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Use of an Enantiomerically Pure Cyclopalladated Complex of (*S*)-*N*,*N*-Dimethyl-α-(2-naphthyl)ethylamine for an Enantioselective Synthesis of a Chiral Diphosphine by an Intramolecular [4+2] Diels–Alder Cycloaddition

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Abstract—The cyclopalladated complex (*S*)-(+)-bis(μ-chloro)bis[*N*,*N*-dimethyl-α-(2-naphthyl)ethylamine-C,N]-dipalladium has been used as a chiral template to promote the intramolecular [4+2] Diels–Alder reaction between diphenylvinylphosphine and 1-phenyl-3,4-dimethylphosphole. The characteristic ^{1}H and $^{31}P\{^{1}H\}$ NMR spectroscopic features of the synthesized compounds are described. Crystal structures of three of the newly synthesized palladium complexes are reported.

Introduction

In the field of synthetic chemistry, the asymmetric Diels–Alder reaction is one of the most powerful methods for the preparation of chiral heterocyclic molecules.[1] A chiral center at the phosphorus atom plays an important role for some instances of catalytic asymmetric hydrogenation and alkylation.[2] Resolution is a tedious and often inefficient process to obtain phosphines with a chiral phosphorus atom.[3] As illustrated herein, the [4+2] Diels–Alder cycloaddition reaction offers a simple and efficient approach to generate P-chiral phosphines without classic separation of diastereomers.[4]

3,4-dimethyl-1-phenylphosphole (DMPP) is a widely studied ligand for transition metal ions.[5] Although free DMPP shows no reactivity towards [4+2] Diels–Alder reactions with dienophiles, we previously reported[6] that coordinated DMPP readily undergoes such cycloaddition reactions.

The aim of this work is to explore the use of a chiral chelate palladium complex (S_C)-**1** to generate a chiral diphosphine from DMPP and diphenylvinylphosphine (DPVP) via an intramolecular [4+2] Diels–Alder cycloaddition.

Results and Discussion

In order to explore the use of complex (S_C)-**1** as a reaction template for an enantioselective synthesis of a chiral diphosphine by an intramolecular [4+2] Diels–Alder cycloaddition we have synthesized the complex (S_C)-**1** in high yield by a slight modification of the literature method.[7]

The chiral monomeric complex (S_C)-**2** was prepared by the reaction of 0.5 equivalent of optically pure organopalladium(II) complex(S_C)-**1** with 1 equivalent of 3,4-dimethyl-1-phenylphosphole (DMPP) in CH_2Cl_2 at ambient temperature (Scheme 1).

DMPP splits the chloride bridges during the course of this reaction and coordinates regiospecifically[8] to (S_C)-**1** to give (S_C)-**2** as a result of the unique electronic directing effects originating from the strong π-accepting aromatic carbon and the σ-donating nitrogen donor of the chiral organopalladium unit.[8] Complex (S_C)-**2** was isolated as stable pale yellow prisms in high yield (94.5%).

The solid-state and solution-phase structures of (S_C)-**2** were elucidated via a combination of X-ray crystallographic and NMR spectroscopic studies. We will first discuss the solid-state structure of (S_C)-**2**.

X-ray quality crystals were obtained by the slow diffusion of diethyl ether into a saturated $CHCl_3$ solution of (S_C)-**2**. Crystallographic data are presented in Table 1. The structural drawing of (S_C)-**2**, along with the adopted numbering scheme is shown in Fig. 1. There are two inequivalent

Keywords: asymmetric synthesis; [4+2] Diels–Alder cycloaddition; chiral diphosphines; X-ray crystallography.

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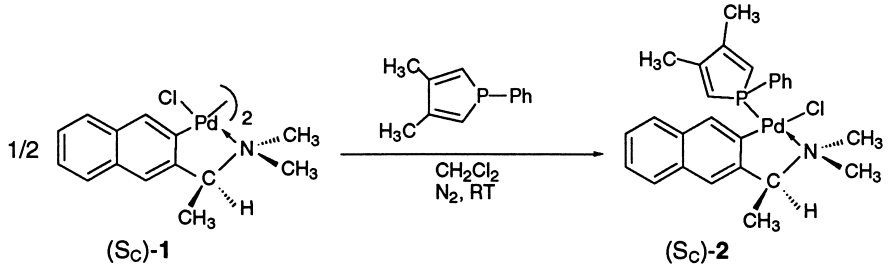


Scheme 1.

Table 1. Crystallographic data for (S_C)-**2**, (S_C,R_P)-**4**, and (R_P)-**7**

Compound	(S_C)-**2**	(S_C,R_P)-**4**	(R_P)-**7**
Emp. formula	$C_{26}H_{29}ClNO_{0.33}PPd$	$C_{40}H_{42}ClNO_5P_2Pd$	$C_{26}H_{26}Cl_2P_2Pd$
Fw	533.66	820.54	577.71
Cryst. syst.	Rhombohedral	Monoclinic	Orthorhombic
a (Å)	33.117(3)	11.3460(9)	10.5072(7)
b (Å)	33.117(3)	8.6256(8)	14.3291(8)
c (Å)	12.364(3)	19.326(2)	17.0373(13)
α (deg)	90	90	90
β (deg)	90	90.579(6)	90
γ (deg)	120	90	90
V (Å^3)	11743(4)	1891.3(3)	2565.1(3)
Z	18[a]	2	4
Space group	*R3*	*P2$_1$*	*P2$_1$2$_1$2$_1$*
ρ_{calcd} (Mg/m^3)	1.358	1.441	1.496
μ (mm^{-1})	0.888	0.690	1.068
Trans. max/min	1.0000/0.9217	0.9683/0.8897	0.9689/0.7528
$R(F)$[c]	0.0707	0.0496	0.0540
$R_W(F)$[b,c]	0.1776	0.0787	0.0850

