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Tetrahedron: *Asymmetry* 14 (2003) 107–112

TETRAHEDRON: *ASYMMETRY*

Novel planar chiral *P*,*N*-[2.2]paracyclophane ligands: synthesis and application in palladium-catalyzed allylic alkylation

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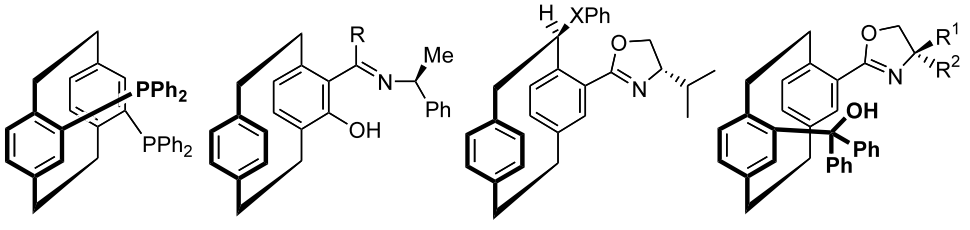
Received 14 October 2002; accepted 18 November 2002

Abstract—A series of planar chiral *P*,*N*-[2.2]paracyclophane ligands were synthesized and applied in enantioselective palladium-catalyzed allylic alkylation, in which the central chirality of [2.2]paracyclophane is the dominant stereocontrol element. The effect of the substituents attached to the phosphorus atom of these ligands on the yield and stereoselectivity of the reaction was also investigated. © 2003 Published by Elsevier Science Ltd.

1. Introduction

Chiral ligands play an important role in asymmetric catalysis and many types of chiral ligands have been developed and used in asymmetric catalysis successfully.[1] Within this area, the development of chiral [2.2]paracyclophane ligands is in its infancy, despite the fact that the structure of [2.2]paracyclophane is unique. Only in the past few years have attempts been made to study enantiopure [2.2]paracyclophane as chiral ligands.[2] Some chiral ligands with the [2.2]paracyclophane skeleton, such as compounds **1**,[2a–c] and **2**,[2m–p] were synthesized and showed their usefulness in asymmetric catalysis (Fig. 1). Most surprisingly, to the best of our knowledge, to date there are few reports on the synthesis and application of planar chiral *P*,*N*-[2.2]paracyclophane ligands, although various kinds of *P*,*N*-bidentate ligands are widely used in asymmetric catalytic processes.[6] Quite recently, as part of a program aimed at the design and application of chiral ligands in asymmetric synthesis[3] we synthesized oxazolinylcyclophane derivatives **3**[4] and **4**[5] and used them as ligands in palladium-catalyzed asymmetric allylic alkylation and asymmetric addition of diethylzinc to aldehydes. The efficiency of these ligands encouraged us to explore other type of [2.2]-paracyclophane ligands. Herein, we disclose the results of our studies on the synthesis of *pseudo*-geminally disubstituted *P*,*N*-[2.2]paracyclophane ligands with planar chirality and their application as ligands for asymmetric palladium-catalyzed allylic alkylation.



1 **2**, R=Me or Ph **3**, X=S or Se **4**

Figure 1. Structure of ligands **1**–**4**.

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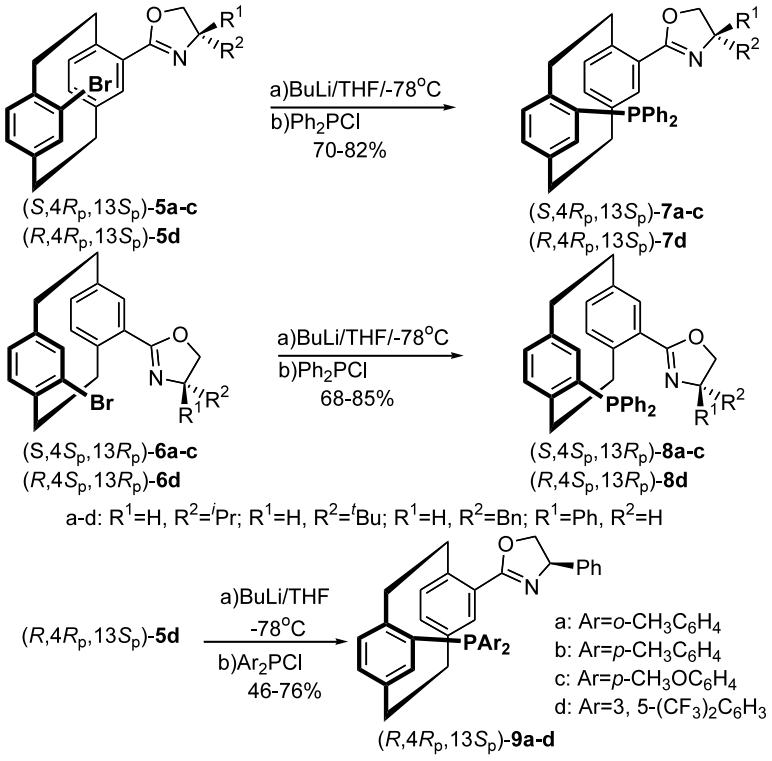
PII: S0957-4166(02)00790-5

