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Chiral tricyclic phosphines derived from 1-(+)-neomenthyl-1,2-diphosphole: Synthesis and applications in asymmetric homogeneous catalysis

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ABSTRACT

A one-step diastereoselective synthesis of bulky *P*-chiral phosphines with a rigid bicyclic [2.2.1] structure was developed employing a cycloaddition reaction of 3,4,5-triphenyl-1-(+)-neomenthyl-1,2-diphosphole (**1**) and maleic acid derivatives. The catalytic activity and asymmetric induction for the prepared enantiopure tricyclic phosphines **2a** and **3a** were evaluated in Pd-catalyzed asymmetric allylic substitution and [3 + 2] organocatalytic cyclization of allenes with activated alkenes (*ee* = 68%). This is the first example of using a chiral phosphine with a P—P bond as ligand in allylic alkylation and organocatalyst in a [3 + 2] annulation.

1. Introduction

The increasing demand for enantiomerically pure pharmaceuticals, agrochemicals, flavors and other fine chemicals has advanced the field of asymmetric catalytic technologies. Today, mainly transition metal complexes with chiral ligands are employed as enantioselective catalysts because they allow carrying out asymmetric synthesis under mild conditions with high selectivity, thus reducing the cost of enantiomerically pure compounds. Phosphines are powerful and versatile ligands in transition metal catalysis [1,2] but also nucleophilic organocatalysts [3,4]. Phosphines based on rigid bicyclic structures (Fig. 1) with the phosphorus atom embedded in a five- or six-membered ring were shown to be highly efficient chiral ligands (BIPNOR A [5], PennPhos B [6], 9-PBN C [7] Briphos D [8], phosphabarrelene E [9], tricyclic phosphinite F [10], 1-phosphanorbornadiene-oxazoline G [11]) and excellent chiral organocatalysts (2-aza-5-phosphabicyclo[2.2.1]heptane H [12], 7-phosphabicyclo-[2.2.1]heptane I [13]). The main structural feature of these chiral phosphines is their rigid framework and a chiral, not racemizable P-atom situated at the bridgehead of a bicyclic system [14], which excludes the conformational flexibility associated with other cyclic chiral phosphines and provides a new motif for chiral phosphine design. However, the preparation of these phosphines is rather complicated and mostly based on expensive starting materials or complex separation of enantiomers.

In this paper we demonstrate that the enantiomerically pure tricyclic P,C-stereogenic phosphines 10-neomenthyl-7,8,9-triphenyl-1,10-diphosphatricyclo[5.2.1.$0^{2,6}$]-deca-8-ene-3,5-diones **2a** and **3a** can be readily obtained by an efficient diastereoselective [4 + 2] cycloaddition reaction of 1-(+)-(S_1,S_2,R_5)-neomenthyl-3,4,5-triphenyl-1,2-diphosphacyclopenta-2,4-diene (**1**) (1-(+)-neomenthyl-1,2-diphosphole) and maleic acid derivatives. The use of enantiopure phosphines **2a** and **3a** as ligands and organocatalysts in asymmetric C—C bond formation reactions is also reported.

2. Experimental

2.1. General methods

All reactions and manipulations were carried out under dry, pure N_2 in standard Schlenk apparatus. THF, toluene and n-hexane were distilled from sodium/benzophenone and stored under nitrogen before use. The NMR experiments were performed at 303 K with a Bruker AVANCE-600 spectrometer equipped with a 5 mm diameter gradient inverse broad-band probe head (600.13 MHz in

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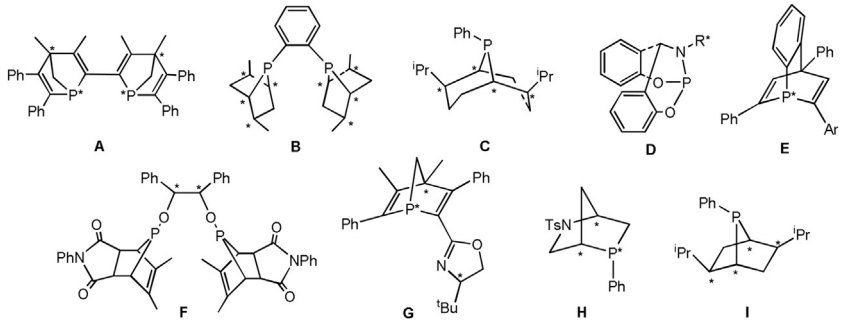

Fig. 1. Selection of rigid bicyclic phosphines (* denotes chiral center).

