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# Pd-catalyzed asymmetric allylic alkylations *via* C–H activation of *N*-allyl imines with glycinate<sup>†</sup>

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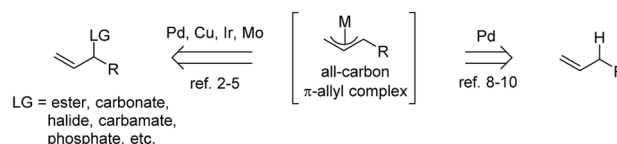
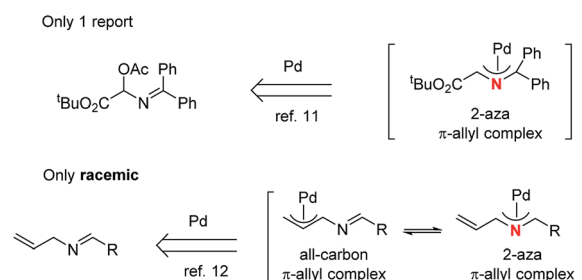
Herein is reported the first example of palladium-catalyzed asymmetric allylic alkylation (AAA) reactions involving 2-aza- $\pi$ -allyl palladium intermediates. The 2-aza- $\pi$ -allyl complex was generated *via* a novel mode of activation of *N*-allyl imines. Pd-catalyzed C(sp<sup>3</sup>)-H activation of *N*-allyl imines and subsequent nucleophilic attack by glycinate delivered vicinal diamino derivatives as the sole regioisomers with high levels of diastereo- and enantio-control in the presence of the chiral, bidentate (S,S)-Cy-DIOP ligand. This procedure is highly atom economical and could also be performed by a simple one-pot operation starting from aldehydes, allyl amines and glycinate under mild conditions. The products of this transformation could be converted into various useful derivatives, where the allyl substitution serves as a unique tool for differentiating the two amino moieties in the products.

## Introduction

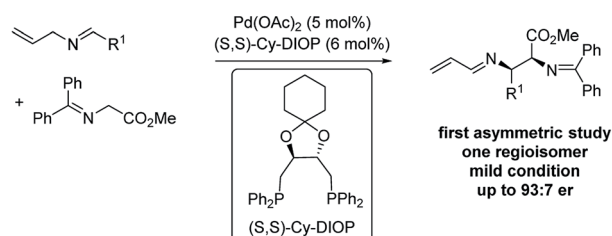
Metal-catalyzed asymmetric allylic alkylation (AAA) reactions fall among one of the most active areas in the realm of organic synthesis due to their broad utility in the construction of a diverse array of enantioenriched products from achiral starting materials.<sup>1</sup> A variety of transition metals, such as palladium,<sup>2</sup> copper,<sup>3</sup> iridium,<sup>4</sup> and molybdenum,<sup>5</sup> have been applied in these transformations. At present, a number of modes exist for the formation of the  $\pi$ -allyl intermediates. The most common has been the use of an allylic leaving group,<sup>2–5</sup> which undergoes ionization in the presence of a Pd(0) complex. A more atom economical strategy<sup>6</sup> uses protonation of a 1,3- or 1,2- (*i.e.* an allene) diene to form the  $\pi$ -allyl intermediate.<sup>7</sup> An interesting attractive method uses C–H activation at the allylic position of a simple olefin. Indeed, our initial work in 1973 on  $\pi$ -allyl palladium chemistry established the feasibility of this process but required a stoichiometric amount of palladium.<sup>8</sup> Recently, catalytic processes involving an allylic hydrogen atom as a “leaving group” under a direct C(sp<sup>3</sup>)-H activation method has emerged as an active area.<sup>9,10</sup> Irrespective of the catalyst, however, one common feature of these AAA reactions is the involvement of all-carbon  $\pi$ -allyl complexes (Fig. 1, path a). To the best of our knowledge, there is only one asymmetric study of the aza analogue of the all-carbon  $\pi$ -allyl complex, and that approach involved the generation of an aza- $\pi$ -allyl complex by ionization of an acetoxy leaving group (path b).<sup>11</sup> Recently, our group disclosed a general and efficient way to access the 2-aza-

$\pi$ -allyl palladium complex, which was employed in the preparation of either a 1-aza-1,3-diene or a 2-aza-1,3-diene as the sole regioisomer based on the choice of nucleophile (path b),<sup>12</sup>

### Previous work:

(a) AAA involving all-carbon  $\pi$ -allyl complex(b) Allylic alkylation involving 2-aza  $\pi$ -allyl complex

### This work:

(c) The first asymmetric allylic alkylation reaction involving 2-aza  $\pi$ -allyl complex

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<sup>†</sup> Electronic supplementary information (ESI) available: Additional details of experimental methods and results. See DOI: 10.1039/c7sc02899gFig. 1 Asymmetric allylic alkylations (AAA) involving a  $\pi$ -allyl complex.<sup>16</sup>

although in a racemic manner. The importance of nitrogen-containing compounds,<sup>13</sup> especially chiral vicinal diamino derivatives,<sup>14</sup> raises the question of an asymmetric transformation using a 2-aza- $\pi$ -allyl complex. Enantioselective direct Mannich reactions<sup>15</sup> of glycinate Schiff bases with activated imines represent a powerful strategy for the preparation of vicinal diamino derivatives, but the imines always require a strong electron-withdrawing group. One way to increase the efficiency would be to break this paradigm by developing an alternative method to perform analogous Mannich reactions with unactivated imines while maintaining high levels of regio-, diastereo-, and especially enantio-selective control. Herein, we present the first example of a Pd-catalyzed asymmetric alkylation of *N*-allyl imines with glycinate Schiff bases by combining the Pd-catalyzed oxidative allylic C–H activation and chiral phosphine ligands (path c). Using glycinate Schiff bases as nucleophiles provides unprecedented access to 2,3-diamino carboxylic acid derivatives asymmetrically.