2. Results and discussion

Ligands **7** and **8** were synthesized as shown in Scheme 1. Enantiopure oxazolinylcyclophane derivatives **5**[5] and **6**[5] were treated with *n*-BuLi in THF at −78°C followed by trapping with diphenylphosphine chloride to afford the desired *P*,*N*-bidentate ligands **7** and **8** with both planar and central chirality, respectively. Using similar procedures the planar chiral *P*,*N*-[2.2]paracyclophane ligands **9a–d** with different electronic properties were prepared from oxazolinylcyclophane **5d** and arylphosphine chlorides having different electron-withdrawing and electron-donating groups on the phenyl ring[7] (Scheme 1).

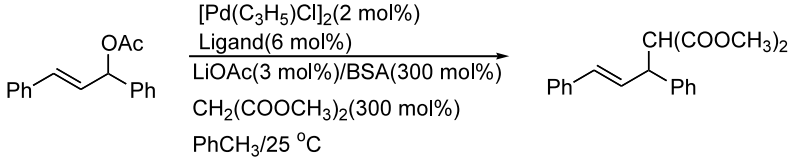
With the target ligands in hand, we turned our attention to investigating their potential utilities in asymmetric catalysis. Asymmetric palladium-catalyzed allylic alkylation[8] was chosen as a model reaction and the results are summarized in Table 1. It was found that all *P*,*N*-ligands **7** and **8** catalyzed the reaction with high reactivity. The reaction completed within several minutes to 3 h and gave the product in almost quantitative yield. After optimization of the reaction conditions and screening of ligands, the ligand **7d**, with a phenyl group at the oxazoline ring gave better results (entry 9). Furthermore, we observed that the identical configuration of products was given when diastereoisomers of ligands, in which only planar chirality differs each other, were employed in this reaction (entry 1 versus entry 2, entry 5 versus entry 6, entry 7 versus entry 8, entry 9 versus entry 10). It seems that the central chirality of ligands, not the planar chirality, is possibly the dominant stereocontrolling element. Similar results were also observed with 1,3-dimethylallylacetate and cyclic allylacetate substrates.[10] It is notable that this outcome is opposite to our previous results, which suggest that the planar chirality of [2.2]paracyclophanes was a decisive factor for controlling the stereochemical outcome of the reactions.[4,5]

In pursuit of better enantioselectivity, we investigated the effect of attaching different aryl substituents to the phosphorus atom of the ligand, which usually results in a change in the electronic and steric hindrance properties. Thus, compounds **9a–d** were used as ligands in the reaction under the standard conditions. From the results shown in Table 1, we found that changing the aryl substituent on the phosphorus atom caused significant effects on the reactivity and enantioselectivity of the reaction. Ligand **9a**, with an *o*-tolyl substituent, showed low reactivity and provided lower enantioselectivity, perhaps as a result of steric hindrance factors (entry 11). In contrast, ligand **9b** with a *p*-tolyl group on phosphorus gave the product with higher ee (entry 12). Even higher enantioselectivity was observed if ligand **9c**, with the electron-donating methoxy group in the *para*-position of the phenyl ring was used (entry 13). We also observed that the reaction time was 180, 60 and 20 min for ligands **9a–c**, respectively. These results indicate that increasing the electron-density on the phosphorus atom favors the reaction, and that ligands with electron-withdrawing groups are less reactive and induce lower asymmetric induction (entry 14).