^{1}H NMR, 150.90 MHz in ^{13}C NMR, and 242.9 MHz in ^{31}P NMR). ^{1}H and ^{13}C NMR chemical shifts were referenced to TMS, and ^{31}P NMR chemical shifts to 85% H_3PO_4. All experiments were carried out using standard Bruker pulse programs. Infrared (IR) spectra were recorded on a Bruker Vector-22 spectrometer. Elemental analysis was accomplished with an automated EuroVector EA3000 CHNS-O elemental analyzer. Optical rotations were measured on a Perkin–Elmer model 341 polarimeter. Chiral HPLC analyses were performed with a chromatograph equipped with a Daicel HPLC column Chiralcel OD-H.

1-(+)-(S_1,S_2,R_5)-neomenthyl-3,4,5-triphenyl-1,2-diphosphacyclopenta-2,4-diene (**1**) [15] and ethyl buta-2,3-dienoate (**9**) [16] were obtained according to literature procedures. Maleic anhydride, N-phenylmaleimide, [{Pd(allyl)Cl}$_2$], *N*,*O*-bis(trimethylsilyl)acetamide (BSA) and (E)-1,3-diphenylallyl acetate were purchased from Aldrich and used without additional purification. Dimethyl malonate (**5**), benzylamine (**6**), ethyl acrylate (**10**) and tert-butyl acrylate (**11**) were distilled before use.

2.2. General method for preparation of phosphines 2a and 3a

Maleic anhydride (0.18 g, 1.84 mmol) or *N*-phenylmaleimide (0.32 g, 1.84 mmol) was added at −30 °C to a solution of 1-(+)-(S_1,S_2,R_5)-neomenthyl-3,4,5-triphenyl-1,2-diphosphacyclopenta-2,4-diene (1) (0.86 g, 1.83 mmol) in 20 ml THF and stirred for 1 h at this temperature and then for 24 h at 0 °C. Then the solution was filtered and the solvent was evaporated at reduced pressure to give 0.99 g (95%) of a mixture of diastereomers (15:1, *d.e.* = 88%). The individual major diastereoisomer **2a** or **3a** was isolated by slow precipitation from a mixture of *n*-hexane and toluene (or THF) (3 ml:3 ml) at −40 °C. The precipitate was isolated and dried to give about 0.50 g (47–50%) 10-neomenthyl-7,8,9-triphenyl-4-oxa-1,10-diphosphatricyclo[5.2.1.0^{2,6}]-deca-8-ene-3,5-dione (**2a**) or 10-neomenthyl-4,7,8,9-tetraphenyl-4-aza-1,10-diphosphatricyclo[5.2.1.0^{2,6}]-deca-8-ene-3,5-dione (**3a**) as pale yellow powders (Scheme 1).

2.3. 10-neomenthyl-7,8,9-triphenyl-4-oxa-1,10-diphosphatricyclo[5.2.1.0^{2,6}]-deca-8-ene-3,5-dione (2a)

