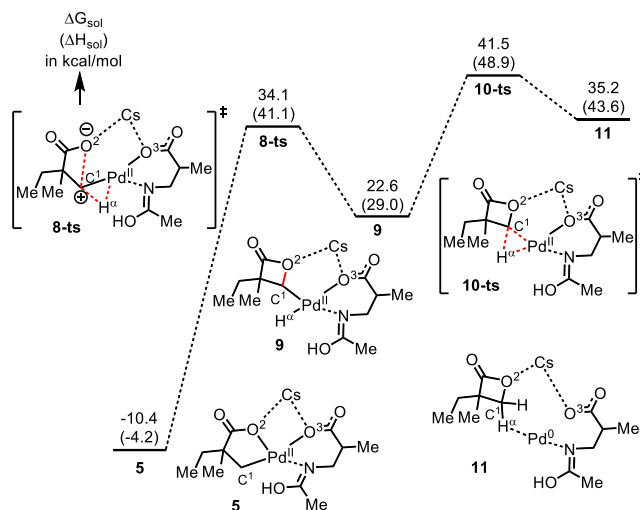
Armed with this knowledge, here, we start our analysis of the C-O bond formation in intermediate **5** by the direct reductive elimination mechanism. We found that the associated C-O reductive elimination free energy barrier (58.3 kcal/mol, at the associated transition state **6-ts**, Figure 1) for this process is prohibitively high, indicating that the direct C(sp<sup>3</sup>)-O reductive elimination is unlikely in aliphatic carboxylic acid complex by the Pd(II) catalyst Pd(CH<sub>3</sub>CN)<sub>2</sub>(MPAA), **2**.

**II.2 Stepwise C-O formation.** Next, we studied the stepwise C(sp<sup>3</sup>)-O bond formation in palladacycle **5**. As previously shown for the C(sp<sup>3</sup>)-O bond formation in palladacycle with the aromatic carboxylic acid, i.e. reaction rBA, it proceeds through the stepwise pathway that occurs via the Pd-O<sup>2</sup>(O=)CR bond dissociation and the following intramolecular S<sub>N</sub>2 nucleophilic substitution steps (see **Scheme 2**). All our attempts to locate transition state associated with the Pd-O<sup>2</sup>(O=)CR bond cleavage in intermediate **5** have led to structure **8-ts** (Figure 2), where the simultaneous Pd-O<sup>2</sup> and C<sup>1</sup>-H<sup>α</sup> bond cleavage, and complementing C<sup>1</sup>-O<sup>2</sup> and Pd-H<sup>α</sup> bond formation occur. This step occurs by 44.5 kcal/mol energy barrier and leads to intermediate **9**, which is 33.0 kcal/mol higher in free energy than pre-reaction complex **5**. Close analyses of **9** show that in this structure the formation of the Pd-C<sup>1</sup>, Pd-H<sup>α</sup>, and C<sup>1</sup>-O<sup>2</sup> bonds, and the cleavage of the Pd-O<sup>2</sup> and C<sup>1</sup>-H<sup>α</sup> bonds are completed. The following C<sup>1</sup>-H<sup>α</sup> reductive elimination in **9** to form the Pd(II)-coordinated lactone, **11**, is the rate-determining step of the investigated stepwise pathway that requires an overall of 51.9 kcal/mol free energy barrier (at **10-ts** relative to **5**). Above presented energetics (Figure 2) show that, the stepwise C-O bond formation in the C-H activation product **5**, which was the most favorable mechanism of the reaction with aromatic benzoic acid (i.e. reaction rBA), is not practical for the Pd(II)-catalyzed and MPAA ligand-enabled lactonization of β-C(sp<sup>3</sup>)-H bond in aliphatic carboxylic acid (i.e. reaction rAA). Our analyses show that the transition state **10-ts** lacks the stabilizing η<sup>3</sup>-(π-benzylic)-Pd(II) interaction. This could be (as emphasized previously<sup>15</sup>) one of the reasons for the calculated large C-O bond formation barrier. Thus, the reaction rAA, most likely, proceeds via the different mechanistic pathway than the intramolecular S<sub>N</sub>2 nucleophilic substitution pathway previously reported for the reaction rBA.<sup>15</sup>

