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Tetrahedron: Asymmetry
Tetrahedron: *Asymmetry* 18 (2007) 1844–1849

Synthesis of novel *P*-stereogenic phenylphosphonamides and their application to Lewis base-catalyzed asymmetric allylation of benzaldehyde

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Received 29 June 2007; accepted 6 August 2007

Abstract—The synthesis of novel *P*-stereogenic phenylphosphonamides **3** and **11** via an intramolecular nucleophilic substitution of *P*-stereogenic phosphoramide **8** is described. These compounds were used as chiral Lewis basic catalysts for the asymmetric allylation of benzaldehyde, providing the corresponding homoallylic alcohol derivatives in up to 54% ee.

1. Introduction

The coordination of Lewis-basic oxygen to a central element (or metal) provides characteristic reactivity to the parent reagents. In 1993, Kobayashi first reported that Lewis-basic molecules such as *N*,*N*-dimethylformamide coordinate to the silicon atom of allyltrichlorosilanes to form reactive hypervalent silicon intermediates for the allylation of aldehydes.[1] Since this pioneering finding, the interaction between silicon atoms and Lewis-basic molecules has been recognized as one of the most important modes of activating organosilanes in organic synthesis.[2] A recent focus in this field is the development of Lewis base-catalyzed asymmetric reactions.[3,4] Chiral Lewis bases, such as chiral phosphoramides,[5,6] formamides,[7] *N*-oxides,[8] phosphine oxides,[9] sulfoxides,[10] and ureas,[11] were designed, synthesized, and applied to the catalytic asymmetric allylation of aldehydes using allyltrichlorosilanes.

Although various types of chiral Lewis bases have been developed, there are few reports of asymmetric reactions using chiral phosphonamides as Lewis base catalysts.[5f,g] We previously reported that *P*-stereogenic diaminophosphine oxide **1** and related compounds are useful chiral preligands in transition metal catalysis.[12,13] These chiral phosphonamides were synthesized from aspartic acid-derived branched triamines through the following three-step reaction sequence: diastereoselective formation of a triaminophosphine intermediate **2**; addition of water to the phosphorus atom via an S_N2-type process, and P(III) to P(V) tautomerization (Scheme 1). This background led us to hypothesize that diastereoselective formation of *P*-stereogenic phosphoramides, followed by intramolecular nucleophilic substitution on the phosphorus atom, would be an efficient synthetic route for *P*-stereogenic phenylphosphonamides such as **3** and **4**. Herein, we describe the synthesis of novel *P*-stereogenic phenylphosphonamides, which can be utilized as chiral Lewis base catalysts for asymmetric allylation of benzaldehyde using allyltrichlorosilanes.

2. Results and discussion

2.1. Synthesis of *P*-stereogenic phenylphosphonamides 3 and 11

Our synthesis started with (*S*)-aspartic acid dianilide **6**, which was prepared from commercially available chiral acid anhydride **5** using a known method[12a] (Scheme 2). First, compound **6** was reacted with 2-iodobenzoyl chloride to give the corresponding triamide, which was transformed