Yield: 0.50 g (47%). M.p. 143 °C. Numbering scheme for NMR assignments is given in Scheme 1. ^{1}H NMR ($CDCl_3$, δ, ppm, *J*, Hz): 0.03 (d, 3H, $^3J_{HH}$ = 6.3, H10'), 0.71 (q, 1H, $^2J_{HH}$ = 12.6, H4a'), 0.85 (m, 1H, H6a'), 0.94 (m, 1H, H5'), 0.95 (d, 3H, $^3J_{HH}$ = 6.5, H9'), 1.00 (d, 3H, $^3J_{HH}$ = 6.5, H8'), 1.14 (m, 1H, H2'), 1.40 (d, 1H, $^2J_{HH}$ = 13.5, H6e'), 1.59–1.75 (m, 2H, H3'), 1.62 (m, 1H, H4e'), 1.70 (m, 1H, H7'), 2.41 (br, 1H, H1'), 4.66 (dd, 1H, $^3J_{HH}$ = 8.7, $^2J_{HP}$ = 10.9, H2), 4.79 (d, 1H, $^3J_{HH}$ = 8.7, H6), 6.69 (d, 2H, $^3J_{HH}$ = 7.8, *o*-Ph8), 6.88 (t, 2H, $^3J_{HH}$ = 7.5, *m*-Ph8), 6.93 (tt, 1H, $^3J_{HH}$ = 7.3, $^4J_{HH}$ = 1.4, *p*-Ph8), 7.07 (d, 2H, $^3J_{HH}$ = 7.3, *o*-Ph9), 7.11 (m, 2H, *m*-Ph7), 7.12 (t, 2H, $^3J_{HH}$ = 6.8, *m*-Ph9), 7.17 (t, 1H, $^3J_{HH}$ = 7.2, *p*-Ph7), 7.26 (t, 1H, $^3J_{HH}$ = 7.5, *p*-Ph9), 8.08 (br, 2H, *o*-Ph7). ^{31}P NMR ($CDCl_3$, δ, ppm, *J*, Hz): 84.7 (d, $^1J_{PP}$ = 207.5, P10), −14.4 (d, $^1J_{PP}$ = 207.5, P1). ^{13}C NMR ($CDCl_3$, δ, ppm, *J*, Hz): 21.6 (s, C9'), 22.2 (s, C10'), 23.3 (br, C8'), 26.1 (d, $^3J_{CP}$ = 9.8, C3'), 28.5 (s, C5'), 30.8 (s, C7'), 36.1 (s, C4'), 37.8 (s, C6'), 40.5 (d, $^1J_{CP}$ = 42.2, C1'), 49.4 (s, C6), 50.6 (d, $^1J_{CP}$ = 41.2, C2), 50.7 (d, $^2J_{CP}$ = 9.8, C2'), 78.0 (d, $^1J_{CP}$ = 36.3, C7), 126.9 (s, *m*-Ph7), 127.6 (s, *p*-Ph8), 127.9 (s, *m*-Ph8), 128.5 (br, *o*-Ph7, *m*-Ph9, *p*-Ph9), 129.4 (s, *p*-Ph7), 130.0 (d, $^3J_{CP}$ = 6.2, *o*-Ph9), 130.8 (s, *o*-Ph8), 143.0 (m, 9, *ipso*-Ph8, *ipso*-Ph9), 158.3 (d, $^2J_{CP}$ = 18.6, C8), 169.6 (s, C3), 171.8 (s, C5). IR (KBr, cm^{-1}): 405 (m), 419 (m), 457 (w), 697 (m), 755 (w), 806 (br.w), 1029 (m), 1084 (w), 1262 (m), 1385 (w), 1456 (w), 1491 (w), 1559 (w), 1634 (br), 1700 (m, CO), 1734 (m, CO), 2961 (w). $[\alpha]^{25}_D$ = −303° (c 0.5, THF). Found: C 74.30, H 6.23, P 10.82%. Calculated for $C_{35}H_{36}O_3P_2$: C 74.19, H 6.40, P 10.93%.

2.4. 10-Neomenthyl-4,7,8,9-tetraphenyl-4-aza-1,10-diphosphatricyclo[5.2.1.0^{2,6}]-deca-8-ene-3,5-dione (3a)