**II.3 TBHP oxidative addition and the Pd(II)/Pd(IV) oxidation.** Thus, above presented computational data showed that neither direct reductive elimination nor the stepwise intramolecular S<sub>N</sub>2 nucleophilic substitution mechanisms for the C(sp<sup>3</sup>)-O bond formation in palladacycle **5** are the productive pathways of the Pd(II)-catalyzed and MPAA ligand-enabled β-C(sp<sup>3</sup>)-H lactonization in aliphatic carboxylic acid. However, the above

presented studies are based on the assumption that the oxidant *does not facilitate the* C(sp<sup>3</sup>)-O bond formation: this assumption was based on our previous findings for the Pd(II)-catalyzed and pyridone ligand-enabled C(sp<sup>3</sup>)-H lactonization in aromatic carboxylic acid, which utilized O<sub>2</sub> as an oxidant.<sup>15</sup> Below, we re-visit this assumption and re-investigate role of oxidant TBHP in the C(sp<sup>3</sup>)-O bond formation during the reaction rAA. Previous studies of the Pd(II)-catalyzed Wacker oxidation of alkenes, as well as the Sharpless-Katsuki epoxidation by the dinuclear titanium complex with TBHP as the oxidant have shown that TBHP might act as the oxygen source.<sup>34,35,36</sup> However, to the best of our knowledge, in literature there is no precedent of oxidative addition of TBHP to the Pd(II) species.

The presented calculations show that addition of TBHP to palladacycle **5** results in the formation of the **5-TBHP** adduct: the energetically most favorable isomers of this adduct are complexes **12** and **14** with stabilization free energy of 6.6 and 3.5 kcal/mol, respectively (Figure 3). As seen from Figure 3, in adduct **12**, TBHP is coordinated to Pd-center via its O<sup>i</sup>Bu end. As a result, it displaces the Cs-O<sup>3</sup>(ligand) interaction and forms the Pd-O<sup>i</sup>Bu and Cs-OH-O(ligand) bonds. In the energetically less favorable adduct **14**, TBHP is coordinated to Pd-center with its hydroxyl oxygen (O<sup>4</sup>) without displacement of the Cs-O<sup>3</sup>(ligand) interaction.



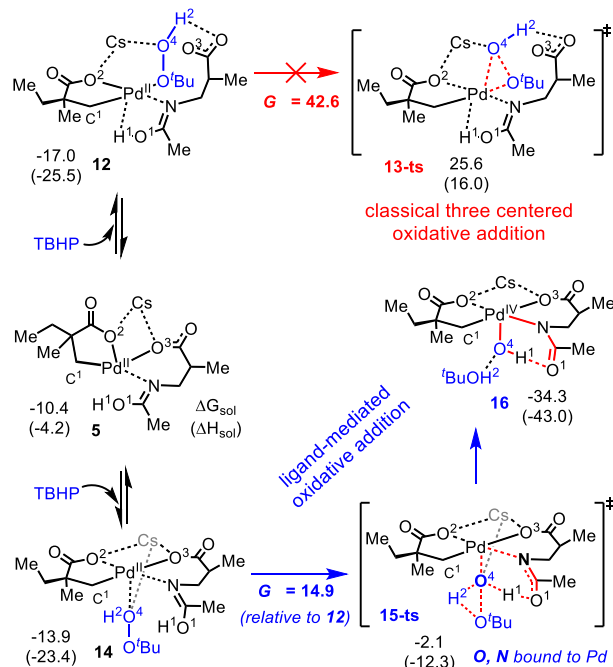
**Figure 2.** The stepwise C(sp<sup>3</sup>)-O bond formation in palladacycle **5** with aliphatic carboxylic acid.

The calculations also show that the classical oxidative addition of TBHP to Pd(II), that proceeds via a three-centered transition state **13-ts**, requires prohibitively (by 42.6 kcal/mol) high free energy barrier. This finding is consistent with lack of precedent of oxidative addition of TBHP to Pd(II) species in the literature. Here we will not discuss this process in detail, while we include all associated structures of this direct oxidative addition pathway in the Supporting Information.

Gratifyingly, we find the kinetically most favorable pathway for the Pd(II)/Pd(IV) oxidation by TBHP, initiated directly from the energetically less favorable conformer **14** (below, we will consider **14** and **12** structures as a Curtin-Hammett equilibrium, and will report the calculated energies from the most favorable isomer **12**).