## Results and discussion

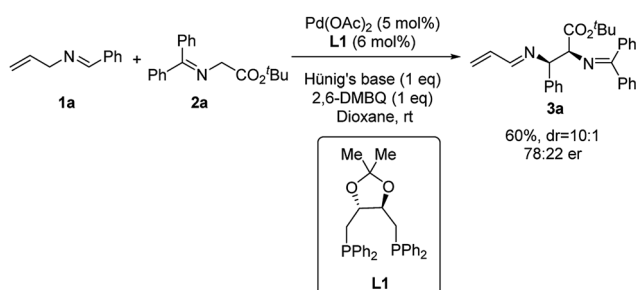
We started our investigation by using *N*-allylbenzylidene imine (**1a**) with *tert*-butyl glycinate (**2a**) as the nucleophile. Initial studies with phosphine ligands were disappointing. Our previous work on Pd-catalyzed asymmetric allylic C–H alkylation<sup>9b</sup> prompted us to initiate our study with chiral phosphoramidite ligands. As shown in the ESI,<sup>†</sup> no desired product was observed with such ligands. Further studies with other common bidentate ligands such as the Trost ligand, BINAP, DuPhos and Walphos ligands did not yield any desired product. On the other hand, surprisingly, the (*R,R*)-DIOP ligand (**L1**) was able to promote this transformation in 60% yield (Scheme 1) with good diastereoselectivity (10 : 1 dr) and modest enantioselectivity (78 : 22 er). Notably, the *N*-crotylbenzylideneimine substrate remained inert under these reaction conditions. Although these results were less promising than we had hoped for, they demonstrated the theoretical potential for an asymmetric reaction involving 2-aza- $\pi$ -allyl palladium intermediates with phosphine ligands.

Encouraged by the promising preliminary results with the (*R,R*)-DIOP ligand in such a catalyst system, we began to explore DIOP analogues for further optimization. One of the main advantages of DIOP is that it offers numerous options for derivatization. According to procedures reported in the

literature for the simple DIOP ligand,<sup>17</sup> several ligands based on the DIOP structure were synthesized and screened (Table 1). The major difference between these synthesized ligands and DIOP is the substitution of the aromatic moieties and structural modification *via* alteration of the acetal backbone, either by opening the ring (**L5**) or by switching it to a different cyclic acetal. As expected, (*S,S*)-DIOP afforded a similar level of enantioselectivity compared to (*R,R*)-DIOP but with opposite absolute stereochemistry. More sterically-hindered ligands like **L3** and **L4** resulted in either low conversion (<5%) or decreased enantioselectivity. Low conversion and poor enantioselectivity were obtained with **L5**, indicating that changing the bite angles of DIOP derivatives by altering the acetal backbone has a significant impact on enantioselectivity. A variety of substitutions for the acetal backbone such as phenyl, di-isopropyl, cyclopentyl, cyclohexyl and cycloheptyl groups were tested, and the highest enantioselectivity (78 : 22 er) was obtained with **L10**. Surprisingly, **L8**, bearing a six-membered ketal tether,<sup>16b</sup> afforded a nearly racemic product. Additionally, we were also interested in improving enantioselectivity by varying the glycinate nucleophiles. As shown in the ESI,<sup>†</sup> the two halves of the glycinate structure are of paramount importance. The highest enantioselectivity (85 : 15 er) was obtained using methyl glycinate (**2b**) as the nucleophile. Further investigation of the non-*C*<sub>2</sub> symmetrical ligands (**L12**, **L14**, **L15** and **L16**) gave product **3b** in a similar yield and with the same enantioselectivity (85 : 15 er) and similar diastereoselectivity compared with that obtained when using **L2** as the ligand. On the other hand, a decrease in enantioselectivity (75 : 25 er) is observed with the analogous *ortho*-ester phenyl ligand (**L13**, see Table 1, entry 13). We hypothesize that this ligand contains secondary interactions between the ester and the metal center, preventing the desired mode of reactivity.

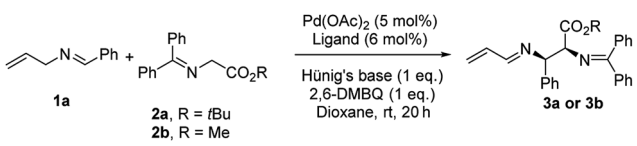
Efforts to improve the enantioselectivity then shifted to examine the solvent effect, the reaction concentration, temperature and bases (see the ESI<sup>†</sup> for details). With a robust set of reaction conditions in hand, we re-examined all the previous ligands to further optimize this transformation. When (*S,S*)-Cy DIOP was employed,<sup>16c</sup> **3b** was isolated in 65% yield with 92 : 8 er, the highest level of enantioinduction among all the ligands examined (Scheme 2).