Yield: 0.55 g (50%). M.p. 151 °C. Numbering scheme for NMR assignments is given in Scheme 1. ^{1}H NMR ($CDCl_3$, δ, ppm, *J*, Hz): 0.04 (d, 3H, $^3J_{HH}$ = 6.3, H10'), 0.72 (q, 1H, $^2J_{HH}$ = 12.3, H4a'), 0.85 (m, 1H, H6a'), 0.93 (m, 1H, H5'), 0.96 (d, 3H, $^3J_{HH}$ = 6.5, H9'), 1.02 (d, 3H, $^3J_{HH}$ = 6.6, H8'), 1.15 (m, 1H, H2'), 1.41 (d, 1H, $^2J_{HH}$ = 13.5, H6e'), 1.58–1.74 (m, 2H, H3'), 1.62 (m, 1H, H4e'), 1.74 (m, 1H, H7'), 2.41 (br, 1H, H1'), 4.67 (dd, 1H, $^3J_{HH}$ = 8.7, $^2J_{HP}$ = 10.9, H2), 4.80 (d, 1H, $^3J_{HH}$ = 8.7, H6), 6.70 (d, 2H, $^3J_{HH}$ = 7.8, *o*-Ph8), 6.87 (t, 2H, $^3J_{HH}$ = 7.5, *m*-Ph8), 6.94 (tt, 1H, $^3J_{HH}$ = 7.3, $^4J_{HH}$ = 1.4, *p*-Ph8), 7.08 (d, 2H, $^3J_{HH}$ = 7.3, *o*-Ph9), 7.12 (m, 2H, *m*-Ph7), 7.13 (t, 2H, $^3J_{HH}$ = 6.9, *m*-Ph9), 7.15 (t, 1H, $^3J_{HH}$ = 7.2, *p*-Ph7), 7.26 (t, 1H, $^3J_{HH}$ = 7.5, *p*-Ph9), 7.32 (m, 2H, NPh), 7.41 (m, 3H,) 8.08 (br, 2H, *o*-Ph7). ^{31}P NMR ($CDCl_3$, δ, ppm, *J*, Hz): 81.2 (d, $^1J_{PP}$ = 200.3, P10), −21.1 (d, $^1J_{PP}$ = 200.3, P1). ^{13}C NMR ($CDCl_3$, δ, ppm, *J*, Hz): 20.6 (s, C9'), 21.2 (s, C10'), 23.4 (br, C8'), 26.3 (d, $^3J_{CP}$ = 9.7, C3'), 28.3 (s, C5'), 30.3 (s, C7'), 36.3 (s, C4'), 37.8 (s, C6'), 41.5 (d, $^1J_{CP}$ = 41.2, C1'), 48.4 (s, C6), 51.6 (d, $^1J_{CP}$ = 43.2, C2), 51.7 (d, $^2J_{CP}$ = 9.8, C2'), 76.7 (d, $^1J_{CP}$ = 38.3, C7), 124.2 (s, C_{Ph}), 124.6 (s, C_{Ph}), 124.9 (s, C_{Ph}), 125.2 (s, C_{Ph}), 126.8 (s, *m*-Ph7), 127.7 (s, *p*-Ph8), 128.0 (s, *m*-Ph8), 128.2 (br, *o*-Ph7, *m*-Ph9, *p*-Ph9), 128.4 (s, *p*-Ph7), 131.0 (d, $^3J_{CP}$ = 6.2, *o*-Ph9), 131.8 (s, *o*-Ph8), 142.0 (m, 9, *ipso*-Ph8, *ipso*-Ph9), 156.3 (d, $^2J_{CP}$ = 18.6, C8), 168.6 (s, C3), 170.8 (s, C5). IR (KBr, cm^{-1}): 406 (m), 420 (m), 457 (w), 697 (m), 755 (w), 812 (br.w), 1029 (m), 1083 (w), 1261 (m), 1383 (w), 1440 (w), 1492 (w), 1560 (w), 1634 (br), 1710 (m, CO), 1721 (m, CO), 2961 (w). $[\alpha]^{25}_D$ = −284° (c 0.5, THF). Found: C 76.80, H 6.39, N 2.34, P 9.79%. Calculated for $C_{41}H_{41}NO_2P_2$: C 76.74, H 6.44, N 2.18, P 9.65%.

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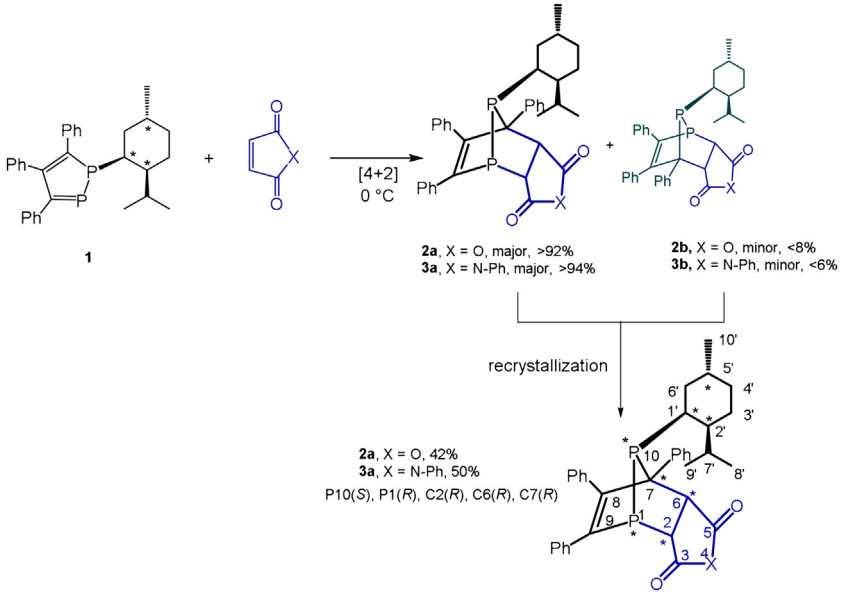

