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β-Amino Alcohol Derived β-Hydroxy- and β-(*o*-Diphenylphosphino)benzoyloxy(*o*-diphenylphosphino)benzamides: An Ester−Amide Ligand Structural Model for the Palladium-Catalyzed Allylic Alkylation Reaction

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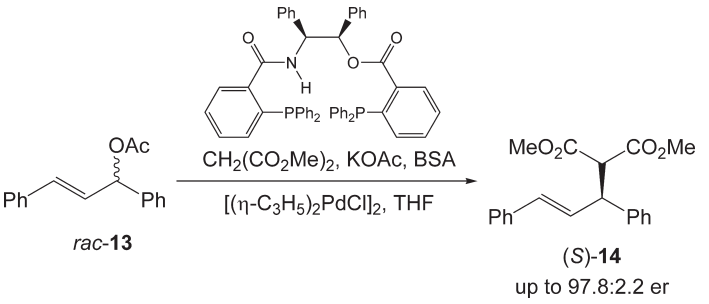

rac-**13**

(*S*)-**14**
up to 97.8:2.2 er

A commercially available collection of β-amino alcohols have been converted to their corresponding β-hydroxy- and β-(*o*-diphenylphosphino)benzoyloxy(*o*-diphenylphosphino)benzamides **11a**−**f** and **12a**−**f** and have been employed in the Tsuji−Trost asymmetric alkylation reaction with 1,3-diphenylpropenyl acetate. With the exception of ligands **11b** and **11f**, the β-hydroxybenzoyloxy (*o*-diphenylphosphino)benzamide ligands **11a**−**f** primarily afforded the (*R*)-enantiomer of the product. In contrast, the bis(phosphine) ligands **12a**−**f** consistently afforded the (*S*)-enantiomer. The best ligand (**12c**) was derived from *cis*-(1*R*,2*S*)-2-amino-1,2-diphenyl-1-ethanol, and when applied in the asymmetric allylic alkylation reaction, it yielded the product in an enantiomeric ratio of 97.8.22 favoring the (*S*)-enantiomer. A computational study was conducted on the conformation that this ligand might adopt in the palladium-catalyzed alkylation reaction as compared to that of the Trost ligand **1a**.

1. Introduction

The palladium-catalyzed asymmetric allylic alkylation reaction[1] known as the Tsuji−Trost reaction has been the subject of intense studies[2] directed toward the design, synthesis, and application of a myriad of chiral, nonracemic ligand scaffolds. Of the ligands that have been prepared and applied in this reaction, the Trost modular phosphine ligands (**1a**,**b**)[3] have proven to be the benchmark for evaluating the efficacy of newly developed phosphine ligands in the asymmetric allylic alkylation reaction. In fact, on the basis of their successful use in a variety of applications, many of these modular ligands are commercially available.[4] The success of these ligands has encouraged the synthesis and application of structurally novel phosphines based on the binaphthyl type ligands,[5] tartrate derived systems,[6] carbohydrates,[7] paracyclophanes,[8] and

(1) Tsuji, J. In *Palladium Reagents and Catalysts: New Perspectives for the 21st Century*; John Wiley & Sons: Chichester, UK, 2004; pp 431−518.
(2) (a) Lu, Z.; Ma, S. *Angew. Chem., Int. Ed.* **2008**, *47*, 258. (b) Trost, B. M. *J. Org. Chem.* **2004**, *69*, 5813. (c) Trost, B. M.; Crawley, M. L. *Chem. Rev.* **2003**, *103*, 2921. (d) Trost, B. M.; Machacek, M. R.; Aponick, A. *Acc. Chem. Res.* **2006**, *39*, 747. (e) Trost, B. M.; Van Vranken, D. L. *Chem. Rev.* **1996**, *96*, 395. (f) Trost, B. M. *Acc. Chem. Res.* **1980**, *13*, 385. (g) Trost, B. M.; Breit, B.; Organ, M. G. *Tetrahedron Lett.* **1994**, *35*, 5817.
(3) (a) Trost, B. M.; Van Vranken, D. L.; Bingel, C. *J. Am. Chem. Soc.* **1992**, *114*, 9327. (b) Trost, B. M.; Van Vranken, D. L. *Angew. Chem., Int. Ed.* **1992**, *31*, 228.
(4) (a) Trost, B. M.; Fandrick, D. R. *Aldrichim. Acta* **2007**, *40*, 59.
(5) Feng, J.; Bohle, D. S.; Li, C. *Tetrahedron: Asymmetry* **2007**, *18*, 1043–1047.
(6) Marques, C. S.; Burke, A. J. *Tetrahedron: Asymmetry* **2007**, *18*, 1804–1808.
(7) Khiar, N.; Navas, R.; Álvarez, E.; Fernández, I. *ARCHIVOC* **2008**, *8*, 211−224.
(8) Jiang, B.; Lei, Y.; Zhao, X. *J. Org. Chem.* **2008**, *73*, 7833–7836.

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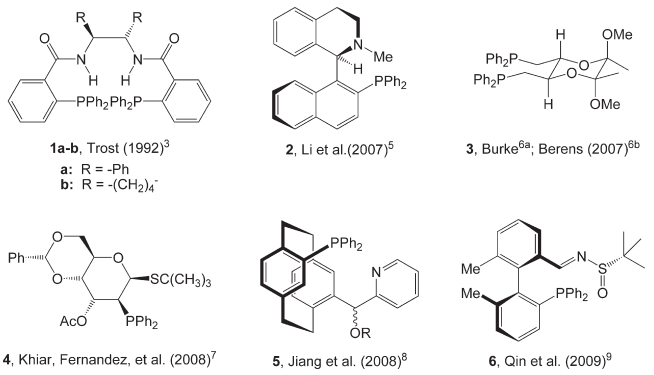


FIGURE 1. Phosphine ligands.

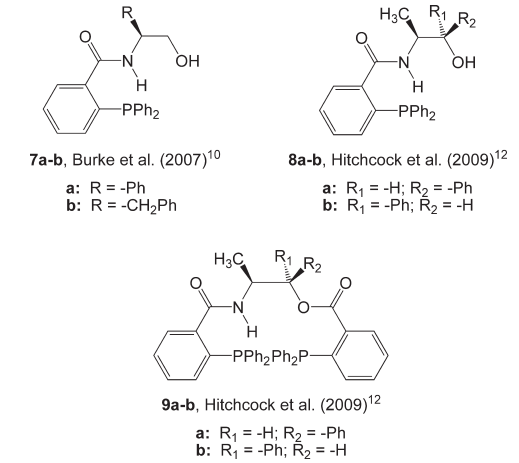


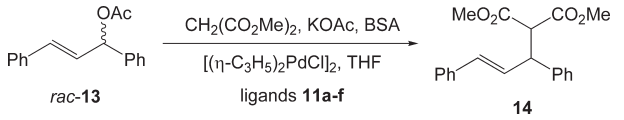
FIGURE 2. β-Hydroxy- and β-(*o*-diphenylphosphino)benzyloxy-(*o*-diphenylphosphino)benzamides.

biphenyl systems[9] (Figure 1). Many of these ligands afford very high enantiomeric excesses when employed in the asymmetric allylic alkylation reaction between 1,3-diphenylpropenyl acetate and dialkyl malonates. However, many of these ligands require significant synthetic efforts to prepare from either chiral, nonracemic materials or racemic materials through resolution.

In 2008, Burke and co-workers,[10] inspired by the earlier work of Mino and co-workers,[11] developed a series of β-hydroxy(diphenylphosphino)benzamides (**7a**,**b**) based on L-phenylglycinol and L-phenylalaninol and applied these systems in the asymmetric alkylation reaction with 1,3-diphenylpropenyl acetate with dimethyl malonate. The products were obtained with enantiomeric excesses that ranged from 17% to 62% ee. Our research group has recently been involved in the application of β-amino alcohols from the genus *Ephedra* and have developed a series of mono- and bis(phosphines) ligands (**8a**,**b**, **9a**,**b**) for application in the Tsuji−Trost reaction (Figure 2). We were gratified to learn that the use of these ligands afforded products with enantiomer excesses ranging from 54% to 88% ee.[12] While not at the level of asymmetric induction provided by some of the ligands in Figure 1, there was still the possibility for further enhancing the effectiveness of this ligand family by changing the nature of the ligand template.