[a] Two inequivalent molecules per asymmetric unit.
[b] The data were refined by the method of full-matrix least-squares on F^2, with the final R indices having $I>2\sigma(I)$.
[c] $R(F)=\sum(|F_o|-|F_c|)^2/\sum(|F_o|)$; $R_w(F)=[\sum\omega(|F_o|-|F_c|)^2/\sum\omega|F_c|^2]^{1/2}$; $\omega=1/\sigma^2(F)^2=\sigma^2(\text{counts})+(pI)^2$.

molecules in the asymmetric unit with very small differences in their overall structures, each having an *S* configuration at the chiral benzylic C atom of the naphthylamino group. The X-ray structure (Fig. 1) shows that (S_C)-**2** has a distorted square planar geometry with the DMPP ligand (soft donor atom) *trans* to the NMe_2 group. These results are similar to those reported[8,9] for X-ray structures of phosphine complexes of palladium containing a chelating naphthylamine moiety. The five-membered chelate rings have puckered envelope conformations with the CCH_3 group in axial (C(38)) and equatorial (C(12)) positions.

The solution structure of (S_C)-**2** was elucidated by $^{31}P\{^1H\}$ and ^1H NMR spectroscopic studies (see Experimental). The

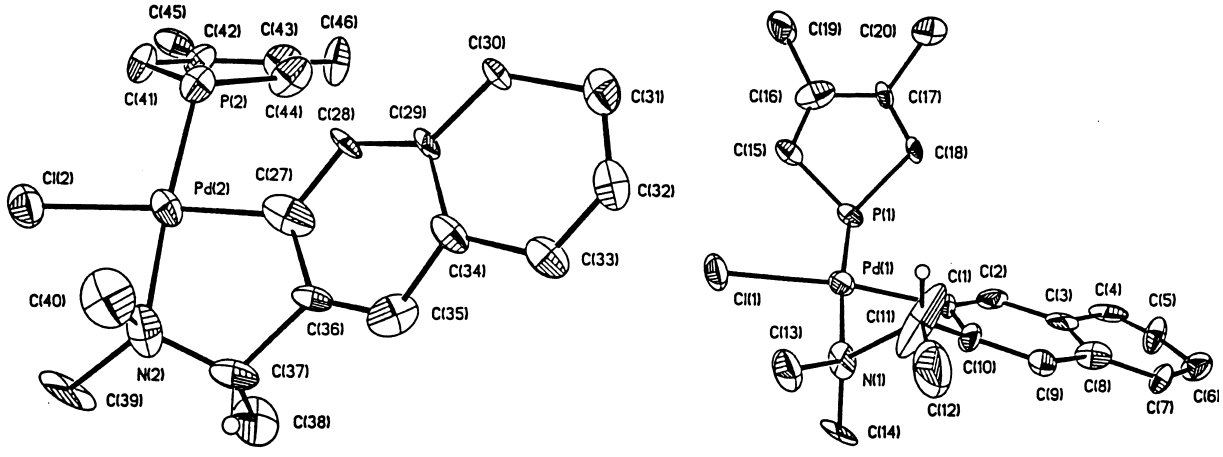
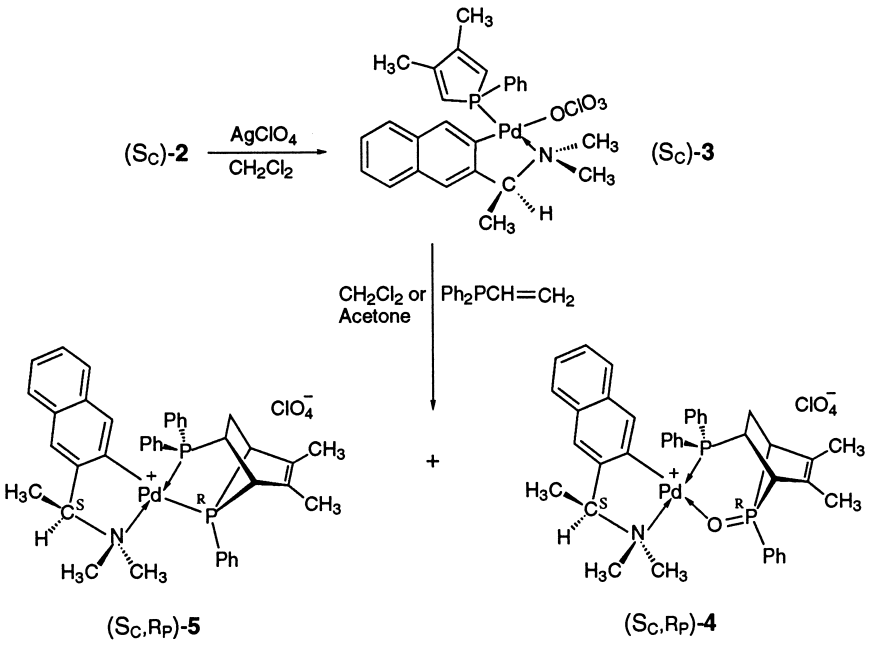


Figure 1. Structural drawings of the two inequivalent molecules of (S_C)-**2** showing the atom numbering schemes (20% probability ellipsoids). Hydrogen atoms have an arbitrary radius of 0.1 Å. Phenyl carbon atoms have been omitted for clarity. Selected bond distances (Å): Pd(1)–C(1), 2.08(2); Pd(1)–P(1), 2.219(6); Pd(1)–N(1), 2.20(2); Pd(1)–Cl(1), 2.327(7). Selected bond angles (deg): C(1)–Pd(1)–N(1), 82.8(8); C(1)–Pd(1)–P(1), 92.2(6); P(1)–Pd(1)–Cl(1), 92.4(3); N(1)–Pd(1)–Cl(1), 92.6(6); N(1)–Pd(1)–P(1), 175.0(6); C(1)–Pd(1)–Cl(1), 172.5(5).