As seen in Figure 3, in complex **14**, TBHP is coordinated to the Pd center from the same side as the N-center of the MPAA ligand. This structural motif (previously reported<sup>20</sup> as a *cis* coordination motif) makes possible involvement of the monoanionic imine ligand in the TBHP O–O bond activation and Pd(II)/Pd(IV) oxidation. Indeed, in the associated transition state **15-ts** (see also Figure 4), not only the <sup>t</sup>BuO–OH bond is breaking and the Pd–O<sup>4</sup>(H) bond is forming, but also the 1,2-hydrogen shift (i.e. H<sup>2</sup>) within the TBHP takes place: from its Pd-coordinated O<sup>4</sup>-center to the O<sup>4</sup>Bu fragment. Simultaneously with these bond-breaking and bond-formation events within the TBHP-fragment, the hydrogen atom (i.e. H<sup>1</sup>) of hydroxyl group of the previously protonated MPAA ligand (i.e. imine ligand) is transferring to the Pd-coordinated O<sup>4</sup> atom of TBHP. This transformation results in generation of the Pd-coordinated amide center.

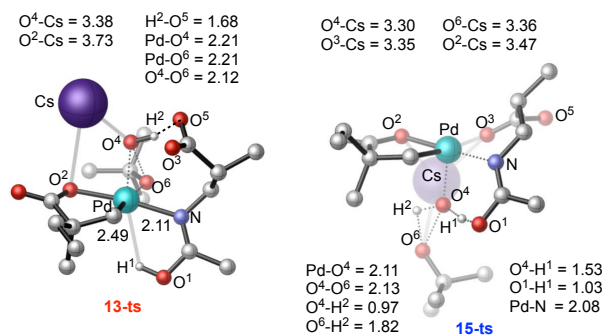


**Figure 3.** The studied classical and ligand-mediated oxidative addition of TBHP to intermediate **5**.

As a result of these multi-component complex transformations, (a) Pd(II) is oxidized to Pd(IV), (b) the oxygen atom (O<sup>4</sup>) from the hydroxyl group of TBHP and the nitrogen atom of MPAA become the two X-type ligand atoms (i.e. the reduced centers) that bind to the metal center, (c) MPAA ligand transforms from the mono-anionic bidentate-coordinated ligand in **14** to the di-anionic bidentate-coordinated one in the oxidative addition product **16**, and (d) the <sup>t</sup>BuO group of TBHP transforms to <sup>t</sup>BuOH. Here, we labeled this complex transformation as a *MPAA ligand mediated Pd(II)/Pd(IV) oxidation by TBHP*. This process has an overall of 14.9 kcal/mol free energy barrier relative to the energetically most favorable pre-reaction complex **12**. Furthermore, the overall reaction **12** → **15-ts** → **16** is exergonic by 17.3 kcal/mol. Thus, the use of the MPAA ligand in combination with TBHP oxidant is critical for promoting of the Pd(II)/Pd(IV) oxidation in course of the β-C(sp<sup>3</sup>)–H bond lactonization in aliphatic carboxylic acid (AA).

Here, we should mention that our calculations (see the Supporting Information) shown that the pyridone ligand enabled Pd(II)/Pd(IV) oxidation with TBHP oxidant requires 22.0

kcal/mol free energy barrier. Comparison of this value with the 14.9 kcal/mol energy barrier for the MPAA ligand mediated Pd(II)/Pd(IV) oxidation by TBHP indicates that the use of MPAA ligand could be better than pyridone ligand in the β-C(sp<sup>3</sup>)–H bond lactonization of aliphatic carboxylic acid (AA) by the Pd-catalyst and TBHP oxidant.



