DOI: 10.1002/adsc.201300225

Palladium-Catalyzed Regioselective and Stereoselective Oxidative Heck Arylation of Allylamines with Arylboronic Acids

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Received: March 16, 2013; Published online: May 15, 2013

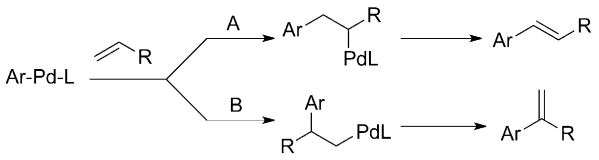
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201300225.

Abstract: A general and convenient palladium-catalyzed oxidative Heck arylation of both *N*-protected and *N*,*N*-diprotected allylic amines with arylboronic acids under mild conditions has been developed. The catalyst system, consisting of $Pd(OAc)_2$ (palladium acetate), AgOAc (silver acetate) and KHF_2 (potassium hydrogen fluoride), could efficiently catalyze the coupling reaction in acetone without the aid of any ligand, leading exclusively to the γ-arylated allylic amine products in good to excellent yields. This method is highlighted with excellent regio- and stereocontrol and remarkable functional group tolerance. The carbamate moiety in allylic amine substrates is of crucial importance to the catalytic performance, and the chelation between the carbonyl O (oxygen) and Pd (palladium) atoms is believed to be responsible for the high regioselectivity and stereoselectivity observed.

Keywords: allylic amines; arylation; oxidative Heck reaction; palladium; regioselectivity

Introduction

Allylic amine derivatives are structural motifs found in many natural and biologically active compounds, and they also serve as valuable synthetic intermediates in various transformations.[1,2] Accordingly, a significant research effort has been put into the efficient construction of these compounds, and a number of methods can now be found in the literature.[3–5] Among these reported methods, the Pd-catalyzed Heck arylation of allylic amines with aryl halides and pseudohalides has been extensively investigated, and useful strategies have been developed to control the product regioselectivity, which arises from the two competing reaction pathways (Scheme 1).[4,5] In recent years, the catalytic oxidative Heck coupling of organoborons with olefins has become a rapidly expanding area of research and is emerging as a powerful complement to the normal Heck reaction, because of its mild conditions, low toxicity, high functional group tolerance and easy availability of organoborons.[6] Considerable advances have been made through the development of more active transition metal catalyst systems,[7–9] and the contributions from the groups of Larhed[8] and Jung[9] are particularly noteworthy. Although a variety of electron-deficient, electron-rich and electron-neutral olefins could be successfully arylated with organoboronic acids and their derivatives to afford high yields and selectivities, examples of the oxidative Heck arylation of allylic amines are very rare, with only one report available in the literature. Sigman et al. revealed that arylboronic esters could undergo regioselective (linear) coupling reaction with allylic amines in the presence of a Pd-carbene catalyst and O_2 (Scheme 1, path A),[7l] but only two *N*,*N*-diprotected allylic amines containing a carbamate moiety were attempted. Therefore, more general and efficient catalyst systems for oxidative Heck coupling of allylic amines with organoborons are desirable.



Scheme 1. Two competing pathways.

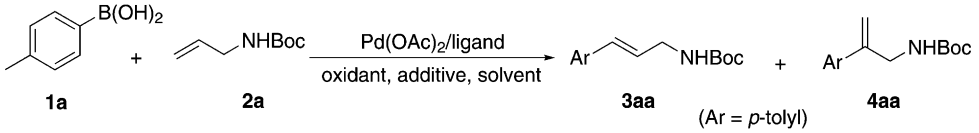
Recently, we found that the combination of $Pd(OAc)_2$ and dppp [1,3-bis(diphenylphosphino)propane] in ethylene glycol constitutes a highly effective catalyst system for the internal Heck arylation of *N*-Boc-allylamine with aryl bromides (Scheme 1, path B),[10a] and $Pd(OAc)_2$ could catalyze the Heck coupling reaction of aryl bromides with bulky *N*,*N*-diprotected allylic amines under ligand-free conditions to give the γ-arylated products in a highly regioselective and stereoselective manner (Scheme 1, path A).[10b] More recently, we have developed a mild and efficient catalytic method for the highly regioselective and stereoselective direct γ-arylation of *N*,*N*-diprotected allylic amines with thiophenes and furans in the presence of $Pd(OAc)_2$ and appropriate oxidants (Scheme 1, path A).[10c] It was found that the use of allylic amine substrates containing a carbamate moiety was crucial to ensure good catalyst performance, and the steric properties of these allylic amines greatly affected the regiocontrol. Encouraged by these results and in continuing our interest in the regioselective arylation of olefins, herein, we report a general and effective palladium catalyst system consisting of $Pd(OAc)_2$ and appropriate additives that efficiently catalyzes the highly regioselective and stereoselective oxidative Heck reaction of organoboronic acids with both *N*-protected allylic amines and *N*,*N*-diprotected allylic amines under ligand-free conditions. The catalyst system displays broad functional group tolerance at both coupling partners, and provides a robust, complementary approach to existing methods.