Scheme 1. Synthesis of chiral *P*,*N*-ligands **7**–**9**.

Table 1. Enantioselective palladium-catalyzed allylic alkylation reaction with planar chiral *P*,*N*-ligands[a]



Entry	Ligand	Time (min)	Yield (%)	Ee (%)[b]	Config.[c]
1[d]	**7a**	20	98	37	*S*
2[d]	**8a**	15	98	6	*S*
3[e]	**7a**	10	98	49	*S*
4	**7a**	90	98	62	*S*
5	**7b**	210	98	11	*S*
6	**8b**	90	98	41	*S*
7	**7c**	60	98	42	*S*
8	**8c**	60	98	29	*S*
9	**7d**	60	98	73	*R*
10	**8d**	90	98	54	*R*
11	**9a**	180	98	6	*R*
12	**9b**	60	98	69	*R*
13	**9c**	20	98	90	*R*
14	**9d**	240	98	49	*R*

[a] Isolated yield after flash chromatography.
[b] Ee determined by HPLC (chiralcel OD column).
[c] Absolute configuration of the product was assigned by comparison with the sign of specific rotation according to the literature data.[9]
[d] KOAc (3 mol%) and CH_2Cl_2 were used.
[e] LiOAc (3 mol%) and CH_2Cl_2 were used.

3. Conclusion

In summary, novel *pseudo*-geminally disubstituted planar chiral *P*,*N*-[2.2]paracyclophane ligands were synthesized and their application as ligands for palladium-catalyzed enantioselective allylic alkylation was demonstrated. The effects of steric and electronic changes in the ligands on the reaction were also demonstrated. Further investigations on the applications of these ligands in asymmetric catalysis are currently in progress.

4. Experimental

4.1. General

All reactions were performed under an atmosphere of argon using oven-dried glassware. Solvents were treated prior to use according to the standard method. ^{1}H NMR spectra were recorded on a Bruker AMX-300 spectrometer in $CDCl_3$ or C_6D_6 at room temperature. Chemical shifts are given in parts per million relative to TMS as an internal standard. Optical rotations were measured using a Perkin–Elmer 241 MC polarimeter with a thermally jacketed 10 cm cell at 25°C (concentration c given as g/100 mL). IR spectra were measured in cm^{-1}, using a Shimadzu IR-440 IR spectrophotometer. Mass spectra and high-resolution mass spectra were taken using HP5989A and Finnigan MAT mass spectrometers, respectively. Elemental analyses were performed on a Foss–Heraeus Vario EL instrument. Ee values were determined by chiral HPLC on a Chiracel OD column.

The commercially available reagents were used as received without further purification. Compound **5**,[5] **6**,[5] Ar_2PCl,[7] PhCHCHCH(OAc)Ph[11] and $[Pd(C_3H_5)Cl]_2$[12] were prepared using literature procedures.

4.2. (S,4R_p,13S_p)-4-Diphenylphosphinyl-13-(4-*iso*-propyl-oxazolin-2-yl)[2.2]paracyclophane, 7a

