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# Palladium-Catalyzed Enantioselective Allylic Substitution in the Presence of Monodentate Furanoside Phosphoramidites

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A library of monodentate furanoside phosphoramidites, easily synthesized from inexpensive D-xylose and optically pure 1,1′-bi-2-naphthol (BINOL), was used as ligands for the palladium-catalyzed allylic alkylation and amination. The matched pair was formed from D-xylose-derivatives and (*S*)-BINOL. The asymmetric induction depends strongly on the substituent at the C5 of the carbohydrate backbone; both bulky 5-*O*-pivaloyl and 5-deoxy derivatives gave excellent results, whereas ligands with trityl protection at position C5 induced low *ee* values with reversal of configuration. The solvent used for the addition is also of great importance with highest enantioselectivities observed in diethyl ether. The best results for both alkylation and amination, up to 98–99% *ee*, were obtained for sterically demanding allylic acetates.

## Introduction

The allylic alkylation reaction, particularly in its enantioselective version, is one of the most powerful and versatile carbon–carbon bond forming reactions. Since the asymmetric catalytic reaction was reported for the first time,[1] enantioselective allylic substitutions have continuously attracted organic chemists. This reaction became a very important tool for the synthesis of natural products.[2] Still, development and successful application of chiral phosphorous ligands to reactions of various substrates and nucleophiles[3] is a challenging goal. The majority of reported effective ligands was based on (bis)phosphines[4] or phosphinooxazolines.[5] During the last decades several new ligands bearing the phosphoramidite moiety were successfully applied for asymmetric allylic substitutions.[6] Naturally occurring carbohydrates have become a popular source of chiral amino alcohols or diamines and are used for the synthesis of diphosphoramidite and phosphite–phosphoramidite ligands.[7] However, to the best of our knowledge, no carbohydrate-based ligands bearing a single donor atom located in the phosphoramidite moiety were reported in this area. If efficient, such ligands would be cheaper and have lower molecular mass than the respective diphosphoramidites. Having in mind our successful application of D-glucosamine-derived diphenylphosphinobenzoic amides in Pd-catalyzed asymmetric allylic alkylation[8] and monophosphoramidite furanosides in Cu-catalyzed 1,4-conjugated addition,[9] we decided to investigate the library of furanoside monophosphoramidites of the general structure presented in Figure 1 as ligands in asymmetric allylic substitutions.

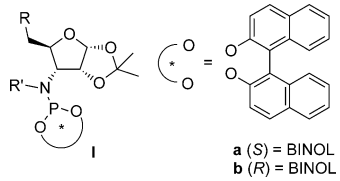


**Figure 1.** Furanoside monophosphoramidite ligands derived from **1**.

## Results and Discussion

### Synthesis of ligands

On the basis of the previous results chose the most promising ligands **L1**–**L5** and **L8** (Figure 2), and the series of phosphoramidite ligands was synthesized starting from D-xylose according to our published procedures.[9] Additionally, on the basis of the observation that decreased steric congestion at position C5 can lead to high asymmetric induction, a new 5-deoxycarbohydrate core was designed and synthesized. The synthesis of ligands **L6** and **L7** was accomplished through the formation of primary and secondary amines **6** and **8**, respectively, as presented at Scheme 1, and subsequent transformation into the respective phosphoramidites. Thus, 1,2-*O*-isopropylidene D-xylose **2** was selectively tosylated at position C5 to give **3**, which was reduced to the 5-deoxy derivative **4**. Alcohol **4** was oxidized to ketone **5** with excellent yield. Reductive amination gave secondary amine **6** in a single step, and formation of oxime **7** followed by $LiAlH_4$ reduction led to primary amine **8**. The reaction of both amines with (*S*)-1,1′-binaphthyl-2,2′-diyl phosphorochloridate gave ligands **L6** and **L7**.

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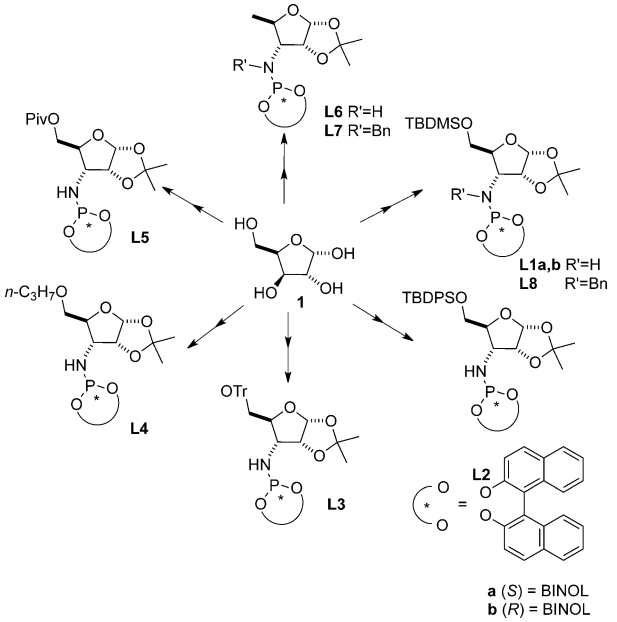
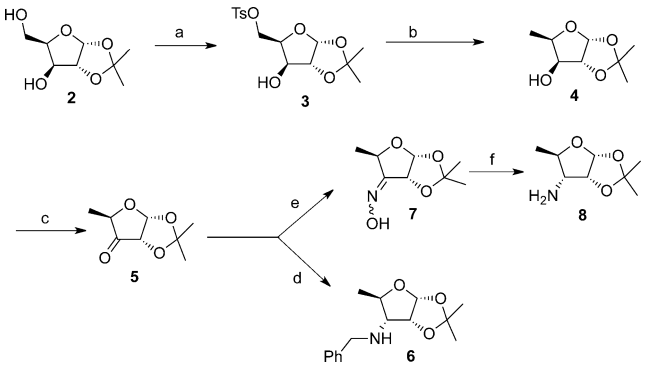


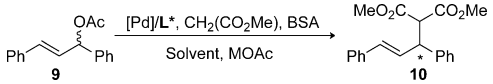

**Figure 2.** Library of the monophosphoroamidite ligands **L1**–**L8**. TBDMSO = *tert*-butyldimethylsilyl, TBDPSO = *tert*-butyldiphenylsilyl, Tr = triphenylmethyl, Piv = pivaloyl.




**Scheme 1.** Reagents and conditions: a) *p*-toluenesulfonyl chloride (TsCl), $Et_3N$, THF, RT, 81% yield; b) $LiAlH_4$, THF, reflux, 82% yield; c) pyridinium dichromate, $Ac_2O$, $CH_2Cl_2$, reflux, 99%; d) benzylamine, $NaBH_4$, 2,2,2-trifluoroethanol, 35 °C, 89% yield; e) $NH_2OH{\cdot}HCl$, EtOH/$H_2O$, 92%; f) $LiAlH_4$, THF, reflux, 55% yield.

## Pd-catalyzed asymmetric allylic alkylation

Having in hand the series of ligands **L1**–**L8**, we tested their ability to catalyze the asymmetric allylic alkylations of (*E*)-1,3-diphenylallyl acetate (Scheme 2). Initially we chose $[Pd(allyl)Cl]_2$ (0.005 equiv.), ligand (0.01 equiv.), dimethyl malonate (3.0 equiv.), *N,O* -bis(trimethylsilyl)acetamide (BSA, 3.0 equiv.), LiOAc (0.01 equiv.), and dichloromethane as a solvent for standard conditions.