Scheme 2.

$^{31}P\{^{1}H\}$ NMR spectrum of (S_C)-**2** in $CDCl_3$ exhibits a sharp singlet at δ 37.28 ppm, indicating that the DMPP is coordinated to the palladium through its phosphorus donor atom. For the NMe_2 unit, two anisochronous proton resonances are found. The diastereotopic nature of the NMe_2 groups can only occur when pyramidal inversion at the nitrogen atom is blocked by its coordination to palladium. The observation of two NMe resonances proves that the five-membered chelate ring found in the solid-state is preserved in solution.

Due to the kinetic stability of the palladium–chlorine bond in (S_C)-**2**, it is necessary to remove the chloro ligand in order to facilitate the subsequent asymmetric [4+2] cycloaddition reactions with DMPP.[6] Thus, as illustrated in Scheme 2, the kinetically labile perchlorato complex (S_C)-**3** was prepared in essentially quantitative yield by treating (S_C)-**2** with $AgClO_4$ in CH_2Cl_2.

In order to follow the stereochemistry of the asymmetric [4+2] cycloaddition process we isolated and characterized (S_C)-**3**. However, it is normally prepared and reacted without isolation. The $^{31}P\{^{1}H\}$ NMR spectrum of (S_C)-**3** in $CDCl_3$ exhibits a sharp singlet at δ 36.60 ppm which is comparable with that of the perchlorate coordinated 1-naphthylamine analog.[9] The ^{1}H NMR spectroscopic data (see Experimental) are similar to those for the chloride complex (S_C)-**3**. NMR spectral data for complex (S_C)-**3** in solution, together with the infrared data in the solid-state[10] (see Experimental) suggest that the perchlorate anion is coordinated to palladium in both states. With these results in mind, we rationalized that the kinetically labile perchlorato ligand in (S_C)-**3** would be readily replaced by a ligand such as diphenylvinylphosphine (DPVP) which would be followed by an asymmetric intramolecular [4+2] cycloaddition reaction with DMPP on the chiral palladium template.

Thus, treating an acetone solution of (S_C)-**3** with DPVP produced the two cycloaddition products (S_C,R_P)-**4** and (S_C,R_P)-**5** in a 1:1.5 ratio (Scheme 2) as evidenced by $^{31}P\{^{1}H\}$ NMR spectroscopy and X-ray crystallography. The $^{31}P\{^{1}H\}$ NMR spectrum of the crude product exhibited a pair of doublets at δ 117.86 ppm and δ 53.22 ppm, and a pair of singlets at δ 71.75 ppm and δ 51.11 ppm. We have previously reported[6] that the low-field resonances (112–125 ppm) are typical of the bridge-head phosphorus adopting the *exo–syn* relative stereochemistry (the PPh_2 group is *trans* to the NMe_2 group while the bridgehead phosphorus is *trans* to the aromatic carbon atom of the naphthylamine ligand). The observation of a pair of doublets in the $^{31}P\{^{1}H\}$ NMR spectrum of the crude product at δ 117.86 ppm and δ 53.22 ppm (^{2}J(PP)=41.1 Hz) indicates that (S_C,R_P)-**5** was formed during the course of this cycloaddition reaction.

X-ray quality crystals of (S_C,R_P)-**4** (Fig. 2) were obtained by the slow diffusion of diethyl ether into a saturated $CHCl_3$ solution of the product mixture. The $^{31}P\{^{1}H\}$ NMR spectrum of the crystallized material exhibited a pair of singlets at δ 71.73 ppm and δ 51.04 ppm. Crystallographic data are presented in Table 1. The X-ray structure proves the structure of the unexpected oxo-substituted diphosphine adduct. The five-membered chelate ring has a puckered envelop conformation and the six-membered chelate ring has a boat conformation. The coordination geometry is distorted square planar with angles at palladium ranging from 82.7(3) to 95.9(3)° and 170.3(3) to 177.8(3)°. The observed Pd–P and Pd–O bond distances are in the normal range.[11]

It is noteworthy that the coordination of the heterobidentate ligand to the *ortho*-metalated naphthylamino palladium(II) unit is remarkably regiospecific with the softer of the two donors taking a position trans to the σ-donating NMe_2 group in the resulting square-planar complex.[8,11] From this

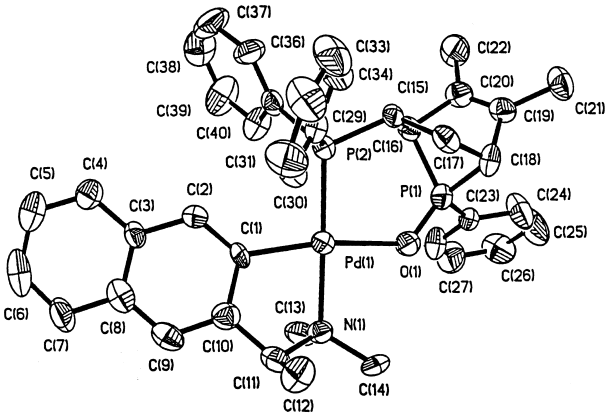


Figure 2. Structural drawing of (S_C,R_P)-**4** showing the atom numbering scheme (40% probability ellipsoids). Hydrogen atoms have been omitted for clarity. Selected bond distances (Å): Pd(1)–C(1), 2.000(8); Pd(1)–N(1), 2.135(7); Pd(1)–O(1), 2.142(6); Pd(1)–P(2), 2.253(2); P(1)–O(1), 1.497(7). Selected bond angles (deg): C(1)–Pd(1)–N(1), 82.7(3); C(1)–Pd(1)–P(2), 95.9(3); N(1)–Pd(1)–O(1), 88.0(3); O(1)–Pd(1)–P(2), 93.5(2); C(1)–Pd(1)–O(1), 170.3(3); N(1)–Pd(1)–P(2), 177.8(3); P(1)–O(1)–Pd(1), 130.9(4).

observation one can conclude that ligand redistribution occurs during the course of the cycloaddition reaction due to the special stereoelectronic nature of the palladium(II) complex containing the ortho-metalated naphthylamine ligand.