n-BuLi (0.75 mL, 1.6 M in hexane, 1.2 mmol) was added dropwise to a solution of (S,4R_p,13S_p)-**5a** (398 mg, 1 mmol) in THF (10 mL) at −78°C. The resulting mixture was stirred for 2 h at this temperature. The mixture was treated with Ph_2PCl (0.36 mL, 2 mmol) and stirred for another 1 h at room temperature. The reaction was quenched with saturated aqueous NH_4Cl solution (10 mL). The organic layer was extracted twice with dichloromethane (15 mL). The combined organic layer was dried over Na_2SO_4 and concentrated in vacuo to give the crude product, which was purified by column chromatography (ethyl acetate/petroleum ether = 1/25) to give (S,4R_p,13S_p)-**7a** as a white solid (358 mg, 71%). $[\alpha]_D^{20} = -92.7$ (c 0.575, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.01 (d, J = 6.8 Hz, 3H), 1.18 (d, J = 6.7 Hz, 3H), 2.15–2.20 (m, 1H), 2.82–2.90 (m, 4H), 3.00–3.10 (m, 2H), 3.38–3.48 (m, 1H), 4.07–4.13 (m, 1H), 4.28–4.33 (m, 1H), 4.50–4.58 (m, 2H), 5.84 (dd, J = 8.1, 1.3 Hz, 1H), 6.48–6.62 (m, 4H), 7.16 (s, 1H), 7.19–7.37 (m, 10H); ^{31}P NMR (161.92 MHz, $CDCl_3$): δ −4.85; MS (EI) m/z (rel. int.): 503 (M^+, 87), 502 (100), 488 (24), 460 (31), 434 (17), 390 (2), 288 (46), 209 (19), 178 (14), 103 (2); IR (KBr): 2955, 1626, 1467, 1432, 1305, 1072, 987, 747 cm^{-1}; Anal. calcd for $C_{34}H_{34}NOP$: C, 81.09; H, 6.80; N, 2.78. Found: C, 80.79; H, 6.86; N, 2.83%.

4.3. (*S*,4*R*$_p$,13*S*$_p$)-4-Diphenylphosphinyl-13-(4-*tert*-butyloxazolin-2-yl)[2.2]paracyclophane, 7b

Compound (*S*,4*R*$_p$,13*S*$_p$)-**5b** was allowed to react according to the procedure for **7a** to afford **7b** (82%) as a white solid. $[\alpha]_D^{20}=-80.6$ (*c* 0.565, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 1.01 (s, 9H), 2.71–2.87 (m, 5H), 2.96–3.01 (m, 1H), 3.30–3.37 (m, 1H), 4.05 (t, $J=9.9$ Hz, 1H), 4.28 (t, $J=9.3$ Hz, 1H), 4.36 (t, $J=10.4$ Hz, 1H), 4.45 (t, $J=9.4$ Hz, 1H), 5.75 (d, $J=7.6$ Hz, 1H), 6.45–6.53 (m, 4H), 7.09–7.33 (m, 11H); ^{31}P NMR (161.92 MHz, $CDCl_3$): δ −5.08; MS (EI) *m*/*z* (rel. int.): 517 (M^+, 78), 516 (100), 502 (45), 460 (56), 434 (16), 288 (74), 209 (28), 178 (21), 103 (3); IR (KBr): 2959, 1627, 1477, 1334, 1077, 986, 761, 747, 705, 508 cm^{-1}; HRMS: Anal. for $C_{35}H_{36}NOP$. Calcd: 517.2514. Found: 517.2524.

4.4. (*S*,4*R*$_p$,13*S*$_p$)-4-Diphenylphosphinyl-13-(4-benzyloxazolin-2-yl)[2.2]paracyclophane, 7c

Compound (*S*,4*R*$_p$,13*S*$_p$)-**5c** was allowed to react according to the procedure for **7a** to afford **7c** (82%) as a white solid. $[\alpha]_D^{20}=-47.5$ (*c* 0.46, $CHCl_3$); ^1H NMR (300 MHz, C_6D_6): δ 2.47–2.60 (m, 3H), 2.64–2.81 (m, 3H), 3.03 (dd, $J=13.5$, 7.5 Hz, 1H), 3.44 (dd, $J=13.5$, 6.6 Hz, 1H), 3.73–6.90 (m, 1H), 4.15–4.26 (m, 2H), 4.59–4.70 (m, 1H), 4.80 (t, $J=10.5$ Hz, 1H), 6.21–6.40 (m, 5H), 6.98–7.24 (m, 9H), 7.28–7.30 (m, 2H), 7.41–7.47 (m, 2H), 7.60 (s, 1H), 7.69–7.74 (m, 2H); ^{31}P NMR (121.45 MHz, $CDCl_3$): δ −4.48; MS (EI) *m*/*z* (rel. int.): 551 (M^+, 62), 550 (100), 536 (10), 460 (24), 288 (33), 209 (15), 178 (12), 91 (14); IR (KBr): 2918, 1642, 1584, 1434, 1031, 981, 752, 748, 699, 500 cm^{-1}; Anal. calcd for $C_{38}H_{34}NOP$: C, 82.73; H, 6.21; N, 2.54. Found: C, 82.52; H, 6.43; N, 2.80%.