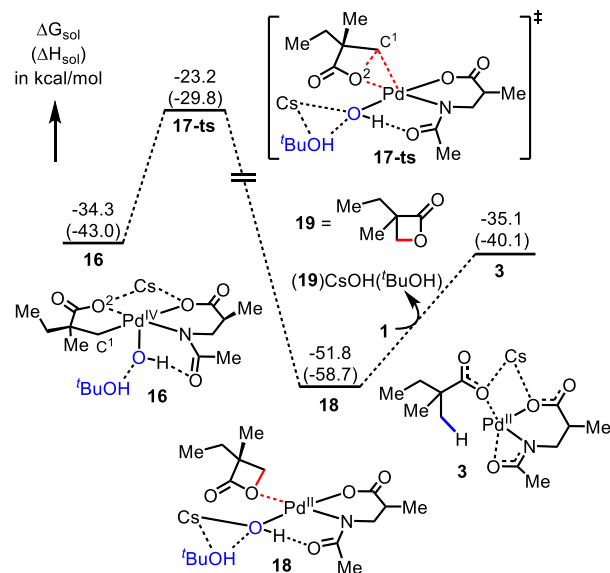
**Figure 4.** Geometries of the classical (**13-ts**) and ligand-mediated (**15-ts**) oxidative addition transition states (some hydrogen atoms are omitted for clarity, and bond distances are given in Å).

**II.4 Reductive elimination and catalyst regeneration.** As it could be anticipated, after the MPAA ligand mediated Pd(II)/Pd(IV) oxidation by TBHP, the C(sp<sup>3</sup>)–O (i.e. C<sup>1</sup>–O<sup>2</sup>, see Figure 5) reductive elimination from the Pd(IV)-intermediate takes place with a small (by 11.1 kcal/mol) free energy barrier at the transition state **17-ts** that leads to the complex **18** with the Pd-coordinated lactone (Figure 5). This step is exergonic by 17.5 kcal/mol. Finally, the addition of the second equivalent of substrate, and dissociation of lactone and (<sup>t</sup>BuOH)CsOH regenerates the pre-reaction intermediate (**3**), which would enter the next catalytic cycle. Final step of the reaction (Figure 5) is endergonic by 16.7 kcal/mol but is feasible under the reported experimental conditions.

Above presented “MPAA ligand mediated Pd(II)/Pd(IV) oxidation by TBHP” phenomena demonstrates the critical importance of not only the use of the MPAA ligand, but also the presence of the hydroxyl group in the peroxide-based oxidants. Indeed, in the rate-limiting Pd(II)/Pd(IV) oxidation transition state **15-ts**, H-atom of the TBHP oxidant participates in the 1,2-hydrogen shift that facilitates the proton-shuttling between imine ligand and the Pd-coordinated hydroxyl oxygen of the peroxide. This finding enables us to conclude that the peroxide-based oxidants with no hydroxyl group, such as <sup>t</sup>BuOO<sup>t</sup>Bu, BzOOBz, BzOO<sup>t</sup>Bu, Lauroyl peroxide etc., are going to be poor Pd(II)/Pd(IV) oxidants in the Pd(II)-catalyzed and MPAA ligand-enabled lactonization of β-C(sp<sup>3</sup>)–H bond in aliphatic carboxylic acid. This conclusion is consistent with the available experiments showing no or little<sup>37</sup> lactonization with peroxide-based oxidants with no hydroxyl group.<sup>12</sup>

Thus, above presented findings show that overall, the Pd(II)-catalyzed and MPAA ligand-enabled β-C(sp<sup>3</sup>)–H lactonization in aliphatic carboxylic acid proceeds via the Pd(II)/Pd(IV) catalytic cycle that includes: (a) the MPAA ligand assisted C–H bond activation via the CMD mechanism and the followed oxidant coordination to the C–H bond activation product; (b) the MPAA ligand mediated Pd(II)/Pd(IV) oxidation by TBHP; (c) the

C(sp<sup>3</sup>)-O reductive elimination from the Pd(IV) intermediate; and (d) catalytic active species regeneration. While the MPAA ligand mediated Pd(II)/Pd(IV) oxidation by TBHP is the rate-determining step of the reaction, the regioselectivity controlling step of the reaction is the C-H bond activation because the reverse C-H bond formation barrier is larger (24.7 kcal/mol) than the forward Pd(II)/Pd(IV) oxidation by TBHP (14.9 kcal/mol, relative to intermediate **12**).