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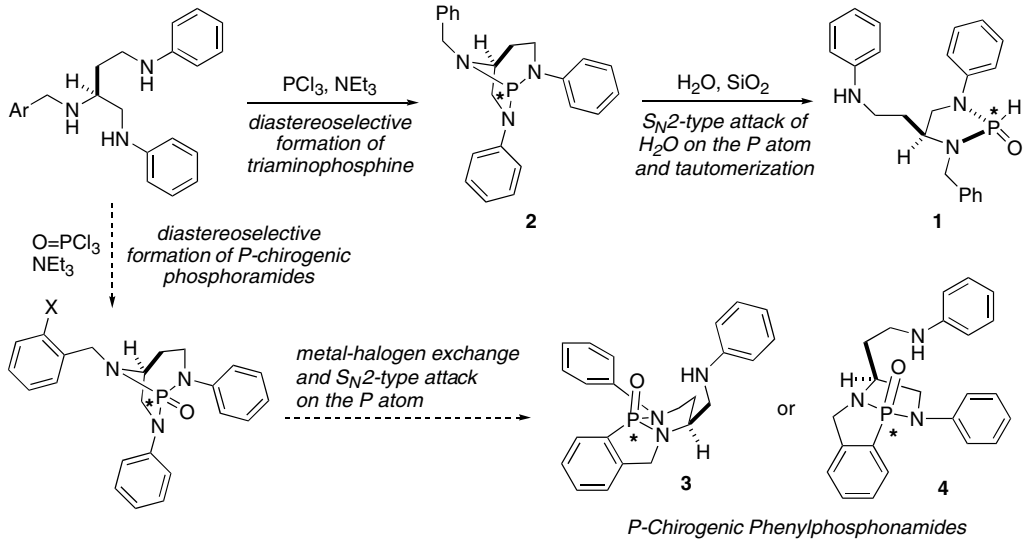
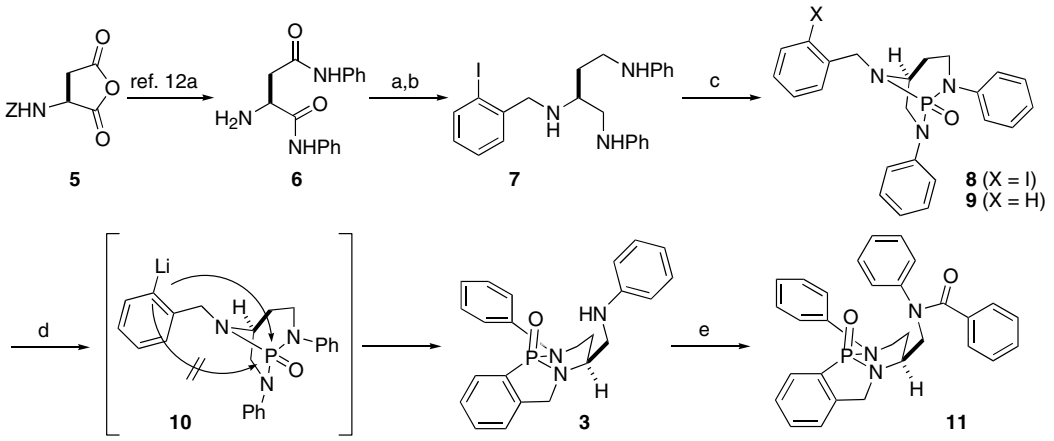
doi:10.1016/j.tetasy.2007.08.006



Scheme 1. Plan for the synthesis of *P*-stereogenic phenylphosphonamides.



Scheme 2. Synthesis of *P*-stereogenic phenylphosphonamides. Reagents and conditions: (a) 2-iodobenzoyl chloride, NEt_3, THF–DMF, rt, 1 h, 92%; (b) $NaBH_4$, I_2, THF, reflux, 8 h, 76%; (c) phosphoryl trichloride, NEt_3, toluene, −78 °C to rt, 18 h, 75%; (d) *n*-BuLi, THF, −78 °C, 1.5 h, then $Na_2SO_4{\cdot}10H_2O$, 78%; (e) *n*-BuLi, THF, −78 °C, 10 min, then benzoyl chloride, −78 °C (10 min) to rt (20 min), 95%.

into chiral branched triamine **7** by treatment with the $BH_3{\cdot}THF$ complex generated from $NaBH_4$ and I_2 in THF in situ. The reaction of triamine **7** with phosphoryl trichloride proceeded diastereoselectively to afford the corresponding *P*-stereogenic phosphoramide **8** in 75% yield. We then examined the transformation of **8** into *P*-stereogenic phenylphosphonamides through an intramolecular nucleophilic substitution. Metal–halogen exchange was performed using 1.1 equiv of *n*-BuLi at −78 °C, and the resulting yellow solution was stirred for 1.5 h at the same temperature. After the reaction was quenched with $Na_2SO_4{\cdot}10H_2O$ at −78 °C, the crude residue was purified by silica gel column chromatography to give a tricyclic phenylphosphonamide adduct in 78% yield, accompanied by the formation of dehalogenated product **9** (11%). The absolute structure of the tricyclic phenylphosphonamide adduct was determined to be **3** by X-ray crystal structure analysis (Fig. 1). The six-membered ring moiety in **3** adopts a boat-like conformation, and the crystal structure indicates that there is a hydrogen bond interaction between