**Scheme 2.** Allylic alkylation of (*E*)-1,3-diphenylallyl acetate. M = Li, K.

**Table 1.** Pd-catalyzed asymmetric allylic alkylation in the presence of ligands **L1**–**L6**.[a]

| Entry | Ligand | Solvent | *t* [h] | Yield[b] [%] | *ee*[c] [%] |
|---|---|---|---|---|---|
| 1 | **L1 a** | $CH_2Cl_2$ | 24 | 86 | 68 (*S*) |
| 2 | **L1 b** | $CH_2Cl_2$ | 20 | 90 | 6 (*S*) |
| 3 | **L2** | $CH_2Cl_2$ | 20 | 96 | 74 (*S*) |
| 4 | **L3** | $CH_2Cl_2$ | 4 | 97 | 24 (*R*) |
| 5 | **L4** | $CH_2Cl_2$ | 20 | 80 | 78 (*S*) |
| 6 | **L5** | $CH_2Cl_2$ | 24 | 87 | 88 (*S*) |
| 7 | **L6** | $CH_2Cl_2$ | 20 | 98 | 88 (*S*) |
| 8 | **L7** | $CH_2Cl_2$ | 24 | 37 | 72 (*S*) |
| 9 | **L8** | $CH_2Cl_2$ | 48 | trace | 60 (*S*) |
| 10 | **L5** | $CH_2Cl_2$ | 24 | 56 | 74 (*S*)[d] |
| 11 | **L5** | THF | 24 | 23 | 48 (*R*)[e] |
| 12 | **L5** | acetonitrile | 24 | 98 | 72 (*S*) |
| 13 | **L5** | toluene | 26 | 68 | 91 (*S*) |
| 14 | **L5** | THF | 48 | 20 | 92 (*S*) |
| 15 | **L5** | $Et_2O$ | 8 | 96 | 95 (*S*) |
| 16 | **L6** | $Et_2O$ | 5 | 99 | 96 (*S*) |

[a] Molar ratio: $[Pd(allyl)Cl]_2$ (0.005 equiv.), ligand (0.01 equiv.), dimethyl malonate (3.0 equiv.), BSA (3.0 equiv.), LiOAc (0.01 equiv.). [b] Isolated yields. [c] The *ee* values were determined by HPLC analysis using a chiral column Chiralcel AD-H. [d] KOAc was used. [e] NaH was used as a base.

Ligands **L7** and **L8**, based on secondary amines, were inefficient and catalyzed the addition with low to extremely low yield (Table 1, entries 8 and 9). Phosphoramidites obtained from primary amines performed much better, except ligands **L1 b** and **L3**. Similarly to the 1,4-addition,[9] also (*R*)-1,1′-bi-2-naphthol (BINOL) makes an unmatched pair with D-xylose (**L1**, entries 1 and 2), and triphenylmethyl-protected ligand **L3** gives addition products with reversed absolute configuration (entry 4). However, enantioselectivities were only moderate for ligands **L1 a**, **L2**, **L4** (entries 1, 3, 5, respectively) and good for ligands **L5** and **L6** (entries 6 and 7). Next, we tried to improve the asymmetric induction by modification of the reaction conditions. The influence of the counterion was investigated by using KOAc instead of LiOAc under standard conditions or using NaH in THF as a base in the presence of ligand **L5**. The presence of potassium slightly diminished the enantioselectivity (entry 10), and the use of NaH led to a reversal of the direction of the asymmetric induction, albeit with only moderate enantioselectivity and a very low yield (entry 11). The effect of the solvent was then investigated. The reaction performed in acetonitrile proceeded with almost quantitative yield, but with lower enantioselectivity (entry 12), in toluene the yield was only moderate, but the enantioselectivity improved to 91% *ee* (entry 13). Further improvement to 92% was observed in THF, but the yield dropped to unacceptable 20% (entry 14). Finally, we decided to try diethyl ether as another ethereal solvent. Surprisingly, not only the enantioselectivity was highest in the series (95%), but also the chemical yield was very high (96%, entry 15). Under these conditions, also the second most promising ligand **L6** catalyzed the reaction with very high *ee* (96%) and nearly quantitative yield (entry 16).

Next, we investigated the influence of the ratio of $[Pd(allyl)Cl]_2$/**L***  (abbreviated as [Pd]/**L***) and the amount of the chiral

**Table 2.** The influence of the amount of the palladium complex on the asymmetric allylic alkylation using **L5** in $CH_2Cl_2$ and $Et_2O$.

| Entry | [Pd]/**L*** ratio [mol/mol] | Reaction time [h] | Yield[a] [%] | *ee*[b] [%] |
|---|---|---|---|---|
| 1 | 0.5:1 | 24 | 87 | 88 (*S*)[c] |
| 2 | 1:1 | 9 | 98 | 86 (*S*)[c] |
| 3 | 1:2 | 24 | 60 | 80 (*S*)[c] |
| 4 | 1.5:1.5 | 9 | 99 | 81 (*S*)[c] |
| 5 | 2:2 | 8 | 99 | 80 (*S*)[c] |
| 6 | 2.5:2.5 | 7 | 99 | 81 (*S*)[c] |
| 7 | 3:3 | 7 | 99 | 82 (*S*)[c] |
| 8 | 0.5:1 | 8 | 96 | 95 (*S*)[d] |
| 9 | 0.5:2 | 24 | 60 | 74 (*S*)[d] |
| 10 | 0.5:0.5 | 24 | 87 | 93 (*S*)[d] |
| 11 | 1:1 | 6 | 97 | 93 (*S*)[d] |
| 12 | 2:2 | 5 | 93 | 95 (*S*)[d] |

[a] Isolated yields. [b] The *ee* values were determined by HPLC analysis using a chiral column Chiralcel AD-H. [c] $CH_2Cl_2$ was used as a solvent. [d] $Et_2O$ was used as a solvent.

complex on the asymmetric induction. The results are presented in Table 2. For all reactions conducted in dichloromethane, the best enantioselectivity was observed for the ratio 0.5:1 [Pd]/**L*** (Table 2, entry 1), other combinations led to decreased selectivity, however, accompanied by almost quantitative yields (entries 2–7). For reactions performed in diethyl ether, again the 0.5:1 [Pd]/**L*** ratio was the best (entry 8), but 1:1 ratio and all its multiplications gave very similar results (entries 10–12). A high excess of the chiral ligand over the palladium complex was proved to be disadvantageous; the product was obtained with moderate *ee* and chemical yield (entry 9).

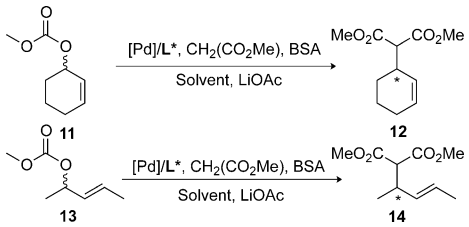
Then, we attempted to improve the enantioselectivity by lowering the reaction temperature. The reaction performed at 5 °C gave the addition product with slightly higher *ee* than that run at room temperature (Table 3, entry 2 vs. 1), however with concomitant decrease of chemical yield and in much longer time. To keep the yield and the reaction time on a reasonable level, we made use of the results presented in Table 2 and performed the reaction at 0 °C using a 2:2 [Pd]/**L*** ratio. After the short time of 6 h the reaction was finished, and not only the yield was very high, but also the enantioselectivity was increased to 98% (entry 3).

**Table 3.** The influence of reaction temperature on the asymmetric allylic alkylation using **L5** in $Et_2O$.[a]

| Entry | *T* [°C] | *t* [h] | Yield[b] [%] | *ee*[c] [%] |
|---|---|---|---|---|
| 1 | 20 | 8 | 96 | 95 (*S*) |
| 2 | 5 | 20 | 84 | 96 (*S*) |
| 3 | 0 | 6 | 94 | 98 (*S*)[d] |

[a] Molar ratio: $[Pd(allyl)Cl]_2$ (0.005 equiv.), **L5** (0.01 equiv.), dimethyl malonate (3.0 equiv.), BSA (3.0 equiv.), LiOAc (0.01 equiv.). [b] Isolated yields. [c] The *ee* values were determined by HPLC analysis using a chiral column Chiralcel AD-H. [d] Molar ratio: $[Pd(allyl)Cl]_2$ (0.02 equiv.), ligand (0.02 equiv.), dimethyl malonate (3.0 equiv.), BSA (3.0 equiv.), LiOAc (0.01 equiv.).