The structural analysis confirms the absolute stereochemistries at P(1), C(11), C(15), C(16), and C(18) to be *R*, *S*, *R*, *S*, and *R*, respectively.

Observation of two ^{1}H NMe resonances and a pair of singlets in the ^{31}P{^{1}H} NMR spectrum of the complex (S_C,R_P)-**4** indicates that the five- and six-membered rings found in the solid-state are also preserved in solution.

Performing the same reaction in CH_2Cl_2 produced (S_C,R_P)-**4** and (S_C,R_P)-**5** in a 1:6 ratio. Thus, the source of the oxygen is related to both adventitious oxygen present in the solvent acetone and the perchlorate anion (vide infra).

As illustrated in Scheme 3, reaction of a CH_2Cl_2 solution of the chloro complex (S_C)-**2** with a stoichiometric amount of $AgBF_4$, removal of the AgCl by filtration, followed by addition of a stoichiometric quantity of DPVP via syringe produced (S_C,R_P)-**6**. The cycloaddition reaction was monitored by ^{31}P{^{1}H} NMR spectroscopy and was found to be complete in 15 days. The ^{31}P{^{1}H} NMR spectrum of the crude product exhibited a characteristic pair of doublets at δ 117.80 ppm and δ 53.36 ppm (^2J(PP)=40.7 Hz), indicating that the cycloaddition product (S_C,R_P)-**6** had been formed on the palladium template.[6,12] The ^{1}H and ^{31}P{^{1}H} NMR spectra of the crude product indicated the presence of (S_C,R_P)-**6** only. The enantiomerically pure compound is highly soluble in most organic solvents and could not be induced to crystallize.

It is noteworthy that changing the chloride scavenger from $AgClO_4$ to $AgBF_4$ and performing the reaction in both acetone and CH_2Cl_2 resulted in the formation of complex (S_C,R_P)-**6** only. Thus, the source of the bridge oxygen in (S_C,R_P)-**4** is mostly related to the perchlorate anion (vide supra).

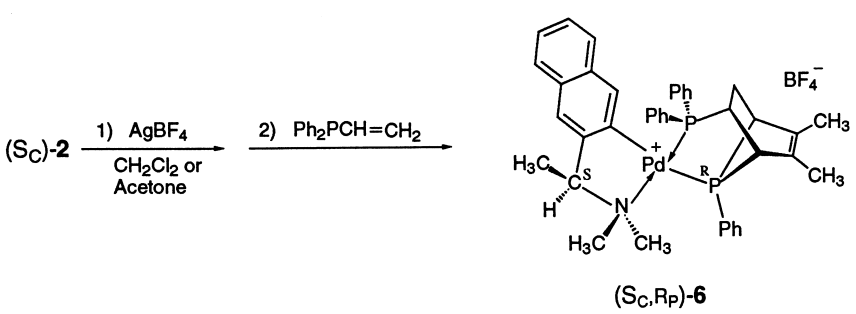
As illustrated in Scheme 4, treatment of the complex (S_C,R_P)-**6** or the mixture of (S_C,R_P)-**4** and (S_C,R_P)-**5** with concentrated HCl (10 M) in acetone removed the chiral naphthylamine auxiliary from the palladium template chemoselectively. The chiral amine auxiliary was recovered from the mother liquor after treatment with NaOH. In other words, the dichloro complex (R_P)-**7** was obtained efficiently from both (S_C,R_P)-**6** and the mixed product, but in an appropriately reduced amount in the latter case.

The ^{31}P{^{1}H} NMR spectrum of (R_P)-**7** in $CDCl_3$ exhibited a pair of doublets. The resonances for the bridge-head phosphorus and the PPh_2 phosphorus nuclei appeared at δ 125.38 ppm, δ 35.75 ppm (^2J(PP)=6.3 Hz), respectively.

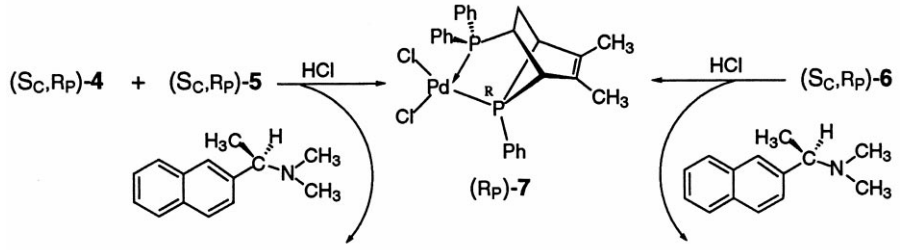
An X-ray analysis of (R_P)-**7** confirms that the enantiomerically pure complex has been formed (Fig. 3) and establishes the absolute stereochemistries at the newly generated P(1), C(1), C(3), and C(4) stereocenters to be *R*, *S*, *R*, and *S*, respectively. Crystallographic data are presented in Table 1. The geometry at palladium is slightly distorted square-planar with angles at Pd in the ranges 83.22(11)–94.25(12)° and 169.29(11)–170.78(11)° and the molecular structure is the same as that previously reported for the racemic complex.