4.5. (*R*,4*R*$_p$,13*S*$_p$)-4-Diphenylphosphinyl-13-(4-phenyloxazolin-2-yl)[2.2]paracyclophane, 7d

Compound (*S*,4*R*$_p$,13*S*$_p$)-**5d** was allowed to react according to the procedure for **7a** to afford **7d** (70%) as a white solid. $[\alpha]_D^{20}=-23.3$ (*c* 0.535, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 2.70–2.85 (m, 5H), 2.99–3.05 (m, 1H), 3.40–3.48 (m, 1H), 4.13 (t, $J=8.4$ Hz, 1H), 4.60 (t, $J=11.0$ Hz, 1H), 4.94 (dd, $J=10.2$, 8..0 Hz, 1H), 5.53 (t, $J=9.7$ Hz, 1H), 5.82 (dd, $J=8.1$, 1.5 Hz, 1H), 6.41–6.49 (m, 2H), 6.61 (s, 2H), 7.04 (s, 1H), 7.15–7.34 (m, 15H); ^{31}P NMR (121.45 MHz, $CDCl_3$): δ −2.74; MS (EI) *m*/*z* (rel. int.): 537 (M^+, 78), 536 (100), 508 (5), 434 (65), 305 (16), 288 (31), 209 (16), 178 (11), 103 (4); IR (KBr): 2924, 1632, 1586, 1434, 1035, 988 cm^{-1}; Anal. calcd for $C_{37}H_{32}NOP$: C, 82.66; H, 6.00; N, 2.61. Found: C, 82.42; H, 6.32; N, 2.46%.

4.6. (*S*,4*S*$_p$,13*R*$_p$)-4-Diphenylphosphinyl-13-(4-*iso*-propyloxazolin-2-yl)[2.2]paracyclophane, 8a

Compound (*S*,4*S*$_p$,13*R*$_p$)-**6a** was allowed to react according to the procedure for **7a** to afford **8a** (71%) as a white solid. $[\alpha]_D^{20}=+4.9$ (*c* 0.65, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 0.92 (d, $J=6.7$ Hz, 3H), 1.12 (d, $J=6.7$ Hz, 3H), 1.87–1.96 (m, 1H), 2.78–2.90 (m, 5H), 3.03–3.10 (m, 1H), 3.46–3.52 (m, 1H), 4.10 (dd, $J=9.1$, 7.7 Hz, 1H), 4.17–4.31 (m, 1H), 4.57–4.64 (m, 2H), 5.85 (dd, $J=7.8$, 1.6 Hz, 1H), 6.47–6.54 (m, 2H), 6.61–6.66 (m, 2H), 7.06 (s, 1H), 7.23–7.27 (m, 5H), 7.31–7.37 (m, 5H); ^{31}P NMR (161.92 MHz, $CDCl_3$): δ −3.46; MS (EI) *m*/*z* (rel. int.): 503 (M^+, 77), 489 (23), 461 (35), 434 (17), 391 (5), 288 (100), 209 (41), 178 (32), 103 (4); IR (KBr): 2959, 1639, 1469, 1434, 1306, 1033, 991, 742, 699, 499 cm^{-1}; Anal. calcd for $C_{34}H_{34}NOP$: C, 81.09; H, 6.80; N, 2.78. Found: C, 81.06; H, 7.02; N, 2.89%.

4.7. (*S*,4*S*$_p$,13*R*$_p$)-4-Diphenylphosphinyl-13-(4-*tert*-butyloxazolin-2-yl)[2.2]paracyclophane, 8b