Scheme 1. Preparation of chiral tricyclic phosphines **2a** and **3a**.

2.5. General procedure for the Pd-catalyzed asymmetric allylic alkylation of rac-1,3-diphenyl-2-propenyl acetate (4) with dimethyl malonate (5) to give 7

A solution of the ligand **2a** or **3a** (0.025 mmol) and [{Pd(allyl)Cl}$_2$] (0.004 g, 0.01 mmol) in THF (1 mL) was stirred at room temperature for 30 min. Then the solution was successively treated with a solution of *rac*-1,3-diphenyl-2-propenyl acetate (**4**) (0.13 g, 0.50 mmol), dimethyl malonate (**5**) (0.17 mL, 1.5 mmol), *N,O*-bis(trimethylsilyl)acetamide (0.37 mL, 1.5 mmol) and sodium acetate (0.01 mmol) in THF (2 mL). The reaction mixture was stirred for 24 h at 25 °C or 50 °C. Then the reaction mixture was quenched with saturated aqueous NH_4Cl, and extracted with diethyl ether. The organic layer was dried over anhydrous Na_2SO_4, filtered and evaporated to dryness. The residue was chromatographed on silica gel (ethyl acetate:*n*-hexane, 1:4) to give dimethyl-(1,3-diphenyl-2-propenyl)malonate (*S*)-7 [17]. The enantiomeric excess was determined by HPLC analysis using a Daicel Chiralcel OD-H column (eluent 2-propanol:*n*-hexane, 1:99; flow rate 0.3 mL/min; detection UV 254 nm; t(*R*) = 18.6 min, t(*S*) = 20.2 min for 4 and t(*R*) = 27.8 min, t(*S*) = 29.3 min for **7** (Table 1).

7: ^{1}H NMR ($CDCl_3$, δ, ppm, *J*, Hz): 3.52 (s, 3H), 3.70 (s, 3H), 3.95 (d, 1H, *J* = 10.9), 4.26 (dd, 1H, *J* = 10.9, *J* = 8.4), 6.32 (dd, 1H, *J* = 15.8, *J* = 8.4), 6.47 (d, 1H, *J* = 15.8), 7.17–7.34 (m, 10H, Ph).

2.6. General procedure for the Pd-catalyzed asymmetric allylic amination of rac-1,3-diphenyl-2-propenyl acetate (4) with benzylamine (6) to give 8

A solution of the ligand **2a** or **3a** (0.025 mmol) and [{Pd(allyl)Cl}$_2$] (0.004 g, 0.01 mmol) in THF (1 mL) was stirred at room temperature for 30 min. The solution was then successively treated with a solution of *rac*-1,3-diphenyl-2-propenyl acetate (**4**) (0.13 g, 0.50 mmol) and benzylamine (**6**) (0.13 g, 1.2 mmol) in THF (1 mL). The reaction mixture was stirring for 24 h at 50 °C. Then the reaction mixture was quenched with saturated aqueous NH_4Cl, and extracted with diethyl ether. The organic layer was dried over anhydrous Na_2SO_4, filtered and evaporated to dryness. The residue was chromatographed on silica gel (ethyl acetate:*n*-hexane, 1:4) to give *N*-((*E*)-1,3-diphenyl-2-propenyl)benzylamine (*S*)-**8** [17]. The enantiomeric excess was determined by HPLC analysis using a Daicel Chiralcel OD-H column (eluent 2-propanol:*n*-hexane, 1:99; flow rate 0.5 mL/min; detection UV 254 nm; retention times: t(*R*) = 45.8 min, t(*S*) = 47.1 min for 8 (Table 1).