Conclusions

We have shown that an optically pure diphosphine can be readily prepared by an asymmetric intramolecular [4+2] Diels–Alder cycloaddition reaction. The use of $AgClO_4$ leads to the formation of the phosphine oxide, while the use of $AgBF_4$ does not. Apparently, the enantiomeric form



Scheme 3.



Scheme 4.

of this same ligand has also been prepared[9] by a similar reaction involving the analogous *N*,*N*-dimethyl-α-(1-naphthyl)ethylamine palladium complex as a template and a similar asymmetric [4+2] cycloaddition with *trans*-$Ph_2PCH{=}C(H)CO_2Et$ has recently been reported.[13] In our hands, however, the 2-naphthylamine is easier to resolve than the 1-naphthylamine, though the latter is commercially available.

Experimental

General

Commercially available, reagent-grade chemicals were used unless otherwise indicated. Reactions involving air-sensitive compounds were performed under a dry nitrogen atmosphere using standard Schlenk line techniques. 3,4-Dimethyl-1-phenylphosphole (DMPP)[14] was prepared by the literature method. Silica gel for column chromatography (grade 200–300 mesh) was obtained from Natland International Corporation. Melting points were determined on a Mel-Temp apparatus and are uncorrected. Elemental analyses were performed by Galbraith Laboratories, Knoxville, TN. FT-IR spectra were recorded on a Perkin–Elmer Spectrum 2000 for the IR region (400–4000 cm^{-1}) as thin films on KBr windows and for the far IR region (710–30 cm^{-1}) as a mineral oil mull on CsI windows (abbreviations: shp=sharp, sh=shoulder, st=strong, w=weak, br=broad). Optical rotations were measured on the specified solutions in a 1-dm cell at 25°C with a Perkin–Elmer Model 141 polarimeter. $^{31}P\{^1H\}$ and ^1H NMR spectra were recorded at 202 and 500 MHz on a Varian Unity Plus-500 FT NMR spectrometer. Proton chemical shifts were referenced to residual solvent resonances and phosphorus chemical shifts were referenced to an external 85% aqueous solution of H_3PO_4. All shifts to low-field high-frequency are positive.

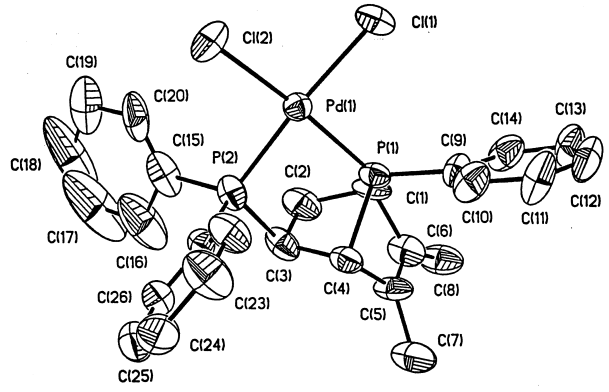


Figure 3. Structural drawing of (R_P)-**7** showing the atom numbering scheme (40% probability ellipsoids). Hydrogen atoms have been omitted for clarity. Selected bond distances (Å): Pd(1)–P(1), 2.219(3); Pd(1)–P(2), 2.250(3); Pd(1)–Cl(1), 2.357(3); Pd(1)–Cl(2), 2.367(3). Selected bond angles (deg): P(1)–Pd(1)–P(2), 83.22(11); P(1)–Pd(1)–Cl(1), 89.79(10); P(2)–Pd(1)–Cl(2), 93.87(12); Cl(1)–Pd(1)–Cl(2), 94.25(12); P(2)–Pd(1)–Cl(1), 169.29(11); P(1)–Pd(1)–Cl(2), 170.78(11).

Synthesis of (*S*)-(+)-bis(μ-chloro)bis[*N*,*N*-dimethyl-α-(2-naphthyl)ethylamine-C,N]dipalladium, [(S_C)-1]

Enantiomerically pure palladium complex (S_C)-**1** was prepared by a slight modification of the literature method.[7] A mixture of 15.0 g (0.085 mol) of palladium(II) chloride and 7.23 g (0.17 mol) of lithium chloride in 150 ml of distilled water was heated and stirred until dissolution was complete (3 h, 50–60°C). The resulting dark red solution was cooled and filtered, and the water was removed on a rotary evaporator while the reaction vessel was warmed in a water bath. This gave Li_2PdCl_4 as a red-purple solid, which was used for the next step without further purification.

The reaction of 15.16 g (0.076 mol) of (*S*)-(−)-*N*,*N*-dimethyl-α-(2-naphthyl)ethylamine[15], 4.45 ml (0.076 mol) of triethylamine and 20.0 g (0.076 mol) of Li_2PdCl_4 in 300 ml of methanol at room temperature gave an immediate yellow precipitate. The resulting reaction mixture was then stirred at ambient temperature for 10 h. The precipitate was isolated by filtration and washed well with methanol. The solid was dried in vacuo and recrystallized from hot benzene to give (S_C)-**1** as yellow crystals: Mp 198–200°C (blackens at 187°C); $[\alpha]_D$ +4.5° (*c* 0.2, $CHCl_3$); 20.3 g (70% yield). Anal. Calcd for $C_{28}H_{32}Cl_2N_2Pd_2$: C, 49.45; H, 4.70; Cl, 10.43. Found: C, 49.27; H, 4.54; Cl, 10.28. ^1H NMR (500 MHz, $CDCl_3$): δ 1.64 (d, ^3J(HH)=7.0 Hz, 3H, CCH_3(major)), 1.66 (d, ^3J(HH)=7.0 Hz, 3H, CCH_3(minor)), 2.65 (s, 3H, NCH_3(minor)), 2.70 (s, 3H, NCH_3(major)), 2.92 (s, 3H, NCH_3(minor)), 2.96 (s, 3H, NCH_3(major)), 4.00 (q, ^3J(HH)=7.0 Hz, 1H, CH (major)), 4.03 (q, ^3J(HH)=7.0 Hz, 1H, CH(minor)), 7.14–7.68 (m, 12H, aromatics). IR (CsI): ν_{Pd-Cl} 317 cm^{-1} (shp, st) and 269 cm^{-1} (shp, w).