Under the optimized conditions, we next explored the generality of the Pd-catalyzed asymmetric allylic alkylations involving 2-aza- $\pi$ -allyl complexes. A wide selection of *N*-allylbenzylidene imines was subjected to the optimized conditions to produce adducts with methyl glycinate donors **2b** (Fig. 2). Both electron-rich and electron-deficient substrates underwent efficient coupling using this protocol, though higher reaction rates were observed for substrates bearing electron-withdrawing groups. The reaction temperature for those substrates could be lowered to  $-4$  °C in order to give higher enantioselectivity (**3c**, **3f** and **3g–3l**). The enantioselectivity is sensitive to the temperature (4 °C,  $-4$  °C and  $-20$  °C), as shown for nitro-substituted *N*-allylimine **3f**: the corresponding 1-aza-1,3-diene was obtained in 66%, 64% and 70% yield and with 85 : 15, 88 : 12 and 90 : 10 er, respectively.<sup>18</sup> Notably, the diastereoselectivity decreased at  $-20$  °C after a prolonged reaction



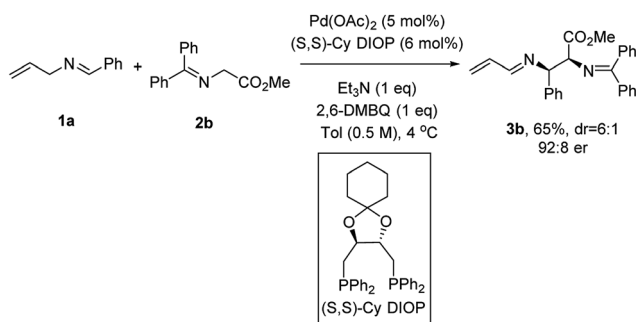
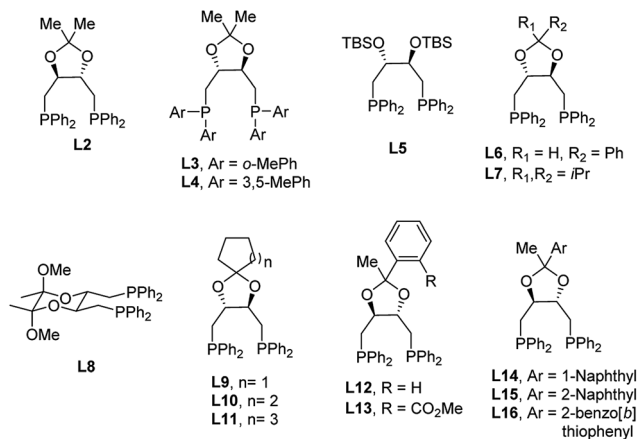
Scheme 1 Preliminary results.



Table 1 Survey of ligands<sup>a</sup>


Entry	Glycinate	Ligand	Yield <sup>b</sup>	dr <sup>c</sup>	er <sup>d</sup>
1	2a	L1	60%	10 : 1	78 : 22
2	2a	L2	62%	10 : 1	23 : 77
3	2a	L3	Trace	—	—
4	2a	L4	65%	8 : 1	70 : 30
5	2a	L5	22%	3 : 1	57 : 43
6	2a	L6	60%	10 : 1	72 : 28
7	2a	L7	64%	10 : 1	71 : 29
8	2a	L8	25%	10 : 1	53 : 47
9	2a	L9	64%	10 : 1	74 : 26
10	2a	L10	67%	11 : 1	78 : 22
11	2a	L11	66%	9 : 1	76 : 24
12	2b	L12	65%	5 : 1	85 : 15
13	2b	L13	58%	6 : 1	75 : 25
14	2b	L14	62%	5 : 1	85 : 15
15	2b	L15	56%	5 : 1	85 : 15
16	2b	L16	62%	6 : 1	85 : 15

<sup>a</sup> Reaction conditions: **1a** (0.1 mmol), **2a** or **2b** (0.1 mmol), Pd(OAc)<sub>2</sub> (5 mol%), ligand (6 mol%), Hünig's base (0.1 mmol), 2,6-DMBQ (0.1 mmol), dioxane, rt, 15–20 h. <sup>b</sup> Isolated yield. <sup>c</sup> Determined by <sup>1</sup>H-NMR. <sup>d</sup> Determined by chiral HPLC.



Scheme 2 Optimized reaction conditions.

time (70 h). An electron-donating substituent (*e.g.* OMe or Me) on the aryl ring proved effective as well, yielding **3d** and **3e** with 89.5 : 10.5 and 86 : 14 er, respectively. An aryl bromide on the imine (**3g**) was well tolerated under the oxidative allylic C–H activation conditions. The position of the substituent on the aryl system had no influence on either the yield or enantioselectivity, though the diastereoselectivity was diminished when the substituents were moved from the *para* to the *meta* to the *ortho* position (**3h–3j**). When a cyano-substituted *N*-allyl imine was employed, the alkylation product (**3k**) was obtained in 70% yield and 11.5 : 88.5 er. An electron-deficient imine bearing a trifluoromethyl group was successfully employed to form the desired product (**3l**) in 72% yield and 91.5 : 8.5 er. Notably, significantly lower enantioselectivity (38% ee) was observed in