8: ^{1}H NMR ($CDCl_3$, δ, ppm, *J*, Hz): 1.75 (br.s, 1H, NH), 3.57 (d, 1H, *J* = 13.4), 3.89 (d, 1H, *J* = 13.4), 4.38 (d, 1H, *J* = 7.3), 6.29 (dd, 1H, *J* = 15.8 and 7.4), 6.57 (d, 1H, *J* = 15.8), 7.14–7.45 (m, 10H, Ph).

2.7. General procedure for the [3 + 2] annulation of ethyl buta-2,3-dienoate (9) with alkyl acrylates 10 or 11

Ethyl buta-2,3-dienoate (**9**) (0.30 mmol, 35 μL) was added under argon atmosphere to a mixture of freshly distilled ethyl acrylate (**10**) (3.0 mmol, 330 μL) and phosphine **2a** or **3a** (5 mol%, 0.015 mmol) in toluene (1.0 mL). The solution was stirred for 12 h at 100 °C. The crude mixture was concentrated in vacuo and purified by flash chromatography on silica gel (10% EtOAc/*n*-hexane). The ratio of the two regioisomers was assigned by ^{1}H NMR spectroscopy. The enantiomeric excess was determined by HPLC analysis using a Daicel Chiralcel OD-H column (eluent 2-propanol:*n*-hexane, 1:99; flow rate 1 mL/min; detection UV 215 nm; retention times: diethyl cyclopent-1-ene-1,3-dicarboxylate (**12a**) [18] 12.1 min (minor) and 13.4 min (major)]; diethyl cyclopent-1-ene-1,2-dicarboxylate (**12b**) [18] 17.5 min (major) and 18.9 min (minor) (Table 2).

12a: ^{1}H NMR ($CDCl_3$, δ, ppm, *J*, Hz): 1.25–1.31(m, 6H, CH_3), 2.80–2.91 (m, 4H, CH_2), 3.23 (dt, 1H, *J* = 7.3, *J* = 9.2, CH), 4.13–4.23 (m, 4H, OCH_2), 6.69 (t, 1H, *J* = 2.5).

12b: ^{1}H NMR ($CDCl_3$, δ, ppm, *J*, Hz): 1.23–1.30 (m, 6H, CH_3), 2.12 (m, 1H, CH_2), 2.30–2.42 (m, 1H, CH_2), 2.47–2.70 (m, 2H, CH_2), 3.76 (m, 1H, CH), 4.21 (m, 4H, OCH_2), 6.95 (t, 1H, *J* = 2.2).

13a: ^{1}H NMR ($CDCl_3$, δ, ppm, *J*, Hz): 1.25 (t, 3H, *J* = 7.2, CH_3), 1.43 (s, 9H, *tert*-CH_3), 2.72–2.85 (m, 4H, CH_2), 3.09–3.15 (m, 1H, CH), 4.17 (q, 2H, *J* = 7.2, OCH_2), 6.64 (m, 1H).

13b: ^{1}H NMR ($CDCl_3$, δ, ppm, *J*, Hz): 1.24 (t, 3H, *J* = 7.1, CH_3), 1.45 (s, 9H, *tert*-CH_3), 2.10 (m, 1H, CH_2), 2.27–2.37 (m, 1H, CH_2), 2.43–2.55 (m, 2H, CH_2), 3.68 (m, 1H, CH), 4.17 (m, 4H, OCH_2), 6.94 (t, 1H, *J* = 2.3).