Results and Discussion

With *p*-tolylboronic acid **1a** as the model substrate and *N*-Boc-allylamine **2a** as the model olefin, we started our screening studies for the establishment of suitable reaction conditions. Initially, the coupling reaction was carried out in acetone at 60 °C in the presence of a catalytic amount of $Pd(OAc)_2$ with O_2 as the oxidant under ligandless conditions, but no reaction occurred (Table 1, entry1). Replacing O_2 with BQ (1,4-benzoquinone) still did not result in any discernible reaction (Table 1, entry 2). Several silver salts were then examined (Table 1, entries 3–8), and the best yield of 46% was obtained in the case of AgOAc (Table 1, entry 5). It is notable that only linear γ-arylated (*E*)-allylic amine **3aa** was produced in all these cases without the *Z* stereoisomer and the branched isomer **4aa** being detected. This is remarkable since the previous observations show that the bulkiness of the substituent on the allylic amine nitrogen has a decisive effect on the regiocontrol, and the arylation of **2a** under ligand-free conditions generally leads to a mixture of γ- and β-arylated allylic amines due to the reduced steric hindrance.[5e,k,10] The performance of copper oxidants was also explored (Table 1, entries 9 and 10), but none of them could work as effectively as AgOAc. Increasing the amount of AgOAc to 2 equivalents could increase the yield to 66% (Table 1, entry 11). Considering the remarkable effect of fluoride ion on promoting the Suzuki–Miyaura reaction[11]and oxidative Heck reaction,[7j,q] we next investigated the effect of fluoride ion in this study. Delightfully, the reaction finished in 8 h in the presence of KHF_2, exclusively affording the desired product **3a** in 95% yield (Table 1, entry 12). The addition of KF and CsF could also enable the reaction to go to completion (Table 1, entries 13 and 14), but the reaction was less efficient due to the formation of the unwanted homcoupling product of **1a**. In order to further improve the efficiency, a survey of solvent effect was made. Lower yields were achieved in CH_3CN and water (Table 1, entries 15 and 16), and the reaction was totally inhibited in DMF, DMSO and NMP (Table 1, entries 17–19). Employing $Pd(OAc)_2$ as the source of palladium was important for this transformation, as catalysts derived from other Pd precursors were not very efficient (Table 1, entries 20–22). The catalyst system comprising $Pd(OAc)_2$, CuF_2 and KHF_2, which has been shown to efficiently catalyze the oxidative Heck arylation of allyl esters with arylboronic acids in a highly regio- and stereoselective manner,[7j] could also work well in our case (Table 1, entry 23). However, the necessity of two equivalents of CuF_2 and KHF_2 made this chemistry less attractive. Further study revealed that the reaction with the $Pd(OAc)_2$/dppp catalyst system[7f] without using the external oxidant, that is, under an N_2 atmosphere, proved to be ineffective as no product formation was observed (Table 1, entry 24). White's protocol, reported to be highly effective for the selective oxidative Heck reaction of arylboronic acids with olefins,[7g] was also tested, but it only afforded an inferior yield of 30% (Table 1, entry 25). Thus the optimal reaction conditions were finally determined as follows: $Pd(OAc)_2$ (5 mol%), AgOAc (2 equiv.) and KHF_2 (1 equiv.) in acetone at 60 °C. It should be stressed that in all cases no observation of allylic migration or partial deprotection was made.

Having the optimal reaction conditions in hand, we next examined the reaction of **2a** with a range of arylboronic acids. As shown in Table 2, all of the reactions proceeded efficiently, providing the expected γ-arylated linear (*E*)-allylic amine products in good to excellent yields. It is worth noting that excellent regioselectivivites (terminal/internal $>99:1$) and stereoselectivities ($E/Z>99:1$) were observed in these transformations, and no regioisomer and stereoisomer could be detected. Notably, this catalyst system tolerated not only functional groups with varying electronic properties, but at different substitution positions as

Table 1. Screening conditions for oxidative Heck arylation of *p*-tolylboronic acid (**1a**) with *N*-Boc-allylamine (**2a**).[a]



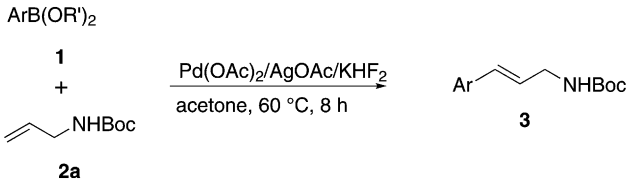
Entry	Solvent	Oxidant (equiv.)	Additive (equiv.)	Yield [%][b]
1	acetone	O_2	none	nd
2	acetone	BQ (1)	none	nd
3	acetone	Ag_2SO_4 (1)	none	12
4	acetone	$AgNO_3$ (1)	none	28
5	acetone	AgOAc (1)	none	46
6	acetone	Ag_2CO_3 (1)	none	30
7	acetone	AgOTf (1)	none	9
8	acetone	Ag_2O (1)	none	40
9	acetone	$Cu(OAc)_2$ (1)	none	nd
10	acetone	CuF_2 (1)	none	nd
11	acetone	AgOAc (2)	none	66
12	acetone	AgOAc (2)	KHF_2 (1)	95
13	acetone	AgOAc (2)	KF (1)	86
14	acetone	AgOAc (2)	CsF (1)	76
15	CH_3CN	AgOAc (2)	KHF_2 (1)	68
16	H_2O	AgOAc (2)	KHF_2 (1)	61
17	DMF	AgOAc (2)	KHF_2 (1)	nd
18	DMSO	AgOAc (2)	KHF_2 (1)	nd
19	NMP	AgOAc (2)	KHF_2 (1)	nd
20[c]	acetone	AgOAc (2)	KHF_2 (1)	80
21[d]	acetone	AgOAc (2)	KHF_2 (1)	60
22[e]	acetone	AgOAc (2)	KHF_2 (1)	80
23[f]	acetone	AgOAc (2)/CuF_2 (1)	KHF_2 (2)	92
24[g]	acetone	none	none	nd
25[h]	dioxane	BQ (2)	AcOH (4)	30

[a] *Reaction conditions*: **1a** (0.5 mmol), **2a** (1.0 mmol), $Pd(OAc)_2$ (0.025 mmol), oxidant, additive, solvent (2.5 mL), 60 °C, 8 h. No **4aa** was detected in all reactions. nd: not detected. Boc = *tert*-butyloxycarbonyl.
[b] Isolated yield.
[c] $PdCl_2$ was used to replace $Pd(OAc)_2$.
[d] $Pd_2(dba)_3$ was used to replace $Pd(OAc)_2$.
[e] $Pd(COCF_3)_2$ was used to replace $Pd(OAc)_2$.
[f] Reaction temperature 85 °C, 5 h.
[g] **1a** (1.0 mmol), **2a** (2.0 mmol), $Pd(OAc)_2$ (2 mol%), dppp (3 mol%), acetone (3 mL), 70 °C, 20 h, N_2.
[h] **1a** (1.5 mmol), **2a** (1.0 mmol), Pd(II)/phenyl bis-sulfoxide (10 mol%), BQ (2.0 mmol), AcOH (4.0 mmol), dioxane (3.0 mL), room temperature, 24 h.