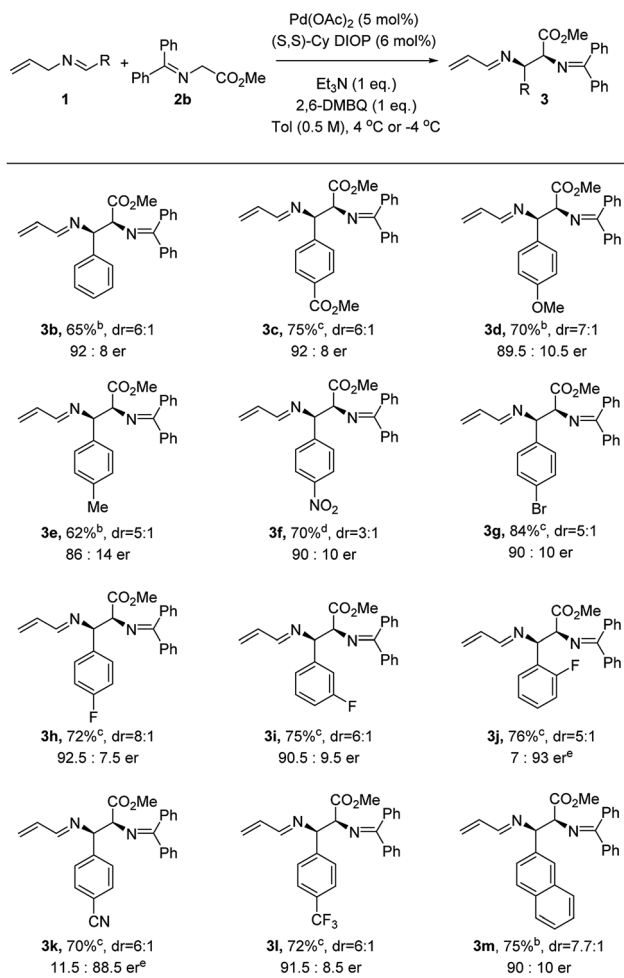


Fig. 2 Substrate scope for *N*-allyl imines. <sup>a</sup>Reaction conditions: **1** (0.5 mmol), **2b** (0.5 mmol), Pd(OAc)<sub>2</sub> (5 mol%), (S,S)-Cy DIOP (6 mol%), Et<sub>3</sub>N (0.5 mmol), 2,6-DMBQ (0.5 mmol), toluene (0.5 M), 4 °C, -4 °C or -20 °C, 30–70 h. The diastereoselectivity was determined by <sup>1</sup>H-NMR spectroscopy of the crude reaction mixture. The yields are those of the isolated products. <sup>b</sup>4 °C. <sup>c</sup>-4 °C. <sup>d</sup>-20 °C. <sup>e</sup>It is assumed that the major diastereomer is the same, although the retention time of the two peaks is inverted.

the direct Mannich reaction<sup>15h</sup> for substrate *p*-trifluoromethyl benzaldehyde with *tert*-butyl glycinate. The corresponding 2-naphthyl imine gave the desired product (**3m**) in 75% yield and 90 : 10 er, but no reaction was observed for the 1-naphthyl variant.

This methodology extends beyond benzenoid imines. Thus, heteroaromatic imine systems were screened (Fig. 3). 2-Substituted benzofuran and benzothiophene gave quite similar results. Further, a 3-substituted indole gave the tryptophan analogue **3p** with 89 : 11 er. The reaction with *N*-allyl  $\alpha$ -methylcinnamyl imine was significantly slower, but the corresponding adduct was isolated in 74% yield with 86.5 : 13.5 er.

With the success of the Pd-catalyzed asymmetric allylic alkylation of *N*-allyl imines, we considered whether a more practical one-pot process from commercially available materials would be feasible by *in situ* generation of the imine.<sup>19</sup> Thus, handling water and air sensitive imines would be avoided. To

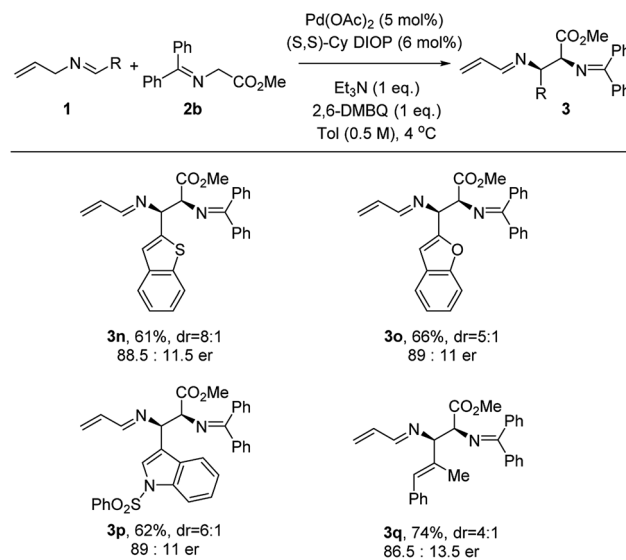


Fig. 3 Substrate scope for heteroaromatic and non-aromatic imines. <sup>a</sup>Reaction conditions: **1** (0.5 mmol), **2b** (0.5 mmol), Pd(OAc)<sub>2</sub> (5 mol%), (S,S)-Cy DIOP (6 mol%), Et<sub>3</sub>N (0.5 mmol), 2,6-DMBQ (0.5 mmol), toluene (0.5 M), 4 °C, 40–70 h. The diastereoselectivity was determined by <sup>1</sup>H-NMR spectroscopy of the crude reaction mixture. The yields are those of the isolated products.

a mixture of Pd(OAc)<sub>2</sub>, ligand, quinone and powdered 4 Å molecular sieves was added a toluene solution of allyl amine, aldehyde, and methyl glycinate **2b**. The only modification of the allylic alkylation procedure was the addition of molecular sieves to facilitate *in situ* imine formation. Comparable yields, diastereoselectivity and enantioselectivity were obtained, as the substrate scope shown in Fig. 4 illustrates. *p*-Bromobenzaldehyde (**4b**) was found to perform well, giving the desired product in 70% yield and 90 : 10 er. Electron-deficient and electron-rich