We report on our efforts in the synthesis and application of a series of β-hydroxy- and β-(*o*-diphenylphosphino)-benzyloxy(*o*-diphenylphosphino)benzamides derived from a series of commercially available β-amino alcohols in the asymmetric allylic alkylation reaction with 1,3-diphenylpropenyl acetate and dimethyl malonate. In addition, a computational study concerning the interaction between the best ligand of this series bound to palladium and 1,3-diphenylpropenyl acetate is carried out.

TABLE 1. Asymmetric Allylic Alkylation with Ligands 11a−f



entry	ligand	time (h)	**13**:ligand: Pd	yield (%)[a]	er (*R*:*S*), (ee)[b]	config[c]
1	**11a**	24	25:1:1	29	87.1:13.0 (74)	*R*
2	**11a**	6	25:1:1	66	86.2:13.8 (72)	*R*
3	**11a**	24	25:1:2	70	89.7:10.3 (79)	*R*
4	**11a**	6	25:1:2	53	86.2:13.8 (72)	*R*
5	**11a**	24	25:2:1	85	89.3:10.7 (79)	*R*
6	**11b**	24	25:1:2	73	37.5:62.5 (25)	*S*
7	**11b**	6	25:1:2	66	6.4:93.6 (87)	*S*
8	**11c**	24	25:1:2	51	81.4:18.6 (63)	*R*
9	**11c**	6	25:1:2	65	64.2:35.8 (28)	*R*
10	**11c**	24	25:1:1	89	82.0:18.0(64)	*R*
11	**11d**	6	25:1:2	58	81.9:18.1 (64)	*R*
12	**11d**	24	25:1:2	80	82.5:17.5 (65)	*R*
13	**11e**	24	25:1:2	nd[d]	nd[d]	nd[d]
14	**11f**	6	25:1:2	58	19.1:80.9 (62)	*S*
15	**11f**	24	25:1:2	80	20.5:79.5 (59)	*S*

[a]Isolated yield after flash chromatography. [b]Enantiomeric ratios determined by CSP HPLC (Chiralcel AD column). [c]The identity of the enantiomer was based on elution from the CSP HPLC column. See ref 10. [d]Not determined.

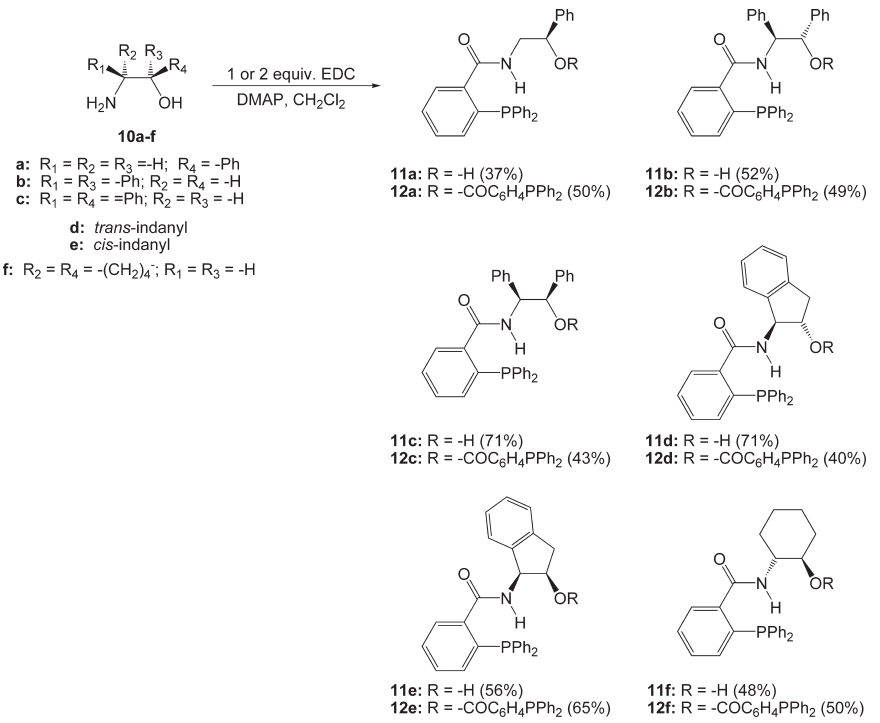
2. Results and Discussion

A series of β-amino alcohols (**10a−f**), both acyclic and cyclic, were coupled with *o*-(diphenylphosphino)benzoic acid, 1 equiv of 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide (EDC), and a catalytic amount of dimethylaminopyridine (DMAP) to afford the β-hydroxy(*o*-diphenylphosphino)-benzamides **11a−f** (Scheme 1). In like fashion, β-amino alcohols (**10a−f**) were also treated with 2 equiv of EDC and catalytic DMAP to generate the corresponding β-(*o*-diphenylphosphino)benzyloxy(*o*-diphenylphosphino)benzamides **12a−f** in yields ranging from 40% to 65%. With these compounds in hand, the asymmetric allylic alkylation reaction was pursued with a catalytic amount of allylpalladium chloride dimer $\{[(\eta^3\text{-}C_3H_5)PdCl]_2\}$, 1,3-diphenylpropenyl acetate, and dimethyl malonate. Potassium acetate and *N*,*O*-bis(trimethylsilyl)-acetamide (BSA) were also employed to facilitate the deprotonation of dimethyl malonate.

The first set of reactions that were carried out were focused on the application of the β-hydroxy benzamides **11a−f** (Table 1). The ratio of the palladium precatalyst, ligand

(9) Lai, H.; Huang, Z.; Wu, Q.; Qin, Y. *J. Org. Chem.* **2009**, *74*, 283–288.
(10) Marinho, V. R.; Rodrigues, A. I.; Burke, A. J. *Tetrahedron: Asymmetry* **2008**, *19*, 454–458.
(11) Mino, T.; Kashihara, K.; Yamashita, M. *Tetrahedron: Asymmetry* **2001**, *12*, 287.
(12) Mahadik, G. S.; Knott, S. L.; Szczepura, L. F.; Hitchcock, S. R. *Tetrahedron: Asymmetry* **2009**, *20*, 1132–1137.

SCHEME 1. Synthesis of (*o*-Diphenylphosphino)benzamides 11a−f and 12a−f



and substrate, and time were varied for the sake of finding an optimal ratio that would afford the best enantioselection. The only related reports on β-hydroxybenzamides being employed in the catalytic asymmetric alkylation did not provide a definitive guide to an optimized ratio.[10−12]