well. Of particulate note is that the sensitive halogen substituent (Br and Cl) in the aromatic ring of arylboronic acids did not affect the yields of the desired products (Table 2, entries 7 and 8), and the obtained products can serve as useful starting materials for further elaboration. Of further interest is that hydroxymethyl group could well survive the reaction conditions, giving the corresponding product in good yield (Table 2, entry 13). Steric effects appear to have little influence on the reaction efficiency, as evidenced by the fact that we encountered no problem in the olefination of arylboronic acids bearing *ortho*-substitutents (Table 2, entries 2, 5, 10). The reaction is not limited to arylboronic acids only; heteroarylboronic acid and alkenylboronic acid participated equally well to afford the corresponding allylic amines in good yields (Table 2, entries 22 and 23). The catalyst system also worked effectively for the highly selective olefination of other organoborons. It was found that arylboronic esters and potassium aryl trifluoroborates[8i] (Table 2, entries 24 and 25) displayed similar reactivity to their boronic acid analogues. Noteworthy is that all the substrates underwent clean conversions without formation of the allylic migration products or homocoupling products.

Encouraged by the successful arylation of **2a**, we then extended our research to other allylic amine derivatives, and the results are shown in Table 3. For *N*-protected allylic amines **2b** and **2c**, high yields of the expected products were obtained under the conditions

Table 2. Oxidative Heck arylation of **2a** with arylboronic acids.[a]



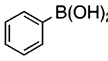
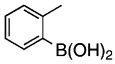
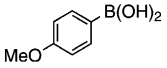
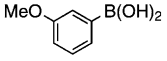
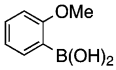
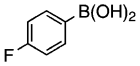
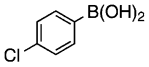
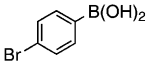
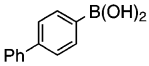
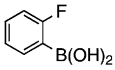
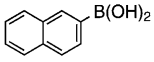
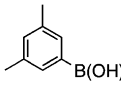
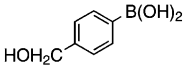
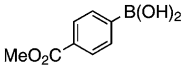
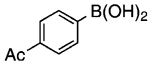
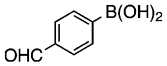
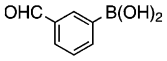
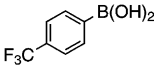
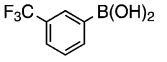
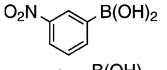
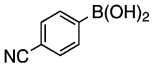
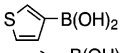
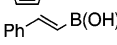
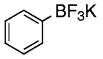
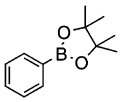
Entry	Arylboronic Acid **1**		Yield [%][b] (Product)
1		**1b**	96 (**3ba**)
2		**1c**	90 (**3ca**)
3		**1d**	91 (**3da**)
4		**1e**	90 (**3ea**)
5		**1f**	90 (**3fa**)
6		**1g**	90 (**3ga**)
7		**1h**	91 (**3ha**)
8		**1i**	90 (**3ia**)
9		**1j**	88 (**3ja**)
10		**1k**	90 (**3ka**)
11		**1l**	83 (**3la**)
12		**1m**	84 (**3ma**)
13		**1n**	82 (**3na**)
14		**1o**	75 (**3oa**)
15		**1p**	73 (**3pa**)
16		**1q**	81 (**3qa**)
17		**1r**	80 (**3ra**)
18		**1s**	87 (**3sa**)
19		**1t**	87 (**3ta**)
20		**1u**	90 (**3ua**)
21		**1v**	90 (**3va**)
22		**1w**	75 (**3wa**)
23		**1x**	83 (**3xa**)

Table 2. (Continued)

Entry	Arylboronic Acid **1**		Yield [%][b] (Product)
24		**1y**	95 (**3ba**)
25		**1z**	93 (**3ba**)

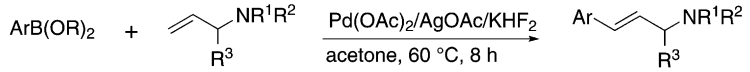
[a] *Reaction conditions*: **1** (0.5 mmol.), **2a** (1.0 mmol), $Pd(OAc)_2$ (5 mol%), AgOAc (1.0 mmol), KHF_2 (0.5 mmol), acetone (2.5 mL), 60 °C, 8 h.
[b] Isolated yield.

established for **2a** regardless of the nature of the substituents on the aryl ring and allylic amine nitrogen, and the regioselectivity and stereoselectivity are similar to that observed in the arylation of **2a** (Table 3, entries 1–8). Similarly, arylation of *N,N*-diprotected allylic amines with various arylboronic acids proceeded smoothly to exclusively afford γ-arylated linear (*E*)-allylic amines in good to excellent yields, and a range of functional groups in both coupling partners were well tolerated (Table 3, entries 9–24). It is notable that the allylamine **2f**, which was previously shown to be less reactive,[7l] could be readily arylated to furnish the expected products (Table 3, entries 15 and 16). The viability of the current catalyst system was further demonstrated in the highly regioselective and stereoselective arylation of α-substituted allylic amine **2j** (Table 3, entries 25 and 26). The frequently encountered partial deprotection in the arylation of *N,N*-diprotected allylic amines did not take place in our case.[5j,10b,c]

We also explored the reaction of β-arylated allylic amines **2k** and **2l** with arylboronic acids, and the desired products were isolated in satisfactory yields (Table 4). It is worth noting that these highly substituted allylic amines have been confirmed to be of *Z* configuration by NMR spectroscopy. However, no reaction was observed in the reaction of electron-rich *N,N*-diethylallylic amine (**2m**). It is believed that the strong coordination of the nitrogen atom of allylic amine **2m** to Pd could cause catalyst poisoning, thereby inhibiting the arylation. Similar poor performance of *N,N*-dialkylallylic amines has been reported recently.[4b,5k,10b,c] It appears that the presence of a carbamate group in allylic amine substrates is necessary for high catalytic activity.