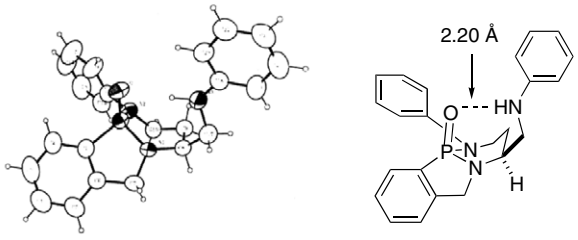


Figure 1. X-ray structure of **3**.

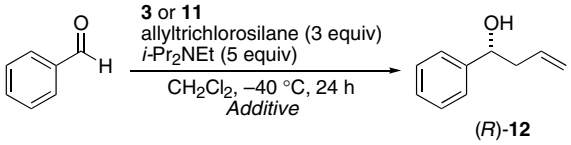
the phosphine oxide moiety and the amino group on the sidearm in **3** (P═O···HN: 2.20 Å). Another possible reaction adduct **4** was not observed in ^1H NMR analysis of the crude residue, indicating that the intramolecular nucleophilic substitution proceeded selectively through one of two possible reaction pathways (Scheme 2, intermediate **10**). In addition, the amine moiety of **3** was protected with a

benzoyl group to provide *P*-stereogenic phenylphosphonamide **11**, bearing a tertiary amide group on the sidearm.

2.2. Application of *P*-stereogenic phenylphosphonamides 3 and 11 to the Lewis base-catalyzed asymmetric allylation of benzaldehyde

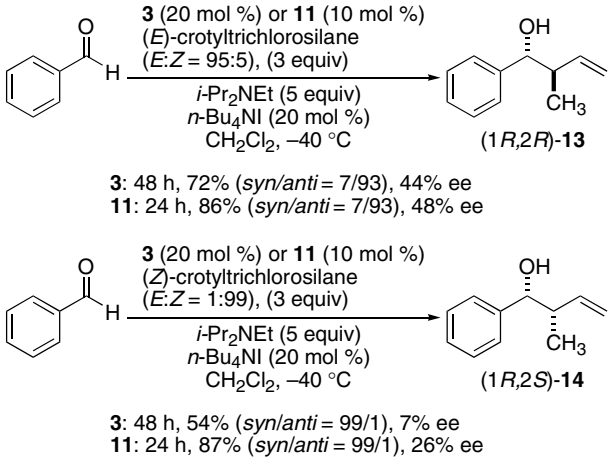
We then attempted to use the enantiomerically pure *P*-stereogenic phenylphosphonamides as chiral Lewis base catalysts. We first examined asymmetric allylation of benzaldehyde with allyltrichlorosilane using **3** as the catalyst (Table 1). When 20 mol % of **3**, 3 equiv of allyltrichlorosilane, and 5 equiv of *i*-Pr_2NEt were used in CH_2Cl_2, the reaction proceeded at −40 °C to give homoallylic alcohol (*R*)-**12** in 58% yield and in 35% ee (entry 1). To improve both the reactivity and enantioselectivity, we investigated the effect of additives. Berrisford and co-workers reported that Lewis base-catalyzed allylation of aldehydes using allyltrichlorosilane was accelerated by tetra-*n*-butylammonium salts.[14] Thus, we performed the reaction in the presence of several tetra-*n*-butylammonium salts (entries 2–7). There was a slight increase in the reactivity and enantioselectivity when tetra-*n*-butylammonium iodide was used as the additive, and homoallylic alcohol (*R*)-**12** was obtained in up to 54% ee (entry 7).[15] We next examined the same reaction using 10 mol % of **11** as the Lewis base catalyst. Although the reaction was sluggish in the absence of tetra-*n*-butylammonium iodide (entry 8), there was an increase in the reactivity when tetra-*n*-butylammonium iodide was added, affording (*R*)-**12** in 81% yield and in 46% ee (entry 9).[16] Moreover, the catalytic asymmetric allylation of benzaldehyde using crotyltrichlorosilanes was examined (Scheme 3). Using 20 mol % of **3** or 10 mol % of **11**, the reaction using (*E*)-crotyltrichlorosilane proceeded at −40 °C in a highly diastereoselective manner to give the *anti*-isomer (1*R*,2*R*)-**13** in 72% yield and 44% ee, and in 86% yield and 48% ee, respectively. Similarly, the reaction using (*Z*)-crotyltrichlorosilane preformed under the same reaction conditions, providing the *syn*-isomer (1*R*,2*S*)-**14** in 54% yield and 7% ee, and in 87% yield and 26% ee, respectively. These results suggest that the present catalytic asymmetric reactions proceed via a six-membered chair-like transition state.