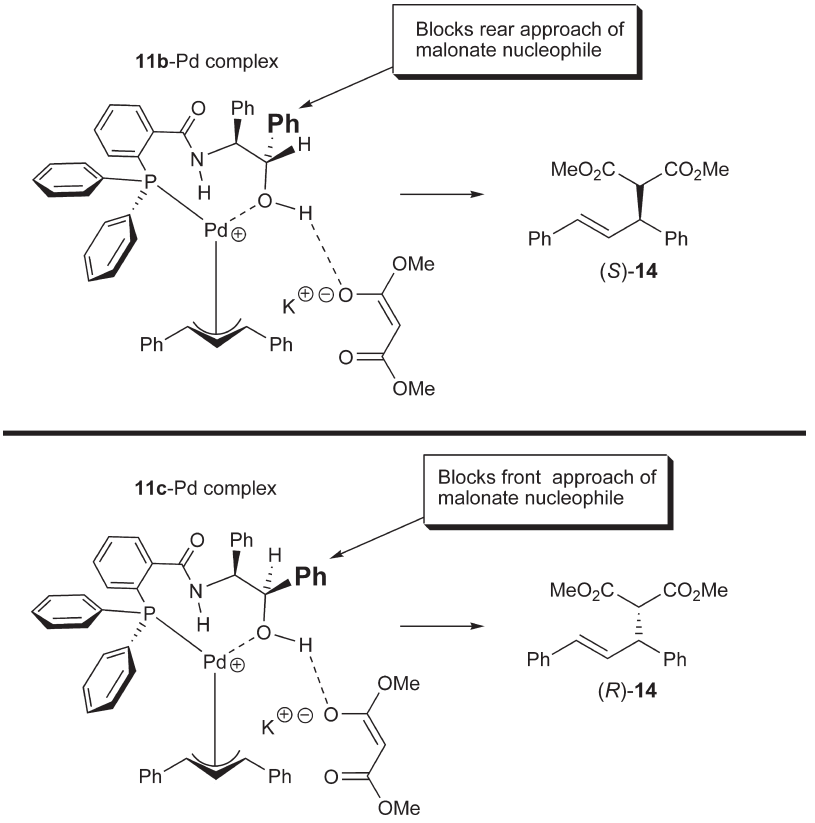
Benzamides **11a** and **11c−e** are structurally related to the (1*R*,2*S*)-norephedrine-based β-hydroxybenzamide **8a** and all of these systems afford the same configuration in the end product, the (*R*)-enantiomer. In contrast, benzamides **11b** and **11f** afforded the (*S*)-enantiomer of the product. These two benzamides (**11b**, **11f**) are related to the diastereomeric (1*S*,2*S*)-pseudonorephedrine-based β-hydroxybenzamide **8b**, which yielded the (*R*)-enantiomer when applied in the asymmetric alkylation.[12] The change in configuration for the malonate product resulting from the application of (1*R*,2*R*)-**11f** was expected as the absolute stereochemistry was opposite to that of the (1*S*,2*S*)-pseudonorephedrine **8b** employed in the earlier study. Yet, the β-hydroxybenzamide **11b** has the same configuration as the (1*S*,2*S*)-pseudonorephedrine benzamide **8b**, but yielded the oppositely configured enantiomer. The origin of the change in enantioselection may be associated with a change in the conformation for **11b** as compared to **8b**. The result of the application of the benzamide **11b** in the asymmetric catalysis reaction is perhaps best evaluated in the context of its diastereomeric counterpart **11c** (Scheme 2). These two ligands afford the malonate product **14** in opposite configurations. For each ligand the stereocenter bearing the amido functional group is the same. On the basis of this observation, the argument can be made that the carbon bearing the alcohol functional group, which is the point of difference for the diastereomers **11b** and **11c**, must have a significant influence over the stereochemical course of the reaction. It is proposed that the alcohol functional group might exert an influence in the approach of the malonate nucleophile to the palladium-bound ligand with the result that that region of the benzylic alcohol is ultimately responsible for the observed asymmetric induction. There may be other reaction pathways but any viable pathways would need to take into account the influence of the stereochemistry at the carbon bearing the alcohol group.

The benzamide **11e** failed to react after multiple attempts to employ this material as a catalyst in the asymmetric allylic alkylation. There was a noticeable darkening of the reaction mixture when ligand **11e** was employed as compared to **11a−d** and **11f** (Figure 3). The reason for this low reactivity is not clear. It is proposed that the poor reactivity of this particular ligand may have been associated with the ready deactivation of the palladium through the proximity of the alcohol moiety. This is the one ligand that has the alcohol group in a locked *syn*-configuration aspect with the (diphenylpshosphino)benzamide.

The bis(phosphine) ligands **12a−f** were also employed in the asymmetric allylic alkylation reaction with dimethyl malonate (Table 2). In contrast to the mono(phosphine) ligands **11a−f**, all of the bis(phosphine) ligands (**12a−f**) afforded the alkylation product as the (*S*)-enantiomer without deviation. Some of these ligands yielded very good enantiomeric excesses of the product while others did not perform well in the asymmetric process.

The application of ligand **12a** afforded a poor enantioselectivity in product formation (9−11% ee). It is believed that the absence of substitution at the carbon bearing the amino group gives rise to a high level of conformational freedom that may be detrimental to the success of the process of asymmetric induction. In the course of characterizing ligands **12a−f** by $^{31}P\{^{1}H\}$ NMR spectroscopy it was determined that the ^{31}P spectrum of **12a** was unique among the diphosphine ligands (see the Supporting Information). Due to the two different electronic environments of each

SCHEME 2. Proposed Reaction Mechanisms for Catalysis with 11b and 11c



phosphorus atom in the diphosphine ligands **12a**−**f**, it was anticipated that each ligand would have two observable signals in their corresponding spectra. This was indeed the case. However, the only exception was compound **12a**, which displayed four resonance signals. Upon inspection, these signals appear to be two sets of doublets centered at −5.29 and −8.85 ppm. However, since the related monophosphine precursor (**11a**) only showed a singlet at −9.92 ppm in its $^{31}P\{^{1}H\}$ NMR spectrum, it is unlikely that the apparent splitting is due to ^{1}H coupling with protons that were not fully decoupled. In addition to this, all of the other diphosphine ligands **12a**−**d** and **12f** only exhibit two resonances under similar conditions. Therefore, coupling between the two nonequivalent phosphorus atoms can be ruled out. It is more likely that compound **12a** exists in two different structural conformations that are in equilibrium undergoing slow interconversion on the NMR time scale; each conformer would have two unique ^{31}P resonances which would lead to four resonances overall. If this proposal is valid, then increasing the temperature of the solution containing **12a** would increase the exchange rate between these two conformers and the individual pairs of two resonances would coalesce into broadened singlets. To test this hypothesis, a variable-temperature NMR study was pursued. Figure 4 shows the $^{31}P\{^{1}H\}$ spectrum of **12a** at 298 and 383 K (in toluene-d_8). The high-temperature spectrum clearly shows that the pairs of peaks have coalesced into two broad singlets, indicative of two conformers undergoing rapid

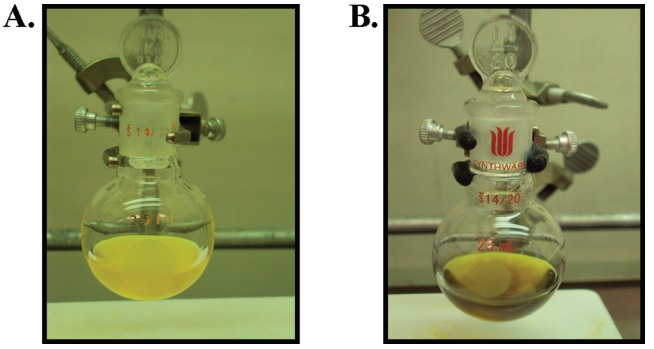


FIGURE 3. Comparison of typical asymmetric catalysts with ligands **11a**−**d** (A) vs. ligand **11e** (B).

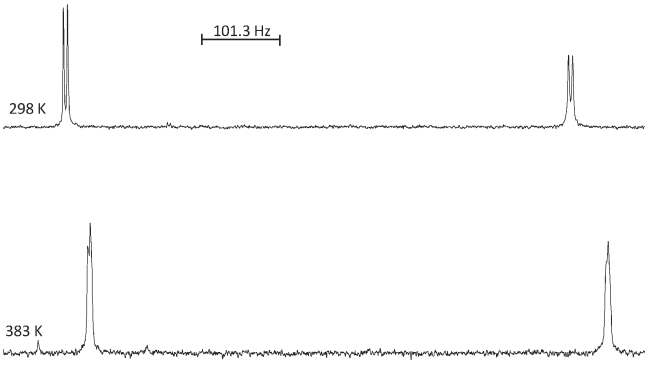
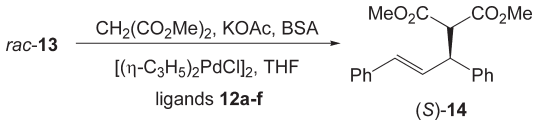


FIGURE 4. The 202.5 MHz $^{31}P\{^{1}H\}$ NMR spectra of a toluene-d_8 solution containing **12a** recorded at 298 and 383 K in a sealed NMR tube. The splitting observed for each resonance in the top spectrum disappears as the temperature is increased to 383 K. The resulting two broad singlets observed at the high temperature strongly suggest the presence of two conformers of **12a** undergoing rapid exchange on the NMR time scale.

