Synthesis and Characterization of a New Chiral Phosphinothiol Ligand Derived from (−)-Menthone and Its Palladium(II) and Platinum(II) Complexes

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The chiral ligand (1*R*,2*S*,5*R*)-1-((diphenylphosphino)methyl)-2-isopropyl-5-methylcyclohexanethiol (**4**) has been prepared from low-cost commercial (−)-menthone in a three-step enantioselective synthesis. Oxidative addition of 2 equiv of this phosphinothiol ligand to $[Pd^0(PPh_3)_4]$ gave the enantiopure bis(phosphinothiolate)palladium(II) complex **5**, which only exists as the trans-P,P geometrical isomer, in both the solid state and solution, owing to the preference of the chelate rings to adopt the λ conformation in which the position of the menthane ring does not allow a conformation of the phenyl groups compatible with the more sterically hindered cis geometry. These stereoelectronic coordination preferences of the chiral phosphinothiolate ligand have been confirmed by the structure of the analogous Pt(II) complex **6**, which also exhibits the trans-P,P geometry exclusively, both in the solid state and in solution. Crystals of **5**·$^1/_2CH_2Cl_2$ and **6**·$^1/_2CH_2Cl_2$ are isomorphic, belonging to the monoclinic crystal system *C*2. Both chiral structures show mononuclear square-planar trans complexes with locked λ chelate ring conformations. Compound **6** represents the first example of a structurally characterized mononuclear bis(phosphinothiolate)platinum(II) complex. Addition of 1 equiv of ligand **4** to a solution of $[PdCl_2(PPh_3)_2]$ gave the less sterically hindered complex chloro(phosphinothiolate)(triphenylphosphine)palladium(II) (**7**), which exhibits the expected cis−trans equilibrium in solution, but strongly displaced to the more sterically stable trans isomer.

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Introduction

Although chelating diphosphines are the prevalent chiral bidentate ligands to achieve catalytic asymmetric transformations, many of these diphosphines have two donor atoms with similar electronic and steric properties (e.g. DIOP, BINAP). To decrease the symmetry of the bidentate ligand, diphosphines with different substituents at each phosphorus have been synthesized (e.g. DIPAMP), and some chemical changes in the phosphorus group have been introduced (e.g. BINAPHOS). However, the ever-increasing need for new catalytic systems has led to the development of mixed-donor ligands, with marked distinction between the coordinating groups, such as P,O, P,N, and P,S donors.[1] In this context, phosphinothiolates are suitable candidates because they are asymmetric chelating ligands with substantial electronic and steric differences between the two donor atoms. Thus, sulfur supports a formal negative charge and, once bound to the metal, can act as a π donor owing to the two nonbonding electron pairs on sulfur. Moreover, the thiolate group has only one substituent, the chain that connects it to the phosphino group. Conversely, phosphorus is neutral and, once bound to the metal, does not support any nonbonding electron pairs, acting as a classical π acceptor. Despite these promising properties, very few chiral optically pure or enantiomerically enriched phosphinothiolate ligands have been described.[2−5] As part of a project on the synthesis of new enantiopure phosphinothiolate complexes of the group 10 metals and on the analysis of the ligand-based stereoelectronic effects that are determinant in the coordination conformations around the metal,[4] we now report the preparation of a new bulky and optically pure phosphinothiol ligand, easily obtained from low-cost commercial (−)-menthone, and its palladium(II) and platinum(II) complexes.