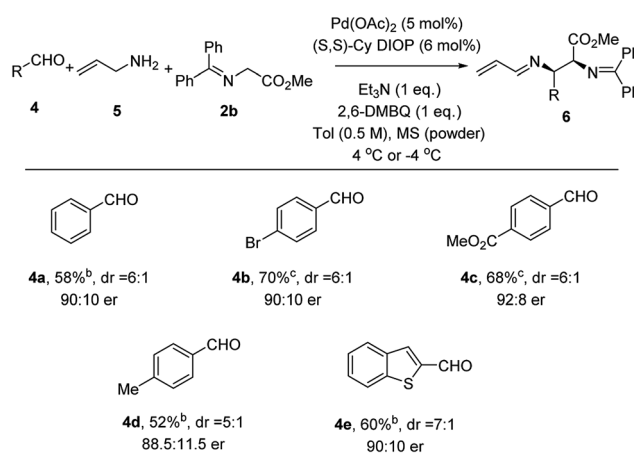


Fig. 4 Substrate scope of the Pd-catalyzed three-component AAA reaction. <sup>a</sup>Reaction conditions: **4** (0.3 mmol), **5** (0.3 mmol), **2b** (0.3 mmol), Pd(OAc)<sub>2</sub> (5 mol%), (S,S)-Cy DIOP (6 mol%), Et<sub>3</sub>N (0.3 mmol), 2,6-DMBQ (0.3 mmol), MS powder (4 Å, 120 mg), toluene (0.5 M), 4 °C or -4 °C, 30–50 h. The diastereoselectivity was determined by <sup>1</sup>H-NMR spectroscopy of the crude reaction mixture. The yields are those of the isolated products. <sup>b</sup>4 °C. <sup>c</sup>-4 °C.

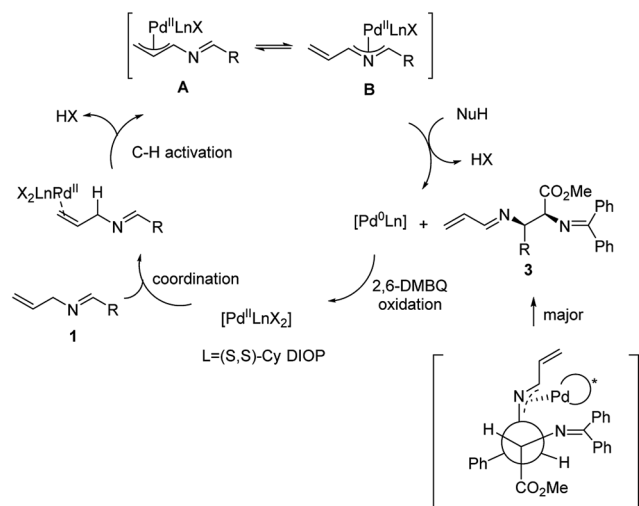


aldehydes, **4c** and **4d**, undergo efficient coupling using this protocol to provide adducts in 68% and 52% yield and 92 : 8 and 88.5 : 11.5 er, respectively. This three-component method could be extended to heteroaromatic systems. When benzo[*b*]thiophene-2-carboxaldehyde **4e** was employed, the alkylation product was obtained in 60% yield and 90 : 10 er.

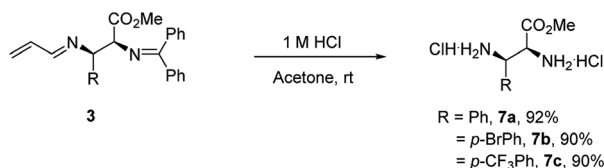
A plausible mechanism of this reaction is shown in Scheme 3. We propose that the catalytic cycle is initiated with the coordination of the Pd<sup>II</sup> complex to the allyl double bond. Subsequent Pd<sup>II</sup>-catalyzed allylic C–H activation generates the all-carbon  $\pi$ -allyl complex **A**, which would be in equilibrium with the 2-aza- $\pi$ -allyl complex **B**. This hypothesis is supported by our previous study.<sup>12</sup> Then, glycinate nucleophiles attack *via* a transition state involving maximum delocalization of charge to give the (*S,R*) or (*R,S*) product **3** with the reduction of the Pd<sup>II</sup> complex to Pd<sup>0</sup>. The facial selectivity that preferentially generates the *S,R*-isomer is rationalized by the minimization of steric interactions within the palladium ligand complex and the ester of the glycinate. Finally, DMBQ-mediated oxidation regenerates Pd<sup>II</sup> to complete the catalytic cycle.

The regioselectivity of the nucleophilic addition derives from preferential attack on intermediate **B** compared to **A**. In our previous study, this regioselectivity was observed with more reactive nucleophiles. Such an observation is consistent with the reaction at the most electrophilic carbon.

Products **3** could be converted to biologically interesting chiral  $\alpha,\beta$ -vicinal diamino acid derivatives (**7a–7c**) in high yields upon hydrolysis under mildly acidic conditions (Scheme 4).