Compound (*S*,4*S*$_p$,13*R*$_p$)-**6b** was allowed to react according to the procedure for **7a** to afford **8b** (85%) as a white solid. $[\alpha]_D^{20}=+21.0$ (*c* 0.56, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 0.89 (s, 9H), 2.70–2.83 (m, 5H), 2.97–3.03 (m, 1H), 3.44–3.50 (m, 1H), 4.05 (t, $J=8.2$ Hz, 1H), 4.19 (t, $J=9.1$ Hz, 1H), 4.49 (dd, $J=9.9$, 8.0 Hz, 1H), 4.58–4.64 (m, 1H), 5.80 (dd, $J=7.8$, 1.5 Hz, 1H), 6.38–6.46 (m, 2H), 6.55–6.60 (m, 2H), 6.89 (d, $J=1.3$ Hz, 1H), 7.16–7.20 (m, 5H), 7.25–7.26 (m, 5H); ^{31}P NMR (161.92 MHz, $CDCl_3$): δ −3.12; MS (EI) *m*/*z* (rel. int.): 517 (M^+, 86), 516 (100), 502 (52), 460 (42), 434 (19), 288 (42), 209 (18), 178 (13), 103 (3), 44 (28); IR (KBr): 2952, 1636, 1476, 1434, 1332, 1029, 983, 744, 701, 506 cm^{-1}; HRMS: Anal. for $C_{35}H_{36}NOP$. Calcd: 517.2530. Found: 517.2532.

4.8. (*S*,4*S*$_p$,13*R*$_p$)-4-Diphenylphosphinyl-13-(4-benzyloxazolin-2-yl)[2.2]paracyclophane, 8c

Compound (*S*,4*S*$_p$,13*R*$_p$)-**6c** was allowed to react according to the procedure for **7a** to afford **8c** (75%) as a white solid. $[\alpha]_D^{20}=+8.2$ (*c* 0.75, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 2.72–2.86 (m, 6H), 2.98–3.04 (m, 1H), 3.33–3.44 (m, 2H), 4.08 (t, $J=8.2$ Hz, 1H), 4.44–4.53 (m, 2H), 4.64–4.70 (m, 1H), 5.79 (d, $J=7.8$ Hz, 1H), 6.42–6.49 (m, 2H), 6.58 (s, 2H), 7.03 (s, 1H), 7.17–7.26 (m, 10H); ^{31}P NMR (161.92 MHz, $CDCl_3$): δ −3.53; MS (EI) *m*/*z* (rel. int.): 551 (M^+, 61), 550 (100), 536 (11), 516 (10), 460 (28), 288 (41), 209 (16), 178 (12), 91 (7); IR (KBr): 2952, 2926, 1638, 1585, 1434, 985, 744 cm^{-1}; Anal. calcd for $C_{38}H_{34}NOP$: C, 82.73; H, 6.21; N, 2.54. Found: C, 82.48; H, 6.35; N, 2.81%.

4.9. (*R*,4*S*$_p$,13*R*$_p$)-4-Diphenylphosphinyl-13-(4-phenyloxazolin-2-yl)[2.2]paracyclophane, 8d

Compound (*R*,4*S*$_p$,13*R*$_p$)-**6d** was allowed to react according to the procedure for **7a** to afford **8d** (68%) as a white solid. $[\alpha]_D^{20}=+46.7$ (*c* 0.525, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 2.81–2.95 (m, 5H), 3.06–3.10 (m, 1H), 3.44–3.50 (m, 1H), 4.43 (t, $J=8.4$ Hz, 1H), 4.51–4.57 (m, 1H), 4.97 (dd, $J=10.3$, 8..0 Hz, 1H), 5.47 (t, $J=9.7$ Hz, 1H), 5.86 (dd, $J=8.2$, 1.2 Hz, 1H), 6.51–6.57 (m, 2H), 6.66 (s, 2H), 7.21–7.39 (m, 13H), 7.54 (d, $J=7.2$ Hz, 2H); ^{31}P NMR (161.92 MHz, $CDCl_3$): δ −4.12; MS (EI) *m*/*z* (rel. int.): 537 (M^+, 83), 536 (100), 508 (5), 434 (41), 305 (12), 288 (45), 209 (23), 178 (16), 103 (5); IR (KBr): 2930, 1636, 1584, 1435, 1036, 985, 746, 697, 499 cm^{-1}; Anal. calcd for $C_{37}H_{32}NOP$: C,

82.66; H, 6.00; N, 2.61. Found: C, 82.40; H, 6.18; N, 2.52%.