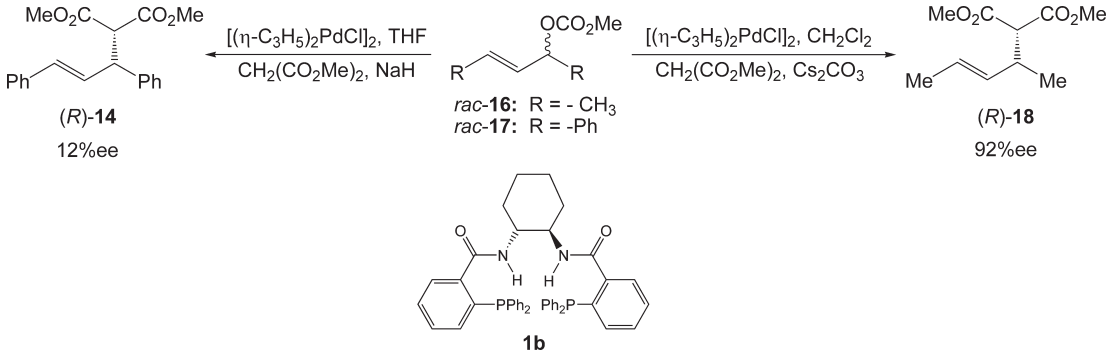
TABLE 2. Asymmetric Allylic Alkylation with 12a−f



entry	ligand	solvent	time (h)	**13**:ligand:Pd	yield (%)[a]	er (*R*:*S*), (ee)[b,c]	config [d]
1	**12a**	THF	24	25:1:1	88	45.2:54.8 (11)	*S*
2	**12a**	THF	6	25:1:1	89	45.4:54.6 (9)	*S*
3	**12b**	THF	24	25:1:1	90	7.3:92.7 (85)	*S*
4	**12b**	THF	24	25:2:1	82	5.5:94.5 (89)	*S*
5	**12b**	THF	24	25:1:2	67	4.8:95.2 (91)	*S*
6	**12c**	THF	24	25:1:1	43	5.5:94.5 (89)	*S*
7	**12c**	THF	6	25:1:1	63	2.2:97.8 (96)	*S*
8	**12c**	THF	6	25:2:1	79	12.8:87.2 (74)	*S*
9	**12c**	THF	6	25:1:2	84	3.2:96.8 (94)	*S*
10	**12d**	THF	6	25:1:1	74	12.7:87.3 (75)	*S*
11	**12d**	THF	24	25:1:1	61	8.9:91.1 (82)	*S*
12	**12d**	toulene	24	25:1:2	88	23.0:77.0 (54)	*S*
13	**12e**	THF	24	25:1:1	86	44.6:55.4 (11)	*S*
14	**12f**	THF	6	25:1:1	< 5	41.6:58.4 (17)	*S*
15	**12f**	THF	24	25:1:1	78	43.4:56.6 (13)	*S*
16	**12f**	THF	24	25:2:1	< 5	48.1:51.9 (4)	*S*
17	**12f**	THF	24	25:1:2	73	46.9:53.1 (6)	*S*

[a]Isolated yield after flash chromatography. [b]Enantiomeric ratios determined by CSP HPLC (Chiralcel AD column). [c]The identity of the enantiomer was based on elution from the CSP HPLC column. See ref 10. [d]Not determined.

SCHEME 3. Trost Ligand 1b in the Asymmetric Allylic Alkylation



exchange on the NMR time scale. The fact that this ligand can exist in these different conformational forms may explain the low enantioselection observed in the alkylation reaction with ligand **12a** (Table 2).

The β-hydroxybenzamides **12e** and **12f** also yielded low levels of enantioselection in the asymmetric allylic alkylation reaction. The rationale for the failure of these two ligands in this process is attributed to structural dynamics associated with the chiral cavity created by the interaction of the palladium(II) with the bis(phosphine) ligands. It has been established by Trost[13] that his ligand **1b** affords low enantioselectivity in the alkylation reaction with methyl 1,3-diphenylpropenylcarbonate, but high enantioselectivity when the smaller allylic substrate methyl 3-penten-2-ylcarbonate was employed (Scheme 3). The rationalization for these observations was that the "chiral pocket" created by the ligand bound palladium catalyst exhibits optimal catalytic and asymmetric efficiency when the allylic substrate is of a smaller size. On the basis of this argument, it is presumed that the palladium-bound ligands **12e** and **12f** must experience significant steric hindrance when interacting with the 1,3-diphenylpropenyl acetate substrate. In contrast to poor enantioselection obtained from the use of **12e** and **12f**, the application of the diphosphine **12d**, the diastereomer of **12e**, afforded enantioselectivities that were significantly better. Because of the stereochemical relationship between trans-diastereomer **12d** and the cis-diastereomer **12e**, it is proposed that the cis-diastereomer must have the diphenylphosphino groups in such a configuration that the phenyl rings of the phosphorus atoms are not well-positioned for the transfer of asymmetry from the chiral scaffold.

The benzamide ligand **12c** afforded the best level of enantioselection for all of the ligands that were prepared. When applied in the asymmetric alkylation reaction, the bisester **14** was obtained with an enantiomeric ratio of 2.2:97.8 (95.6% ee). A model for the asymmetric induction leading to the observed enantioselection was developed by using the Trost "wall/flap" model[14]

(13) Trost, B. M.; Krueger, A. C.; Bunt, R. C.; Zambrano, J. *J. Am. Chem. Soc.* **1996**, *118*, 6520.

(14) (a) Trost, B. M.; Machacek, M. R.; Aponick, A. *Acc. Chem. Res.* **2006**, *39*, 747. (b) Trost, B. M. *Chem. Pharm. Bull.* **2002**, *50*, 1. (c) Yamaguchi, M.; Yabuki, M.; Yamagishi, T.; Sakai, K.; Tsubomura, T. *Chem. Lett.* **1996**, 241.

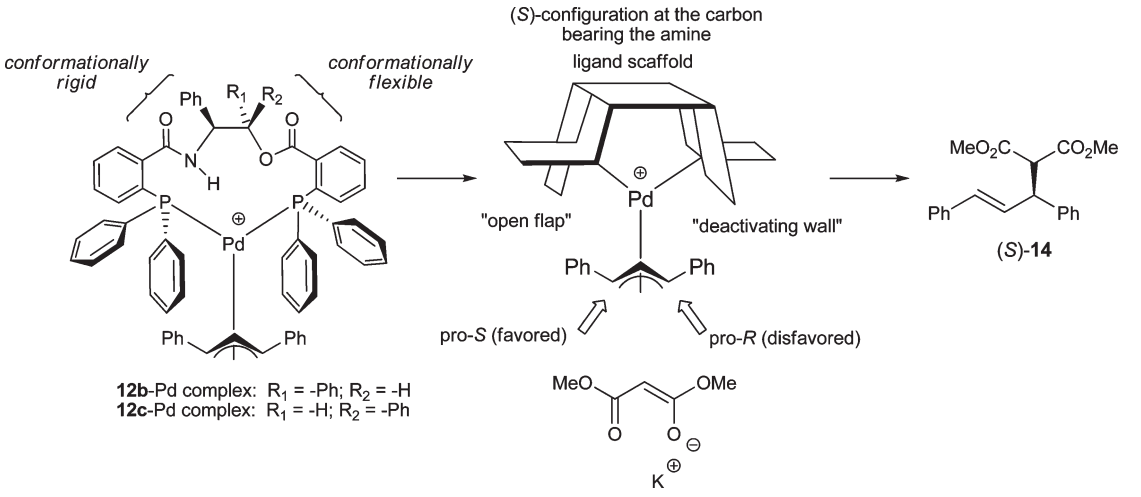


FIGURE 5. Trost model for asymmetric induction in the allylic alkylation pathway.

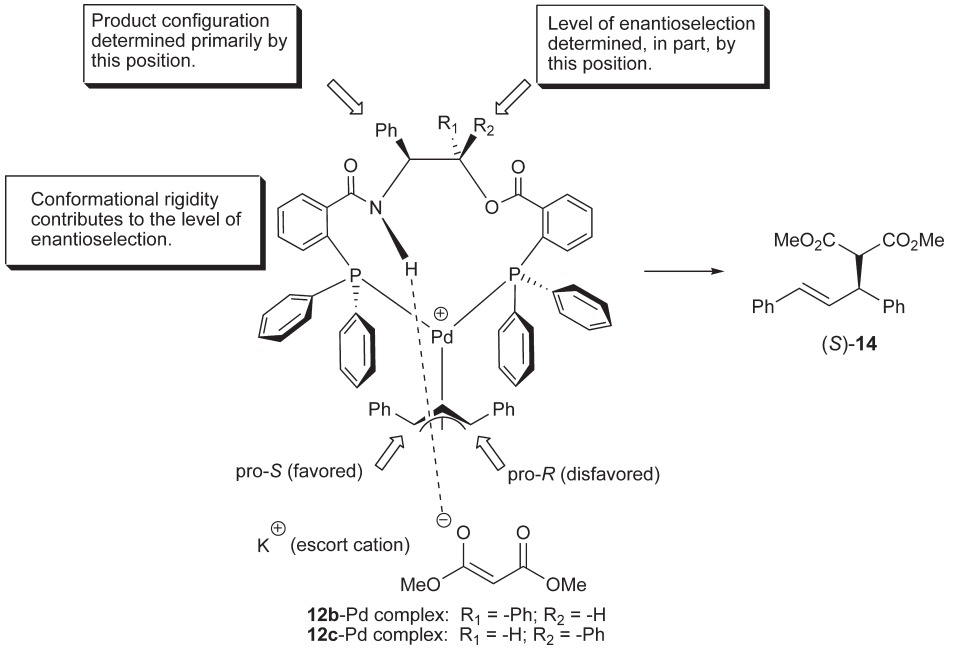


FIGURE 6. Lloyd−Jones−Norrby model asymmetric induction in the allylic alkylation reaction.