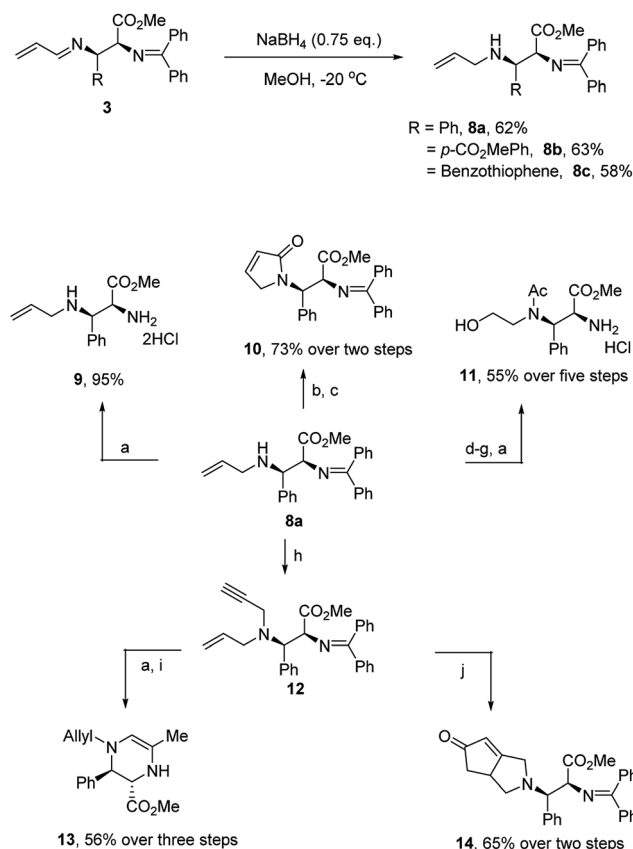


Scheme 3 Plausible catalytic cycle.

Scheme 4 Hydrolysis of products **3**.

This process also provides a mechanism to establish the relative and absolute stereochemistry of this new process. A comparison of the spectral data of product **7a** with reports in the literature<sup>20a,20b</sup> confirms it is either the *S,R*- or *R,S*-isomer (*i.e.* not the *R,R*- or *S,S*-isomer). The absolute configuration was established by its optical rotation of  $[\alpha]_D^{25} = +11.0^\circ$  ( $c = 1.0$ , CHCl<sub>3</sub>, 92 : 8 er), which agrees with that reported for the *S,R*-isomer,  $[\alpha]_D^{25} = +16.0^\circ$  ( $c = 1.0$ , CHCl<sub>3</sub>, >99% ee).<sup>20c</sup>

To further demonstrate the utility of this reaction, we converted the products to other useful amino derivatives (Scheme 5). The adduct **3b** was treated with sodium borohydride at  $-20^\circ\text{C}$  for 15 min to give the imine product **8a** in 62% yield. The bis-benzylidene imine moiety was inert under these conditions and no epimerization was observed. Thus, the corresponding products **8b** and **8c** were obtained in 63% and 58% yield, respectively. Now, the two imine moieties could be easily differentiated after the reduction of 1-aza-1,3-diene. For example, product **9** was prepared in 95% yield after the hydrolysis of **8a** (see Scheme 5). In addition, the allyl group of the products **8** could serve as a useful handle for further functionalization. For example, *N*-acylation with acryloyl chloride



Scheme 5 Derivatization of AAA products. Conditions: (a) 1 M HCl, acetone, rt; (b) acryloyl chloride, Et<sub>3</sub>N, DCM, rt; (c) Grubbs II (5 mol%), DCM, rt; (d) Ac<sub>2</sub>O, Et<sub>3</sub>N, DMAP (cat), DCM, rt; (e) K<sub>2</sub>O<sub>5</sub>·2H<sub>2</sub>O (5 mol%), NMO (2 eq.), acetone, rt; (f) NaIO<sub>4</sub> (2 eq.), Et<sub>2</sub>O/H<sub>2</sub>O (2 : 1), rt; (g) NaBH<sub>4</sub> (0.5 eq.), 0 °C; (h) propargyl bromide, K<sub>2</sub>CO<sub>3</sub>, CH<sub>3</sub>CN, 80 °C; (i) IPrAuNTf<sub>2</sub> (5 mol%), DCM, rt; (j) Co<sub>2</sub>(CO)<sub>8</sub> (1.05 eq.), DCM, rt; then Me<sub>3</sub>NO (6 eq.), MS powder, rt.





followed by metathesis led to the dihydropyrrolenone **10**. The product could also be converted to amino alcohol **11** after a dihydroxylation, oxidation, reduction and hydrolysis sequence. Simple propargylation to enyne **12** proceeded in high yield. Subjection of the enyne to hydrolysis followed by Au(I)-catalyzed cyclization provided the tetrahydropyrazine **13**. On the other hand, subjection of enyne **12** to the conditions of a Pauson–Khand reaction smoothly produced the [3.3.0]-azabicyclooctanone **14** in good yield.

## Conclusions

In summary, we have developed the first example of Pd-catalyzed asymmetric allylic alkylation (AAA) involving a 2-aza- $\pi$ -allyl intermediate with (*S,S*)-Cy DIOP. The effectiveness of this chiral bidentate bis-phosphine is particularly surprising given the expectation that such phosphines would be incompatible with the oxidative conditions of such a C–H activation mechanism. Further, the total failure of the phosphoramidite ligand, which was successful in our all-carbon  $\pi$ -allyl oxidative allylation, highlights the uniqueness of the ligand choice. When glycinate was employed as the nucleophile, a wide variety of synthetically important  $\alpha,\beta$ -diamino ester derivatives were isolated in high yields, with good diastereo- and enantioselectivity and complete regioselectivity. The substrate scope was extended from aromatic imines to heteroaromatic and alkenylidene imines. This procedure is highly atom economical and it also could be performed in a simple one-pot operation under mild conditions. The utility of this method was further demonstrated with diverse functionalization of the adducts. The juxtaposition of functionality available from this process provides access to a diverse range of structures possessing an  $\alpha,\beta$ -vicinal diamino acid as a common motif. Furthermore, the reaction is quite amenable to scale-up. Thus, running the reaction with *N*-allyl-benzylidene imine on a 5 mmol scale gave the product **3b** in a slightly improved yield of 67% and with identical diastereoselectivity and enantioselectivity as on a 0.5 mmol scale.