4.10. (R,4R_p,13S_p)-4-Di(2-methylphenyl)phosphinyl-13-(4-phenyloxazolin-2-yl)[2.2]paracyclophane, 9a

Compound (S,4R_p,13S_p)-**5d** was allowed to react according to the procedure for **7a** to afford **9a** (76%) as a white solid (except for being quenched with (o-$CH_3C_6H_4)_2$PCl). $[\alpha]_D^{20}=-58.8$ (c 0.325, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.39 (s, 3H), 2.72 (s, 3H), 2.75–2.99 (m, 5H), 3.11–3.18 (m, 1H), 3.26–3.31 (m, 1H), 4.12 (dd, $J=9.7$, 8.1 Hz, 1H), 4.54–4.61 (m, 1H), 4.98 (dd, $J=10.1$, 7.8 Hz, 1H), 5.59 (t, $J=9.8$ Hz, 1H), 5.85 (dd, $J=8.6$, 2.0 Hz, 1H), 6.50 (dd, $J=7.7$, 1.4 Hz, 1H), 6.62 (dd, $J=7.9$, 6.1 Hz, 1H), 6.76 (s, 2H), 6.88–7.40 (m, 14H); ^{31}P NMR (121.45 MHz, $CDCl_3$): δ −18.62; MS (EI) m/z (rel. int.): 565 (M^+, 40), 550 (100), 462 (24), 316 (31), 209 (11), 131 (3), 103 (6); IR (KBr): 2923, 1634, 1586, 1451, 1273, 1034, 988, 750, 699, 521, 454 cm^{-1}; HRMS: Anal. for $C_{39}H_{36}NOP$. Calcd: 565.2550. Found: 565.2563.

4.11. (R,4R_p,13S_p)-4-Di(4-methylphenyl)phosphinyl-13-(4-phenyloxazolin-2-yl)[2.2]paracyclophane, 9b

Compound (S,4R_p,13S_p)-**5d** was allowed to react according to the procedure for **7a** to afford **9b** (56%) as a white solid (except for being quenched with (p-$CH_3C_6H_4)_2$PCl). $[\alpha]_D^{20}=-29.5$ (c 0.40, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.01 (s, 3H), 2.06 (s, 3H), 2.55–2.62 (m, 3H), 2.66–2.85 (m, 3H), 3.94–4.04 (m, 2H), 4.89 (dd, $J=10.3$, 7.9 Hz, 1H), 5.13 (t, $J=11.8$ Hz, 1H), 5.78 (t, $J=9.8$ Hz, 1H), 6.26–6.43 (m, 4H), 6.49 (d, $J=7.5$ Hz, 1H), 6.92 (d, $J=7.6$ Hz, 2H), 7.05–7.19 (m, 5H), 7.34 (dd, $J=7.3$, 1.4 Hz, 2H), 7.46 (m, 3H), 7.63 (t, $J=7.7$ Hz, 2H); ^{31}P NMR (121.45 MHz, $CDCl_3$): δ −4.27; MS (EI) m/z (rel. int.): 565 (M^+, 64), 564 (100), 462 (51), 333 (24), 316 (46), 223 (36), 178 (17), 106 (25), 91 (54); IR (KBr): 2922, 1637, 1495, 1452, 1185, 1033, 988, 807, 699, 510 cm^{-1}; Anal. calcd for $C_{39}H_{36}NOP$: C, 82.81; H, 6.41; N, 2.48. Found: C, 82.59; H, 6.94; N, 2.32%.

4.12. (R,4R_p,13S_p)-4-Di(4-methoxylphenyl)phosphinyl-13-(4-phenyloxazolin-2-yl)[2.2]paracyclophane, 9c