Table 1. Asymmetric allylation of benzaldehyde using allyltrichlorosilane in the presence of *P*-stereogenic phenylphosphonamides **3** and **11**



Entry	Catalyst (mol %)	Additive (mol %)	Yield[a] (%)	ee[b] (%)
1	**3** (20)	—	58	35
2	**3** (20)	*n*-Bu_4NOTf (20)	65	44
3	**3** (20)	*n*-Bu_4NBF_4 (20)	68	42
4	**3** (20)	*n*-Bu_4NCl (20)	60	23
5	**3** (20)	*n*-Bu_4NBr (20)	48	45
6	**3** (20)	*n*-Bu_4NI (20)	69	52
7	**3** (20)	*n*-Bu_4NI (50)	62	54
8	**11** (10)	—	53	47
9	**11** (10)	*n*-Bu_4NI (20)	84	46

[a] Isolated yield.
[b] Determined by HPLC analysis.



Scheme 3. Asymmetric allylation of benzaldehyde using crotyltrichlorosilanes in the presence of *P*-stereogenic phenylphosphonamides **3** and **11**.

3. Conclusion

In conclusion, we succeeded in the synthesis of novel *P*-stereogenic phenylphosphonamides **3** and **11**. The synthesis was achieved by the intramolecular nucleophilic substitution of *P*-stereogenic phosphoramide **8**, where one of two possible reaction pathways occurred selectively. These compounds could be utilized as chiral Lewis base catalysts for asymmetric allylation of benzaldehyde. Studies of other catalytic asymmetric reactions using structurally optimized *P*-stereogenic phenylphosphonamides are currently in progress.

4. Experimental

4.1. General

Infrared (IR) spectra were recorded on a JASCO FT/IR 230 Fourier transform infrared spectrophotometer. NMR spectra were recorded on a JEOL ecp 400 spectrometer, operating at 400 MHz for ^1H NMR, 100 MHz for ^{13}C NMR, and 160 MHz for ^{31}P NMR. Chemical shifts in $CDCl_3$, were reported downfield from TMS (=0 ppm) for ^1H NMR. For ^{13}C NMR, chemical shifts were reported downfield from TMS (=0 ppm) or in the scale relative to the solvent signal [$CHCl_3$ (77.0 ppm)] as an internal reference. Optical rotations were measured on a JASCO P-1020 polarimeter. EI mass spectra were measured on JEOL GC mate. The enantiomeric excess (ee) was determined by HPLC analysis. HPLC was performed on JASCO HPLC systems consisting of the following: pump, PU-980; detector, UV-970, measured at 254 nm; column, DAICEL CHIRALCEL OD-H; mobile phase, 2-propanol/hexane. Reactions were carried out in dry solvent under argon

atmosphere. Other reagents were purified by the usual methods.

4.2. Synthesis of *P*-stereogenic phenylphosphonamides 3 and 11

Compound **6** was prepared from commercially available *N*-benzyloxycarbonyl-(*S*)-aspartic anhydride using a known method, see: Ref. 12a.