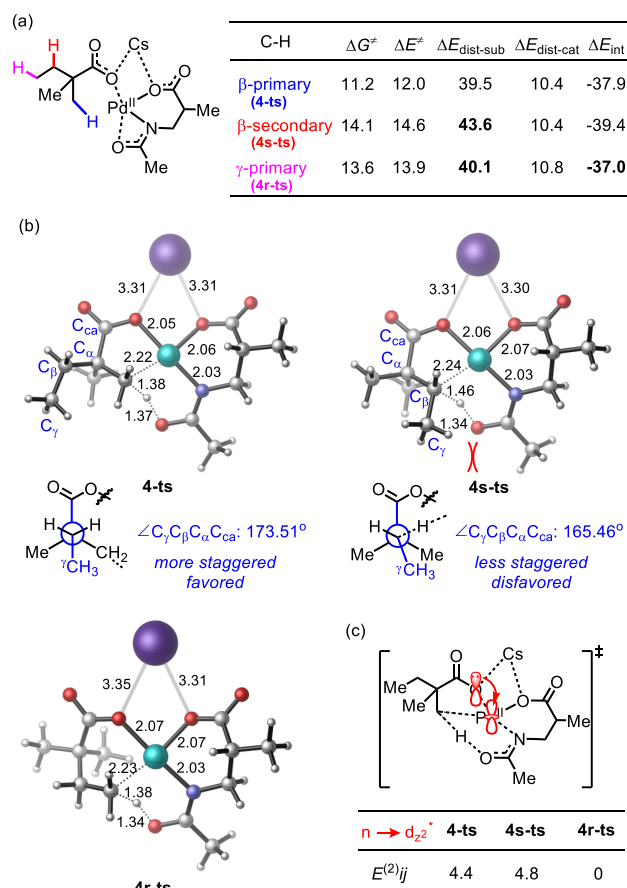
**Figure 5.** Energy profile for the C-O reductive elimination in Pd(IV)-intermediate **16**, and the catalyst regeneration from intermediate **18**.

### III. Selective $\beta$ -primary, $\beta$ -secondary, and $\gamma$ -primary C-H bond lactonization in aliphatic carboxylic acid.

To validate above made conclusion on the regioselectivity controlling C-H activation step of the reaction, we have calculated the  $\beta$ -primary,  $\beta$ -secondary, and  $\gamma$ -primary C-H bond activation barriers in the utilized aliphatic carboxylic acid (**1**). These calculations (see Figure 6), consistent with available experiments,<sup>12</sup> show that the  $\beta$ -primary C-H bond activation requires less energy barrier (11.2 kcal/mol, at the transition state **4-ts**), than the  $\beta$ -secondary (14.1 kcal/mol, at the transition state **4s-ts**), and  $\gamma$ -primary (13.6 kcal/mol, at the transition state **4r-ts**) C-H bond activations (see Figure 6a and 6b).

To gain insights into the regioselectivity-controlling factors, we performed the distortion/interaction analyses.<sup>38-45</sup> In these analyses, the (aliphatic carboxylic)-cesium unit is assigned to be the substrate (*sub*), and the remaining part of the system is labeled as a catalyst (*cat*) (see SIs for more details). Data presented in Figure 6a show that the calculated difference between the  $\beta$ -primary (**4-ts**) and  $\beta$ -secondary (**4s-ts**) C-H bond activation barriers is, mostly, due to the larger unfavorable distortion of substrate in transition state **4s-ts** (Figure 6a). This is well reflected by the corresponding geometries.<sup>46</sup> However, the calculated difference between the  $\beta$ -primary (**4-ts**) and  $\gamma$ -primary (**4r-ts**) C-H bond activation barriers is result of both the larger unfavorable distortion and smaller *sub-cat* in-

teraction energies in **4r-ts**. The calculated larger distortion energy in **4r-ts** compared to **4-ts** can be explained by the formation of the six-membered vs five-membered ring chelated palladacycle, respectively.<sup>47,48</sup> The smaller *sub-cat* interaction energy in **4r-ts** compared to **4-ts** is manifested in (a) the calculated Pd-O bond distances, and (b) the donor-acceptor interaction energy ( $E^{(2)}_{ij}$ ) between the lone-pair of oxygen n(O) of *sub* with unoccupied  $d_{z^2}$  orbital of Pd(II)-center in these transition states, respectively (Figure 6c).