Taking all the data presented in Table 2, Table 3 and Table 4 into account, it is evident that the arylation shows almost negligible sensitivity to the steric characteristics of the substituent on the allylic amine nitrogen, but the electronic properties of the substrates has a significant impact on the catalytic activity and selectivity. Recently Jiao and his co-workers reported high levels of regio-, and stereocontrol ex-

Table 3. Oxidative Heck arylation of allylic amines **2b–i** with arylboronic acids.[a]



1 **2b–j** **3**

2b: R^1= Ac, R^2 = H, R^3 = H; **2c**: R^1 = Cbz, R^2 = H, R^3 = H; **2d**: R^1 = Boc, R^2 = Me, R^3 = H;
2e: R^1 = CH_2(1-Naph), R^2 = CO_2Et, R^3 = H; **2f**: R^1 = Cbz, R^2 = Me, R^3 = H;
2g: R^1 = Boc, R^2 = Boc, R^3 = H; **2h**: R^1 = Boc, R^2 = Cbz, R^3 = H; **2i**: R^1, R^2 = Pht, R^3 = H;
2j: R^1, R^2 = Pht, R^3 = Me

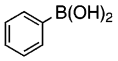
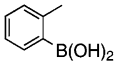
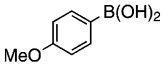
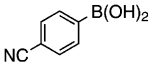
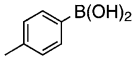
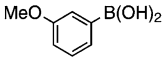
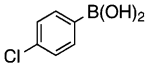
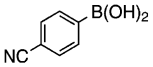
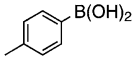
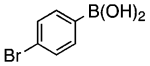
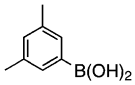
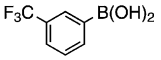
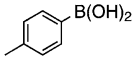
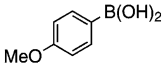
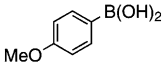
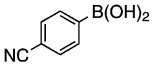
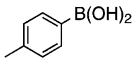
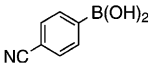
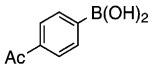
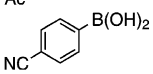
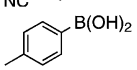
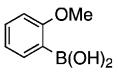
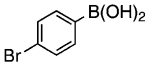
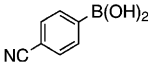
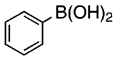
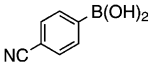
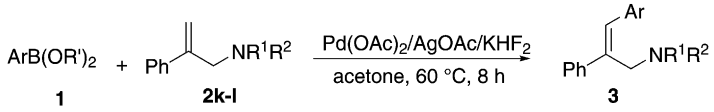
Entry	Arylboronic Acid **1**		Allylic amine **2**	Yield [%][b] (Product)
1		**1b**	**2b**	90 (**3bb**)
2		**1c**	**2b**	91 (**3cb**)
3		**1d**	**2b**	89 (**3db**)
4		**1v**	**2b**	85 (**3vb**)
5		**1a**	**2c**	90 (**3ac**)
6		**1e**	**2c**	89 (**3ec**)
7		**1h**	**2c**	90 (**3hc**)
8		**1v**	**2c**	82 (**3vc**)
9		**1a**	**2d**	83 (**3ad**)
10		**1i**	**2d**	81 (**3id**)
11		**1m**	**2d**	80 (**3md**)
12		**1t**	**2d**	82 (**3td**)
13		**1a**	**2e**	80 (**3ae**)
14		**1b**	**2e**	81 (**3be**)
15		**1d**	**2f**	85 (**3df**)
16		**1v**	**2f**	87 (**3vf**)
17		**1a**	**2g**	82 (**3ag**)
18		**1v**	**2g**	90 (**3vg**)
19		**1p**	**2h**	75 (**3ph**)
20		**1v**	**2h**	85 (**3vh**)
21		**1a**	**2i**	89 (**3ai**)
22		**1f**	**2i**	81 (**3fi**)

Table 3. (Continued)

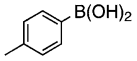
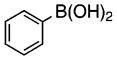
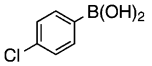
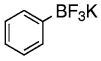
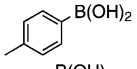
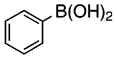
Entry	Arylboronic Acid **1**		Allylic amine **2**	Yield [%][b] (Product)
23		**1i**	**2i**	83 (**3ii**)
24		**1v**	**2i**	93 (**3vi**)
25		**1b**	**2j**	79 (**3bj**)
26		**1v**	**2j**	80 (**3vj**)

[a] *Reaction conditions*: **1** (0.5 mmol.), **2** (1.0 mmol), $Pd(OAc)_2$ (5 mol%), AgOAc (1.0 mmol), KHF_2 (0.5 mmol), acetone (2.5 mL), 60 °C, 8 h.
[b] Isolated yield.

Table 4. Oxidative Heck arylation of allylic amines **2k** and **2l** with arylboronic acids.[a]

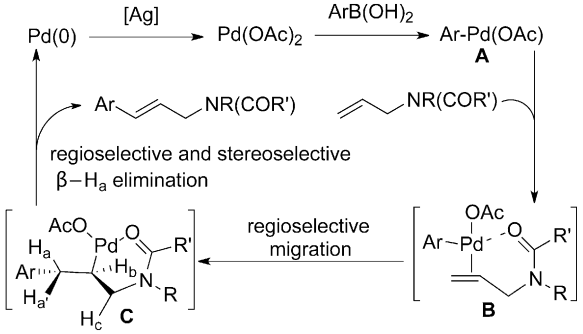


2k: R^1 = H, R^2 = Boc;
2l: R^1, R^2 = Pht

Entry	Arylboronic Acid **1**		Allylic amine **2**	Yield [%][b] (Product)
1		**1a**	**2k**	70 (**3ak**)
2		**1b**	**2k**	73 (**3bk**)
3		**1h**	**2k**	69 (**3hk**)
4		**1y**	**2k**	74 (**3bk**)
5		**1a**	**2l**	67 (**3al**)
6		**1b**	**2l**	65 (**3bl**)