Compound (S,4R_p,13S_p)-**5d** was allowed to react according to the procedure for **7a** to afford **9c** (46%) as a white solid (except for being quenched with (p-$CH_3OC_6H_4)_2$PCl). $[\alpha]_D^{20}=-31.2$ (c 0.32, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.74–2.94 (m, 3H), 3.04–3.14 (m, 3H), 3.77 (s, 3H), 3.81 (s, 3H), 4.18–4.25 (m, 1H), 4.60–4.70 (m, 1H), 5.02 (t, $J=8.5$ Hz, 1H), 5.61 (t, $J=9.8$ Hz, 1H), 5.88 (dd, $J=8.9$, 1.5 Hz, 1H), 6.50–6.52 (m, 2H), 6.67 (s, 2H), 6.80 (dd, $J=8.7$, 1.9 Hz, 2H), 6.87 (t, $J=8.7$, 1.9 Hz, 2H), 7.19–7.43 (m, 10H); ^{31}P NMR (121.45 MHz, $CDCl_3$): δ −5.92; MS (EI) m/z (rel. int.): 597 (M^+, 30), 596 (100), 493 (50), 389 (5), 348 (23), 317 (7), 239 (15), 131 (1), 103 (5), 77 (3); IR (KBr): 2926, 1636, 1593, 1497, 1284, 1246, 1176, 1094, 1029, 826, 796, 699, 532 cm^{-1}; HRMS: Anal. for $C_{39}H_{36}NO_3P$. Calcd: 597.2433. Found: 597.2433.

4.13. (R,4R_p,13S_p)-4-Di(3,5-di(trifluoromethyl)phenyl)-phosphinyl-13-(4-phenyloxazolin-2-yl)[2.2]-paracyclophane, 9d

Compound (S,4R_p,13S_p)-**5d** was allowed to react according to the procedure for **7a** to afford **9d** (46%) as a white solid (except for being quenched with (3,5-$(CF_3)_2C_6H_3)_2$PCl). $[\alpha]_D^{20}=+10.6$ (c 0.355, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.81–3.03 (m, 4H), 3.08–3.25 (m, 2H), 3.47–3.58 (m, 1H), 4.24 (dd, $J=9.1$, 8.2 Hz, 1H), 4.69 (t, $J=10.3$ Hz, 1H), 4.92 (dd, $J=10.1$, 8.3 Hz, 1H), 5.61 (t, $J=9.8$ Hz, 1H), 5.74 (dd, $J=7.6$, 1.2 Hz, 1H), 6.67–6.73 (m, 4H), 7.08 (s, 1H), 7.28–7.31 (m, 5H), 7.64 (d, $J=6.5$ Hz, 2H), 7.80 (d, $J=6.4$ Hz, 2H), 7.86 (s, 1H), 7.92 (s, 1H); ^{31}P NMR (121.45 MHz, $CDCl_3$): δ −2.16; MS (EI) m/z (rel. int.): 809 (M^+, 40), 808 (100), 790 (22), 705 (20), 596 (10), 491 (7), 336 (7), 233 (17), 131 (7), 103 (9), 77 (5); IR (KBr): 2931, 1639, 1354, 1279, 1133, 899, 703, 682, 520 cm^{-1}; HRMS: Anal. for $C_{41}H_{28}F_{12}NOP$. Calcd: 809.1717. Found: 809.1724.

4.14. General procedure for the palladium-catalyzed allylic substitutions of *rac*-1,3-diphenyl-2-propenyl acetate

$[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (3.7 mg, 0.01 mmol) and proper ligand (0.03 mmol) were dissolved in dry $PhCH_3$ (2 mL), and then stirred for 0.5 h at rt under an argon atmosphere. To this solution was added *rac*-1,3-diphenyl-2-propenyl acetate (126 mg, 0.5 mmol) and continuously stirred for another 0.5 h. To the resulting solution were successively added dimethylmalonate (0.17 mL, 1.5 mmol), N,O-bis(trimethylsilyl)acetamide (0.37 mL, 1.5 mmol) and lithium acetate (0.015 mmol). The reaction mixture was stirred at room temperature and monitored by TLC. After completion, the reaction mixture was diluted with CH_2Cl_2 (15 mL) and washed twice with saturated aqueous ammonium chloride. The organic phase was dried over anhydrous Na_2SO_4 and then concentrated under reduced pressure. The residue was purified by column chromatography (ethyl acetate/petroleum ether = 1/7) to give the pure product. The enantiomeric excesses were determined by HPLC analysis (Chiracel OD column, hexane: isopropanol (80:20); flow rate = 0.7 mL/min; $t_R=18.7$ min, $t_S=20.4$ min).

Acknowledgements

Financial support from the National Natural Science Foundation of China, the Major Basic Research Development Program (Grant No. G2000077506), National Outstanding Youth Fund, Chinese Academy of Sciences, and Shanghai Committee of Science and Technology is gratefully acknowledged.

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