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Palladium catalyzed intramolecular nucleophilic addition of allylic species, generated from allene, to aryl aldehydes and ketones

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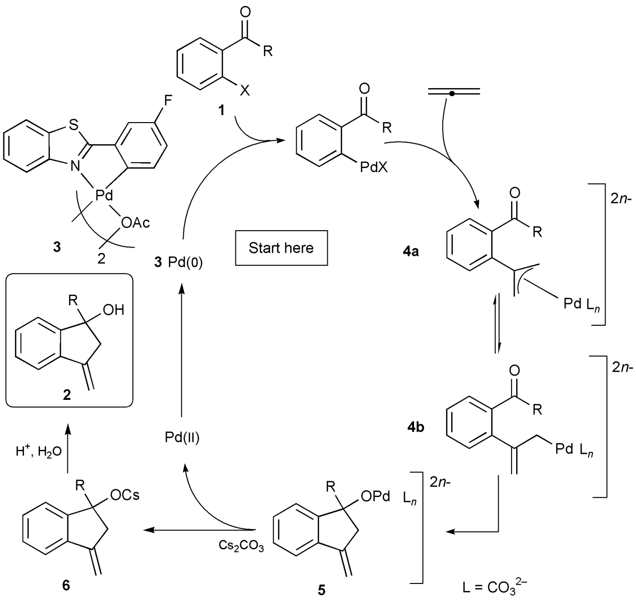
2-Haloaryl aldehydes and ketones react with allene (1 atm) in the presence of 2 mol% of a non-phosphine cyclopalladated catalyst to afford cyclopentenols and cyclohexenols *via* nucleophilic cyclisation of intermediate π-allylpalladium species. A possible mechanism for this unusual reactivity is suggested.

One of the major features of palladium catalysed processes is their tolerance of a wide range of functional groups. However, the versatility of palladium catalysts would be considerably enhanced if they incorporated, in a predictable way, reaction with functional groups heretofore immune to palladium catalysts. Arguably the most important 'immune' functional group is the carbonyl group. We[1,2] and others[3] have recently reported bimetallic Pd/In catalysis that permits both inter- and intramolecular allylation of carbonyl groups. Others have reported intramolecular vinylation and arylation of carbonyl groups[4] or nitriles[5] *via* undefined nucleophilic palladium species. In addition palladium(II)-catalysed aldol reactions have been reported.[6]

Allylation of carbonyl compounds is well known for the nucleophilic allyl derivatives of main group metals[7] whereas π-allylpalladium(II) species are usually electrophilic.[8] In order to explore the desired unusual reactivity of π-allylpalladium(II) species we elected to utilize a novel non-phosphine-containing palladacycle **3**[9] as catalyst and allene as the source of the π-allyl species (Scheme 1).

2-Iodo- and 2-bromobenzaldehyde **1a** and **1b** were found to react with allene (1 atm) in DMF at 80 °C over 18 h in the presence of 2 mol% **3** and Cs_2CO_3 (2 mol eq.) to afford the desired benzocyclopentenol **2a** (Table 1, entry 1). The iodoaldehyde **1a** was more reactive than bromoaldehyde **1b**. The reaction proved to be general for a range of substrates, **1b–1f** furnishing both 5-membered, **2a–2d**, and 6-membered, **2e**, **2f**, products. Arylalkyl ketones (Table 1, entry 2) and diaryl ketones (Table 1, entries 3,4) reacted to give the expected products with formation of 5-membered products proving more efficient than formation of 6-membered products for the limited examples surveyed thus far. 2-(2-Bromophenyl)indane-1,3-dione **1f** gave **2f** (Table 1, entry 6), the product of dehydration of the expected cyclohexenol. The processes described herein occur under significantly milder conditions than the other reported examples of nucleophilic Pd^{II} species. Evidence to hand thus far[9] suggests that palladacycle **3** functions *via* controlled release of Pd^0 nanoparticles[11] and that Scheme 1 involves Pd^0/Pd^{II} rather than Pd^{II}/Pd^{IV}.[12]



Scheme 1

Cs_2CO_3 was the superior base of those (Cs_2CO_3, K_2CO_3, KOAc) tested. Possible mechanisms for the processes described herein and those reported previously[3–5] must account for the fact that only intramolecular processes forming 5- and 6-membered rings have been observed. A possible rationalization is shown in Scheme 1.