4.2.1. N^2-(2-Iodobenzyl)-N^1,N^4-diphenylbutane-1,2,4-triamine 7. To a stirred mixture of **6** (1.13 g, 4 mmol) and triethylamine (0.84 mL, 6 mmol) in THF/DMF (40 mL/3 mL) at 0 °C was added 2-iodobenzoyl chloride (1.28 g, 4.8 mmol), and the reaction mixture was stirred for 1 h at room temperature. The reaction was quenched with aqueous saturated $NaHCO_3$, and the mixture was extracted with AcOEt. The organic layer was washed with H_2O (×2), and evaporated under reduced pressure. The residue obtained was washed by ether to give the corresponding triamide as a white solid (1.88 g, 92%). IR (KBr) ν 3293, 1647, 1642, 1599, 1529, 1499, 1443, 1331, 1164, 754, 691 cm^{-1}; ^1H NMR ($CDCl_3$): δ 2.82 (dd, $J = 7.6$, 15.2 Hz, 1H), 2.96 (dd, $J = 7.2$, 15.2 Hz, 1H), 5.00 (ddd, $J = 7.2$, 7.6, 7.6 Hz, 1H), 7.01–7.04 (m, 2H), 7.15–7.20 (m, 1H), 7.27–7.47 (m, 6H), 7.58–7.66 (m, 4H), 7.87–7.89 (m, 1H), 8.84 (d, $J = 7.6$ Hz, 1H), 10.01 (s, 1H), 10.09 (s, 1H); ^{13}C NMR ($CDCl_3$): δ 36.9, 49.9, 92.3, 118.0 (×2), 118.3 (×2), 122.0, 122.3, 126.8, 127.3, 127.6 (×2), 127.6 (×2), 129.9, 137.8, 138.0, 138.0, 140.9, 166.9, 167.7, 168.1; EI-LRMS m/z 513 (M^+), 420; EI-HRMS. Calcd for $C_{23}H_{20}IN_3O_3$ (M^+): 513.0549. Found: 513.0547; $[\alpha]_D^{24} = -16.8$ (c 0.94, DMF). To a stirred mixture of triamide (5.13 g, 10 mmol), $NaBH_4$ (2.84 g, 75 mmol) in THF (100 mL) at 0 °C was added a THF solution of I_2 (7.61 g, 30 mmol, 60 mL of THF) over 1 h, and the resulting mixture was refluxed for 8 h. After cooling down to room temperature, the reaction was quenched by the addition of 2 M HCl. The mixture was refluxed again for 3 h, then cooled down to 0 °C. After the solution was basified by the addition of 1 M NaOH, the mixture was extracted with AcOEt (×2), and the combined organic layers were washed with brine and dried over Na_2SO_4. After concentration in vacuo, the crude residue was purified by flash column chromatography (SiO_2, hexane/AcOEt 7/1–2/1) to give **7** as a yellow oil (3.56 g, 76%). IR (neat) ν 3401, 3049, 2922, 2850, 1602, 1504, 1470, 1433, 1319, 1256, 748, 692 cm^{-1}; ^1H NMR ($CDCl_3$): δ 1.91–1.96 (m, 2H), 3.08–3.31 (m, 5H), 3.88 (s, 2H), 6.57–6.73 (m, 6H), 6.96–6.99 (m, 1H), 7.15–7.20 (m, 4H), 7.30–7.31 (m, 2H), 7.81–7.83 (m, 1H), amine protons could not be detected in ^1H NMR; ^{13}C NMR ($CDCl_3$): δ 31.8, 41.3, 46.2, 54.9, 55.3, 77.2, 99.8, 112.9 (×2), 113.0 (×2), 117.5, 117.6, 128.5, 129.2 (×2), 129.2 (×2), 130.2, 139.6, 141.3, 148.0, 148.2; EI-LRMS m/z 471 (M^+); EI-HRMS. Calcd for $C_{23}H_{26}IN_3$ (M^+): 471.1171. Found: 471.1153; $[\alpha]_D^{23} = -2.4$ (c 0.64, $CHCl_3$).