(Figure 5) and the newly developed Lloyd−Jones−Norrby model[15] that involves hydrogen bonding of the ligand with the incoming nucleophile. In the context of both of these models, it is important to note that the diastereomeric ligands **12b** and **12c**[16] yielded enantioselectivities that were in the ≥90% ee range. This would suggest that the stereochemistry at the carbon bearing the amide is one of the key facilitators of the asymmetric induction.[17] The Trost model assumes the use of a C_2-symmetric ligand as the scaffold for the asymmetric process. The palladium-bound ligands **12b** and **12c** are β-benzoyloxyamides that would be expected to exhibit more conformational freedom than the Trost ligands **1a** and **1b**, potentially leading to lower enantioselectivities.[2f] Despite this, the conveyance of the asymmetry from these ligands is successfully transmitted to the prochiral allylic substrate as evidenced by the moderately high level of enantioselection.

Recently, Lloyd−Jones and Norrby proposed that the Trost model may be limited in terms of relaying a more comprehensive analysis of the key events that occur in the process of enforcing the formation of the new chiral center in the substrate.[15] The collected research suggested that hydrogen bonding from the amide contained in the ligand to the approaching nucleophile was also important in terms of determining the stereochemical outcome of the reaction. Figure 6 illustrates this model with ligands **12b** and **12c** with

(15) (a) Butts, C. P.; Filali, E.; Lloyd-Jones, G. C.; Norrby, P.; Sale, D. A.; Schramm, Y. *J. Am. Chem. Soc.* **2009**, *131*, 9945–9957. (b) Lloyd-Jones, G. C.; Stephen, S. C.; Fairlamb, I. J.; Martorell, A.; Dominguez, B.; Tomlin, P. M.; Murray, M.; Fernandez, J. M.; Jeffrey, J. C.; Riis-Johannessen, G. T. *Pure Appl. Chem.* **2004**, *76*, 589–601. (c) Fairlamb, I. J.; Lloyd-Jones, G. C. *Chem. Commun.* **2000**, 2447. (d) Butts, C. P.; Crosby, J.; Lloyd-Jones, G. C.; Stephen, S. C. *Chem. Commun.* **1999**, 1707.

(16) No attempt was made to isolate the palladium complexes of **12b** or **12c**. The preparation of independent stoichiometric mixtures of **12b** and **12c** with the palladium precatalyst has been inconclusive and will be the subject of future studies.

(17) The Trost model of the asymmetric induction was originally designed for (1*R*,2*R*)-diamine. The ligands described in Figures 3 and 4 possess the *S*-configuration at the carbon bearing the amide.

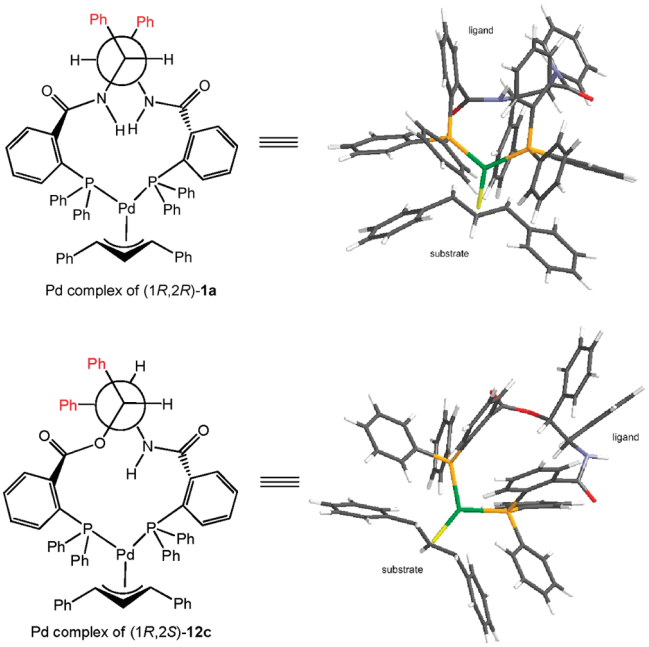


FIGURE 7. Semiempirical PM3 modeled ligand Trost modular ligand **1a** and *β*-benzoyloxy amide **12c**. Red = oxygen, blue = nitrogen, gold = phosphorus, green = palladium.

the ligand adopting a similar conformation about the palladium complex as was depicted in the Trost model of Figure 3.

A computational study was conducted with the objective of evaluating the conformational aspects of the palladium-bound **12c** versus that of the palladium-bound Trost ligand **1a**. Thus, a conformational search was conducted. Conformation searching of ligands **12c** and **1a** was carried out by using the MMFF force field. Low-energy conformers of ligands which met acceptable end-to-end distance criteria were then bound to palladium and subjected to additional conformation searching by using the Semiempirical PM3 methodology. The lowest energy conformers were obtained and the structures for the palladium complexes **12c** and **1a** are shown in Figure 7. The palladium-bound Trost ligand **1a** has an element of C_2-symmetry imparted by the ligand, whereas the palladium-bound complex **12c** deviated from a symmetrical structure.

This deviation from a more symmetric form is believed to be due, in some part, to the *syn*-configuration of the phenyl rings and the presence of the conformationally flexible ester functional group. Computationally, there was another conformer for **12c** that was within 1 kcal/mol that was similar in structure. At room temperature, there are most likely a number of conformers that, on average, converge to the conformer depicted. It is proposed that this distortion away from the C_2-symmetry allows for complex **12c** to interact with large substrates such as the 1,3-diphenylpropenyl acetate to give good enantiomeric excesses. It must be noted that the calculations were conducted in the gas phase and that there may be solvent effects that are not taken into account.

3. Conclusion

The (mono)phosphine ligands **11a**−**f** primarily afforded the *R*-enantiomer and the bis(phosphine) ligands **12a**−**f** exclusively yielded the *S*-enantiomer. The observed stereochemistry of the products of these reactions was rationalized based on the Trost model and the Lloyd−Jones−Norrby model. On the basis of the results obtained here, there is the potential for the development of even more effective *β*-(*o*-diphenylphosphino)benzoyloxy(*o*-diphenylphosphino)benzamide ligands in the palladium-catalyzed asymmetric allylic reaction. Research is underway in this area.

4. Experimental Section

(*R*)-2-(Diphenylphosphino)-*N*-(2-hydroxy-2-phenylethyl)-benzamide (11a). To a 250 mL nitrogen-purged round-bottomed flask were added (*R*)-(−)-2-amino-1-phenyl-1-ethanol (0.350 g, 2.55 mmol), DMAP (0.062 g, 0.510 mmol), dichloromethane (7 mL), 2-(diphenylphosphino)benzoic acid (0.781 g, 2.55 mmol), and EDC (0.538 g, 2.80 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 6:4). Viscous wax (37%), $[\alpha]^{24}_D$ −32.1 (*c* 0.50, $CHCl_3$); IR (nujol) (cm^{-1}) 3312, 1634, 1581, 1310, 1160, 744, 698; ^{1}H NMR (500 MHz, $CDCl_3$) *δ* (ppm) 3.20 (ddd, *J* = 4.9, 8.6,12.4 Hz, 1H), 3.6 3 (ddd, *J* = 3.2, 7.0, 12.4 Hz, 1H), 3.65 (d, *J* = 3.9 Hz, 1H), 4.63−4.66 (m, 1H), 6.56 (t, *J* = 5.2 Hz, 1H), 6.94−6.98 (m, 1H), 7.19−7.31 (m, 17H), 7.47−7.51 (m, 1H); ^{13}C NMR ($CDCl_3$) *δ* 47.8, 72.8, 125.7, 127.5, 127.6, 127.7, 128.3, 128.47, 128.49, 128.52, 128.54, 128.7, 128.8, 130.1, 133.6, 133.7, 133.80, 133.84, 134.0, 135.8, 136.0, 136.5, 136.6, 136.7, 136.8, 140.8, 141.0, 141.5, 169.9; ^{31}P{^{1}H} NMR ($CDCl_3$) −9.92 ppm; ESI-HRMS calcd for $C_{27}H_{24}NO_2P$ ($M + H^+$) 426.1623, found 426.1620.