[a] *Reaction conditions*: **1** (0.5 mmol.), **2** (1.0 mmol), $Pd(OAc)_2$ (5 mol%), AgOAc (1.0 mmol), KHF_2 (0.5 mmol), acetone (2.5 mL), 60 °C, 8 h.
[b] Isolated yield.

hibited in Pd-catalyzed arylation of allylic esters which were ascribed to the coordination of the carbonyl O to palladium.[7j,12] In our current investigation, this chelation effect may contribute similarly to the excellent regioselectivity and stereoselectivity observed. Accordingly, a plausible mechanism is suggested in Scheme 2. The palladium intermediate **A** generated by transmetallation of the aryl group from boron to palladium reacts with the allylic amine to form the neutral intermediate **B**. The coordination between the carbonyl O atom and Pd atom facilitates a highly regioselective migration of the aryl moiety to give intermediate **C**, in which H_a is ideally positioned, following rotation around the C–C bond, in a *syn* relationship with Pd to undergo regio- and stereoselective β-H



Scheme 2. Proposed mechanism for oxidative Heck arylation of allylic amines with arylboronic acids.

elimination to furnish the expected product. Finally, oxidation of the Pd(0) species by AgOAc regenerates the Pd(II) to complete the catalytic cycle. Similar chelation-assisted regio- and stereocontrol has also been reported in the arylation of allyl derivatives and vinyl derivatives.[4b,5k,7g,j,8e,f,13,14]

Conclusions

In summary, we have developed an efficient palladium catalyst system for oxidative Heck reactions of both *N*-protected and *N*,*N*-diprotected allylic amine derivatives with a wide range of arylboronic acids to give the γ-arylated allylic amines in good to excellent yields. The reaction proceeded highly regio- and stereoselectively under mild conditions in the absence of ligand, and a wide range of functionalities in both coupling partners could be well tolerated. Many factors, such as solvent, allylic amine derivative, oxidants and additives, influenced the catalytic efficacy, and the allylic amine substrates containing a carbamate moiety were found to be essential for securing high regioselectivity and stereoselectivity due to carbonyl coordination to Pd. This approach provides a simple and efficient pathway to access various synthetically useful γ-arylated allylic amines. Efforts focusing on the synthetic application and the mechanism of this coupling reaction are currently being made in our lab, and will be reported in due course.

Experimental Section

General Methods

Unless otherwise noted, all experiments were carried out in air. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker Model Avance DMX 400 Spectrometer (^{1}H 400 MHz and ^{13}C 106 MHz, respectively). Chemical shifts (δ) are given in ppm and are referenced to residual solvent peaks, and coupling constants (*J*) are reported in Hertz. The arylboronic acids and their derivatives, catalysts and other common materials and solvents are commercially available, and were used as received without further purification.

General Procedure for the Oxidative Heck Arylation of Allylic Amines

To an oven-dried pressure tube were sequentially added arylboronic acid **1** (0.5 mmol), allylic amine **2** (1.0 mmol), $Pd(OAc)_2$ (5.6 mg, 0.025 mmol), AgOAc (167 mg, 1.0 mmol), KHF_2 (39 mg, 0.5 mmol) and acetone (2.5 mL), and the reaction mixture was heated and stirred vigorously at 60 °C for 8 h in the sealed tube. Then the tube was removed from the oil bath and cooled to room temperature. The reaction mixture was concentrated by evaporation under vacuum and the residue was purified by column chromatography on silica gel using a mixture of ethyl acetate and hexane (10/90 to 15/85) to give the pure product.

(*E*)-*tert*-Butyl 3-*p*-tolylallylcarbamate (3aa): white solid; mp 87 °C. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 7.28$ (d, $J = 7.92$ Hz, 2H), 7.13 (d, $J = 7.96$ Hz, 2H), 6.49 (d, $J = 15.84$ Hz, 1H), 6.16 (dt, $J = 6.12$, 15.60 Hz, 1H), 4.70 (br, 1H), 3.92 (s, 2H), 2.35 (s, 3H), 1.49 (s, 9H); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta = 155.8$, 137.4, 133.9, 131.4, 129.3, 126.3, 125.3, 79.4, 42.8, 28.4, 21.2; HR-MS (ESI): $m/z = 270.1461$, calcd. for $C_{15}H_{21}NNaO_2$ $[M+Na]^+$: 270.1465.

(*E*)-*tert*-Butyl 3-(3-methoxyphenyl)allylcarbamate (3ea): colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 7.23$ (t, $J = 7.92$ Hz, 1H), 6.96 (d, $J = 7.68$ Hz, 1H), 6.90 (t, $J = 2.2$ Hz, 1H), 6.80 (dd, $J = 2.12$, 8.16 Hz, 1H), 6.48 (d, $J = 15.84$ Hz, 1H), 6.20 (dt, $J = 6.04$, 15.60 Hz, 1H), 4.81 (br, 1H), 3.92 (s, 2H), 3.82 (s, 3H), 1.49 (s, 9H); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta = 159.8$, 155.8, 138.2, 131.3, 129.5, 126.8, 119.8, 113.3, 111.7, 79.5, 55.2, 42.7, 28.4; HR-MS (ESI): $m/z = 286.1412$, calcd. for $C_{15}H_{21}NNaO_3$ $[M+Na]^+$: 286.1414.

(*E*)-Benzyl 3-(4-cyanophenyl)allyl(methyl)carbamate (3vf): yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 7.60$ (d, $J = 8.24$ Hz, 2H), 7.44 (m, 7H), 6.45 (m, 1H), 6.32 (m, 1H), 5.19 (s, 2H), 4.11 (m, 2H), 2.98 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta = 141.0$, 136.7, 132.4, 130.6, 130.1, 129.0, 128.5, 128.1, 128.0, 126.9, 118.9, 110.9, 67.3, 51.0, 50.6, 34.7, 33.9; HR-MS (ESI): $m/z = 329.1258$, calcd. for $C_{19}H_{18}N_2NaO_2$ $[M+Na]^+$: 329.1260.