Most of the ligands used for the palladium-catalyzed allylic substitution give excellent results for bulky substrates such as **9** but do not perform well with less demanding cycloalkenyl acetates or aliphatic allylic acetates such as **11** or **13**, respectively (Scheme 3). Although some ligands like the Trost ligands




**Scheme 3.** Allylic alkylation of sterically nondemanding allylic acetates.

behave differently, our ligands follow this trend. The reaction of cyclohexenyl acetate with dimethyl malonate was very sluggish, especially in $Et_2O$, yields were low and enantioselectivities at best moderate (Table 4, entries 1–3). We tried to improve *ee* by introducing bulkier counterions to the nucleophile, but this

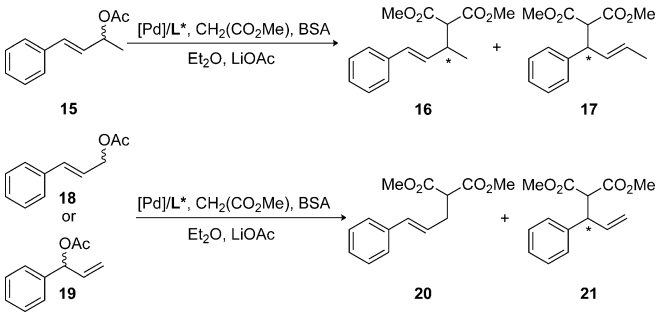
**Table 4.** Pd-catalyzed asymmetric allylic alkylation of cyclohexenyl acetate in the presence of ligands **L5** and **L6**.

| Entry | Ligand | Substrate | Solvent | *t* [h] | Yield[c] [%] | *ee* [%] |
|---|---|---|---|---|---|---|
| 1[a] | **L5** | **11** | $CH_2Cl_2$ | 24 | 23 | 20 (*S*)[d] |
| 2[a] | **L5** | **11** | $Et_2O$ | 72 | 26 | 49 (*S*)[d] |
| 3[b] | **L6** | **11** | $Et_2O$ | 120 | 43 | 52 (*S*)[d] |
| 4[b] | **L6** | **11** | $Et_2O$ | 24 | 35 | 10 (*R*)[d,e] |
| 5[b] | **L6** | **11** | THF | 24 | 38 | 12 (*R*)[d,f] |
| 6[b] | **L3** | **13** | $CH_2Cl_2$ | 24 | 97 | 7 (*S*)[g] |
| 7[b] | **L5** | **13** | $Et_2O$ | 24 | 94 | 9 (*S*)[g] |
| 8[b] | **L6** | **13** | $Et_2O$ | 24 | 93 | 16 (*S*)[g] |

[a] Molar ratio: $[Pd(allyl)Cl]_2$ (0.005 equiv.), ligand (0.01 equiv.), dimethyl malonate (3.0 equiv.), BSA (3.0 equiv.), LiOAc (0.01 equiv.). [b] Molar ratio: $[Pd(allyl)Cl]_2$ (0.02 equiv.), ligand (0.02 equiv.), dimethyl malonate (3.0 equiv.), BSA (3.0 equiv.), LiOAc (0.01 equiv.). [c] Isolated yields. [d] The *ee* values were determined by HPLC analysis using a chiral column Chiralcel AS-H. [e] Tetraheptylammonium chloride was added. [f] NaH was used as a base. [g] The *ee* values were determined by GC analysis using a chiral column Intercap Chiramix.

method, developed and successfully used by Trost, did not work properly in our case. Although the enantioselectivity changed by approximately 60 percentage points, this was accompanied by the reversal of the direction of the asymmetric induction, so the net results were 10 and 12% *ee* with *R* configuration (entries 4 and 5). Similarly, addition to pent-3-en-2-yl carbonate proceeded with excellent yield and very low asymmetric induction (entries 6–8).

Finally, we investigated the regioselectivity of the addition to unsymmetrical substrates (Scheme 4). For (*E*)-4-phenylbut-3-en-2-yl acetate **15** the attack of the nucleophile was directed to the less hindered allylic terminus. However, the 3.5:1 ratio was not impressive and the enantioselectivity moderate in the




**Scheme 4.** Allylic alkylation of unsymmetrical substrates.

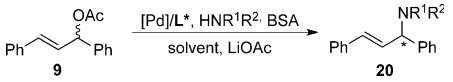
presence of ligand **L5** for both products. In the presence of ligand **L6** the ratio was slightly worse, but *ee* was high, unfortunately for the minor product, whereas it was very low for the major one.

The addition to cinnamyl alcohol acetate **18** and 1-phenylallyl acetate **19** was, as expected for palladium-catalyzed allylic substitution, highly regioselective toward the linear product (Table 5).

**Table 5.** Pd-catalyzed asymmetric allylic alkylation using (*E*)-4-phenylbut-3-en-2-yl acetate as the substrate.[a]

| Entry | Ligand | Substrate | *t* [h] | Regioselectivity | Yield[b] [%] | *ee*[c] (**16**) [%] | *ee*[c] (**17**) [%] | *ee*[c] (**21**) [%] |
|---|---|---|---|---|---|---|---|---|
| 1[d] | **L5** | **15** | 24 | **16**/**17** 3.5:1 | 36 | 45 | 32 | – |
| 2 | **L6** | **15** | 24 | **16**/**17** 3:1 | 34 | 8 | 90 | – |
| 3 | **L5** | **18** | 24 | **20**/**21** 94:6 | 73 | – | – | 68 (*S*) |
| 4 | **L6** | **19** | 2.5 | **20**/**21** 93:7 | 95 | – | – | 79 (*S*) |

[a] Molar ratio: $[Pd(allyl)Cl]_2$ (0.005 equiv.), ligand (0.01 equiv.), amine (3.0 equiv.), BSA (3.0 equiv.), LiOAc (0.01 equiv.), $Et_2O$ as a solvent. [b] Isolated yields. [c] The *ee* values were determined by HPLC analysis using a chiral column Chiralcel OD-H. [d] $CH_2Cl_2$ as a solvent.




**Scheme 5.** Allylic amination of (*E*)-1,3-diphenylallyl acetate. $HNR^1R^2$ = primary or secondary amine.

## Pd-catalyzed asymmetric allylic amination

Next, we turned our attention to the asymmetric allylic amination of allylic acetate **9** (Scheme 5). The first results were rather disappointing. The addition of benzylamine in the presence of **L5** proceeded with very low yield, low conversion, and moderate enantioselectivity even in the presence of increased amounts of the catalyst (Table 6, entries 1–3). The addition in the absence of BSA did not proceed at all (entry 4). However, replacement of the primary amine with the secondary one completely changed the picture. The addition of morpholine in the presence of 0.05 mol% of palladium complex was completed after only 3 h in 95% isolated yield and 96% *ee* (entry 5). The reaction in the presence of the increased amount of the catalyst was even more selective (entry 6), and the reaction performed at 0 °C proceeded with almost complete selectivity, albeit with slightly diminished chemical yield (entry 7). However, the chemical yield was improved if the solvent was changed to $CH_2Cl_2$, but with a simultaneous drop of the enantioselectivity (entry 8). The attempt to increase both values by performing the reaction in a mixture of solvents ($Et_2O$/$CH_2Cl_2$ 1:2) failed and both yield and *ee* were lower than in pure $Et_2O$ (entry 9). The addition of piperidine proceeded with >99% *ee*, but with only 21% conversion (97% isolated yield, entry 10), and the addition of pyrrolidine resulted in moderate *ee* and yield (entry 11). However, modification of the reaction conditions and conducting the reaction with a smaller excess of pyrrolidine and BSA led to a significant improvement of the enantioselectivity to 98% *ee* (entry 12).

Then, we turned our attention to the second best ligand in asymmetric alkylations, **L6**. The results were comparable to those obtained with **L5**. However, some improvements were observed. Addition of benzylamine proceeded in dichloromethane with almost acceptable conversion (41–45%) and good