(*R*)-2-(2-(Diphenylphosphino)benzamido)-1-phenylethyl 2-(Diphenylphosphino)benzoate (12a). To a 250 mL nitrogen-purged round-bottomed flask were added (*R*)-(−)-2-amino-1-phenylethanol (0.300 g, 2.19 mmol), DMAP (0.267 g, 2.19 mmol), dichloromethane (10 mL), 2-(diphenylphosphino)benzoic acid (1.34 g, 4.37 mmol), and EDC (0.838 g, 4.37 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 6:4). Viscous wax (50%), $[\alpha]^{24}_D$ 27.4 (*c* 0.26, $CHCl_3$); IR (nujol) (cm^{-1}) 1714, 1651, 1584, 1247, 1108, 743, 696; ^{1}H NMR (500 MHz, $CDCl_3$) *δ* (ppm) 3.18 (ddd, *J* = 3.6, 10.3, 13.0 Hz, 1H), 3.98 (ddd, *J* = 3.2, 8.6, 13.0, Hz, 1H), 5.93 (dd. *J* = 3.0, 10.3 Hz, 1H), 6.88−6.90 (m, 1H), 6.93−6.97 (m, 1H), 7.12−7.49 (m, 30 H), 7.65−7.67 (m, 1H), 8.10−8.12 (m, 1H); ^{13}C NMR ($CDCl_3$) *δ* 44.2, 126.5, 127.7, 128.2, 128.4, 128.42, 128.5, 128.54, 128.6, 128.7, 128.74, 128.8, 128.82, 128.9, 129.1, 130.1, 132.1, 132.3, 133.4, 133.5, 133.7, 133.8, 133.9, 134.0, 134.15, 134.2, 134.3, 134.9, 135.2, 135.3, 136.9, 137.0, 137.01, 137.1, 137.2, 137.3, 137.45, 137.5, 137.54, 137.6, 137.7, 140.9, 141.1, 166.3, 168.6; ^{31}P{^{1}H} NMR ($CDCl_3$) −5.28, −5.31, −8.84, −8.86 ppm; ^{31}P NMR also suggests impurity present in less than 5%; ESI-HRMS calcd for $C_{46}H_{37}NO_3P_2$ ($M + H^+$) 714.2327, found 714.2335.

2-(Diphenylphosphino)-*N*-(1*S*,2*S*)-2-hydroxy-1,2-diphenylethylbenzamide (11b). To a 250 mL nitrogen-purged round-bottomed flask were added (*S*,*S*)-(−)-2-amino-1,2-diphenylethanol (0.300 g, 1.41 mmol), DMAP (0.034 g, 0.281 mmol), dichloromethane (10 mL), 2-(diphenylphosphino)benzoic acid (0.430 g, 1.41 mmol), and EDC (0.297 g, 1.55 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 7:3). Viscous wax (52%), $[\alpha]^{23}_D$ −35.4 (*c* 0.55, $CHCl_3$); IR (nujol) (cm^{-1}) 3343, 1642, 1579, 1314, 1184; ^1H NMR (500 MHz, $CDCl_3$) δ (ppm) 3.59 (s, 1H), 4.70 (d, J = 7.8 Hz, 1H), 5.18 (dd, J = 8.1, 10.0 Hz, 1H), 6.61 (d, J = 9.0 Hz, 1H), 6.78−6.80 (m, 1H), 6.85−6.89 (m, 1H), 7.01−7.29 (m, 21H), 7.34−7.37 (m, 1H); ^{13}C NMR ($CDCl_3$) 60.6, 77.4, 126.5, 127.1, 127.4, 127.5, 128.2, 128.21, 128.3, 128.5, 128.6, 128.7, 128.8, 128.83, 128.9, 128.94, 130.2, 133.55, 133.58, 133.75, 133.78, 134.3, 134.8, 134.9, 136.2, 136.3, 136.7, 136.8, 138.5, 140.4, 141.43, 141.7, 169.2; $^{31}P\{^1H\}$ NMR ($CDCl_3$) −10.98 ppm; ESI-HRMS calcd for $C_{33}H_{28}NO_2P$ (M + H^+) 502.1936, found 502.1925.

(1*S*,2*S*)-2-(2-(Diphenylphosphino)benzamido)-1,2-diphenylethyl 2-(diphenylphosphino)benzoate (12b). To a 250 mL nitrogen-purged round-bottomed flask were added (*S*,*S*)-(−)-2-amino-1,2-diphenylethanol (0.494 g, 2.32 mmol), DMAP (0.283 g, 2.32 mmol), dichloromethane (10 mL), 2-(diphenylphosphino)benzoic acid (1.42 g, 4.63 mmol), and EDC (1.00 g, 4.63 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 7:3). Viscous wax (49%), $[\alpha]^{24}_D$ −30.0 (*c* 0.52, $CHCl_3$); IR (nujol) (cm^{-1}) 3404, 1716, 1666, 1583, 1338, 1146; ^1H NMR (500 MHz, $CDCl_3$) δ (ppm) 5.65 (t, J = 8.3 Hz, 1H), 6.20 (d, J = 7.7 Hz, 1H), 6.90−6.95 (m, 1H), 7.00−7.46 (m, 37 H), 8.28−8.29 (m, 1H); ^{13}C NMR ($CDCl_3$) 58.0, 78.6, 127.2, 127.4, 127.9, 127.93, 128.0, 128.1, 128.2, 128.24, 128.3, 128.32, 128.4, 128.43, 128.5, 130.0, 131.8, 132.1, 133.3, 133.4, 133.5, 133.6, 133.7, 133.76, 133.8, 133.84, 134.1, 134.4, 135,6, 135.8, 136.7, 136.9, 137.0, 137.1, 137.2, 137.4, 137.44, 137.6, 137.65, 137.7, 139.9, 140.1, 141.2, 141.5, 165.7, 168.1; $^{31}P\{^1H\}$ NMR ($CDCl_3$) −4.43, −10.76 ppm; ESI-HRMS calcd for $C_{52}H_{41}NO_3P_2$ (M + H^+) 790.2640, found 790.2635.

2-(Diphenylphosphino)-*N*-(1*R*,2*S*)-2-hydroxy-1,2-diphenylethylbenzamide (11c). To a 250 mL nitrogen-purged round-bottomed flask were added (1*R*,2*S*)-2-amino-1,2-diphenylethanol (0.494 g, 2.32 mmol), DMAP (0.057 g, 0.463 mmol), dichloromethane (6 mL), 2-(diphenylphosphino)benzoic acid (0.709 g, 2.32 mmol), and EDC (0.488 g, 2.55 mmol). The reaction mixture was allowed to stir for 24 h and was quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by recrystallization in ether and hexanes (1:2). Viscous wax (71%), $[\alpha]^{24}_D$ −37.9 (*c* 1.00, $CHCl_3$); IR (nujol) (cm^{-1}) 3350, 1623, 1522, 1220; ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 5.17(d, J = 3.3 Hz, 1H), 5.28(dd, J = 5.4 Hz,1H), 6.72 (br s, 1H), 6.81 (d, J = 7.5 Hz, 3H), 6.99−7.02 (m, 5H), 7.11 (t, J = 2.86 Hz, 3H), 7.16−7.42 (m, 13H), 7.61−7.64 (m, 1H); ^{13}C NMR ($CDCl_3$) 60.6, 75.7, 126.4, 127.3, 127.5, 127.8, 127.9, 128.2, 128.3, 128.31, 128.7, 128.71, 128.8, 128.9, 129.1, 129.3, 130.4, 133.7, 133.7, 133.8, 133.9, 134.3, 136.2, 139.8, 168.8; $^{31}P\{^1H\}$ NMR ($CDCl_3$) −10.73 ppm; ESI-HRMS calcd for $C_{33}H_{29}NO_2P$ (M + H^+) 502.1936, found 502.1946.