(*Z*)-2-(2-Phenyl-3-p-tolylallyl)isoindoline-1,3-dione (3al): white solid, mp 83.6 °C. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta =$ 7.71 (m, 2H), 7.61 (m, 2H), 7.50 (t, $J = 8.1$ Hz, 4H), 7.28 (d, $J = 7.8$ Hz, 2H), 7.22 (d, $J = 7.9$ Hz, 3H), 6.91 (s, 1H), 4.99 (s, 2H), 2.38 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta =$ 168.1, 139.9, 136.8, 136.5, 134.2, 133.9, 133.7, 131.8, 129.1, 129.0, 128.3, 127.5, 127.0, 123.1, 37.9, 21.3; HR-MS (ESI): $m/z = 376.1311$, calcd. for $C_{24}H_{19}NNaO_2$ $[M+Na]^+$: 376.1308.

Acknowledgements

Financial support from the National Natural Science Foundation of China (21072225, 21172258 and 91127039), the Fundamental Research Funds for the Central Universities, and the Research funds of Renmin University of China (11XNL011) is greatly acknowledged.

References

[1] a) R. B. Cheikh, R. Chaabouni, A. Laurent, P. Mison, A. Nafti, *Synthesis* **1983**, 685–700; b) B. M. Trost, D. L. Van Vranken, *Chem. Rev.* **1996**, *96*, 395–422; c) D. Basavaiah, A. J. Rao, T. Satyanarayana, *Chem. Rev.* **2003**, *103*, 811–892; d) Z. Lu, S. Ma, *Angew. Chem.* **2008**, *120*, 264–303; *Angew. Chem. Int. Ed.* **2008**, *47*, 258–297; e) B. M. Trost, T. Zhang, J. D. Sieber, *Chem. Sci.* **2010**, *1*, 427–440.

[2] For some recent examples, see: a) X. Sun, L. Zhou, W. Li, X. Zhang, *J. Org. Chem.* **2008**, *73*, 1143–1146; b) T. Jiang, J. Li, *Chem. Commun.* **2009**, 7236–7238; c) B. Weiner, A. Baeza, T. Jerphagnon, B. L. Feringa, *J. Am. Chem. Soc.* **2009**, *131*, 9473–9474; d) G. C. Tsui, F.

Menard, M. Lautens, *Org. Lett.* **2010**, *12*, 2456–2459; e) A. D. Worthy, C. L. Joe, T. E. Lightburn, K. L. Tan, *J. Am. Chem. Soc.* **2010**, *132*, 14757–14759; f) X. Zhao, D. Liu, H. Guo, Y. Liu, W. Zhang, *J. Am. Chem. Soc.* **2011**, *133*, 19354–19357; g) H. Wang, Y. Wang, D. Liang, L. Liu, J. Zhang, Q. Zhu, *Angew. Chem.* **2011**, *123*, 5796–5799; *Angew. Chem. Int. Ed.* **2011**, *50*, 5678–5681; h) A. J. Young, M. C. White, *Angew. Chem.* **2011**, *123*, 6956–6959; *Angew. Chem. Int. Ed.* **2011**, *50*, 6824–6827; i) R. J. DeLuca, M. S. Sigman, *J. Am. Chem. Soc.* **2011**, *133*, 11454–11457; j) M.-B. Li, Y. Wang, S.-K. Tian, *Angew. Chem.* **2012**, *124*, 3022–3025; *Angew. Chem. Int. Ed.* **2012**, *51*, 2968–2971; k) B. A. Hopkins, J. P. Wolfe, *Angew. Chem.* **2012**, *124*, 10024–10028; *Angew. Chem. Int. Ed.* **2012**, *51*, 9886–9890.

[3] For some recent examples, see: a) V. Pace, F. Martinez, M. Fernandez, J. V. Sinisterra, A. R. Alcantara, *Org. Lett.* **2007**, *9*, 2661–2664; b) M. Utsunomiya, Y. Miyamoto, J. Ipposhi, T. Ohshima, K. Mashima, *Org. Lett.* **2007**, *9*, 3371–3374; c) D. F. Fischer, Z. Xin, R. Peters, *Angew. Chem.* **2007**, *119*, 7848–7851; *Angew. Chem. Int. Ed.* **2007**, *46*, 7704–7707; d) R. E. Kinder, Z. Zhang, R. Widenhoefer, *Org. Lett.* **2008**, *10*, 3157–3159; e) G. Liu, G. Yin, L. Wu, *Angew. Chem.* **2008**, *120*, 4811–4814; *Angew. Chem. Int. Ed.* **2008**, *47*, 4733–4736; f) T. Nishikata, B. H. Lipshutz, *Chem. Commun.* **2009**, 6472–6474; g) T. Nagano, S. Kobayashi, *J. Am. Chem. Soc.* **2009**, *131*, 4200–4201; h) H. Hikawa, Y. Yokoyama, *J. Org. Chem.* **2011**, *76*, 8433–8439; i) R. Ghosh, A. Sarkar, *J. Org. Chem.* **2011**, *76*, 8508–8512; j) M. E. Harvey, D. G. Musaev, J. D. Bois, *J. Am. Chem. Soc.* **2011**, *133*, 17207–17216; k) K. Ye, H. He, W. Liu, L. Dai, G. Helmchen, S. You, *J. Am. Chem. Soc.* **2011**, *133*, 19006–19014; l) K. Das, R. Shibuya, Y. Nakahara, N. Germain, T. Ohshima, K. Mashima, *Angew. Chem.* **2012**, *124*, 154–158; *Angew. Chem. Int. Ed.* **2012**, *51*, 150–154; m) T. Xiong, Y. Li, L. Miao, Q. Zhang, Q. Zhang, *Chem. Commun.* **2012**, *48*, 2246–2248; n) D. Banerjee, R. V. Jagadeesh, K. Junge, H. Junge, M. Beller, *Angew. Chem.* **2012**, *124*, 11724–11728; *Angew. Chem. Int. Ed.* **2012**, *51*, 11556–11560; o) K. Chen, Y. Li, S. A. Pullarkat, P.-H. Leunga, *Adv. Synth. Catal.* **2012**, *354*, 83–87; p) T. Ohshima, J. Ipposhi, Y. Nakahara, R. Shibuya, K. Mashimab, *Adv. Synth. Catal.* **2012**, *354*, 2447–2452.