**Table 6.** Pd-catalyzed asymmetric allylic amination in the presence of ligands **L1**–**L7**.[a]

| Entry | Ligand | Solvent | $HNR_1R_2$ | [Pd]/**L*** [mol%] | *t* [h] | Yield[b] [%] | *ee*[c] [%] |
|---|---|---|---|---|---|---|---|
| 1 | **L5** | $Et_2O$ | benzylamine | 0.5:1 | 24 | 15 | 86 (*R*) |
| 2 | **L5** | $CH_2Cl_2$ | benzylamine | 2:4 | 24 | 21 | 83 (*R*) |
| 3 | **L5** | $CH_2Cl_2$ | benzylamine | 3:3 | 24 | 37 | 85 (*R*) |
| 4 | **L5** | $Et_2O$ | benzylamine | 3:3 | 48 | NR | –[d] |
| 5 | **L5** | $Et_2O$ | morpholine | 0.5:1 | 3 | 95 | 96 (*R*) |
| 6 | **L5** | $Et_2O$ | morpholine | 3:3 | 3 | 96 | 98 (*R*) |
| 7 | **L5** | $Et_2O$ | morpholine | 3:3 | 7 | 83 | 99 (*R*)[e] |
| 8 | **L5** | $CH_2Cl_2$ | morpholine | 3:3 | 6 | 91 | 83 (*R*) |
| 9 | **L5** | $Et_2O/CH_2Cl_2$ (1:2) | morpholine | 3:3 | 8 | 78 | 87 (*R*) |
| 10 | **L5** | $Et_2O$ | piperidine | 3:3 | 24 | 21 | >99 (*R*) |
| 11 | **L5** | $Et_2O$ | pyrrolidine | 3:3 | 24 | 66 | 74 (*R*) |
| 12 | **L5** | $Et_2O$ | pyrrolidine | 3:3 | 5 | 80 | 98 (*R*)[f] |
| 13 | **L6** | $CH_2Cl_2$ | benzylamine | 0.5:1 | 24 | 45 | 89 (*R*) |
| 14 | **L6** | $Et_2O/CH_2Cl_2$ | benzylamine | 0.5:1 | 24 | 41 | 93 (*R*)[g] |
| 15 | **L6** | $Et_2O$ | morpholine | 0.5:1 | 5 | 97 | 97 (*R*) |
| 16 | **L6** | $Et_2O$ | pyrrolidine | 0.5:1 | 6 | 91 | 98 (*R*)[g] |
| 17 | **L6** | $Et_2O$ | pyrrolidine | 0.5:1 | 24 | 72 | 95 (*R*) |
| 18 | **L6** | $CH_2Cl_2$ | pyrrolidine | 0.5:1 | 8 | 95 | 92 (*R*)[g] |
| 19 | **L6** | $Et_2O/CH_2Cl_2$ (5:1) | pyrrolidine | 0.5:1 | 6 | 95 | 95 (*R*)[g] |
| 20 | **L6** | $Et_2O$ | piperidine | 0.5:1 | 24 | 32 | 98 (*R*)[f] |
| 21 | **L6** | $Et_2O/CH_2Cl_2$ | piperidine | 0.5:1 | 20 | 63 | 99 (*R*)[g] |
| 22 | **L6** | $Et_2O$ | *N*-benzylpiperazine | 0.5:1 | 3.5 | 89 | 99 (*R*)[d] |
| 23 | **L5** | $Et_2O$ | *p*-MeOBnNH$_2$ | 3:3 | 24 | 28 | 90 (*R*)[f] |
| 24 | **L6** | $Et_2O$ | *p*-MeOBnNH$_2$ | 0.5:1 | 24 | 23 | 88 (*R*)[g] |
| 25 | **L7** | $CH_2Cl_2$ | BnNH$_2$ | 0.5:1 | 24 | 18 | 64 (*R*) |
| 26 | **L7** | $CH_2Cl_2$ | BnNH$_2$ | 1:2 | 24 | 45 | 65 (*R*) |

[a] Molar ratio: amine (3.0 equiv.), BSA (3.0 equiv.), LiOAc (0.01 equiv.). [b] Isolated yields. [c] The *ee* values were determined by HPLC. [d] Without BSA. [e] Reaction carried out at 0 °C. [f] Molar ratio: amine (1.5 equiv.), BSA (1.05 equiv.), LiOAc (0.01 equiv.). [g] Molar ratio: amine (1.5 equiv.), BSA (1.5 equiv.), LiOAc (0.01 equiv.).

enantioselectivity (Table 6, entry 13), and conducting this reaction in the mixture of solvents led to a better enantioselectivity (entry 14). Moreover, the addition of pyrrolidine performed in the mixture of solvents proceeded with very good chemical yield and enantioselectivity (entry 19), whereas the reactions performed in diethyl ether (entry 17) or dichloromethane (entry 18) alone furnished the product with diminished yield ($Et_2O$) or *ee* ($CH_2Cl_2$). Addition of piperidine and *N*-benzylpiperazine proceeded with excellent enantioselectivity and good to very good yields (entries 21 and 22, respectively). Reaction with *p*-methoxybenzylamine gave similar results to those obtained for benzylamine (entries 23 and 24) and no reaction occurred with dibenzylamine, cyclohexylamine, phthalimide, *n*$BuNH_2$ and *i*$PrNH_2$.

The addition of benzylamine conducted in the presence of tertiary phosphoramidite **L7** led to worse results than those obtained for ligands **L5** and **L6**, so further research using ligand **L7** and other amines was not continued.

## Conclusions

We developed new carbohydrate ligands bearing a single phosphoramidite moiety and applied them successfully to the asymmetric allylic substitution. The high enantioselectivities (up to 99%) achieved for (*E*)-1,3-diphenylallyl acetate are comparable or better than those reported for phosphite–phosphoramidite or diphosphoramidite ligands. The results are highly dependent on the solvent used for the reaction, the steric congestion introduced by the substituent at C5 of the carbohydrate core, and/or the bulkiness of the counterion of the nucleophile. The explanation of these results requires further thorough studies of the transition states of the addition. So far, we were unable to obtain X-ray-quality crystals of the palladium complexes, however, efforts are underway. The envisioned studies will help to understand, why the change from the bulky *tert*-butyldimethylsilyl and pivaloyl protection to the even bulkier trityl one resulted in the reversal of the direction of the asymmetric induction. Another problem that has to be explained is the similar selectivity observed for pivaloyl-protected ligand **L5** and the least sterically demanding ligand **L6**. In the light of results obtained for ligands **L2**–**L4** and **L3**, this behavior is quite obscure. Hopefully, the obtained knowledge will help to modify the structure of ligands and reaction conditions to make them more selective for less sterically demanding substrates.

## Experimental Section

### General

Melting points were determined using a Kofler hot stage apparatus. Specific rotations were recorded using a PerkinElmer PE-241 polarimeter with a thermally jacketed 10 cm cell. $^1H$, $^{13}C$ NMR, and $^{31}P$ spectra were recorded in $CDCl_3$ using Varian 200 Unity Plus, Bruker 300, and Varian 500 Unity Plus spectrometers. All chemical shifts are quoted in parts per million relative to $Me_4Si$ (d, 0.00 ppm) as an internal standard or $H_3PO_4$ ($^{31}P$) as an external standard. Mass spectra were recorded on a Mariner instrument (Biosystem), Quatro LC Micromass, and LCT Micromass TOF HiRes apparatus. Infrared spectra were recorded on an FTIR Jasco 6200 spectrometer in $CH_2Cl_2$ solution or KBr pellet. Reactions were performed under atmosphere of argon using Schlenk techniques if necessary. Flash column chromatography was performed on silica gel (Kieselgel-60, Merck, 230–400 mesh). HPLC was conducted on Diacel Chiracel OD-H, AD-H, AS-H columns. Analytical gas chromatography was conducted on chiral column Intercap Chiramix. Compounds **L1**–**L5** and **L8** are known and were prepared by our own or modified literature method.[9]

### 1,2-*O*-Isopropylidene-α-D-xylofuranoside (2)

To the round-bottom flask containing acetone (260 mL) and concentrated sulfuric acid (10 mL), D-xylose (10 g, 67 mmol) was added. The mixture was stirred for 30 min and a solution of $Na_2CO_3$ (13 g, 66 mmol) in water (120 mL) was slowly added. The mixture was further stirred for 3 h, and the pH was brought to >7 by the addition of solid $Na_2CO_3$. Inorganic salts were filtered off, and the remaining solution was evaporated under vacuum. The crude product was purified by flash chromatography (EtOAc/hexanes 6:4, v/v) to give 1,2-*O*-isopropylidene-α-D-xylofuranoside **2** as a colorless oil (8.46 g, 44.6 mmol, 68% yield) solidifying upon standing in the freezer. $[\alpha]_D^{20} = -19.6$ ($c = 1.0$, $CHCl_3$), lit.[10] $[\alpha]_D^{20} = -13.9$ ($c = 0.34$, $CHCl_3$), lit.[11] $[\alpha]_D^{20} = -22.4$ ($c = 1.1$, $CHCl_3$). $^1H$ NMR: $\delta = 6.00$ (d, $J = 3.6$ Hz, 1H), 4.53 (d, $J = 3.6$ Hz, 1H), 4.20–3.85 (m, 4H), 3.10–2.80 (m, 1H), 1.49 (s, 3H), 1.33 ppm (s, 3H). $^{13}C$ NMR: $\delta =$ 112.1, 150.1, 85.9, 78.8, 61.4, 27.0, 26.4 ppm.