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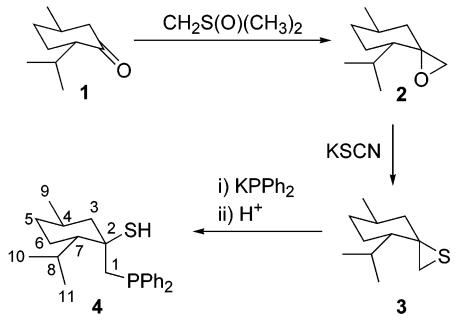
Scheme 1. Three-Step Stereoselective Synthesis of the New Phosphinothiol Ligand 4



Results and Discussion

(1*R*,2*S*,5*R*)-1-((Diphenylphosphino)methyl)-2-isopropyl-5-methylcyclohexanethiol (**4**) was prepared from (−)-menthone (**1**) in a three-step synthesis according to Scheme 1. In the first step, reaction of menthone with dimethylsulfoxonium methylide gave (1*S*,4*S*,7*R*)-4-isopropyl-7-methyl-1-oxaspiro[2.5]octane (**2**) in good yield (80%). Epoxide **2** presents the transferred methylene in an equatorial position, in agreement with previously reported results using other substituted cyclohexanones.[6] Compound **2** was transformed into the corresponding episulfide, (1*R*,4*S*,7*R*)-4-isopropyl-7-methyl-1-thiaspiro[2.5]octane (**3**), using thiourea or potassium thiocyanate.[7] This reaction was somewhat slow, even using a large excess of the sulfur transfer agent. The yields were modest (35−40%), but as the reagents are easily available, the procedure is still convenient. In keeping with the stereochemistry of the reaction, a mechanism involving two Walden inversions, one for each oxirane carbon, is proposed, indicating that the stereochemistry of the resulting episulfide **3** is opposite to that of the starting material.[7] Regioselective ring opening of thiirane **3** with 1 equiv of $KPPh_2$ gave (1*R*,2*S*,5*R*)-1-((diphenylphosphino)methyl)-2-isopropyl-5-methylcyclohexanethiol (**4**) in good yield (76%) and purity. Phosphinothiol **4** proved to be stable toward the reaction of sulfur transfer from the tertiary carbon to the phosphorus.[3]

Compounds **2**−**4** were structurally characterized in solution by NMR spectroscopy. In compound **4**, the methylenic protons near the phosphine group are diastereotopic, showing a ^2J coupling constant with the phosphorus atom, as can be seen in the ^1H and $^1H\{^{31}P\}$ NMR spectra (Figure 1). In the $^{13}C\{^1H\}$ NMR spectrum, the four aliphatic carbons close to the phosphine group (C_1, C_2, C_3, C_7) appear as doublets by coupling to the phosphorus atom. In the $^{31}P\{^1H\}$ NMR spectrum, compound **4** shows a single resonance at −22.75 ppm.

The complex bis[(1*R*,2*S*,5*R*)-1-((diphenylphosphino)-methyl)-2-isopropyl-5-methylcyclohexanethiolato]palladium(II) (**5**) was obtained (60%) via the oxidative addition of 2 equiv of ligand **4** to $[Pd^0(PPh_3)_4]$ at room temperature (Scheme 2). This method proved superior in yield and product purity to the alternative halide substitution route, in both acid and basic media.[8] The

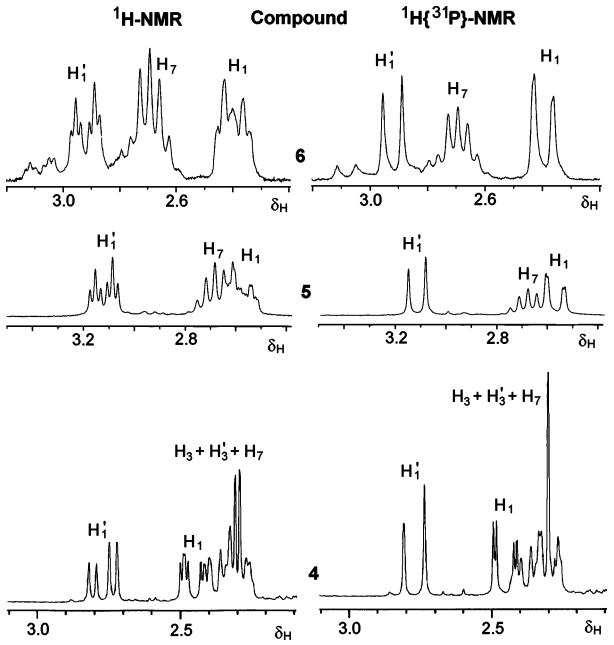
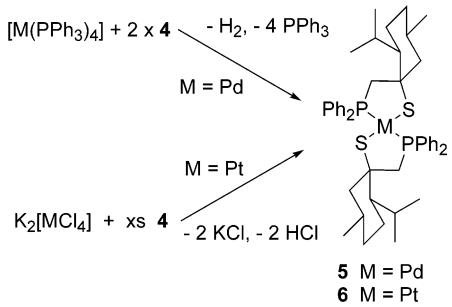