The spectrum exhibits distinct resonances for the CCH_3, NCH_3 and CH nuclei which may be assigned to those of the *cis* and *trans* isomers.[16] The relative intensities of the NMe_2 resonances and the two CH resonances are 1.2 to 1. A

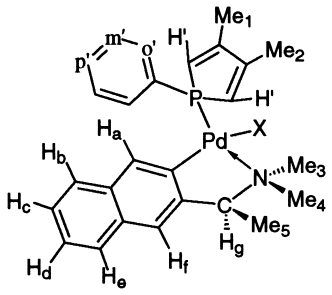
variable temperature NMR study of this isomerization process will be reported in the near future.

Synthesis of chloro(*S*)-[2-[1-(dimethylamino)ethyl]-3-naphthalenyl-C,N][3,4-dimethyl-1-phenylphosphole-P]palladium(II), [(S_C)-2]

To 2.0 g (2.94 mmol) of the palladium complex (S_C)-**1** in 150 ml of CH_2Cl_2 under a nitrogen atmosphere was added 1.16 ml (6.17 mmol) of 3,4-dimethyl-1-phenylphosphole via syringe. Upon addition of the phosphole, a light orange transparent solution formed. This solution was stirred magnetically for 10 h at ambient temperature. The solution was reduced in volume to ca. 5 ml via rotary evaporation, and *n*-hexane was added to precipitate the product as a yellow solid. The precipitate was isolated by filtration, washed with several small portions of a hexane–ether (1:1) mixture, and air-dried. The solid was recrystallized from CH_2Cl_2/hexane–ether, forming pale yellow prisms: Mp 186–188°C; $[\alpha]_D$ +26.8° (*c* 0.2, CH_2Cl_2); 2.93 g (94.5% yield). Anal. Calcd for $C_{26}H_{29}ClNPPd$: C, 62.81; H, 5.83; Cl, 7.13. Found: C, 62.73; H, 5.69; Cl, 7.02. $^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$): δ 37.28 (s, 1P, DMPP). ^1H NMR (500 MHz, $CDCl_3$): δ 1.71 (d, ^3J(HH)=6.5 Hz, 3H, Me_5), 2.08 (s, 3H, Me_1), 2.09 (s, 3H, Me_2), 2.72 (d, ^4J(PH)=3.0 Hz, 3H, Me_3), 2.87 (d, ^4J(PH)=2.0 Hz, 3H, Me_4), 4.01 (qd, ^3J(HH)=6.5 Hz, ^4J(PH)=4.0 Hz, 1H, H_g), 6.68 (d, ^2J(PH)=32.5 Hz, 1H, H′), 6.78 (d, ^2J(PH)=32.5 Hz, 1H, H′), 7.28–7.98 (m, 11H, aromatics).

Synthesis of perchlorato(*S*)-[2-[1-(dimethylamino)ethyl]-3-naphthalenyl-C,N][3,4-dimethyl-1-phenylphosphole-P]-palladium(II), [(S_C)-3]

To 1.3 g (2.46 mmol) of (S_C)-**2** in 20 ml of CH_2Cl_2 was added 0.51 g (2.46 mmol) of $AgClO_4$. The suspension was stirred magnetically in the dark for 45 min. The resulting mixture was filtered through a layer of Celite to remove AgCl. The pale yellow filtrate was reduced in volume to ca. 2 ml via rotary evaporation, and *n*-hexane was added to precipitate the product as a pale yellow solid. The complex was isolated by filtration, washed with several small portions of the hexane–ether (1:1) mixture and air dried: Mp 186–188°C; $[\alpha]_D$ +35.5° (*c* 0.2, CH_2Cl_2); 1.39 g (95% yield). Anal. Calcd for $C_{26}H_{29}ClO_4NPPd$: C, 52.74; H, 4.90; Cl, 5.99. Found: C, 52.58; H, 5.03; Cl, 6.12.



X = Cl, (S_C)-**2**

X = ClO_4, (S_C)-**3**

$^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$): δ 36.60 (s, 1P, DMPP). ^1H NMR (500 MHz, $CDCl_3$): δ 1.71 (d, ^3J(HH)=6.5 Hz, 3H, Me_5), 2.12 (dd, ^4J(HH)=2.0 Hz, ^4J(PH)=1.5 Hz, 3H, Me_1), 2.13 (dd, ^4J(HH)=2.0 Hz, ^4J(PH)=1.5 Hz, 3H, Me_2), 2.71 (d, ^4J(PH)=3.0 Hz, 3H, Me_3), 2.90 (d, ^4J(PH)=2.0 Hz, 3H, Me_4), 4.03 (qd, ^3J(HH)=6.5 Hz, ^4J(PH)=6.0 Hz, 1H, H_g), 6.52 (d, ^2J(PH)=32.5 Hz, 1H, H′), 6.62 (d, ^2J(PH)=32.5 Hz, 1H, H′), 7.08 (d, ^4J(PH)=6.5 Hz, 1H, H_a), 7.29 (d, ^4J(HH)=1.0 Hz, 1H, H_f), 7.31 (ddd, ^3J(HH)=8.0 Hz, ^3J(HH)=6.5 Hz, ^4J(HH)=1.0 Hz, 1H, H_c), 7.36 (ddd, ^3J(HH)=8.0 Hz, ^3J(HH)=6.5 Hz, ^4J(HH)=2.0 Hz, 1H, H_d), 7.43 (d, ^3J(HH)=8.0 Hz, 1H, H_b), 7.44–7.51 (m, 3H, $H_{m',p'}$), 7.69 (d, ^3J(HH)=8.0 Hz, 1H, H_e), 7.94 (m, 3H, $H_{o'}$). IR (KBr): ν_3 1131, 1017 cm^{-1} (shp, st), ν_4 925 cm^{-1} (shp, w). (ClO_4).