### 1,2-*O*-Isopropylidene-5-*O*-tosyl-α-D-xylofuranoside (3)

To a magnetically stirred solution of **2** (8.46 g, 44.6 mmol) and $Et_3N$ (12.44 mL, 89.2 mmol) in THF (40 mL) at 0 °C, a solution of TsCl (8.5 g, 49.06 mmol) in THF (20 mL) was added dropwise. The mixture was stirred overnight at ambient temperature. As soon as thin-layer chromatography evidenced the disappearance of the substrate, the reaction was quenched with MeOH and solvents were evaporated. The residue was dissolved in EtOAc (50 mL) and washed with $H_2O$ (15 mL), saturated with $NaHCO_3$ (15 mL) and brine (15 mL). The organic phase was dried over anhydrous $MgSO_4$, filtered, and evaporated under vacuum. The residue was recrystallized from hexane/ethyl acetate to give **3** (12.44 g, 36.12 mmol, 81% yield) as white crystals. $[\alpha]_D^{20} = -18.5$ ($c = 1.0$, $CHCl_3$), lit.[12] $[\alpha]_D^{26} = -13.6$ ($c = 1.5$, $CHCl_3$). M.p. 133–134 °C, lit.[13] m.p. 134–135 °C. $^1H$ NMR: $\delta = 7.80$ (d, $J = 8.4$ Hz, 2H), 7.35 (d, $J = 8.2$ Hz, 2H), 4.53 (d, $J = 3.5$ Hz, 1H), 4.35–4.25 (m, 2H), 4.20–4.10 (m, 1H), 3.20–3.05 (m, 2H), 2.45 (s, 3H), 1.45 (s, 3H), 1.29 ppm (s, 3H). $^{13}C$ NMR: $\delta =$ 145.2, 132.4, 130.0, 128.9, 128.0, 112.0, 105.0, 85.1, 76.6, 74.2, 66.9, 26.8, 26.2, 21.6 ppm.

### 1,2-*O*-Isopropylidene-5-deoxy-α-D-xylofuranoside (4)

Magnetically stirred solution of **3** (12.44 g, 36.12 mmol) in THF (80 mL) was cooled to 0 °C, $LiAlH_4$ (1.64 g, 43.34 mmol) was added in portions, and the mixture was heated to reflux for 2 h. The mixture was cooled to 0 °C, EtOAc (50 mL) was added slowly, followed by a dropwise addition of $H_2O$ (3.4 mL), 15% NaOH (3.4 mL) and $H_2O$ (10.3 mL). The suspension was stirred for 30 min, inorganic salts were filtered off by using Celite pad, and the suspension was washed thoroughly with EtOAc (3×30 mL). The combined extracts were washed with brine and dried over anhydrous $MgSO_4$, filtered, and evaporated under vacuum. Residue was purified by flash chro-

matography (EtOAc/hexane 4:6, v/v) to give **4** (5.16 g, 29.63 mmol, 82% yield) as a white solid. $[\alpha]_D^{20} = -21.2$ ($c = 1.0$, $CHCl_3$), lit.[14] $[\alpha]_D^{20} = -15.6$ ($c = 2.0$, $CHCl_3$), lit.[15] $[\alpha]_D^{29} = -20.7$ ($c = 1.9$, $CHCl_3$). M.p. = 82–83 °C, lit.[13] m.p. 82–83 °C. $^1$H NMR: $\delta = 5.89$ (d, $J = 3.9$ Hz, 1H), 4.53 (d, $J = 3.6$ Hz, 1H), 4.31 (dq, $J = 6.4$ Hz, 2.7 Hz, 1H), 3.90–4.10 (m, 1H), 1.94 (d, $J = 4.2$ Hz, 1H), 1.50 (s, 3H), 1.35–1.25 ppm (m, 6H). $^{13}$C NMR: $\delta = 111.4$, 104.3, 85.5, 76.3, 76.0, 26.5, 26.1, 12.7 ppm.

### 1,2-*O*-Isopropylidene-3-oxo-5-deoxy-α-D-xylofuranoside (5)

To the magnetically stirred solution of **4** (5.16 g, 29.63 mmol) in $CH_2Cl_2$ (60 mL), pyridinium dichromate (7.8 g, 20.74 mmol) and freshly distilled $Ac_2O$ (9.23 mL, 97.78 mmol) were added and the mixture was heated to reflux for 1.5 h. As soon as thin-layer chromatography evidenced the disappearance of the substrate, the reaction was cooled to RT and EtOAc (100 mL) was added. The reaction mixture was filtered through a pad of silica gel. The solids were thoroughly washed with EtOAc and the filtrate was co-evaporated twice with toluene (10 mL) by using a rotary evaporator to give **5** (5.05 g, 29.33 mmol, 99% yield) as a colorless solid. $[\alpha]_D^{20} = +129.0$ ($c = 1.0$, $CHCl_3$), lit.[16] $[\alpha]_D^{23} = +181.4$ ($c = 1.6$, $CHCl_3$), lit.[17] $[\alpha]_D^{21} = +175.0$ ($c = 0.5$, $CHCl_3$). M.p. 40–41 °C, lit.[16] m.p. 39–41 °C. $^1$H NMR: $\delta = 6.05$ (d, $J = 4.5$ Hz, 1H), 4.44 (q, $J = 6.9$ Hz, 1H), 4.35 (d, $J = 4.5$ Hz, 1H), 1.51 (s, 3H), 1.40 (s, 3H), 1.32 ppm (d, $J = 6.9$ Hz, 3H). $^{13}$C NMR: $\delta = 209.7$, 114.3, 102.2, 75.6, 73.7, 27.5, 27.0, 15.4 ppm.

### 1,2-*O*-Isopropylidene-3-oxo-5-deoxy-α-D-xylofuranoside oxime (7)

To the magnetically stirred solution of **5** (5.05 g, 29.33 mmol) in 75% EtOH (80 mL), $NH_2OH{\cdot}HCl$ (6.52 g, 93.86 mmol) and $NaHCO_3$ (8.13 g, 96.79 mmol) were added and the mixture was heated to reflux for 3.5 h. After cooling, the mixture was extracted with $Et_2O$ (3×40 mL), the combined extracts were washed with brine and dried over anhydrous $MgSO_4$, filtered, and evaporated under vacuum. The residue was purified by flash chromatography (EtOAc/hexanes 3:7, v/v) to give **7** (5.05 g, 26.98 mmol, 92% yield) as a white solid. $[\alpha]_D^{20} = +252.9$ ($c = 1.0$, $CHCl_3$), lit.[16] $[\alpha]_D^{22} = +245.5$ ($c = 1.0$, $CHCl_3$). M.p. 89–90 °C (petroleum ether), lit.[16] m.p. 90.5–91 °C, lit.[18] mp. = 89 °C. $^1$H NMR: $\delta = 5.93$ (d, $J = 4.5$ Hz, 1H), 5.31 (dd, $J = 4.5$ Hz, 1.2 Hz, 1H), 4.83 (qd, $J = 5.4$ Hz, 0.9 Hz, 1H), 1.53 (s, 3H), 1.46–1.37 ppm (m, 6H). $^{13}$C NMR: $\delta = 103.7$, 78.2, 76.6, 73.8, 72.7, 27.0, 26.9, 17.2 ppm.

### 1,2-*O*-Isopropylidene-3-amino-3,5-dideoxy-α-D-ribofuranoside (8)

The magnetically stirred solution of **7** (5.05 g, 26.98 mmol) in THF (100 mL) was cooled to 0 °C, $LiAlH_4$ (2.05 g, 53.96 mmol) was added in portions, and the mixture was heated to reflux for 1.5 h. The mixture was cooled to 0 °C, diluted with $Et_2O$ (100 mL) and $H_2O$ (2.5 mL), and 15% NaOH (2.5 mL) and $H_2O$ (7.7 mL) were added dropwise. The suspension was stirred for 30 min, inorganic salts were filtered off by using Celite pad, and the suspension was washed thoroughly with $CH_2Cl_2$ (3×30 mL). The combined extracts were washed with brine and dried over anhydrous $MgSO_4$, filtered, and evaporated under vacuum. The residue was purified by flash chromatography ($CH_2Cl_2$/MeOH 95:5, v/v) to give **8** (2.57 g, 14.84 mmol, 55% yield) as a colorless oil. $[\alpha]_D^{20} = +55.1$ ($c = 1.0$, $CHCl_3$), lit.[16] $[\alpha]_D^{23} = +164.8$ ($c = 1.0$, $CHCl_3$). $^1$H NMR: $\delta = 5.78$ (d, $J =$ 3.9 Hz, 1H), 4.47 (t, $J = 4.2$ Hz, 1H), 3.80–3.66 (m, 1H), 2.74–2.64 (m, 1H), 1.53 (s, 3H), 1.41 (s, 2H), 1.34 (s, 3H), 1.31 ppm (d, $J = 6.3$ Hz, 3H). $^{13}$C NMR: $\delta = 111.5$, 103.8, 80.6, 76.6, 61.0, 26.4, 26.3, 16.9 ppm. ($CH_2Cl_2$): $\tilde{\nu}_{max} = 3386$, 3316, 2979,1376, 1214, 1017, 874 cm$^{-1}$. High-resolution electrospray ionization mass spectrometry (HRESIMS) [$M^+$+Na] calcd for [$C_8H_{15}NO_3$+Na]: 196.0950; found: 196.0948.