4.2.2. 8-(2-Iodobenzyl)-2,7-diphenyl-2,7,8-triaza-1-phosphabicyclo[3.2.1]octane 1-oxide 8. To a stirred solution of **7** (1.24 g, 2.63 mmol) and triethylamine (1.40 mL, 10.3 mmol) in toluene (13.2 mL) at −78 °C was added phosphoryl trichloride (0.27 mL, 2.89 mmol) slowly. The reaction temperature was gradually warmed up to room temperature, and then the mixture was kept stirring for 12 h. The reaction mixture was filtered, concentrated, and then purified by flash column chromatography (SiO_2, hexane/AcOEt/$CHCl_3$ 600/100/7–100/100/2) to give **8** as a white solid (850 mg, 75%). IR (KBr) ν 2939, 2881, 1601, 1494, 1317, 1295, 1265, 1145, 763, 752 cm^{-1}; ^1H NMR ($CDCl_3$): δ 1.44–1.55 (m, 1H), 2.48–2.55 (m, 1H), 3.39–3.43 (m, 1H), 3.53–3.80 (m, 3H), 4.02–4.08 (m, 1H), 4.26 (dd, $J = 5.6$ (*P*NC*H*), 15.6 Hz, 1H), 4.42 (dd, $J = 8.0$ (*P*NC*H*), 15.6 Hz, 1H), 6.88–7.11 (m, 5H), 7.18–7.39 (m, 7H), 7.60–7.62 (m, 1H), 7.84–7.86 (m, 1H); ^{13}C NMR ($CDCl_3$): δ 25.5, 47.5 (d, $J = 1.5$ Hz), 49.4 (d, $J = 9.9$ Hz), 50.5 (d, $J = 3.1$ Hz), 53.3 (d, $J = 4.6$ Hz) 99.3, 115.0 (d, $J = 5.3$ Hz) (×2), 120.7, 122.5, 122.5, 123.5, 128.5, 128.8 (×2), 129.2 (×2), 129.2 (×2), 129.7, 139.4, 139.6, 141.6 (d, $J = 6.5$ Hz), 145.1; ^{31}P NMR ($CDCl_3$): δ 15.9; EI-LRMS m/z 515 (M^+); EI-HRMS. Calcd for $C_{23}H_{23}IN_3OP$ (M^+): 515.0623. Found: 515.0611; $[\alpha]_D^{23} = +21.0$ (c 0.62, $CHCl_3$).

4.2.3. *P*-Stereogenic phenylphosphonamide 3. To a stirred mixture of **8** (103 mg, 0.2 mmol) in THF (3 mL) at −78 °C was added *n*-BuLi (0.146 mL, 0.22 mmol, 1.5 M solution in *n*-hexane), and the resulting mixture was stirred for 1.5 h at a temperature below −60 °C. The reaction (yellow solution) was quenched by the addition of $Na_2SO_4 \cdot 10H_2O$, and the resulting mixture was stirred for 10 min (the reaction turned to clear solution). After diluting with AcOEt, the reaction mixture was washed with water, brine, and dried over Na_2SO_4. After concentration in vacuo, the crude residue was purified by flash column chromatography (SiO_2, hexane/AcOEt 2/1–1/2) to give **3** as a pale yellow solid (60.6 mg, 78%). Mp 78–80 °C; IR (KBr) ν 3584, 3354, 3018, 2859, 2400, 1731, 1602, 1496, 1298, 1215, 1174, 1099, 756 cm^{-1}; ^1H NMR ($CDCl_3$): δ 2.28–2.36 (m, 1H), 2.49–2.52 (m, 1H), 3.41–3.60 (m, 4H), 3.73–3.80 (m, 1H), 4.20 (dd, $J = 6.4$ (*P*NC*H*), 14.0 Hz, 1H), 4.63 (broad peak (N*H*), 1H), 4.71 (dd, $J = 6.4$ (*P*NC*H*), 14.0 Hz, 1H), 6.69–6.72 (m, 4H), 7.04–7.07 (m, 1H), 7.17–7.21 (m, 2H), 7.25–7.46 (m, 6H), 7.56–7.60 (m, 1H); ^{13}C NMR ($CDCl_3$): δ 30.3 (d, $J = 6.9$ Hz), 47.2, 48.3, 55.3 (d, $J = 17.2$ Hz), 56.7, 113.0 (×2), 117.3, 120.4 (d, $J = 4.2$ Hz) (×2), 122.8, 123.6 (d, $J = 10.7$ Hz), 127.6 (d, $J = 11.9$ Hz), 127.9 (d, $J = 13.0$ Hz), 129.2 (×2), 129.3 (×2), 131.4 (d, $J = 2.6$ Hz), 141.3 (d, $J = 22.1$ Hz), 145.0, 148.1; ^{31}P NMR ($CDCl_3$): δ 26.0; EI-LRMS m/z 389 (M^+); EI-HRMS. Calcd for $C_{23}H_{24}N_3OP$ (M^+): 389.1657. Found: 398.1663; $[\alpha]_D^{23} = +335.3$ (c 0.25, $CHCl_3$). X-ray data of compound **3**: Collected at 21 °C, $C_{23}H_{24}N_3OP = 389.44$, yellow rhombic crystal, $a = 11.493(1)$ Å, $b = 7.061(1)$ Å, $c = 13.034(1)$ Å, $V = 1020.7(4)$ Å^3, $P21$, $Z = 2$, $D = 1.27$ g/cm^3, $R(F) = 0.039$, $R_W(F) = 0.041$, GOF = 0.422. Crystallographic data (excluding structure factors) for this compound have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC-652149. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44(0)-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].