[4] a) K. Olofsson, M. Larhed, A. Hallberg, *J. Org. Chem.* **2000**, *65*, 7235–7239; b) K. Olofsson, H. Sahlin, M. Larhed, A. Hallberg, *J. Org. Chem.* **2001**, *66*, 544–549; c) J. Wu, J. F. Marcous, I. W. Davis, P. J. Reider, *Tetrahedron Lett.* **2001**, *42*, 159–162; d) C. A. Baxter, E. Cleator, M. Alam, A. J. Davies, A. Goodyear, M. O'Hagan, *Org. Lett.* **2010**, *12*, 668–671; e) L. Qin, X. Ren, Y. Lu, Y. Li, J. Zhou, *Angew. Chem.* **2012**, *124*, 6017–6021; *Angew. Chem. Int. Ed.* **2012**, *51*, 5915–5919.

[5] a) P. Y. Johnson, J. Q. Wen, *J. Org. Chem.* **1981**, *46*, 2767–2771; b) C. A. Busacca, Y. Dong, *Tetrahedron Lett.* **1996**, *37*, 3947–3950; c) D. Alvisi, E. Blart, B. F. Bonini, G. Mazzanti, A. Ricci, P. Zani, *J. Org. Chem.* **1996**, *61*, 7139–7146; d) Y. Dong, C. A. Busacca, *J. Org. Chem.* **1997**, *62*, 6464–6465; e) D. H. B. Ripin, D. E. Bourassa, T. Brandt, M. J. Castaldi, H. N. Frost, J. Hawkins, P. J. Johnson, S. S. Massett, K. Neumann, J. Phillips, J. W. Raggon, P. R. Rose, J. L. Rutherford, B. Sitter, A. M. Stewart, M. G. Vetelino, L. Wei, *Org. Process Res. Dev.* **2005**, *9*, 440–450; f) N. Galaffu, S. P. Man, R. D. Wilkes, J. R. H. Wilson, *Org. Process Res. Dev.* **2007**, *11*, 406–413; g) A. Dhami, M. F. Mahon, M. D. Lloyd, M. D. Threadgill, *Tetrahedron* **2009**, *65*, 4751–4765; h) M. V. Reddington, D. C. Bryant, *Tetrahedron Lett.* **2011**, *52*, 181–183; i) E. W. Werner, M. S. Sigman, *J. Am. Chem. Soc.* **2011**, *133*, 9692–9695; j) S. Cacchi, G. Fabrizi, A. Goggiamani, A. Sferrazza, *Org. Biomol. Chem.* **2011**, *9*, 1727–1730; k) P. Prediger, L. F. Barbosa, Y. Genisson, C. R. D. Correia, *J. Org. Chem.* **2011**, *76*, 7737–7749.

[6] a) E. Negishi, A. de Meijere, *Handbook of Organopalladium Chemistry for Organic Synthesis*, Wiley-Interscience, New York, **2002**; b) B. Karimi, H. Behzadnia, D. Elhamifar, P. F. Akhavan, F. K. Esfahani, A. Zamani, *Synthesis* **2010**, 1399–1427; c) Y. Su, N. Jiao, *Current Organic Chemistry* **2011**, *15*, 3362–3388; d) W. Shi, C. Liu, A. Lei, *Chem. Soc. Rev.* **2011**, *40*, 2761–2776.

[7] a) H. A. Dieck, R. F. Heck, *J. Org. Chem.* **1975**, *40*, 1083–1090; b) C. S. Cho, S. Uemura, *J. Organomet. Chem.* **1994**, *465*, 85–92; c) X. Du, M. Suguro, K. Hirabayashi, A. Mori, *Org. Lett.* **2001**, *3*, 3313–3316; d) A. Inoue, H. Shinokubo, K. Oshima, *J. Am. Chem. Soc.* **2003**, *125*, 1484–1485; e) J. D. Crowley, K. D. Hanni, A.-L. Lee, D. A. Leigh, *J. Am. Chem. Soc.* **2007**, *129*, 12092–12093; f) J. Ruan, X. Li, O. Saidi, J. Xiao, *J. Am. Chem. Soc.* **2008**, *130*, 2424–2425; g) J. H. Delcamp, A. P. Brucks, M. C. White, *J. Am. Chem. Soc.* **2008**, *130*, 11270–11271; h) P. R. Likhar, M. Roy, S. Roy, M. S. Subhas, M. L. Kantam, B. Sreedhar, *Adv. Synth. Catal.* **2008**, *350*, 1968–1974; i) D.-C. Xiong, L.-H. Zhang, X.-S. Ye, *Org. Lett.* **2009**, *11*, 1709–1712; j) Y. Su, N. Jiao, *Org. Lett.* **2009**, *11*, 2980–2983; k) Y. Leng, F. Yang, K. Wei, Y. Wu, *Tetrahedron* **2010**, *66*, 1244–1248; l) E. W. Werner, M. S. Sigman, *J. Am. Chem. Soc.* **2010**, *132*, 13981–13983; m) Y. Liu, D. Li, C.-M. Park, *Angew. Chem.* **2011**, *123*, 7471–7474; *Angew. Chem. Int. Ed.* **2011**, *50*, 7333–7336; n) M. Chen, J. Wang, Z. Chai, C. You, A. Lei, *Adv. Synth. Catal.* **2012**, *354*, 341–346; o) Y. Li, Z. Qi, H. Wang, X. Fu, C. Duan, *J. Org. Chem.* **2012**, *77*, 2053–2057; p) C. Zheng, D. Wang, S. S. Stahl, *J. Am. Chem. Soc.* **2012**, *134*, 16496–16499; q) Z. He, S. Kirchberg, R. Frohlich, A. Studer, *Angew. Chem.* **2012**, *124*, 3759–3762; *Angew. Chem. Int. Ed.* **2012**, *51*, 3699–3702.