(1*R*,2*S*)-2-(2-(Diphenylphosphino)benzamido)-1,2-diphenylethyl 2-(Diphenylphosphino)benzoate (12c). To a 250 mL nitrogen-purged round-bottomed flask were added (1*R*,2*S*)-2-amino-1,2-diphenylethanol (0.494 g, 2.32 mmol), DMAP (0.283 g, 2.316 mmol), dichloromethane (10 mL), 2-(diphenylphosphino)benzoic acid (1.42 g, 4.63 mmol), and EDC (0.888 g, 4.63 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by recrystallization in ether and hexanes (1:2). White solid (43%), $[\alpha]^{23}_D$ +9.6 (*c* 1.00, $CHCl_3$); mp 220−223 °C; IR (nujol) (cm^{-1}) 3350, 1623, 1522, 1220; ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 5.58 (dd, J = 4.1, 8.8 Hz, 1H), 6.21 (d, J = 4.1 Hz, 1H), 6.91−6.99 (m, 8H), 7.06−7.31 (m, 26H), 7.38−7.41 (m, 3H), 7.54−7.57 (m, 1H), 7.97−8.00 (m, 1H); ^{13}C NMR ($CDCl_3$) 57.8, 78.6, 126.8, 127.4, 127.9, 128.0, 128.03, 128.1, 128.14, 128.2, 128.4, 128.42, 128.5, 128.6, 128.62, 128.7, 130.1, 130.5, 131.9, 133.6, 133.7, 133.76, 133.8, 133.9, 133.93, 134.0, 134.1, 134.5, 134.8, 135.0, 136.3, 136.4, 136.5, 136.7, 137.0, 137.04, 137.1, 137.2, 137.3, 137.6, 137.7, 139.9, 140.1, 141.0, 141.2, 166.0, 167.9; $^{31}P\{^1H\}$ NMR ($CDCl_3$) −5.45, −9.72 ppm; ESI-HRMS calcd for $C_{52}H_{42}NO_3P_2$ (M + H^+) 790.2640, found 790.2649.

2-(Diphenylphosphino)-*N*-((1*S*,2*S*)-2-hydroxy-2,3-dihydro-1*H*-inden-1-yl)benzamide (11d). To a 250 mL nitrogen-purged round-bottomed flask were added (1*S*,2*S*)-(+)-*trans*-1-amino-2-indanol (0.200 g, 1.34 mmol), DMAP (0.033 g, 0.268 mmol), dichloromethane (10 mL), 2-(diphenylphosphino)benzoic acid (0.411 g, 1.34 mmol), and EDC (0.283 g, 1.48 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 6:4). Viscous wax (71%), $[\alpha]^{24}_D$ 25.7 (*c* 0.30, $CHCl_3$); IR (nujol) (cm^{-1}) 1628, 1583, 1306, 1154, 742, 723; ^1H NMR (500 MHz, $CDCl_3$) δ (ppm) 2.87 (dd, J = 8.1, 15.8 Hz, 1H), 3.21 (dd, J = 7.9, 15.8 Hz, 1H), 4.24 (dd, J = 7.9, 14.2 Hz, 1H), 4.55 (s, 1H), 5.03 (t, J = 5.8 Hz, 1H), 6.59−6.61 (m, 1H), 6.93−6.97 (m, 1H), 7.12−7.39 (m, 16 H), 7.66−7.68 (m, 1H); ^{13}C NMR ($CDCl_3$) 38.3, 64.8, 81.1, 123.0, 125.0, 127.1, 128.3, 128.34, 128.4, 128.66, 128.7, 128.72, 128.74, 128.8, 129.1, 129.14, 130.5, 133.7, 133.8, 133.9, 133.91, 134.0, 135.7, 135.8, 135.9, 136.0, 136.1, 136.2, 138.7, 139.9, 140.1, 140.4, 171.13; $^{31}P\{^1H\}$ NMR ($CDCl_3$) −9.21 ppm; ^{31}P NMR also suggests impurity present in less than 5%; ESI-HRMS calcd for $C_{28}H_{24}NO_2P$ (M + H^+) 438.1623, found 438.1618.

(1*S*,2*S*)-1-(2-(Diphenylphosphino)benzamido)-2,3-dihydro-1*H*-inden-2-yl 2-(Diphenyphosphino)benzoate (12d). To a 250 mL nitrogen-purged round-bottomed flask were added (1*S*,2*S*)-(+)-*trans*-1-amino-2-indanol (0.200 g,1.34 mmol), DMAP (0.066 g, 0.536 mmol), dichloromethane (10 mL), 2-(diphenylphosphino)benzoic acid (0.821 g, 2.68 mmol), and EDC (0.514 g, 2.68 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 6:4). Viscous wax (40%), $[\alpha]^{24}_D$ 6.9 (*c* 0.54, $CHCl_3$); IR (nujol) (cm^{-1}) 1707, 1645, 1584, 1252, 742, 695; ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm) 2.74 (dd, J = 7.0, 16.2 Hz, 1H), 3.25 (dd, J = 7.5, 16.2 Hz, 1H), 5.27 (dd, J = 7.1, 13.9 Hz, 1H), 5.72 (apparent triplet, J = 7.1 Hz, 1H), 6.32 (dd, J = 1.0, 8.4 Hz, 1H), 6.89−6.95 (m, 1H), 7.08−7.38 (m, 29 H), 7.60−7.62 (m, 1H), 8.11−8.14 (m, 1H); ^{13}C NMR ($CDCl_3$) 36.2, 59.4, 80.7, 124.45, 124.5, 124.6, 127.3, 128.0, 128.02, 128.29, 128.3, 128.33, 128.4, 128.44, 128.5, 128.54, 128.66, 128.7, 128.8, 130.2, 131.15, 131.2, 132.0, 133.65, 133.7, 133.8, 133.9, 133.94, 134.0, 134.03, 134.1, 135.8, 135.9, 136.7, 136.8, 137.0, 137.1, 137.7, 137.8, 138.0, 138.1, 138.7, 139.4, 140.3, 140.5, 140.8, 141.0, 166.6, 169.0; ^{31}P{^{1}H} NMR ($CDCl_3$) −4.40, −10.17 ppm; ESI-HRMS calcd for $C_{47}H_{37}NO_3P_2$ (M + H^+) 726.2327, found 726.2313.

2-(Diphenylphosphino)-*N*-((1*R*,2*S*)-2-hydroxy-2,3-dihydro-1*H*-inden-1-yl)benzamide (11e). To a 250 mL nitrogen-purged round-bottomed flask were added (1*R*,2*S*)-(+)*cis*-1-amino-2-indanol (0.500 g, 3.35 mmol), DMAP (0.082 g, 0.670 mmol), dichloromethane (10 mL), 2-(diphenylphosphino)benzoic acid (1.03 g, 3.35 mmol), and EDC (0.707 g, 3.69 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$).The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 6:4). Viscous wax (56%); $[\alpha]^{23}_D$ 34.4 (*c* 0.54, $CHCl_3$); IR (nujol) (cm^{-1}) 1716, 1270, 1248, 744, 696; ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm) 2.81 (dd, J = 1.5, 16.6 Hz, 1H), 2.99 (dd, J = 5.0, 16.6 Hz, 1H), 3.06 (s, 1H), 4.52 (d, J = 3.1 Hz, 1H), 5.35 (dd, J = 5.0, 8.3 Hz, 1H), 6.66 (d, J = 8.3 Hz, 1H), 6.98−7.01 (m, 1H), 7.09−7.31 (m, 16 H), 7.60−7.62 (m, 1H); ^{13}C NMR ($CDCl_3$) 39.3, 58.1, 73.1, 124.3, 124.9, 126.8, 127.6, 127,64, 127.8, 140.2, 141.2, 141.4, 128.4, 128.5, 128.7, 128.8, 130.1, 133.5, 133.65, 133.7, 133.8, 134.0, 135.4, 135.5, 136.3, 136.4, 136.5, 136.54, 169.4; ^{31}P{^{1}H} NMR ($CDCl_3$) −10.04 ppm; ESI-HRMS calcd for $C_{28}H_{24}NO_2P$ (M + H^+) 438.1623, found 438.1618.