### 1,2-*O*-Isopropylidene-3-benzylamino-3,5-dideoxy-α-D-ribofuranoside (6)

The magnetically stirred solution of **5** (0.172 g, 1.0 mmol) in 2,2,2-trifluoroethanol (2 mL) was warmed to 37 °C and, after 5 min, benzylamine (0.11 mL, 1.01 mmol) was added dropwise. The mixture was stirred at this temperature for 15 min. After this time the $NaBH_4$ (0.076 g, 2.0 mmol) was added portionwise. The suspension was stirred for another 15 min, filtered through silica gel pad, and solids were washed twice with EtOAc (10 mL). The volatiles were evaporated and the residue was purified by flash chromatography (EtOAc/hexane 1:9, v/v) to give **6** (0.234 g, 0.89 mmol, 89% yield) as a colorless oil. $[\alpha]_D^{20} = +160.0$ ($c = 1.0$, $CHCl_3$). $^1$H NMR: $\delta = 7.42$–7.20 (m, 5H), 5.75 (d, $J = 3.9$ Hz, 1H), 4.54 (t, $J = 4.2$ Hz, 1H), 3.94 (d, $J = 13.5$ Hz, 1H), 3.83–3.69 (m, 2H), 2.60–2.51 (m, 1H), 1.90 (s, 1H), 1.51 (s, 3H), 1.34 (s, 3H), 1.30 ppm (d, $J = 6.3$ Hz, 3H). $^{13}$C NMR: $\delta =$ 140.2, 128.3, 128.0, 127.0, 111.4, 104.2, 77.3, 75.8, 66.5, 52.0, 26.5, 26.4, 17.5 ppm. ($CH_2Cl_2$): $\tilde{\nu}_{max} = 3341$, 3028, 2979, 1455, 1214, 1099, 1015, 875 cm$^{-1}$. HRESIMS [$M^+$+H] calcd for [$C_{15}H_{21}NO_3$+H]: 264.1594; found: 264.1603.

### General procedure for the synthesis of ligands L1–L6

The amine **8** (0.5 mmol) was placed in a Schlenk tube and dissolved in THF (1 mL). Subsequently, $Et_3N$ (140 μL, 1 mmol) was added, the mixture was cooled to 0 °C, and a 0.35 M solution of (*S*)-1,1′-binaphthyl-2,2′-diyl phosphorochloridate (1.57 mL, 0.55 mmol) in toluene was added dropwise. The mixture was stirred at RT for 4 h, diluted with $Et_2O$ (10 mL), filtered through silica gel pad, and the solids were washed twice with $Et_2O$ (20 mL). The volatiles were evaporated and the residue was purified by flash chromatography (EtOAc/hexanes 1:9 v/v) to give ligands **L1**–**L6** as white foams.

### 1,2-*O*-Isopropylidene-3-((11bS)-dinaphtho[2,1-d:1′,2′-f][1,3,2]dioxaphosphepin-4-ylamino)-3,5-dideoxy-α-D-ribofuranoside (L6)

Yield 88% (214 mg). $[\alpha]_D^{20} = +444.0$ ($c = 1.0$, $CHCl_3$). M.p. 149–150 °C. $^{31}$P NMR: $\delta = 151.15$ ppm. $^1$H NMR: $\delta = 8.01$–7.49 (m, 1H), 7.94–7.89 (m, 3H), 7.55–7.51 (m, 1H), 7.46–7.39 (m, 4H), 7.30–7.22 (m, 3H), 5.76 (d, $J = 4.0$ Hz, 1H), 4.58 (t, $J = 4$ Hz, 1H), 3.78–3.68 (m, 1H), 3.59–3.49 (m, 1H), 3.25–3.13 (m, 1H), 1.44 (s, 3H) 1.39 (s, 3H), 1.35 ppm (d, $J = 6$ Hz, 3H). $^{13}$C NMR: $\delta = 151.8$, 149.1, 147.3, 147.2, 132.7, 132.6, 131.5, 131.1, 130.4, 129.4, 128.4, 128.3, 127.0, 126.9, 126.2, 126.1, 125.0, 124.8, 122.8, 121.7, 111.8, 103.7, 80.0, 59.9, 69.7, 26.5, 26.4, 16.7 ppm. (KBr): $\tilde{\nu}_{max} = 3325$, 3067, 2981, 1230, 1019, 950, 822 cm$^{-1}$. HRESIMS [$M^+$+Na] calcd for [$C_{28}H_{26}NO_5$+Na]: 510.1446; found: 510.1440.

### General procedure for the synthesis of ligands L7

The amine **6** (0.5 mmol) was placed in the Schlenk tube and dissolved in THF (1 mL). The mixture was cooled to −78 °C and *n*BuLi (2.2 M in toluene, 227 μL, 0.5 mmol) was added dropwise. After 10 min, the reaction mixture was allowed to warm up to 0 °C and

a 0.35 M solution of (*S*)-1,1′-binaphthyl-2,2′-diyl phosphorochloridate (1.57 mL, 0.55 mmol) in toluene was added dropwise. The mixture was stirred at RT for 5 h, diluted with $Et_2O$ (10 mL), filtered through silica gel pad, and the solids were washed twice with $Et_2O$ (20 mL). The volatiles were evaporated and the residue was purified by flash chromatography (EtOAc/hexanes 1:9, v/v) to give ligands **L7** as a white foam.

### 1,2-*O*-Isopropylidene-3-((11bS)-dinaphtho[2,1-d:1′,2′-f][1,3,2]dioxaphosphepin-4-yl(benzylamino)-3,5-dideoxy-α-D-ribofuranoside (L7)

Yield 58% (167 mg). $[\alpha]_D^{20} = +265.6$ ($c = 1.0$, $CHCl_3$). M.p. 117–119 °C. $^{31}$P NMR: $\delta = 144.63$ ppm. $^1$H NMR: $\delta = 8.00$ (d, $J = 8.5$ Hz, 1H), 7.94–7.90 (m, 1H), 7.85–7.78 (m, 2H), 7.61–7.57 (m, 1H), 7.45–7.15 (m, 12H), 5.60 (d, $J = 4.5$ Hz, 1H), 4.61–4.51 (m, 1H), 4.16–4.06 (m, 2H), 3.99–3.86 (m, 1H), 2.94–2.83 (m, 1H), 1.71 (s, 3H), 1.36 (s, 3H), 1.29 ppm (d, $J = 6$ Hz, 3H). $^{13}$C NMR: $\delta = 150.1$, 150.0, 146.1, 138.8, 132.8, 132.6, 131.4, 130.6, 130.4, 130.3, 130.0, 129.9, 129.5, 128.4, 128.3, 128.2, 127.3, 127.1, 127.0, 126.1, 126.0, 124.9, 124.6, 122.0, 121.9, 121.8, 112.0, 103.6, 72.2, 71.9, 60.4, 50.7, 26.6, 26.5, 16.8 ppm. (KBr): $\tilde{\nu}_{max} = 3057$, 2975, 1589, 1258, 1230, 1021, 948, 822 cm$^{-1}$. HRESIMS [$M^+$+Na] calcd for [$C_{35}H_{32}NO_5P$+Na]: 600.1910; found: 600.1881.

### General procedures for the palladium-catalyzed allylic alkylation of allylic acetates in the presence of L1–L8

Procedure A: The ligand **L*n*** (0.01 mmol) and $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (1.8 mg, 0.005 mmol) were placed in a Schlenk tube and dissolved in an appropriate solvent (2 mL). After 30 min stirring under argon, a solution of allylic acetate (1 mmol) in the same solvent (2 mL) was added. A resulting yellow solution was stirred for another 30 min, then dimethyl malonate (350 μL, 3.0 mmol), *N,O*-bis(trimethylsilyl)acetamide (740 μL, 3.0 mmol), and a pinch of the acetate salt were added. The reaction mixture was stirred for the required time and quenched with the addition of saturated $NH_4Cl_{aq}$ (5 mL). The mixture was extracted with $Et_2O$ (2×20 mL). Combined organic layers were washed with brine and dried over anhydrous $MgSO_4$, filtered, and evaporated under vacuum. The residue was purified by flash chromatography (hexane/EtOAc 95:5, v/v) to give the desired product.