[8] a) M. M. S. Andappan, P. Nilsson, M. Larhed, *Chem. Commun.* **2004**, 218–219; b) M. M. S. Andappan, P. Nilsson, H. von Schenck, M. Larhed, *J. Org. Chem.* **2004**, *69*, 5212–5218; c) P.-A. Enquist, J. Lindh, P. Nilsson, M. Larhed, *Green Chem.* **2006**, *8*, 338–343; d) P.-A. Enquist, P. Nilsson, P. Sjoberg, M. Larhed, *J. Org. Chem.* **2006**, *71*, 8779–8786; e) J. Lindh, P.-A. Enquist, A. Pilotti, P. Nilsson, M. Larhed, *J. Org. Chem.* **2007**, *72*, 7957–7962; f) A. Trejos, A. Fardost, S. Yahiaoui, M. Larhed, *Chem. Commun.* **2009**, 7587–7589; g) S. Yahiaoui, A. Fardost, A. Trejos, M. Larhed, *J. Org. Chem.* **2011**, *76*, 2433–2438; h) A. Nordqvist, C. Bjorkelid, M. Andaloussi, A. M. Jansson, S. L. Mowbray, A. Karlen, M. Larhed, *J. Org. Chem.* **2011**, *76*, 8986–8998; i) J. Sav-

marker, J. Lindh, P. Nilsson, P. J. R. Sjçberg, M. Larhed, *ChemistryOpen* **2012**, *1*, 140–146.
[9] a) J. P. Parrish, Y. C. Jung, S. I. Shin, K. W. Jung, *J. Org. Chem.* **2002**, *67*, 7127–7130; b) Y. C. Jung, R. K. Mishra, C. H. Yoon, K. W. Jung, *Org. Lett.* **2003**, *5*, 2231–2234; c) C. H. Yoon, K. S. Yoo, S. W. Yi, R. K. Mishra, K. W. Jung, *Org. Lett.* **2004**, *6*, 4037–4039; d) K. S. Yoo, C. H. Yoon, K. W. Jung, *J. Am. Chem. Soc.* **2006**, *128*, 16384–16393; e) K. S. Yoo, C. P. Park, C. H. Yoon, S. Sakaguchi, J. O'Neill, K. W. Jung, *Org. Lett.* **2007**, *9*, 3933–3935; f) S. Sakaguchi, K. S. Yoo, J. O'Neill, J. H. Lee, T. Stewart, K. W. Jung, *Angew. Chem.* **2008**, *120*, 9466–9469; *Angew. Chem. Int. Ed.* **2008**, *47*, 9326–9329.
[10] a) Y. Deng, Z. Jiang, M. Yao, D. Xu, L. Zhang, H. Li, W. Tang, L. Xu, *Adv. Synth. Catal.* **2012**, *354*, 899–907; b) Z. Jiang, L. Zhang, C. Dong, B. Ma, W. Tang, L. Xu, Q. Fan, J. Xiao, *Tetrahedron* **2012**, *68*, 4919–4926; c) Z. Jiang, L. Zhang, C. Dong, Z. Cai, W. Tang, H. Li, L. Xu, J. Xiao, *Adv. Synth. Catal.* **2012**, *354*, 3225–3230.
[11] a) J. Ichikawa, T. Moriya, T. Sonoda, H. Kobayashi, *Chem. Lett.* **1991**, 961–964; b) S. W. Wright, D. L. Hageman, L. D. McClure, *J. Org. Chem.* **1994**, *59*, 6095–6097; c) J. P. Wolfe, S. L. Buchwald, *Angew. Chem.* **1999**, *111*, 2570–2573; *Angew. Chem. Int. Ed.* **1999**, *38*, 2413–2416; d) J. P. Wolfe, R. A. Singer, B. H. Yang, S. L. Buchwald, *J. Am. Chem. Soc.* **1999**, *121*, 9550–9561; e) A. F. Littke, C. Dai, G. C. Fu, *J. Am. Chem. Soc.* **2000**, *122*, 4020–4028; f) R. A. Batey, T. D. Quach, *Tetrahedron Lett.* **2001**, *42*, 9099–9103.
[12] a) D. Pan, A. Chen, Y. Su, W. Zhou, S. Li, W. Jia, J. Xiao, Q. Liu, L. Zhang, N. Jiao, *Angew. Chem.* **2008**, *120*, 4807–4810; *Angew. Chem. Int. Ed.* **2008**, *47*, 4729–4732; b) D. Pan, M. Yu, W. Chen, N. Jiao, *Chem. Asian J.* **2010**, *5*, 1090–1093; c) D. Pan, N. Jiao, *Synlett* **2010**, 1577–1588.
[13] a) M. Oestreich, *Eur. J. Org. Chem.* **2005**, 783–792; b) M. Oestreich, *The Mizoroki–Heck reaction*, Wiley, Chichester, **2009**.
[14] For selected examples, see: a) P. Nilsson, M. Larhed, A. Hallberg, *J. Am. Chem. Soc.* **2001**, *123*, 8217–8225; b) P. Mauleon, I. Alonso, J. C. Carretero, *Angew. Chem.* **2001**, *113*, 1331–1333; *Angew. Chem. Int. Ed.* **2001**, *40*, 1291–1293; c) T. Llamas, R. G. Arrayas, J. C. Carretero, *Adv. Synth. Catal.* **2004**, *346*, 1651–1654; d) K. Itami, Y. Ushiogi, T. Nokami, Y. Ohashi, J.-i. Yoshida, *Org. Lett.* **2004**, *6*, 3695–3698; e) G. K. Datta, P. Nordeman, J. Dackenberg, P. Nilsson, A. Hallberg, M. Larhed, *Tetrahedron: Asymmetry* **2008**, *19*, 1120–1126; f) H.-M. Guo, W.-H. Rao, H.-Y. Niu, L.-L. Jiang, L. Liang, Y. Zhang, G.-R. Qu, *RSC Adv.* **2011**, *1*, 961–963; g) H. S. Lee, K. H. Kim, S. H. Kim, J. N. Kim, *Adv. Synth. Catal.* **2012**, *354*, 2419–2426.

