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The first example of palladium-catalyzed intermolecular allylaryloxylation of an internal alkyne by allyl aryl ethers

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The allylaryloxylation of an internal alkyne by allyl aryl ethers was realized by $\mathrm{Pd(dba)_2/P(OPh)_3}$ catalyst system to afford *cis* adducts in moderate yields.

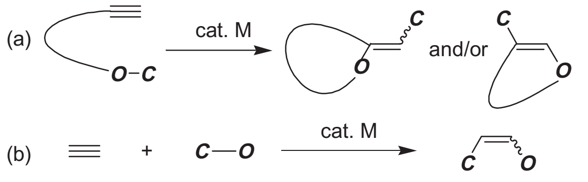
The simultaneous addition of carbon and oxygen functional groups across the carbon–carbon triple bonds is very useful transformation to prepare compound with a vinyl ether framework by a single step. Some transition-metal catalyzed intramolecular additions based on this strategy have been reported (Scheme 1a).[1] Furthermore, nickel catalyzed intermolecular C—O bond additions to alkynes accompanied by elimination of carbon monoxide and isocyanate have recently been developed.[2] However, to the best of our knowledge, intramolecular direct addition of C—O bond to alkyne has not been documented (Scheme 1b).[3]

On the other hand, we have reported a series of palladium and platinum catalyzed decarbonylative and CO-retained inter- and intramolecular carbothiolation and carboselenation of alkynes.[4–6]

Herein reported is the first example of intramolecular direct addition of C—O bond to an alkyne. Because we have reported that ethyl phenylpropiolate (**1a**) exhibited high reactivity toward the insertion into the S—Pt bond of *trans*-$\mathrm{Pt(Cl)(SAr)(PPh_3)_2}$ as well as the Pt-catalyzed decarbonylative carbothiolation,[5f] the reaction of **1a** with allyl phenyl ether (**2a**) was examined (Table 1). Although $\mathrm{Pd(PPh_3)_4}$ showed the catalytic activity, the yield of the anticipated product **3a** was very low (entry 1).

Contrary to the case of the aryl thiolation and acyl thiolation of alkynes by thioesters,[5b,m] $\mathrm{Pt(PPh_3)_4}$ did not exhibit the catalytic activity (entry 2). Other phosphine ligands such as $\mathrm{P(C_6H_4CF_3\text{-}}p)$, $\mathrm{PCy_3}$, $\mathrm{P(2\text{-}furyl)_3}$, dppm, dppp, dppf, and dppBz with the combination of $\mathrm{Pd(dba)_2}$ did catalyze the reactions, but the yields were unsatisfactory (Entries 3–9). Platinum dichloride ($\mathrm{PtCl_2}$), which is known to be an efficient catalyst for the intramolecular carboalkoxylation,[1a,c] did not catalyze the formation of **3a** (entry 10). While the reaction with $\mathrm{Pd(dba)_2}$/dppe as a catalyst afforded the anticipated **3a** in 36% yield (entry 11), the use of dppe with the combination of other transition-metal complexes such as $\mathrm{Rh(PPh_3)_3Cl}$, $\mathrm{[Rh(cod)_2Cl]_2}$, and $\mathrm{Ru(PPh_3)_3Cl_2}$ have failed (Entries 12–14). Neither *N*,*P* nor *N*,*N* bidentate ligand showed catalytic activity (Entries 15 and 16). Although $\mathrm{Pd(dba)_2/P(OEt)_3}$ was not active (entry 17), $\mathrm{Pd(dba)_2/P(OAr)_3}$ catalyzed the reactions to afford the desired **3a** (Entries 18–24). When 2 equiv of **1a** for **2a** was employed, the yield of **3a** was improved (entry 18 vs entry 19). Among examined, the combination of $\mathrm{Pd(dba)_2/P(OPh)_3}$ with 2 equiv of **1a** gave the best yield to furnish **3a** in 52% isolated yield as a thermodynamically stable oil (entry 20).

The structure of **3** was unambiguously determined by HSQC, HMBC, and 2D-NOESY spectroscopies using **3b** (vide infra) as a representative compound. As for the by-products of the reaction,



Scheme 1. Transition-metal catalyzed intra- and intermolecular addition of C—O bond to alkynes.