Synthesis of (S_C,R_P)-4 and (S_C,R_P)-5

To 1.3 g (2.2 mmol) of (S_C)-**3** in 80 ml of acetone under nitrogen was added 0.44 ml (2.2 mmol) of DPVP via syringe, and the reaction mixture was stirred magnetically for 15 days at ambient temperature. The solvent was removed under reduced pressure to give a brownish (foamy) solid residue. This solid was purified by column chromatography on silica gel with acetone–ethyl acetate (3:1) as eluant. This resulted in a very dark brown band (containing elemental Pd and organic impurities) at the top of the column and a pale yellow band, which moved with the solvent front. The pale yellow eluate was collected and evaporated in vacuo. The resulting pale yellow (foamy) solid was dissolved in a minimum amount of CH_2Cl_2 and diethyl ether was added to precipitate the crude product as an off-white solid. The product was isolated by filtration, washed with several small portions of diethyl ether, and air-dried. The product obtained (1.5 g) was shown by $^{31}P\{^1H\}$ NMR spectroscopy to be a 1:1.5 mixture of the (S_C,R_P)-**4** and (S_C,R_P)-**5**. The reaction was monitored by $^{31}P\{^1H\}$ NMR spectroscopy and was found to be complete in 15 days. Increasing the reaction time to 21 days produced the mixture in the same chemical yield and ratio as described above.

The complex (S_C,R_P)-**4** was separated from the product mixture by fractional crystallization from $CHCl_3$/ether as colorless crystals: Mp 225–227°C; $[\alpha]_D$ −15.7° (*c* 0.2, CH_2Cl_2); 0.67 g (37.5% isolated yield). Anal. Calcd for $C_{40}H_{42}ClO_5NP_2Pd$: C, 58.57; H, 5.12; Cl, 4.32. Found: C, 58.49; H, 5.01; Cl, 4.26.

$^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$): δ 71.73 (s, 1P, P(1)), 51.04 (s, 1P, P(2)). ^1H NMR (500 MHz, $CDCl_3$): δ 1.62 (s, 3H, Me_1), 1.68 (s, 3H, Me_2), 1.83 (d, ^3J(HH)=6.5 Hz, 3H, Me_5), 2.08 (dddddd, $^3J(P_1H_4)$=28.4 Hz, $^2J(H_3H_4)$=13.5 Hz, $^3J(P_2H_4)$=11.5 Hz, $^3J(H_2H_4)$=10.9 Hz, $^3J(H_3H_5)$=3.0 Hz, $^3J(H_4H_5)$=1.0 Hz, 1H, H_4), 2.54 (apparent tdd, $^3J(P_1H_3)$=$^3J(P_2H_3)$=19.0 Hz, $^2J(H_3H_4)$=13.5 Hz, $^3J(H_3H_5)$=3.0 Hz, 1H, H_3), 2.63 (d, $^4J(P_2H)$=3.0 Hz, 3H, Me_3), 2.79 (d, $^4J(P_2H)$=2.0 Hz, 3H, Me_4), 2.91 (apparent tt, $^2J(P_1H_1)$=$^2J(P_2H_1)$=5.0 Hz, $^3J(H_1H_2)$=$^4J(H_1H_5)$=1.0 Hz, 1H, H_1), 3.02 (dddddd, $^3J(P_1H_2)$=21.0 Hz, $^2J(H_3H_4)$=13.5 Hz, $^2J(P_2H_2)$=12.5 Hz, $^3J(H_2H_4)$=10.9 Hz, $^3J(H_2H_3)$=5.2 Hz, $^3J(H_1H_2)$=1.0 Hz, 1H, H_2), 3.25 (dddd, $^2J(P_1H_5)$=6.5 Hz, $^3J(H_3H_5)$=3.0 Hz, $^3J(H_1H_2)$=$^3J(H_4H_5)$=$^4J(H_1H_3)$=1.0 Hz, 1H, H_5), 4.08 (qd, ^3J(HH)=6.5 Hz, $^4J(P_2H)$=4.5 Hz, 1H, H_g), 6.13 (d, $^4J(P_2H)$=6.5 Hz, 1H, H_a), 6.82 (dd, ^3J(HH)=8.0 Hz, ^4J(HH)=1.2 Hz, 1H, H_b), 7.12 (ddd, ^3J(HH)=8.0 Hz, ^3J(HH)=7.0 Hz, ^4J(HH)=1.2 Hz, 1H, H_d), 7.26 (ddd, ^3J(HH)=8.0 Hz, ^3J(HH)=7.0 Hz, ^4J(HH)=

0.5 Hz, 1H, H_c), 7.43 (s, 1H, H_f), 7.64–7.42 (m, 9H, $H_{m,p}$(Ph)), 7.62 (dd, ^3J(HH)=8.0 Hz, ^4J(HH)=0.5 Hz, 1H, H_e), 7.73 (m, 2H, H_o(Ph)), 8.00 (m, 2H, H_o(Ph)), 8.20 (m, 2H, H_o(Ph)).

