Pd-Catalyzed Hydroamination of Alkoxyallenes with Azole Heterocycles: Examples and Mechanistic Proposal

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Supporting Information

ABSTRACT: Palladium-catalyzed regio- and enantioselective addition of azole heterocycles to alkoxyallenes was developed (up to 92% yields and up to 94% ee). DFT calculations suggest a new Pd(0)-driven mechanistic pathway proceeding through protonation of the Pd-coordinated allene (4-PdL₂), which develops a strongly nucleophilic character at the central C atom.

The palladium-catalyzed addition of nitrogen nucleophiles to alkoxyallenes is a straightforward conversion to form the corresponding allylic N,O-acetals under mildly basic conditions. These reactive structures have been used as key intermediates in the synthesis of biologically active heterocycles and natural products. Examples from our group include the stereoselective synthesis of the natural product L-baikiaen and a formal total synthesis of the alkaloid quinolizidine 233A. To follow up on these results, we envisioned that also aromatic nitrogen nucleophiles, so-called azole heterocycles, would be of particular interest as reactants in such hydroaminations. Thus, we explored the potential of catalytic and enantioselective reactions at the azole nitrogen to gain access to a broad range of chiral, heteroaromatic allylic N,O-acetals. Additionally, while palladium hydride species have been invoked as reactive intermediates in most of the hydroamination studies, our current computational investigations argue against such intermediates. We present herewith DFT calculations that suggest an alternative mechanistic pathway that proceeds via coordination of the allene to Pd(0), and protonation with imidazole of the resulting 4-PdL₂ species at the central carbon atom (TS-1).

Gratifyingly, the first attempt in the presence of a catalytic amount of Pd(OAc)₂/dppp (1,3-bis(diphenylphosphino)propane) in refluxing THF provided the desired product 3a in 82% yield as a single regioisomer (entry 1). Similar results were obtained by changing catalyst, temperature, and solvent (entries 2–5). Unexpectedly, in the absence of additional base and under the optimal reaction conditions (2.5 mol % of Pd₂dba₃, 5.0 mol % of dppp in THF) the reaction went to completion in 4 h at 60 °C, yielding the desired N,O-acetal 3a in 93% yield (entry 6).

Along with these results, different heterocyclic systems containing the azole framework were subjected to the reaction conditions, and the results are summarized in Table 1. The reactions were carried out under the optimal conditions, yielding the desired products in good to excellent yields.

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Table 1. Reaction Optimization

<table>
<thead>
<tr>
<th>entry</th>
<th>base</th>
<th>catalyst</th>
<th>yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DBU</td>
<td>Pd(OAc)₂/dppp</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>DBU</td>
<td>Pd₂(dba)₃/dppp</td>
<td>87</td>
</tr>
<tr>
<td>3</td>
<td>DBU</td>
<td>Pd(PPh₃)₃</td>
<td>85</td>
</tr>
<tr>
<td>4</td>
<td>DBU</td>
<td>Pd₂(dba)₃/dppp</td>
<td>62</td>
</tr>
<tr>
<td>5</td>
<td>DBU</td>
<td>Pd₂(dba)₃/dppp</td>
<td>78</td>
</tr>
<tr>
<td>6</td>
<td>DBU</td>
<td>Pd₂(dba)₃/dppp</td>
<td>93</td>
</tr>
</tbody>
</table>

Conditions: Pd catalyst (5.0 mol %), dppp (5.0 mol %), THF (3.0 mL), 60 °C, 12 h. Isolated yield. °23 °C. MeCN, reflux.
optimized reaction conditions (Scheme 1A). Generally, the anticipated N,O-acetals 3a–w were obtained in modest to excellent yields (54–92%). In the case of asymmetrically substituted imidazoles, mixtures of the 4- and 5-substituted isomers 3e–h were obtained. Thus, 4-nitroimidazole and imidazole-4-carbaldehyde were converted into C-4 allylic N,O-acetals 3e and 3f in good yields with nearly complete regioselectivity. In contrast, 4-methylimidazole and 4-iodoimidazole showed almost no regioselectivity, yielding a close to 1:1 mixture of the 4- and 5-substituted isomers 3g and 3h. Remarkably, in the case of pyrrole, only degradation of allene 1a was observed. Changing the conditions (solvent, temperature, Pd catalysts, addition of base) did not lead to product either. In contrast, pyrrole substituted with electron-withdrawing groups, in particular, pyrrole-2-carbaldehyde and pyrrole-2-carbonitrile, showed nearly the same reaction rates as imidazole and gave the desired products in good yields (72 and 83% for 3j and 3k, respectively). Azole heterocycles with multiple N-nucleophilic centers also showed good reactivity in the intermolecular addition to benzoxylallene (1a). To our delight, the corresponding triazole-containing N,O-acetals 3q and 3r were formed with good selectivity.

Next, we examined the asymmetric version of Pd-catalyzed hydroamination of imidazole (2a) with a variety of alkoxyallenes (Scheme 1B). Here, we evaluated several commercially available chiral bisphosphine ligands, solvents, and additives (for detailed information on the optimization, see the Supporting Information). Our strategy was based on the work on Pd- and Rh-catalyzed asymmetric additions onto allenes. Modifying their procedure and performing the reaction in the presence of Pd2(dba)3 (2.5 mol %) and (R,R)-DACH-naphthyl Trost ligand L1 (5 mol %), we were pleased to observe that a number of alkoxyallene analogues reacted well with imidazole giving rise to products (S)-3s–w and (S)-3a, not only in good yields but in most cases also with high enantioselectivities (up to 94% ee). To indicate the broader scope and reveal the absolute configuration of the obtained products, we performed the reaction with 1,3-dimethylxantine theophylline and allene (1a), and the crystal structure of the major enantiomer of product 3q (74%, 92% ee) was elucidated. The absolute configuration was assigned to be S in all cases based on the X-ray data of 3q and the corresponding N,O-acetals 3q and 3r were formed with good selectivity.
the CD profiles of the other products (see the SI), which is in correspondence with the expected stereochemistry.