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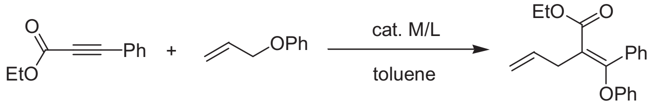
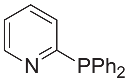
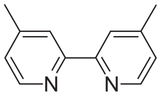
Table 1
Screening of transition-metal catalysts for the addition of **2a** to **1a**[a]



1a **2a** **3a**

Entry	M	L	**3a** (%)[b]
1	$Pd(PPh_3)_4$	None	4
2	$Pt(PPh_3)_4$	None	0
3	$Pd(dba)_2$	$P(C_6H_4CF_3\text{-}p)_3$	1
4	$Pd(dba)_2$	PCy_3	25
5	$Pd(dba)_2$	P(2-furyl)$_3$	3
6	$Pd(dba)_2$	dppm	9
7	$Pd(dba)_2$	dppp	10
8	$Pd(dba)_2$	dppf	7
9	$Pd(dba)_2$	dppBz	9
10	$PtCl_2$	None	0
11	$Pd(dba)_2$	dppe	36
12	$Rh(PPh_3)_3Cl$	dppe	0
13	$[Rh(cod)_2Cl]_2$	dppe	0
14	$Ru(PPh_3)_3Cl_2$	dppe	0
15	$Pd(dba)_2$		0
16	$Pd(dba)_2$		0
17	$Pd(dba)_2$	$P(OEt)_3$	0
18	$Pd(dba)_2$	$P(OC_6H_4OMe\text{-}p)_3$	29
19[c]	$Pd(dba)_2$	$P(OC_6H_4OMe\text{-}p)_3$	52
20[c]	$Pd(dba)_2$	$P(OPh)_3$	60 (52)[d]
21[c]	$Pd(dba)_2$	$P(OC_6H_4Me\text{-}p)_3$	52
22[c]	$Pd(dba)_2$	$P(OC_6H_4Cl\text{-}p)_3$	58
23[c]	$Pd(dba)_2$	$P(OC_6H_3OMe\text{-}p)_3$	25
24[c]	$Pd(dba)_2$	$P(OC_6H_4OCF_3\text{-}p)_3$	20
25[e]	$Pd(dba)_2$	$P(OPh)_3$	63

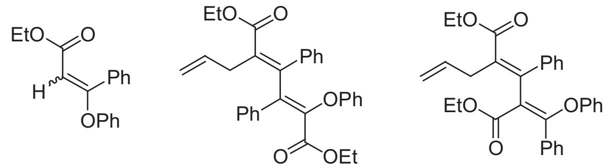
[a] Unless otherwise noted, **1a** (1.2 mmol), **2a** (1.0 mmol), M (5 mol %), L (12 mol % for monodentate, and 6 mol % for bidentate ligand) was treated under toluene reflux for 24 h.

[b] NMR yield.

[c] 2 mmol of **1a**.

[d] Isolated yield.

[e] 2 mmol of methyl phenylpropiolate (**1b**) in stead of **1a**.



4 **5** **6**

Scheme 2. Structures of possible by-products.

compound **4**, the adduct of PhOH to **1a** as well as **5** or **6**, in which two molecules of **1a** are incorporated, were indicated by ^{1}H NMR and mass spectroscopies together with a small amount of isomer of **3** (Scheme 2). The reaction of methyl phenylpropiolate (**1b**) with **2a** afforded the corresponding adduct in a moderate yield (entry 25). The reaction is quite sensitive to substituents in Ar of EtOC(O)CCAr (**1**). Unfortunately, introductions of electron-donating, electron-withdrawing, and *o*-hydroxyl groups totally suppressed the reactions (Scheme 3, **1c**–**1f**). The alkyne **1g** with $C(O)OCH_2Cl_3$ group, which is a good substituent for $PtCl_2$ catalyzed intramolecular trans addition of C—O bond, did not promote the present transformation.[1a] The substitution of Ph by 2-thienyl group (**1h**), C(O)OEt by 3-pyridyl (**1i**), and C(O)OEt by C(O)Me (**1j**) also hampered the reactions.

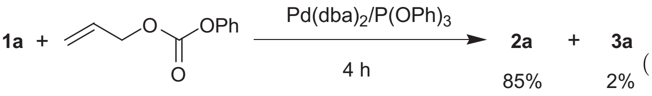
The results of the additions of **2** with different substituents to **1a** were summarized in Table 2. It turned out that no clear relationship between electronic effect and yield of **3** was observed: The corresponding **3** were produced in a range of 16–60% yields. On the other hand, no reaction took place by the treatment of $CH_2{=}C(Ph)CH_2OPh$ (**2j**) with **1a**.

The possible reaction mechanisms for the present Pd-catalyzed allylaryloxylation of **1a** by **2** are shown in Scheme 4.

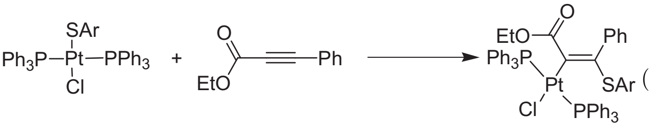
The reaction can be triggered by the oxidative addition of **2** to Pd(0) complex to afford π-allyl palladium **7**.[7] Then regio- and stereoselective *cis* insertion of **2** into either O—Pd bond or C—Pd bond can furnish **8** or **9**. Then C—C or C—O bond-forming reductive elimination from the Pd(II) complex can conclude one catalytic cycle.

To get information about the reaction mechanism, the reaction of **1a** with ally phenyl carbonate ($C_3H_5OC(O)OPh$, **10**) was examined (Eq. (1)).