## Experimental section

### 1. General procedure for the Pd-catalyzed asymmetric allylic alkylation involving $\pi$ -allyl intermediate

An oven-dried Pyrex microwave vial was charged with Pd(OAc)<sub>2</sub> (5.6 mg, 0.025 mmol), (*S,S*)-Cy DIOP (16.2 mg, 0.03 mmol) and 2,6-dimethylbenzoquinone (70 mg, 0.5 mmol), and was sealed with a rubber septum. The vial was evacuated and filled with nitrogen three times in an interval of 10 min. In a separate sealed nitrogen flushed vial, glycinate (0.5 mmol) and *N*-allyl imine (0.5 mmol) were taken in freshly distilled toluene (1 ml). The solution was cannulated to the microwave vial with the palladium catalyst. Et<sub>3</sub>N (50 mg, 0.5 mmol) was added to the resulting turbid solution and it was allowed to stir at 4 °C or –4 °C for 35–60 h. Upon completion (monitored by crude NMR), the solvent was removed *in vacuo* and the residue was purified by flash chromatography over silica gel (pre-neutralized with 3% Et<sub>3</sub>N in hexane), eluting with EtOAc/hexane/Et<sub>3</sub>N, to give the product.

### 2. General procedure for the three-component reaction

An oven-dried Pyrex microwave vial was charged with Pd(OAc)<sub>2</sub> (3.4 mg, 0.015 mmol), (*S,S*)-Cy DIOP (10.1 mg, 0.018 mmol), 2,6-dimethylbenzoquinone (42 mg, 0.3 mmol) and molecular sieves (4 Å, 120 mg), and was sealed with a rubber septum. The vial was evacuated and filled with nitrogen three times in an interval of 10 min. In a separate sealed nitrogen flushed vial, aldehyde (0.3 mmol), allyl amine (0.3 mmol) and glycinate **2e** (0.3 mmol) were dissolved in freshly distilled toluene (0.6 mL). The solution was cannulated to the microwave vial with the palladium catalyst. Et<sub>3</sub>N (30 mg, 0.3 mmol) was added to the resulting turbid solution and it was allowed to stir at 4 °C or –4 °C for 35–60 h. Upon completion (monitored by crude NMR), the solvent was removed *in vacuo* and the residue was purified by flash chromatography over silica gel (pre-neutralized with 3% Et<sub>3</sub>N in hexane), eluting with EtOAc/hexane/Et<sub>3</sub>N, to give the product.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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## References

- (a) Transition Metal Catalyzed Enantioselective Allylic Substitution in Organic Synthesis, in *Topics in Organometallic Chemistry*, ed. U. Kazmaier, Springer, 2012, vol. 38; (b) N. A. Butt and W. Zhang, *Chem. Soc. Rev.*, 2015, **44**, 7929.
- (a) B. M. Trost and D. L. Van Vranken, *Chem. Rev.*, 1996, **96**, 395; (b) B. M. Trost and M. L. Crawley, *Chem. Rev.*, 2003, **103**, 2921; (c) B. M. Trost, *J. Org. Chem.*, 2004, **69**, 5813; (d) Z. Lu and S. Ma, *Angew. Chem., Int. Ed.*, 2008, **47**, 258; (e) B. M. Trost, T. Zhang and J. D. Sieber, *Chem. Sci.*, 2010, **1**, 427.
- (a) H. Yorimitsu and K. Oshima, *Angew. Chem., Int. Ed.*, 2005, **44**, 4435; (b) A. Alexakis, J. E. Bäckvall, N. Krause, O. Pàmies and M. Diéguez, *Chem. Rev.*, 2008, **108**, 2796; (c) C. A. Falciola and A. Alexakis, *Eur. J. Org. Chem.*, 2008, 3765.
- (a) G. Helmchen, A. Dahnz, P. Dübon, M. Schelwies and R. Wiehofen, *Chem. Commun.*, 2007, 675; (b) J. F. Hartwig and L. M. Stanley, *Acc. Chem. Res.*, 2010, **43**, 1461; (c) S. Krautwald and E. M. Carreira, *J. Am. Chem. Soc.*, 2017, **139**, 5627.
- B. M. Trost, *Org. Process Res. Dev.*, 2012, **16**, 185.
- B. M. Trost, *Science*, 1991, **254**, 1471.
- P. Koschker and B. Breit, *Acc. Chem. Res.*, 2016, **49**, 1524.
- B. M. Trost and T. J. Fullerton, *J. Am. Chem. Soc.*, 1973, **95**, 292.
- (a) D. J. Covell and M. C. White, *Angew. Chem., Int. Ed.*, 2008, **47**, 6448; (b) B. M. Trost, D. A. Thaisrivongs and E. J. Donckele, *Angew. Chem., Int. Ed.*, 2013, **52**, 1523; (c)