The key features of Scheme 1 are that coordination of the carbonate anions to Pd^{II} produces anionic η^3- and η^1-species **4a** and **4b**. The η^1-species **4b** is then postulated to undergo bond shift as depicted in **8** or **9**. The ability of carbonate to function as a mono- or hemilabile bidentate ligand might also be a factor. A common problem to both Scheme 1 and the previously reported nucleophilic vinyl and aryl palladium(II) species[4,5] is the mechanism by which Pd^{II} is reduced to Pd^0 to allow catalyst recycling. It is instructive that the reactions reported herein and the related work[4,5] all employ DMF as solvent. It is clear that DMF from certain sources contains formate impurities,[13] or that such impurities may be generated *in situ*, and these then react with Pd^{II} to produce HPdX which is then converted by base to Pd^0. In Yamamoto's examples, addition of 5 mol eq. of a primary alcohol is necessary. Although the role of the primary alcohol is not entirely clear it is not, apparently, active as a reductant for Pd^{II} to Pd^0.

The potentially bidentate CO_3^{2-} anion might be expected to be more effective in generating a carbon nucleophile perhaps *via* trace amounts of allyl anion **9** whose effective molarity[14] would be high, which would account for the failure to observe the analogous intermolecular reactions.

It seems likely that anionic Pd^{II} species may be important in the nucleophilic processes reported herein and those reported previously by Yamamoto.[4] Larock's nitrile–alkyne examples[5] do not employ inorganic bases but polyhalo anionic Pd^{II} species would appear to play a role in these phosphine free cases employing R_4NCl[14]. Although anionic Pd^{II} species have been detected in Heck reactions[14] they were not catalytically active in this reaction.

A further interesting and unresolved feature in many instances of Pd^0 nanoparticle catalysis is whether the catalytic processes occur on the surface of the nanoparticle at edges and/or vertices or in homogeneous solution by substrate leaching of the Pd^0.

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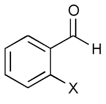
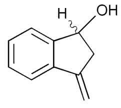
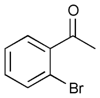
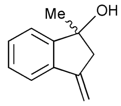
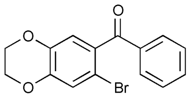
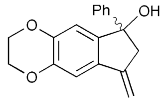
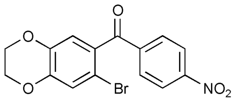
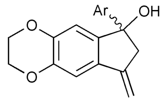
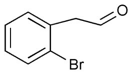
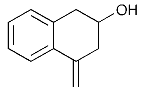
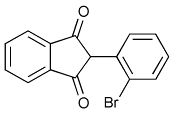
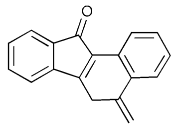
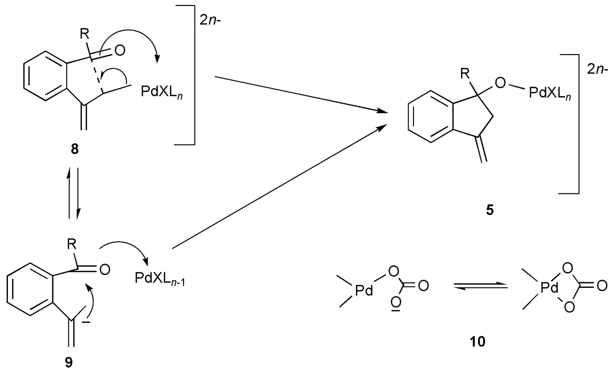
Table 1 Generation and intramolecular capture of allylic species from **1a–j** and allene catalysed by **3**[a]

Entry	Substrates	Temp[b]/°C	Time/h	Products	Yield[c] %
1	 **1a**	80	18	 **2a**	90(95[d])
2	 **1b**	90	18	 **2b**	70(90[d])
3	 **1c**	88	21	 **2c**	70(75[d])
4	 **1d**	88	18	 **2d**	81
5	 **1e**	80	18	 **2e**	34
6	 **1f**	90	23	 **2f**	45

[a] Reactions carried out in DMF employing 2 mol% catalyst and Cs_2CO_3 (2 mol eq.). [b] Oil bath temperature. [c] Isolated yield. [d] Conversion calculated by ^{1}H-NMR.



Further studies of these and related processes are underway.

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