Figure 1. ^1H (left) and $^1H\{^{31}P\}$ (right) NMR spectra of ligand **4** and its Pd^{II} (**5**) and Pt^{II} (**6**) *trans*-bis(phosphinothiolate) complexes. The trans geometries of **5** and **6** are evidenced by the observation of virtual coupling to ^{31}P in the signals of the methylenic protons, H_1 and $H_{1'}$, that appear as pseudo-triplets owing to coupling with two equivalent, mutually trans phosphorus nuclei. In complex **6** ^{195}Pt satellites were also observed for proton $H_{1'}$.

Scheme 2. Oxidative Addition of 2 Equiv of Ligand 4 to $[Pd^0(PPh_3)_4]$, Giving the Chiral *trans*-Bis(phosphinothiolato)palladium(II) Complex 5 as the Only Product[a]



[a] Addition of an excess of the ligand to $K_2[PtCl_4]$ produced the analogous Pt(II) complex 6.

trans geometry of the complex in solution was determined by the NMR analysis. In the ^1H NMR the methylenic protons near the phosphine groups appear as pseudo-triplets owing to coupling with two equivalent, mutually trans phosphorus nuclei (Figure 1).[4,8] This virtual coupling was also observed in the $^{13}C\{^1H\}$ NMR, in which the four aliphatic carbons close to the phosphorus and the aromatic carbons (except for those in the para positions) also appear as pseudo-triplets. Furthermore, for all aromatic carbons two different signals were observed (Figure 2), strongly suggesting that the menthane cyclic system, attached to the backbone of the five-membered-ring-forming bidentate ligand, controls the absolute conformations of the chelate ring (vide infra), which in turn locks the phenyl

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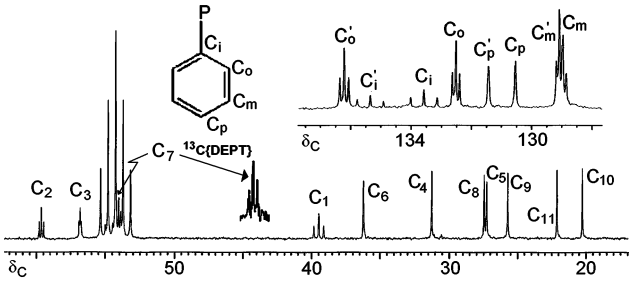

Figure 2. $^{13}C\{^1H\}$ NMR of **5**, the trans geometry being evidenced by the observation of virtual coupling to ^{31}P in the signals of all but one of the aromatic carbons and the four aliphatic carbons close to the phosphorus. For all aromatic carbons there are two signals suggesting locked, nonequivalent pseudo-axial and pseudo-equatorial phenyl rings in the same diphenylphosphino group.

substituents of each diphenylphosphino group into nonequivalent pseudo-axial and pseudo-equatorial positions.