4.2.4. *P*-Stereogenic phenylphosphonamide 11. To a stirred mixture of **3** (78.0 mg, 0.2 mmol) in THF (3 mL) at −78 °C was added *n*-BuLi (0.146 mL, 0.22 mmol, 1.5 M solution in *n*-hexane), and the resulting mixture was stirred at the same temperature. After 10 min, benzoyl chloride (51 μL, 0.44 mmol) was added to the reaction, and the resulting mixture was stirred for 10 min at −78 °C, and then stirred for 20 min at room temperature. The reaction was quenched with aqueous saturated $NaHCO_3$, and the mixture was extracted with AcOEt. The organic layer was washed with brine, dried over Na_2SO_4, and then concentrated under reduced pressure. The obtained residue was purified by flash column chromatography (SiO_2, hexane/AcOEt 1/3) to give **11** as a white solid (94.0 mg, 94%). IR (KBr) ν 3449, 2925, 2850, 1648, 1596, 1494, 1298, 1222, 1175, 699 cm^{-1}; ^1H NMR ($CDCl_3$): δ 2.21–2.34 (m, 1H), 2.38–2.48 (m, 1H), 3.44–3.58 (m, 2H), 4.19–4.29 (m, 3H), 4.31 (dd, $J = 6.4$ (*P*NC*H*), 14.4 Hz, 1H), 4.87 (dd, $J = 6.0$ (*P*NC*H*), 14.4 Hz, 1H), 7.02–7.56 (m, 19H); ^{13}C NMR ($CDCl_3$): δ 31.6 (d, $J = 7.6$ Hz), 47.1 (d, $J = 3.1$ Hz), 55.9, 56.1 (d, $J = 7.2$ Hz), 58.5, 120.2 (d, $J = 3.8$ Hz) (×2), 122.6, 123.4 (d, $J = 10.7$ Hz), 126.4, 127.1 (×2), 127.5 (d, $J = 11.4$ Hz), 127.7 (d, $J = 13.4$ Hz), 127.8 (×2), 128.5, 128.9 (×2), 129.1 (×2), 129.2 (×2), 130.0, 130.1, 131.2 (d, $J = 2.1$ Hz), 141.1 (d, $J = 22.2$ Hz), 144.7, 145.1 (d, $J = 5.4$ Hz), 170.9; ^{31}P NMR ($CDCl_3$): δ 24.3; EI-LRMS m/z 493 (M^+); EI-HRMS. Calcd for $C_{30}H_{28}N_3O_2P$ (M^+): 493.1919. Found: 493.1898; $[\alpha]_D^{23} = +68.8$ (c 0.83, $CHCl_3$).