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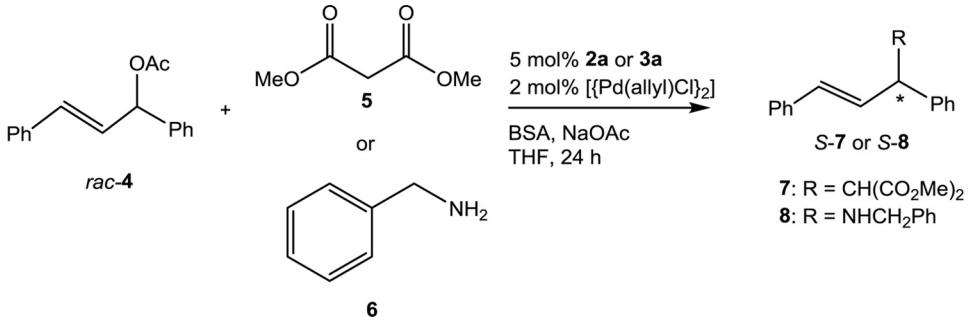
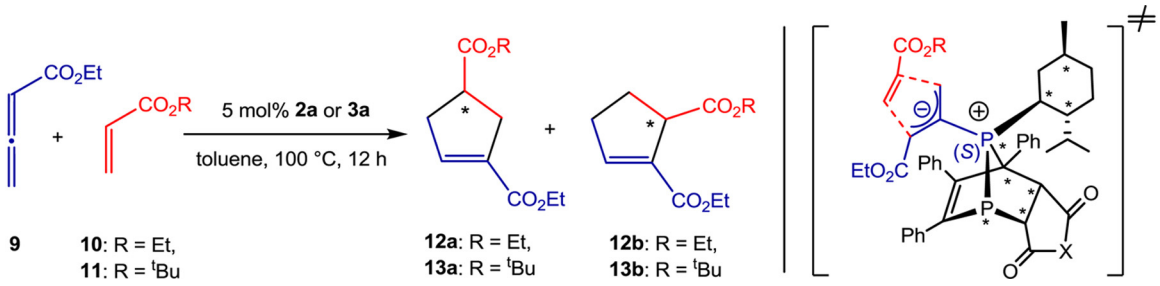
Table 1
Palladium-catalyzed allylic substitution.



Entry	L	T, °C	Product	Conversion, %	*ee*, % (*S*)
1	**2a**	25	**7**	65	14
2	**2a**	50	**7**	99	12
3	**3a**	25	**7**	67	15
4	**3a**	50	**7**	96	14
5	**2a**	50	**8**	94	22
6	**3a**	50	**8**	95	25

Table 2
Phosphine-catalyzed asymmetric [3 + 2] annulation (left) and a proposed transition state (right).



Entry	Phosphine	R	Conversion, %	**a**:**b**	*ee* for **a**,%	*ee* for **b**,%
1	**2a**	Et	89	62:38	48	21
2	**2a**	^{t}Bu	93	78:22	59	22
3	**3a**	Et	91	61:39	52	20
4	**3a**	^{t}Bu	96	79:21	68	23

3. Results and discussion

1-(+)-neomenthyl-1,2-diphosphole (**1**) with chiral substitutent reacts with achiral derivatives of maleic acid (maleic anhydride and *N*-phenylmaleimide) at 25 °C to give the corresponding [4 + 2] cycloadducts **2a** and **3a** with high diastereoselectivity (d.r. >8:1, *d.e.* > 80) (Scheme 1). The stereoselectivity of the cycloaddition reaction increased at −30 °C giving an even better *d.e.* up to 88% and higher yields for the main diastereomers **2a** or **3a**.

The main diastereoisomers **2a** and **3a** were isolated by slow precipitation from a mixture of *n*-hexane and toluene at −40 °C with 47–50% yields. In the $^{31}P\{^1H\}$ NMR spectra of the enantiopure *P*-chiral tricyclic phosphines **2a** and **3a** two doublets are observed at ∼+80 ppm and ∼−20 ppm with $^1J_{PP}$ = 208 Hz. The ^1H and $^{13}C\{^1H\}$ NMR spectra of **2a** and **3a** are unremarkable and are consistent of one set of signals indicating scalemic tricyclic phosphines. Additionally, the structure of chiral phosphines was clearly proved by a 1D/2D NMR correlation methods, the absolute configuration of **2a** and **3a** can be assigned as 10P: *S*, 1P: *R*, 2C: *R*, 6C: *R*, 7C: *R* [15]. Thus, the asymmetric diastereoselective Diels-Alder reaction of chiral 3,4,5-triphenyl-1-(+)-neomenthyl-1,2-diphosphole (**1**) with maleic acid derivatives was used for the selective synthesis of enantiopure tricyclic phosphines **2a** and **3a**.

According to X-ray data of related 1,10-diphosphanorbornene derivatives which are accessible through [4 + 2] cycloaddition reaction of 1-alkyl-1,2-diphospholes [19], each phosphorus atom has a typical pyramidal environment. The sum of bond angles at the two phosphorus atoms of **2a** and **3a** is different: for caged P1 ∼270°, and for bridging P10 ∼300° [20–22]. There are eight chiral centers in **2a** and **3a** (Scheme 1); P1 has *R* and P10 has *S* configuration [15].