**Figure 6.** (a) Calculated free energy barriers for different C-H bond activations, and results of the distortion/interaction analysis; (b) Geometry structures for the studied C-H bond activation transition states; (c) NBO second-order perturbative interaction analysis (energies and bond distances are given in kcal/mol and Å, respectively).

### CONCLUSIONS

Comparison of key mechanistic details of the Pd(II)-catalyzed and pyridone ligand assisted C(sp<sup>3</sup>)-H lactonization in aromatic *o*-methyl benzoic acid (BA) (reaction rBA),<sup>15</sup> and the Pd(II)-catalyzed and MPAA ligand-enabled lactonization of  $\beta$ -C(sp<sup>3</sup>)-H lactonization in aliphatic carboxylic acid (AA) (reaction rAA) has shown that (see Scheme 3):

(a) True substrates and catalytic active species of both reactions are the counter-cation (from the base) coordinated original organic substrate, and the Pd(II)-ligand (pyridone or MPAA) system, respectively.

(b) In both reactions, the targeted C–H bond cleavage occurs via the concerted metalation-deprotonation (CMD) mechanism, where the Pd(II)-coordinated anionic ligand (pyridone or MPAA, respectively) acts as a proton acceptor.

(c) In the reaction rBA, the C–O bond formation proceeds via the *intramolecular*  $S_N2$  nucleophilic substitution mechanism via the rate-determining transition state with the  $\eta^3$ -( $\pi$ -benzylic)–Pd(II) interaction.<sup>15</sup> The presence of the  $\eta^3$ -( $\pi$ -benzylic)–Pd(II) and the potassium–O(carboxylate) interactions are critical for the C–O formation.

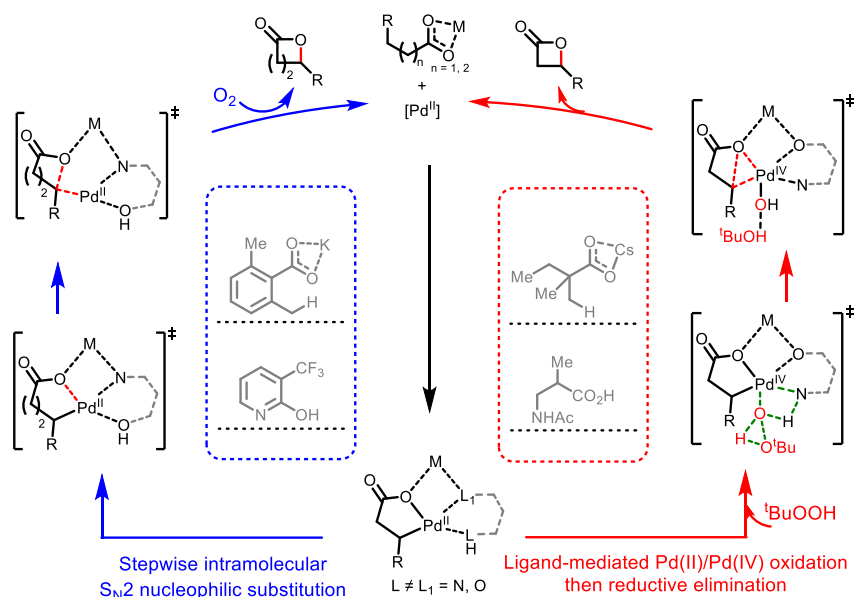
(d) Lack of the stabilizing  $\eta^3$ -( $\pi$ -benzylic)–Pd(II) interaction, in course of the reaction rAA, makes the *intramolecular*  $S_N2$  nucleophilic substitution mechanism of the  $\beta$ -C(sp<sup>3</sup>)–H lactonization in aliphatic carboxylic acid by the Pd(II)/MPAA catalyst not feasible. Astoundingly, the use of TBHP oxidant, in combination with the MPAA ligand, opened energetically more favorable reaction path, which we called as *MPAA ligand mediated Pd(II)/Pd(IV) oxidation by TBHP then the C–O reductive elimination from the Pd(IV) intermediate pathway*. Overall, this unprecedented mechanistic pathway requires 14.9 kcal/mol free energy barrier (for the Pd(II)/Pd(IV) oxidation) and is exergonic by 17.3 kcal/mol.