After separating the complex (S_C,R_P)-**4** from a $CHCl_3/Et_2O$ solution of the product mixture the volume of the filtrate was reduced to ca. 3 ml via rotary evaporation and *n*-hexane was added to precipitate complex (S_C,R_P)-**5** as an off-white solid (0.70 g, 40%) that could not be crystallized from any of the solvents tried: Mp 184–186°C; $[\alpha]_D$ −11.4° (*c* 0.2, CH_2Cl_2). $^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$): δ 117.86 (d, $^2J(P_1P_2)$=41.1 Hz, 1P, P_1), 53.22 (d, $^2J(P_1P_2)$=41.1 Hz, 1P, P_2). ^1H NMR (500 MHz, $CDCl_3$): the chemical shifts are similar to those observed for complex (S_C,R_P)-**4**.

It is noteworthy that performing the reaction in CH_2Cl_2 resulted in the formation of a yellow-orange solid residue. Further work up of this residue produced the product as a 6:1 mixture of (S_C,R_P)-**5** and (S_C,R_P)-**4**, respectively, as evidenced by $^{31}P\{^1H\}$ NMR spectroscopy.

Synthesis of (S_C,R_P)-6

To 1.3 g (2.46 mmol) of (S_C)-**2** in 50 ml of CH_2Cl_2 under nitrogen was added 0.48 g (2.46 mmol) of $AgBF_4$, and the reaction mixture was stirred magnetically for 45 min. The resulting mixture was filtered through a layer of celite to remove AgCl. To the pale yellow filtrate under nitrogen was added 0.49 ml (2.46 mmol) of DPVP via syringe, and the reaction mixture was stirred magnetically for 15 days at ambient temperature. The solvent was removed under reduced pressure to give a yellow-orange solid residue. This residue was purified by column chromatography on silica gel with CH_2Cl_2–ethyl acetate (3:1) as eluant. This resulted in an orange-brown band (containing elemental Pd and organic impurities) at the top of the column and a pale yellow band, which moved with the solvent front. The pale yellow eluate was collected and evaporated in vacuo, giving a pale yellow (foamy) solid. This solid was dissolved in a minimum amount of CH_2Cl_2 and diethyl ether was added to precipitate the complex (S_C,R_P)-**6** as an off-white solid that could not be crystallized from any of the solvents tried: Mp 186–188°C; $[\alpha]_D$ −12.6° (*c* 0.2, CH_2Cl_2); 1.26 g (65% yield). Anal. Calcd for $C_{40}H_{42}BF_4NP_2Pd$: C, 60.69; H, 5.31. Found: C, 60.57; H, 5.24. $^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$): δ 117.80 (d, $^2J(P_1P_2)$=40.7 Hz, 1P, P_1), 53.36 (d, $^2J(P_1P_2)$=40.7 Hz, 1P, P_2). ^1H NMR (500 MHz, $CDCl_3$): The ^1H chemical shifts are similar to those observed for (S_C,R_P)-**4**.

It is noteworthy that performing the reaction in acetone produced the complex in chemical and optical yields similar to those described above. Interestingly, using $AgBF_4$ as a chloride scavenger and performing the reaction in both CH_2Cl_2 and acetone resulted in the formation of complex (S_C,R_P)-**6** only as evidenced by $^{31}P\{^1H\}$ NMR spectroscopy.

Synthesis of (R_P)-7

To 1.2 g (1.5 mmol) of (S_C,R_P)-**6** in 80 ml of acetone was added 2.5 ml (10 M) of HCl, and the reaction mixture was refluxed for 20 min. An off-white precipitate of (R_P)-**7** formed in solution during this period. The product was isolated by filtration and recrystallized from CH_2Cl_2–Ether: Mp>270°C; $[\alpha]_D$ −13.5° (*c* 0.2, CH_2Cl_2); 0.74 g (85% yield). Anal. Calcd for $C_{26}H_{26}Cl_2P_2Pd$: C, 54.07; H, 4.50; Cl, 12.28. Found: C, 54.00; H, 4.43; Cl, 12.22. The $^{31}P\{^1H\}$ and ^1H NMR spectra are identical to those previously reported for the racemic material.[17] Similarly, treatment of the acetone solution of the mixture of products, ((S_C,R_P)-**4** and (S_C,R_P)-**5**), with HCl produced the complex (R_P)-**7** in chemical and optical yields similar to those described above. The chiral naphthylamine auxiliary (0.26 g, 88%) was recovered from the mother liquor after treatment with NaOH.

X-Ray data collection and processing

Crystal data and details of data collection are given in Table 1. Pale yellow prisms of (S_C)-**2** were obtained by slow diffusion of a 1:1 mixture of hexane–ether into a saturated CH_2Cl_2 solution. Colorless prisms of (S_C,R_P)-**4** were grown by slow diffusion of ether into a saturated $CHCl_3$ solution. Pale yellow prisms of (R_P)-**7** were obtained from a CH_3OH solution.

A suitable crystal of each compound was mounted on a glass fiber and placed on a Siemens P4 diffractometer. Intensity data were collected in the ω mode at 25°C with graphite monochromated MoKα radiation (λ=0.71073 Å). Three check reflections, monitored every 100 reflections, showed random (<2%) variation during the data collections. The data were corrected for Lorentz, polarization effects, and absorption (using an empirical model derived from azimuthal data collections). Scattering factors and corrections for anomalous dispersion were taken from a standard source.[18] Calculations were performed with the Siemens SHELXTL Plus (version 5.03) software package on a PC. The structures were solved by direct methods. Anisotropic thermal parameters were assigned to non-hydrogen atoms where appropriate. The phenyl groups of (S_C)-**2** were refined as rigid bodies. Hydrogen atoms were refined at calculated positions with a riding model in which the C–H vector was fixed at 0.96 Å. The data were refined by the method of full-matrix least-squares on F^2. Final cycles of refinement gave the $R(F)$ and $R_w(F)$ values presented in Table 1, where $\omega^{-1}=\sigma^2F+0.001F^2$. Absolute configurations were determined by refinements of the Flack parameter.[19]

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