Procedure B: The ligand **L*n*** (0.01 mmol) and $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (1.8 mg, 0.005 mmol) were placed in a Schlenk tube and dissolved in dry THF (2 mL). After 30 min stirring under argon, a solution of allylic acetate (1 mmol) in THF (2 mL) was added. The resulting yellow solution was stirred for another 30 min, and then a freshly prepared solution of sodium dimethyl malonate (350 μL, 3.0 mmol) in THF (2 mL) was added. The reaction mixture was stirred for the require time and quenched with the addition of saturated $NH_4Cl_{aq}$ (5 mL). The mixture was extracted with $Et_2O$ (2×20 mL). Combined organic layers were washed with brine and dried over anhydrous $MgSO_4$, filtered, and evaporated under vacuum. Residue was purified by flash chromatography (hexanes/EtOAc 95:5, v/v) to give the desired product.

### (−)-(*S, E*)-Dimethyl 2-(1,3-diphenyl-2-propenyl)malonate

98% *ee* $[\alpha]_D^{20} = -22.3$ ($c = 1.0$, $CHCl_3$), [lit.[19] $[\alpha]_D^{20} = -19.9$ ($c = 0.55$, $CHCl_3$), 96% *ee* (*S*)]. $^1$H NMR: $\delta = 7.36$–7.17 (m, 10H), 6.49 (d, $J = 15.9$ Hz, 1H), 6.32 (dd, $J = 16$ Hz, 8 Hz, 1H), 4.27 (dd, $J = 7.9$ Hz, 3 Hz, 1H), 3.96 (d, $J = 11$ Hz, 1H), 3.70 (s, 3H), 3.25 ppm (s, 3H). $^{13}$C NMR: $\delta = 168.2$, 167.7, 140.3, 136.8, 131.8, 129.1, 128.4, 128.5, 127.9, 127.5, 127.2, 126.3, 57.7, 52.6, 52.4, 49.2 ppm. Daicel Chiralcel AD-H, hexane/*i*PrOH = 9:1, flow rate 0.8 mL min$^{-1}$, detected at 254 nm. $t_R = 15.8$ min for enantiomer (*R*), and $t_R = 21.2$ min for enantiomer (*S*).

### (−)-(*S, E*)-Dimethyl 2-(cyclohex-2-enyl)malonate

52% *ee* $[\alpha]_D^{20} = -29.3$ ($c = 1.0$, $CHCl_3$), [lit.[20] $[\alpha]_D^{20} = +32.1$ ($c = 0.91$, $CHCl_3$), 74% *ee* (*R*)]. $^1$H NMR: $\delta = 5.78$ (m, 1H), 5.52 (m, 1H), 3.75 (s, 3H), 3.74 (s, 3H), 3.29 (d, $J = 9.4$ Hz, 1H), 2.91 (m, 1H), 2.00 (m, 2H), 1.80–1.27 ppm (m, 4H). $^{13}$C NMR: $\delta = 169.1$, 129.9, 127.5, 57.0, 52.6, 35.6, 26.8, 25.1, 21.0 ppm. Daicel Chiralcel AS-H, hexane/*i*PrOH = 96:4, flow rate 1.0 mL min$^{-1}$, detected at 230 nm. $t_R = 6.0$ min for enantiomer (*S*), and $t_R = 6.9$ min for enantiomer (*R*).

### (−)-(*S,E*)-Dimethyl 2-(pent-3-en-2-yl)malonate

16% *ee* $[\alpha]_D^{20} = -10.2$ ($c = 1.0$, $CHCl_3$), [ lit.[20] $[\alpha]_D^{20} = -25.1$ ($c = 1.1$, $CHCl_3$), 74% *ee* (*S*)]. $^1$H NMR: $\delta = 5.53$ (dq, $J = 15.2$ Hz, 6.4 Hz, 1H), 5.48 (ddq, $J = 15.2$ Hz, 6.2 Hz, 1.6 Hz, 3H), 5.30 (dk, $J = 9.0$ Hz, 6.4 Hz, 1H), 3.73 (s, 3H), 3.69 (s, 3H), 3.27 (d, $J = 9.0$ Hz, 1H), 1.63 (dd, $J = 6.4$ Hz, 1.6 Hz, 3H), 1.28 ppm (d, $J = 6.6$ Hz, 3H). $^{13}$C NMR: $\delta = 169.0$, 132.5, 126.5, 58.2, 52.5, 52.4, 37.6, 18.6, 18.1 ppm. GC analysis was performed by using a chiral column Intercap Chiramix at 108 °C constant. $t_R = 15.2$ min for the minor, and $t_R = 15.7$ min for the major product.

### (*E*)-Dimethyl 2-(4-phenylbut-3-en-2-yl)malonate

$^1$H NMR (300 MHz): $\delta = 7.37$–7.15 (m, 5H), 6.45 (d, $J = 15.9$ Hz, 1H), 6.12 (dd, $J = 15.9$ Hz, 8.7 Hz, 1H), 3.75 (s, 3H), 3.67 (s, 3H), 3.40 (d, $J = 9$ Hz, 1H), 3.20–3.05 (m, m, 1H), 1.19 ppm (d, $J = 6.9$ Hz, 3H). Daicel Chiralcel OD-H, hexane/*i*PrOH = 99:1, flow rate 0.3 mL min$^{-1}$, detected at 254 nm. $t_R = 36.7$ min for the minor and $t_R = 44.7$ min for the major product.

### (*E*)-Dimethyl 2-(1-phenylbut-2-enyl)malonate

$^1$H NMR: $\delta = 7.37$–7.15 (m, 5H), 5.64–5.53 (m, 2H), 4.04 (dd, $J = 11.0$ Hz, 7.2 Hz, 1H), 3.82 (d, $J = 10.9$ Hz, 1H), 3.73 (s, 3H), 3.48 (s, 3H), 1.63 ppm (d, $J = 4.8$ Hz, 3H). Daicel Chiralcel OD-H, hexane/*i*PrOH = 99:1, flow rate 0.3 mL min$^{-1}$, detected at 215 nm. $t_R = 25.3$ min for the minor, and $t_R = 27.9$ min for the major product.

### (*S*)-Dimethyl 2-(1-phenylallyl)malonate

$^1$H NMR: $\delta = 7.25$–7.17 (m, 5H), 6.05–5.93 (m, 1H), 5.17–5.05 (m, 2H), 4.16–4.05 (m, 1H), 3.75 (s, 3H), 3.51 ppm (s, 3H). Daicel Chiralcel OJ-H, hexane/*i*PrOH = 93:7, flow rate 0.5 mL min$^{-1}$, detected at 220 nm. $t_R = 32.4$ min for enantiomer (*S*), and $t_R = 35.6$ min for enantiomer (*R*).

### General procedure for the palladium-catalyzed allylic amination of 9 in the presence of ligands L5–L7

The ligand **L*n*** (0.01 mmol) and $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (1.8 mg, 0.005 mmol) was placed in a Schlenk tube and dissolved in an appropriate solvent (4 mL). After 30 min stirring under argon, a solution of allylic acetate (1 mmol) in the same solvent (2 mL) was added. The resulting yellow solution was stirred for another

30 min, then an amine (350 μL, 3.0 mmol), *N,O*-bis(trimethylsilyl)acetamide (740 μL, 3.0 mmol) and a pinch of the acetate salt were added. The reaction was stirred for the required time and quenched with the addition of saturated $NH_4Cl_{aq}$ (5 mL). The mixture was extracted with $Et_2O$ (2×20 mL). The combined organic layers were washed with brine and dried over anhydrous $MgSO_4$, filtered, and evaporated under vacuum. The residue was purified by flash chromatography (hexanes/EtOAc 95:5, v/v) to give the desired product.