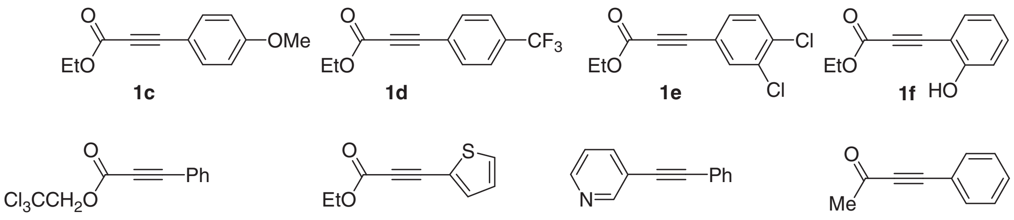
After 4 h under toluene reflux, the decarbonylated **2a** was produced in 85% yield together with 2% of **3a**. One possible explanation of this fact is that even when the π-allyl Pd-complex such as **7** was generated via oxidative addition of **10** to Pd(0) and the subsequent elimination of CO_2, **1a** is hardly incorporated into the palladium complex and the equilibrium between **2**/Pd(0) and **7** strongly leans to the former side. For the insertion of **1a** into the groups 16 and 10 element bond, we have already reported that the *cis* insertion of **1a** into the S—Pt bond of *trans*-$Pt(Cl)(SAr)(PPh_3)_2$ (**11**) with Pt at the α-carbon of CO_2Et and SAr at α-carbon of Ph group (Eq. (2)).[5f] It should be noted that the Pt-OEt distance (3.0 Å) of the resultant vinyl platinum **12** was within the sum of the van der Waals radii (3.2 Å), implying that the interaction between Pt and O atoms plays a crucial role in achieving regioselective *cis* insertion of **1a** into the S—Pt bond of **11**.



10 (1)



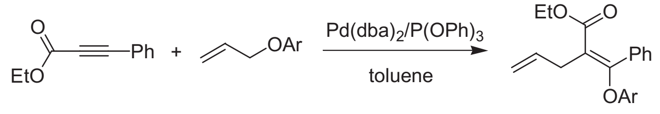
11 **1a** **12** (2)



1c **1d** **1e** **1f** **1g** **1h** **1i** **1j**

Scheme 3. Inert allynes toward the addition of **2a**.

Table 2
Palladium-catalyzed addition of **2** to **1a**[a]

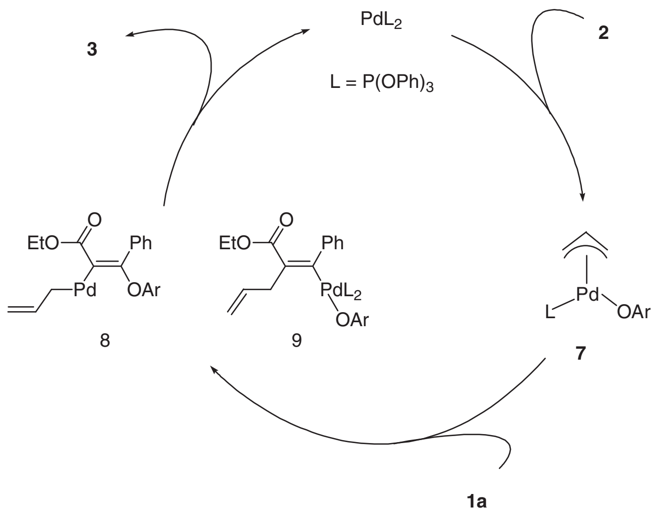


1a **2** **3**

Entry	Ar	2	3	yield (%)[b]
1	Ph	**2a**	**3a**	60 (52) [b]
2	C_6H_4Me-*p*	**2b**	**3b**	31
3	C_6H_4OMe-*p*	**2c**	**3c**	18
4	$C_6H_4NO_2$-*p*	**2d**	**3d**	40
5	$C_6H_4CF_3$-*p*	**2e**	**3e**	46
6	C_6H_4CN-*p*	**2f**	**3f**	44
7	$C_6H_4C(O)Me$-p	**2g**	**3g**	16
8	C_6H_4Cl-*o*	**2h**	**3h**	41
9	C_6H_4Ph-*p*	**2i**	**3i**	49

[a] **1a** (2.0 mmol), **2** (1.0 mmol), Pd(dba)$_2$ (5 mol %), P(OPh)$_3$ (12 mol %) was treated under toluene reflux for 24 h.

[b] Isolated yield.



Scheme 4. Possible reaction mechanisms.

On the basis of above discussion, we propose the mechanism involving the formation of **7**, regio- and stereoselective cis insertion of **1a** into the O—Pd bond of **7** to produce vinyl palladium **8**, and the following C—C bond-forming reductive elimination of **3** as the most probable pathway. Although the room to improve the reactivity and selectivity still remain unsolved, we believe that the potential of direct addition of C—O bond to unsaturated bond is presented by this study.

Acknowledgments

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