The enantiopure *P,C*-stereogenic phosphines **2a** and **3a** were tested as chiral ligands and organocatalysts in asymmetric reactions known to be efficiently catalyzed by monophosphines or their organometallic complexes.

Metal-catalyzed asymmetric allylation has become a powerful method for the efficient formation of carbon–element bonds in a highly enantioselective manner, and has been applied successfully in the total synthesis of many natural products [23,24]. Therefore, catalytic allylic substitution reactions were studied with palladium complexes formed *in situ* from **2a** and **3a** and 2 mol% [{Pd(allyl)Cl}$_2$] (Table 1). Treatment of (*E*)-1,3-diphenylallyl acetate (**4**) with dimethyl malonate (**5**) in the presence of **2a** or **3a** and [{Pd(allyl)Cl}$_2$] as catalyst precursor gave the allylated malonate **7** (14% *ee* with **2a** and 15% *ee* with **3a**). The same procedure with benzylamine (**6**) as nucleophile gave the allylamine derivative **8** in ca. 95% yield (22 or 25% *ee*).

To the best of our knowledge, this is the first example of using chiral phosphines with a P—P bond as ligands in contrast to the well-known P—C, P—O, or P—N ligands widely used in asymmetric catalysis. Diphosphines **2a** and **3a** have two chiral phosphorus centers with different configuration (*R* and *S*), which could be a reason for the low enantioselectivity in allylic substitution (Table 1).

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Phosphines **2a** and **3a** were also employed in organocatalytic [3 + 2] cyclization between ethyl buta-2,3-dienoate (**9**) and selected olefins (ethyl acrylate (**10**) and *tert*-butyl acrylate (**11**)) to afford functionalized cyclopentenes [25,26], which are important synthons in the total syntheses of natural products and medicinally important agents [4]. The asymmetric reaction was performed with 5 mol% of **2a** or **3a** by mixing ethyl buta-2,3-dienoate (**9**) and alkyl acrylate **10** or **11** in toluene and heating up to 100 °C (there is no reaction or low conversion at lower temperatures). With these two substrates, good regioselectivity (**a**:**b** = 79:21) and enantioselectivity (up to 68% *ee* for **3a**) were observed (Table 2). Changing the size of the ester group in the electron-deficient olefin alters the regio- and enantioselectivity. With phosphine **3a**, the enantioselectivity increases with the size of the ester increases (entry 3, Et, 52% *ee*; entry 4, ^{t}Bu, 68% *ee*). A similar trend was observed with phosphine **2a** (entries 1 and 2).

In particular, the enantioselectivity is considerably higher with **3a** (68% *ee*, entry 4) than with known phosphines such as BINAP and BPE (12% and 6% *ee* [18]), which illustrates the effects of using a rigid bicyclic [2.2.1] structure rather than the conformationally more flexible 5-membered rings. Thus, there was also excellent regioselectivity and enantioselectivity of this reaction for related rigid monocyclic [27–29] or bicyclic [12,18] monodentate chiral phosphines.

It was previously shown that the bridging phosphorus atom P10 of 10-alkyl-7,8,9-triphenyl-1,10-diphosphatricyclo[5.2.1.0^{2,6}]-deca-8-ene-3,5-diones is involved in oxidation and sulfurization reactions [30]. Since the catalytic [3 + 2] cyclization is initiated by a nucleophilic attack of the phosphine at ethyl buta-2,3-dienoate (**9**) leading to a resonance-stabilized phosphonium dienolate, only the bridging phosphorus atom P10 should be involved here as well (Table 2, right).

4. Conclusions

The new class of chiral phosphines with P-P bond reported here with a rigid [2.2.1] phosphabicyclic structure, namely 1,10-diphosphanorbornenes, can be employed as ligands in Pd-catalyzed asymmetric allylation (25% *ee*) and organocatalysts in phosphine-catalyzed [3 + 2] cyclization between allenes and activated alkenes (68% *ee*). While these preliminary results reveal good yields but only moderate enantioselectivity, the facile synthesis of these new enantiopure chiral ligands should allow versatile modulation of electronic and steric effects to achieve higher enantioselectivity in asymmetric catalysis.

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