#### (−)-(*R, E*)-4-(1,3-Diphenyl-2-propenyl)morpholine

99% *ee* $[\alpha]_D^{20} = -7.8$ ($c = 1.0$, $CHCl_3$), [lit.[21] $[\alpha]_D^{25} = -7.4$ ($c = 0.34$ $CHCl_3$), 76% *ee* (*R*) ], [lit.[22] $[\alpha]_D^{24} = -8.4$ ($c = 0.7$, $CHCl_3$), 95% *ee* (*R*). $^1$H NMR: $\delta = 7.46–7.12$ (m, 10H), 6.57 (d, $J = 15.6$ Hz, 1H), 6.27 (dd, $J = 16$ Hz, 8.8 Hz, 1H), 3.78 (d, $J = 8.6$ Hz, 1H), 3.71 (t, $J = 4.6$ Hz, 4H), 2.64–2.28 ppm (m, 4H). $^{13}$C NMR: $\delta = 141.7$, 136.9, 131.8, 131.6, 128.9, 128.7, 128.2, 127.8, 127.5, 126.6, 75.0, 67.4, 52.4 ppm. Daicel Chiralcel OD-H, hexane/*i*PrOH = 9:1, flow rate 1.0 mL min$^{-1}$, detected at 254 nm. $t_R = 6.9$ min for enantiomer (*S*), and $t_R = 12.3$ min for enantiomer (*R*).

#### (−)-(*R, E*)-*N*-(1,3-Diphenyl-2-propenyl)pyrrolidine

98% *ee* $[\alpha]_D^{20} = -2.5$ ($c = 1.0$, $CHCl_3$), [lit.[23] $[\alpha]_D^{20} = +2.9$ ($c = 1.0$, $CHCl_3$), 68% *ee* (*S*). $^1$H NMR: $\delta = 7.44–7.12$ (m, 10H), 6.55 (d, $J = 15.6$ Hz, 1H), 6.40 (dd, $J = 15.6$ Hz, 8.4 Hz, 1H), 2.60–2.36 (m, 4H), 1.85–1.68 ppm (m, 4H). $^{13}$C NMR: $\delta = 143.2$, 137.1, 133.2, 129.8, 128.6, 128.5, 127.7, 127.4, 127.1, 126.4, 74.4, 53.2, 23.4 ppm. Daicel Chiralcel OD-H, hexane/*i*PrOH = 200:1, flow rate 0.3 mL min$^{-1}$, detected at 254 nm. $t_R = 14.2$ min for enantiomer (*R*), and $t_R = 15.2$ min for enantiomer (*S*).

#### (−)-(*R, E*)-*N*-(1,3-Diphenyl-2-propenyl)-*N*-benzylpiperazine

99% *ee* $[\alpha]_D^{20} = -30.5$ ($c = 1.0$, $CHCl_3$), lit.[23] $[\alpha]_D^{20} = +15.4$ ($c = 1.0$, $CHCl_3$), 58% *ee* (*S*). M.p. 117–119 °C. $^1$H NMR: $\delta = 7.44–7.12$ (m, 15H), 6.54 (d, $J = 15.8$ Hz, 1H), 6.30 (dd, $J = 15.8$ Hz, 8.6 Hz, 1H), 3.81 (d, $J = 8.8$ Hz, 1H), 2.70–2.26 ppm (m, 8H). $^{13}$C NMR: $\delta = 142.1$, 138.3, 137.1, 132.0, 131.4, 129.4, 128.7, 128.6, 128.3, 128.2, 127.6, 127.3, 127.2, 126.5, 74.5, 63.3, 53.5, 51.7 ppm. Daicel Chiralcel OD-H, hexane/*i*PrOH = 200:1, flow rate 0.3 mL min$^{-1}$, detected at 254 nm. $t_R = 26.2$ min for enantiomer (*S*), and $t_R = 28.4$ min for enantiomer (*R*).

#### (−)-(*R, E*)-*N*-(1,3-Diphenyl-2-propenyl)piperidine

99% *ee* $[\alpha]_D^{20} = -13.4$ ($c = 1.0$, $CHCl_3$), lit.[21] $[\alpha]_D^{25} = -11.7$ ($c = 0.32$, $CHCl_3$), 56% *ee* (*R*). $^1$H NMR: $\delta = 7.48–7.10$ (m, 10H), 6.53 (d, $J = 15.8$ Hz, 1H), 6.33 (dd, $J = 15.8$ Hz, 8.6 Hz, 1H), 3.80 (d, $J = 8.4$ Hz, 1H), 2.60–2.20 (m, 4H), 1.66–1.50 (m, 4H), 1.50–1.32 ppm (m, 2H). $^{13}$C NMR: $\delta = 142.6$, 137.3, 132.5, 131.1, 128.7, 128.6, 128.2, 127.5, 127.1, 126.5, 74.9, 52.9, 26.4, 24.9 ppm. Daicel Chiralcel AD-H, hexane/*i*PrOH = 9:1 flow rate 0.5 mL min$^{-1}$, detected at 254 nm. $t_R = 8.2$ min for enantiomer (*R*), and $t_R = 9.2$ min for enantiomer (*S*).

#### (−)-(*R, E*)-*N*-(*p*-Methoxybenzyl)-(1,3-diphenyl-2-propenyl)-amine

88% *ee* $[\alpha]_D^{20} = -26.5$ ($c = 0.7$, $CHCl_3$), lit.[24] $[\alpha]_D^{23} = +28.2$ ($c = 0.82$, $CHCl_3$), 94% *ee* (*S*), [ lit.[25] $[\alpha]_D^{23} = -30.5$ ($c = 0.82$, $CHCl_3$), 98% *ee* (*R*)]. $^1$H NMR: $\delta = 7.46–7.15$ (m, 12H), 6.90–6.83 (m, 2H), 6.57 (d, $J = 15.9$ Hz), 6.31 (dd, $J = 15.9$ Hz, 7.5 Hz, 1H), 4.38 (d, $J = 7.5$ Hz, 1H), 3.80 (s, 3H), 3.75–3.68 (m, 2H), 1.67 ppm (s, 1H). $^{13}$C NMR: $\delta = 158.6$, 143.0, 137.0, 132.7, 132.5, 130.3, 129.4, 128.6, 128.5, 127.5, 127.4, 127.3, 126.4, 113.8, 64.5, 55.3, 50.8 ppm. Daicel Chiralcel AD-H, hexane/*i*PrOH = 94:6, flow rate 0.7 mL min$^{-1}$, detected at 254 nm. $t_R = 15.6$ min for enantiomer (*S*), and $t_R = 17.2$ min for enantiomer (*R*).

#### (*R, E*)-*N*-Benzyl-(1,3-diphenyl-2-propenyl)amine

93% *ee* $[\alpha]_D^{20} = -18.2$ ($c = 1.0$, $CHCl_3$), lit.[6f] $[\alpha]_D^{25} = -18.5$ ($c = 1.0$, $CHCl_3$), 94% *ee* (*S*). $^1$H NMR: $\delta = 7.46–7.19$ (m, 15H), 6.58 (d, $J = 16$ Hz, 1H), 6.31 (dd, $J = 15.9$, 7.4 Hz, 1H), 4.40 (d, $J = 7.4$ Hz, 1H), 3.78 (s, 2H), 1.70 ppm (s, 1H). $^{13}$C NMR: $\delta = 143.1$, 140.6, 137.1, 132.8, 130.5, 128.8, 128.7, 128.6, 128.4, 127.7, 127.6, 127.50, 127.1, 126.9, 126.6, 64.7, 64.8, 51.6 ppm. Daicel Chiralcel OD-H, hexane/*i*PrOH = 99:1,flow rate 0.5 mL min$^{-1}$, detected at 254 nm. $t_R = 24.8$ min for enantiomer (*R*), and $t_R = 27.5$ min for enantiomer (*S*).

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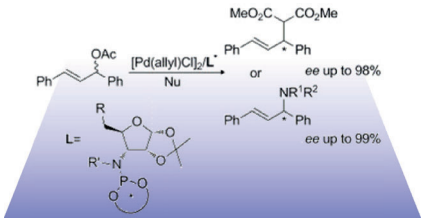
**Palladium-Catalyzed Enantioselective Allylic Substitution in the Presence of Monodentate Furanoside Phosphoramidites**




**Single is better:** New carbohydrate ligands bearing a single 1,1′-bi-2-naphthol (BINOL)-derived phosphoramidite moiety are developed and successfully applied to the palladium-catalyzed asymmetric allylic substitution. The enantioselectivities are equal or better than those obtained for similar systems containing two BINOL moieties and reach up to 99% *ee*.