(e) The use of MPAA ligand in the reaction rAA is critically important: it acts as a proton acceptor in the C–H bond deprotonation, and as a proton donor during the Pd(II)/Pd(IV) oxidation by TBHP.

(f) Equally, the use of the peroxide-based oxidants, such as RO–OH, with the hydroxyl group is necessary because, in the rate-limiting Pd(II)/Pd(IV) oxidation transition state, H-atom of this group participates in the 1,2-hydrogen shift that facilitates the proton-shuttling between imine ligand (of MPAA) and coordinated peroxide oxygen. To the best of our knowledge, it is the first demonstration of the *Pd(II)/Pd(IV) oxidation by TBHP*. However, one also should comment that peroxides like mCPBA and CMHP with the hydroxyl group, but highly complex R-fragments may require special attentions.

Thus, above presented data show that outcome of the Pd(II)-catalyzed and ligand enabled C–H bond lactonization is critically dependent on the nature of substrate, oxidant, ligand, and base. We believe that uncovered intimate insights in this work will enable our colleagues in designing more efficient Pd(II)-catalyzed C–H bond lactonization strategies applicable for the wide scope of substrate.

**Scheme 3. The Mechanisms of the Pd(II)-Catalyzed and Pyridone Ligand Assisted Lactonization of C(sp<sup>3</sup>)–H in Aromatic *o*-Methyl Benzoic Acid (left), and the Pd(II)-Catalyzed and MPAA Ligand-Enabled Lactonization of  $\beta$ -C(sp<sup>3</sup>)–H in Aliphatic Carboxylate Acid (right).**



### Computational Details

All the geometry optimizations were performed using Gaussian 09 suite of program<sup>49</sup> at the B3LYP<sup>50–52</sup> density functional powered by Grimme's empirical dispersion-correction (D3)<sup>53</sup> (denoted as B3LYP-D3). Lanl2dz/6-31G(d,p) basis sets were used for Pd, Cs/all-other-atoms respectively, in which the Hay-Wadt effective core potentials<sup>54,55</sup> were considered for Pd and Cs. Single point energy calculations were performed at the

optimized geometries using the SDD/6-311++G(d,p) basis sets for Pd, Cs/all-other-atoms. Frequency calculations at the same level of theory as the geometry optimizations confirmed the nature of the reported stationary structures and provided thermal corrections to the energies. Intrinsic reaction coordinate (IRC) calculations were performed for selected transition states to ensure their true nature and properly connect reac-

tants and products. Solvent effects were incorporated in geometry optimizations, frequency calculations, and single point energy calculations at the SMD<sup>56</sup> solvent model. 2-methyl-1-propanol is used to mimic of the HFIP as it has the closest dielectric parameters with HFIP. 3D geometries were prepared using CYLView software.<sup>57</sup>  $\Delta G_{\text{sol}}(\Delta H_{\text{sol}})$  (in kcal/mol) are given in figures unless otherwise stated.

**SUPPORTING INFORMATION:** Reaction energies of the cesium carboxylate (**1**) and active catalyst (**2**) formation; The C-H bond activation in aliphatic carboxylic acid catalyzed by the Pd(II)-catalyst and pyridone ligand; The bond activation in *o*-methyl benzoic acid catalyzed by the Pd(II)-catalyst and MPAA ligand; The calculated C-H bond activation barriers in aliphatic carboxylic acid with the Pd(II)-pyridone, and *o*-methyl benzoic carboxylic acid with the Pd(II)-MPAA; The classical Pd(II)/Pd(IV) oxidation by TBHP; The details of the distortion/interaction analyses; The details of the pyridone ligand mediated Pd(II)-to-Pd(IV) oxidation by TBHP oxidation; The classical Pd(II)/Pd(IV) oxidation by AcOO<sup>t</sup>Bu; Full free energy profile of the reaction; C-O reductive elimination from the Pd(II) intermediate with one additional CH<sub>2</sub> moiety in substrate; Energies and cartesian coordinates for all calculated species; Additional References.

## ASSOCIATED CONTENT

**Supporting Information.** Energetics and Cartesian coordinates for all reported structures. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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### Notes

The authors declare no competing financial interest.

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## Pd(II)-Catalyzed C-H Lactonization: *Substrate, Ligand, and Oxidant Effects*