- P.-S. Wang, H.-C. Lin, Y.-J. Zhai, Z.-Y. Han and L.-Z. Gong, *Angew. Chem., Int. Ed.*, 2014, **53**, 12218; (d) B. M. Trost, E. J. Donckele, D. A. Thaisrivongs, M. Osipov and J. T. Masters, *J. Am. Chem. Soc.*, 2015, **137**, 2776; (e) P.-S. Wang, P. Liu, Y.-J. Zhai, H.-C. Lin, Z.-Y. Han and L.-Z. Gong, *J. Am. Chem. Soc.*, 2015, **137**, 12732; (f) S. E. Ammann, W. Liu and M. C. White, *Angew. Chem., Int. Ed.*, 2016, **55**, 9571; (g) H.-C. Lin, P.-S. Wang, Z.-L. Tao, Y.-G. Chen, Z.-Y. Han and L.-Z. Gong, *J. Am. Chem. Soc.*, 2016, **138**, 14354.
- 10 For selected reviews of C–H functionalization, see: (a) X. Chen, K. M. Engle, D.-H. Wang and J.-Q. Yu, *Angew. Chem., Int. Ed.*, 2009, **48**, 5094; (b) R. Giri, B.-F. Shi, K. M. Engle, N. Maugel and J.-Q. Yu, *Chem. Soc. Rev.*, 2009, **38**, 3242; (c) T. W. Lyons and M. S. Sanford, *Chem. Rev.*, 2010, **110**, 1147; (d) J. Wencel-Delord, T. Droge, F. Liu and F. Glorius, *Chem. Soc. Rev.*, 2011, **40**, 4740; (e) D. A. Colby, A. S. Tsai, R. G. Bergman and J. A. Ellman, *Acc. Chem. Res.*, 2012, **45**, 814; (f) R.-Y. Zhu, M. E. Farmer, Y.-Q. Chen and J.-Q. Yu, *Angew. Chem., Int. Ed.*, 2016, **55**, 10578; (g) J. He, M. Wasa, K. S. L. Chan, Q. Shao and J.-Q. Yu, *Chem. Rev.*, 2017, **117**, 8754; (h) O. Daugulis, J. Roane and L. D. Tran, *Acc. Chem. Res.*, 2015, **48**, 1053.
- 11 M. J. O'Donnell, N. Chen, C. Zhou and A. Murray, *J. Org. Chem.*, 1997, **62**, 3962.
- 12 B. M. Trost, S. Mahapatra and M. Hansen, *Angew. Chem., Int. Ed.*, 2015, **54**, 6032.
- 13 (a) N. C. Miltenburg and W. Boogerd, *Cancer Treat. Rev.*, 2014, **40**, 872; (b) A. W. Schmidt, K. R. Reddy and H.-J. Knolker, *Chem. Rev.*, 2012, **112**, 3193.
- 14 (a) A. Viso, R. F. de la Pradilla, A. García and A. Flores, *Chem. Rev.*, 2005, **105**, 3167; (b) A. Viso, R. F. de la Pradilla, M. Tortosa, A. García and A. Flores, *Chem. Rev.*, 2011, **111**, PR1.
- 15 For metal- or organocatalytic Mannich reactions of glycine imines, see: (a) L. Bernardi, A. S. Gothelf, R. G. Hazell and K. A. Jørgensen, *J. Org. Chem.*, 2003, **68**, 2583; (b) X. X. Yan, Q. Peng, Q. Li, K. Zhang, J. Yao, X. L. Hou and Y. D. Wu, *J. Am. Chem. Soc.*, 2008, **130**, 14362; (c) S. Kobayashi, R. Yazaki, K. Seki and Y. Yamashita, *Angew. Chem., Int. Ed.*, 2008, **47**, 5613; (d) J. Hernández-Toribio, R. Gómez Arrayás and J. C. Carretero, *J. Am. Chem. Soc.*, 2008, **130**, 16150; (e) D. Shang, Y. Liu, X. Zhou, X. Liu and X. Feng, *Chem.–Eur. J.*, 2009, **15**, 3678; (f) J. Hernández-Toribio, R. Gómez Arrayás and J. C. Carretero, *Chem.–Eur. J.*, 2010, **16**, 1153; (g) G. Liang, M. C. Tong, H. Tao and C. J. Wang, *Adv. Synth. Catal.*, 2010, **352**, 1851; (h) J. S. Bandar and T. H. Lambert, *J. Am. Chem. Soc.*, 2013, **135**, 11799; (i) G. A. Cutting, N. E. Stainforth, M. P. John, G. Kociok-Köhn and M. C. Willis, *J. Am. Chem. Soc.*, 2007, **129**, 10632; (j) K. Juhl, N. Gathergood and K. A. Jørgensen, *Angew. Chem., Int. Ed.*, 2001, **40**, 2995.
- 16 Generally, Pd-catalyzed AAA with DIOP ligand gave poor enantioselectivity, see: (a) B. M. Trost and P. E. Strege, *J. Am. Chem. Soc.*, 1977, **99**, 1649; (b) C. S. Marques and A. J. Burke, *Tetrahedron: Asymmetry*, 2007, **18**, 1804. Rh-catalyzed coupling of carboxylic acids with terminal alkynes for the preparation of branched allylic esters utilizing DIOP ligand gave excellent enantioselectivity, see: (c) P. Koschker, M. Kahny and B. Breit, *J. Am. Chem. Soc.*, 2015, **137**, 3131.
- 17 (a) T. P. Dang and H. B. Kagan, *Chem. Commun.*, 1971, 481; (b) H. B. Kagan and T. P. Dang, *J. Am. Chem. Soc.*, 1972, **94**, 6429.
- 18 see ESI.†
- 19 M. M. Salter, J. Kobayashi, Y. Shimizu and S. Kobayashi, *Org. Lett.*, 2006, **8**, 3533.
- 20 (a) A. Viso, R. Fernández de la Pradilla, M. L. López-Rodríguez, A. García, A. Flores and M. Alonso, *J. Org. Chem.*, 2004, **69**, 1542; (b) G. Cremonesi, P. Dalla Croce, M. Gallanti and C. La Rosa, *Tetrahedron*, 2014, **70**, 2054; (c) T. Arai, A. Mishiro, E. Matsumura, A. Awata and M. Shirasugi, *Chem.–Eur. J.*, 2012, **18**, 11219.