(1*R*,2*S*)-1-(2-(Diphenylphosphino)benamido)-2,3-dihydro-1*H*-inden-2-yl 2-(Diphenylphosphino)benzoate (12e). To a 250 mL nitrogen-purged round-bottomed flask were added (1*R*,2*S*)-(+)-*cis*-1-amino-2-indanol (0.108 g, 0.724 mmol), DMAP (0.088 g, 0.724 mmol), dichloromethane (7 mL), 2-(diphenylphosphino)benzoic acid (0.444 g, 1.45 mmol), and EDC (0.277 g, 1.45 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 6:4). Viscous wax (65%), $[\alpha]^{23}_D$ 66.9 (*c* 0.49, $CHCl_3$); IR (nujol) (cm^{-1}) 3249, 1715, 1660, 1585, 1215, 762, 696; ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm) 2.67 (d, J = 17.6 Hz, 1H), 3.13 (dd, J = 4.6, 17.6 Hz, 1H), 5.88 (d, J = 7.0 Hz, 1H), 6.60 (t, J = 8.2 Hz, 1H), 6.71 (t, J = 7.2 Hz, 1H), 6.83−7.40 (m, 29H), 7.55−7.57 (m, 1H), 7.90 (s, 1H), 8.12−8.14 (m, 1H); ^{13}C NMR ($CDCl_3$) 37.6, 55.6, 77.2, 124.3, 124.3, 124.7, 127.0, 127.8, 127.81, 128.2, 128.21, 128.3, 128.32, 128.34, 128.4, 128.41, 128.5, 128.53, 128.6, 128.7, 129.72, 131.8, 131.9, 132.1, 132.7, 132.9, 133.7, 133.8, 133.9, 133.91, 134.2, 134.7, 135.1, 135.2, 135.27, 135.3, 136.1, 136.3, 136.7, 136.8, 137.1, 137.2, 137.23, 137.3, 137.8, 137.9, 138.9, 140.7, 141.9, 142.1, 166.8, 169.2; ^{31}P{^{1}H} NMR ($CDCl_3$) −5.73, −10.06 ppm; ^{31}P NMR also suggests impurity present in less than 5%; ESI-HRMS calcd for $C_{47}H_{37}N\,O_3P_2$ (M + H^+) 726.2327, found 726.2337.

2-(Diphenylphosphino)-*N*-((1*R*,2*R*)-2-hydroxycyclohexyl)-benzamide (11f). To a 250 mL nitrogen-purged round-bottomed flask were added (1*R*,2*R*)-*trans*-2-aminocyclohexanol (0.350 g, 2.31 mmol), DMAP (0.056 g, 0.462 mmol), dichloromethane (10 mL), 2-(diphenylphosphino)benzoic acid (0.707 g, 2.308 mmol), and EDC (0.487 g, 2.54 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 6:4). Viscous wax (48%), $[\alpha]^{24}_D$ −32.1 (*c* 0.50, $CHCl_3$); IR (nujol) (cm^{-1}) 1716, 1270, 1248, 744, 696; ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm) 0.83−0.98 (m, 2H), 1.07−1.33 (m, 2H), 1.58−1.67 (m, 2H), 1.81−1.84 (m, 1H), 1.95−1.98 (m, 1H), 3.20 (td, J = 4.4, 10.4 Hz, 1H), 3.66−3.73 (m, 1H), 6.01 (d, J = 7.6 Hz, 1H), 6.96−6.98 (m, 1H), 7.24−7.36 (m, 13H), 7.60−7.63 (m, 1H); ^{13}C NMR ($CDCl_3$) 23.8, 24.4, 30.9, 33.6, 56.1, 74.3, 128.06, 128.1, 128.5, 128.6, 128.62, 128.7, 128.9, 128.92, 129.0, 130.1, 133.5, 133.6, 133.7, 133.7, 134.0, 134.5, 136.1, 136.2, 136.3, 141.6, 141.9, 170.0; ^{31}P{^{1}H} NMR ($CDCl_3$) −10.96 ppm; ^{31}P NMR also suggests impurity present in less than 5%; ESI-HRMS calcd for $C_{25}H_{26}\,NO_2\,P$ (M + H^+) 404.1779, found 404.1765.

(1*R*,2*R*)-(2-(Diphenylphosphino)benzamido)cyclohexyl 2-(Diphenylphosphino)benzoate (12f). To a 250 mL nitrogen-purged round-bottomed flask were added (1*R*,2*R*)-*trans*-2-aminocyclohexanol (0.350 g, 2.31 mmol), DMAP (0.282 g, 2.31 mmol), dichloromethane (10 mL), 2-(diphenylphosphino)benzoic acid (1.41 g, 4.62 mmol), and EDC (0.885 g, 4.62 mmol). The reaction mixture was allowed to stir for 24 h and then quenched with the addition of 3 M HCl (2 × 50 mL). The organic layer was diluted with dichloromethane (100 mL), washed with brine (50 mL), and dried with magnesium sulfate ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 6:4). Viscous wax (50%), $[\alpha]^{23}_D$ 64.3 (*c* 0.51, $CHCl_3$); IR (nujol) (cm^{-1}) 1698, 1656, 1583, 1256, 1156, 743, 693; ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm) 0.83−0.97 (m, 2H), 1.11−1.27 (m, 1H), 1.35−1.43 (m, 1H), 1.55−1.67 (m, 2H), 1.90 (t, J = 13.5 Hz, 2H), 4.12 (td, J = 4.1, 12.0 Hz, 1H), 4.73 (td, J = 4.4, 11.4 Hz,

1H), 6.04 (d, $J = 8.9$ Hz, 1H), 6.87−6.90 (m, 1H), 7.14−7.46 (m, 26H), 8.15−8.18 (m, 1H); ^{13}C NMR ($CDCl_3$) 23.8, 24.0, 30.7, 31.4, 52.5, 75.3, 127.3, 128.1, 128.11, 128.14, 128.16, 128.2, 128.22, 128.24, 128.3, 128.4, 128.42, 129.7, 131.0, 131.7, 133.4, 133.5, 133.6, 133.64, 133.9, 133.94, 134.1, 135.7, 135.9, 137.1, 137.2, 137.4, 137.5, 137.7, 137.8, 137.9, 138.0, 140.0, 140.2, 140.9, 141.1, 166.7, 168.2; $^{31}P\{^1H\}$ NMR ($CDCl_3$) −4.71, −9.84 ppm; ESI-HRMS calcd for $C_{44}H_{39}NO_3P_2$ ($M + H^+$) 692.2483, found 692.2484.

General Procedure for the Catalytic Asymmetric Allylic Alkylation Reactions (Table 2, Entry 7). To a 50 mL nitrogen-purged round-bottomed flask were added ligand (0.053 g, 0.067 mmol), $[(\eta^3\text{-}C_3H_5)PdCl]_2$ (0.025 g, 0.068 mmol), KOAc (0.006 g, 0.068 mmol), THF (4 mL), BSA (1.3 mL, 5.100 mmol), 1,3-diphenylpropenyl acetate (0.456 g, 1.700 mmol), and $CH_2(CO_2Me)_2$ (0.6 mL, 5.100 mmol). The reaction mixture was allowed to stir for 6 h at 25 °C and then quenched with the addition of 1 M HCl (50 mL) and ammonium chloride (50 mL). The organic layer was diluted with ether (50 mL), washed with brine (50 mL), and dried ($MgSO_4$). The solvents were removed via rotary evaporation and the product was isolated by flash column chromatography (hexanes:EtOAc, 9:1). The products were analyzed by HPLC, using an AD column. ^1H NMR (500 MHz, $CDCl_3$) δ (ppm) 3.44 (s, 3H), 3.62 (s, 3H), 3.88 (d, $J = 10.9$ Hz, 1H), 4.19 (dd, $J = 8.8$, 10.8 Hz, 1H), 6.26 (dd, $J = 8.60$, 15.8 Hz, 1H), 6.40 (d, $J = 15.8$ Hz, 1H), 7.10−7.25 (m, 10 H); ^{13}C NMR ($CDCl_3$) 49.2, 52.4, 52.6, 57.6, 126.4, 127.1, 127.5, 127.9, 128.5, 128.7, 129.1, 131.8, 136.8, 140.2, 167.7, 168.2.

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Supporting Information Available: Copies of ^1H, ^{13}C, and ^{31}P NMR spectra for new compounds **11a**−**f** and **12a**−**f** and HPLC traces for the asymmetric allylic alkylations. This material is available free of charge via the Internet at http://pubs.acs.org.