4.3. Experimental procedure

4.3.1. Lewis base-catalyzed asymmetric allylation of benzaldehyde using allyltrichlorosilane. (*R*)-1-Phenyl-3-butene-1-ol 12.[9c] To a stirred mixture of **3** (15.5 mg, 0.04 mmol), *n*-Bu_4NI (14.9 mg, 0.04 mmol), *i*-Pr_2NEt (172 μL, 1 mmol) in CH_2Cl_2 (0.4 mL) at −40 °C was added allyltrichlorosilane (87 μL, 0.6 mmol). After stirring for 30 min, benzaldehyde (20 μL, 0.2 mmol) was added to the reaction and kept stirring for 24 h at the same temperature. The reaction was quenched with aqueous saturated $NaHCO_3$, and the mixture was extracted with AcOEt (×2). The combined organic layers were washed with brine, dried over Na_2SO_4, and then concentrated in vacuo. The obtained residue was purified by flash column chromatography (SiO_2, hexane/AcOEt 15/1) to give 1-phenyl-3-butene-1-ol **12** as a colorless oil (20.3 mg, 69%, 52% ee). The enantiomeric excess was determined by HPLC analysis (DAICEL CHIRALCEL OD-H, 2-propanol/hexane 5/95, flow rate 0.5 mL/min, t_R 18.0 min [(*S*)-isomer] and 20.0 min [(*R*)-isomer], detection at 254 nm). $[\alpha]_D^{22} = +28.7$ [c 0.18, $CHCl_3$, 52% ee (*R*)].

4.3.2. Lewis base-catalyzed asymmetric allylation of benzaldehyde using (*E*)-crotyltrichlorosilane. (1*R*,2*R*)-*anti*-2-methyl-1-phenyl-3-butene-1-ol 13.[9c] To a stirred mixture of **11** (19.7 mg, 0.04 mmol), *n*-Bu_4NI (29.5 mg, 0.08 mmol), *i*-Pr_2NEt (346 μL, 1.2 mmol) in CH_2Cl_2 (0.8 mL) at −40 °C was added (*E*)-crotyltrichlorosilane ($E/Z = 95/5$) (188 μL, 1.2 mmol). After stirring for 30 min, benzaldehyde (41 μL, 0.4 mmol) was added to the reaction and kept stirring for 24 h at the same temperature. The reaction was quenched with aqueous saturated $NaHCO_3$, and the mixture was extracted with AcOEt (×2). The combined organic layers were washed with brine, dried over Na_2SO_4, and then concentrated in vacuo. The obtained residue was purified by flash column chromatography (SiO_2, hexane/AcOEt 15/1) to give a mixture of *syn*- and *anti*-2-methyl-1-phenyl-3-butene-1-ol as a colorless oil (55.7 mg, 86%, *syn*/*anti* = 7/93, 48% ee). The enantiomeric excess of the *anti*-isomer was determined by HPLC analysis (DAICEL CHIRALCEL OD-H, 2-propanol/hexane 1/100, flow rate 0.5 mL/min, t_R 34.9 min [(1*S*,2*S*)-isomer] and 40.2 min [(1*R*,2*R*)-isomer], detection at 254 nm).

4.3.3. (1*R*,2*S*)-*syn*-2-Methyl-1-phenyl-3-butene-1-ol 14.[9c] This compound was prepared according to the experimental procedure for the Lewis base-catalyzed asymmetric allylation. The enantiomeric excess of the *syn*-isomer was determined by HPLC analysis (DAICEL CHIRALCEL OD-H, 2-propanol/hexane 1/100, flow rate 0.5 mL/min, t_R 37.7 min [(1*S*,2*R*)-isomer] and 42.0 min [(1*R*,2*S*)-isomer], detection at 254 nm). $[\alpha]_D^{23} = +6.2$ (c 1.09, $CHCl_3$, 26% ee, (1*R*,2*S*)-isomer).

Acknowledgment

This work was supported in part by Grant-in Aid for Encouragement of Young Scientists (A) from the Ministry of Education, Culture, Sports, Science, and Technology, Japan.

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