The mechanism of the Pd-catalyzed additions of pronucleophiles with relatively acidic protons to allenes has been thoroughly investigated by Trost. Experimental studies have shown that this process is initiated by oxidative addition of palladium into the acidic C−H bond to form a cationic Pd−H species (Scheme 2). This intermediate can readily react with the allene, thereby generating a π-allylpalladium species (8). Addition of the anion of the pronucleophile to this intermediate through trajectories a or b then forms the products with regeneration of the Pd(0) catalyst.

Since no studies have been reported on the protonation of low-valent palladium with weak acids (e.g., imidazole), we turned to DFT calculations to shed light on a plausible mechanism for our alkoxyallene/imidazole reaction and considered initially a pathway similar to that outlined in Scheme 2. Indeed, our preliminary calculations showed that 8 (X = imidazolide, L2 = 1,3-bis(dimethylphosphino) propane, dmpp) is a reasonable intermediate for the reaction. Its computed free energy value was 5.6 kcal/mol lower than the sum of the initial substrates (6 + imidazole + allene 1a, Scheme 2), and its reaction with the imidazolide nucleophile preferentially occurs through the a trajectory (8.0 kcal/mol lower than b) to form the N,O-acetal product, in agreement with the experimental findings.

However, some critical inconsistencies were evidenced around the participation of intermediate 7 in the mechanism (Scheme 2) since its existence was incompatible with the following data: (a) A determining preference of 18.9 kcal/mol for the coordination of Pd(0) to allene 1a over imidazole (2a) was found (10a vs 9, Figure 1), severely compromising any further participation of palladium species 9 and TS-3 in the mechanism of the reaction. (b) The formation of H−Pd−X− species of type 7 has been exclusively described for strong H−X acids, and the hydride has not been observed when weaker acids were used. In agreement with these experimental facts, the computed equilibrium between Pd(0) and trifluoroacetic acid is shifted toward the formation of cationic H−Pd+ species 7 by 4.8 kcal/mol (Scheme 2), while using imidazole as a proton source, the hydride is disfavored by 22.5 kcal/mol. (c) The combination of factors a and b affords an unrealistic energy of 41.1 kcal/mol for hydride 7 over 10a, and even the formation of other less unstable Pd−H species (e.g., 12, see SI) is unreachable by any means (Figure 1). We can safely state that in these conditions, H−Pd+ species would never form. Therefore, the intriguing findings that intermediates 10a and 8 participate in the mechanism but are at the same time not connected through the cationic H−Pd+ species 7 led us to search for a pathway to connect both intermediates. Gratifyingly, after some computational effort, a new transition state (TS-1) was located for the direct protonation of the Pd-coordinated allene with imidazole with a moderate activation barrier of 19.7 kcal/mol (Figure 1). The structure is highly interesting and original and implies that the allene, after coordination to Pd(0) in 10a, becomes sufficiently basic at the central C atom to deprotonate imidazole.

Indeed, a very high-in-energy local minimum structure (11, 19.1 kcal/mol higher than 10a) was located during the intrinsic reaction coordinate (IRC) of the transition state TS-1, corresponding to a bidentate coordination mode of allene to palladium with high nucleophilic carbone character. The carbene-like species 11 is so close in energy (ΔΔG⧧ = 0.6 kcal/mol)
mol) to the transition state that it could not be considered a stable reaction intermediate, but it is still very informative, revealing that during the protonation trajectory from 10a to TS-1, the allene bends and develops a significant negative charge at the central C atom. Finally, the attack of the imidazolidine to 8 was found to occur through pathway a, as in Scheme 2 (TS-2a, Figure 1), with an activation free energy of 11.3 kcal/mol.

In conclusion, we have developed highly effective Pd-catalyzed protocols for the addition of a wide scope of azole heterocycles to alkoxyallenes providing a unique way to synthesize aromatic allylic heterocycles to alkoxyallenes providing a unique way to synthesize aromatic allylic heterocycles to alkoxyallenes providing a unique way to synthesize aromatic allylic heterocycles to alkoxyallenes providing a unique way to synthesize aromatic allylic heterocycles to alkoxyallenes providing a unique way to synthesize aromatic allylic heterocycles to alkoxyallenes providing a unique way to synthesize aromatic allylic heterocycles to alkoxyallenes. A nonconventional Pd(0)-driven mechanistic pathway was proposed based on the DFT calculations of the studied process. This should be considered as an alternative pathway for nonacidic nucleophiles, where highly favorable coordination of allene to the palladium considered as an alternative pathway for nonacidic nucleophiles, where highly favorable coordination of allene to the palladium considered as an alternative pathway for nonacidic nucleophiles, where highly favorable coordination of allene to the palladium considered as an alternative pathway for nonacidic nucleophiles, where highly favorable coordination of allene to the palladium considered as an alternative pathway for nonacidic nucleophiles, where highly favorable coordination of allene to the palladium considered as an alternative pathway for nonacidic nucleophiles, where highly favorable coordination of allene to the palladium considered as an alternative pathway for nonacidic nucleophiles, where highly favorable coordination of allene to the palladium considered as an alternative pathway for nonacidic nucleophiles, where highly favorable 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