It is noteworthy that for complex **5** we have not observed the chemical equilibrium between trans and cis geometries typical of these types of complexes in solution.[3,4,8] Bis-chelate **5** shows a single and sharp resonance at δ_P 50.10 in the $^{31}P\{^1H\}$ NMR spectrum, for both freshly prepared and aged solutions. Apparently, in this case the geometry is controlled by the bulk of the $-PPh_2$ groups, as the trans-P,P arrangement is sterically more stable than the cis-P,P configuration, which places the bulky groups close to each other. However, it is intriguing that similar five-membered bis-chelate palladium(II) complexes also with $-PPh_2$ groups, such as bis[1-(diphenylphosphino)-3-(benzyloxy)propane-2-thiolato]palladium(II), in which the absolute chelate ring conformations are also controlled by a ring substituent in the bidentate ligand, albeit less sterically demanding, exhibit the cis−trans chemical equilibrium in solution.[4] It would seem that the steric interactions of the two $-PPh_2$ groups is not the only cause for the fact that the cis isomer of **5** is not observed, as the phenyl groups can rotate to accommodate each other in a cis isomer.[9] We suggest that it is because of the menthane ring interference that the phenyl groups cannot adopt a conformation compatible with the cis geometry, forcing **5** to exist only in the trans-P,P form with high geometrical rigidity. In any case, these stereochemical restrictions are a direct consequence of the projection of the bulkiness of the menthane cyclic system attached to the chelate ligand backbone toward the phosphrous and sulfur bonding atoms.

To further support the prevalence of these structural restrictions, we have also prepared the analogous bis-chelate platinum(II) complex **6** (55% isolated yield, Scheme 2). The case of platinum(II) is especially relevant, given its strong electronic preference to form cis-P,P complexes. In the $^{31}P\{^1H\}$ NMR, bis-chelate **6** shows a sharp resonance at δ_P 48.81 with a coupling constant of $^1J_{Pt-P} = 2784$ Hz, similar to those observed for simpler bis(phosphinothiolate)platinum(II) complexes, such as $[Pt(SCH_2CH_2PPR_2)_2]$ (R = Me, Ph), for which cis-P,P geometries have been assumed.[10] On the other hand, as in the case of the palladium complex **5**, the ^1H NMR shows the methylenic protons H_1 and H_1' as pseudo-triplets owing to the typical virtual coupling produced by the trans-P,P arrangements (Figure 1). This effect was also observed in the $^{13}C\{^1H\}$ NMR, which presents the four aliphatic carbons close to the phosphorus and the aromatic carbons (except for those in the para positions) also as pseudo-triplets. These $^1H-^{31}P$ and $^{13}C-^{31}P$ virtual couplings show that the geometry of complex **6** in solution is trans-P,P, despite the $^1J_{Pt-P}$ coupling constant value.

Interestingly, the ^{195}Pt NMR of bis-chelate **6** shows a single signal at δ_{Pt} −4873 as a triplet of pseudo-triplets owing to coupling with the two equivalent phosphorus nuclei ($^1J_{Pt-P} = 2784$ Hz) and to the nonequivalent methylenic protons H_1 and H_1' with a similar coupling constant ($^3J_{Pt-H} \approx 66$ Hz). This $^1H-^{195}Pt$ coupling was observed in the ^1H NMR only for $H_{1'}$, most probably because of the excessive broadness of the signal corresponding to H_1 (Figure 1).

Therefore, considering the results in both cases, palladium and platinum, the nonexistence of the cis-P,P complexes is attributed to the strict steric restrictions imposed by the bulky menthane cyclic system attached to the chelate ligand backbone, which precludes any accommodation of the $-PPh_2$ groups and effectively surmounts any electronic coordination preferences.

To confirm the trans-P,P arrangement of complexes **5** and **6** in the solid state, XRD studies were carried out on the isomorphic crystals of **5**·$^1/_2CH_2Cl_2$ and **6**·$^1/_2CH_2Cl_2$ obtained from CH_2Cl_2−hexane. Crystal data for both structures are given in Table 1. Selected bond lengths and bond angles are listed in Table 2. The chiral crystal structures reveal a mononuclear square-planar trans arrangement for both complexes (Figure 3). The planarity of the MS_2P_2 group is slightly distorted (mean

Table 1. Crystallographic Data for 5·$^1/_2CH_2Cl_2$ and 6·$^1/_2CH_2Cl_2$

	5·$^1/_2CH_2Cl_2$	6·$^1/_2CH_2Cl_2$
formula	$C_{46}H_{60}P_2PdS_2$·$^1/_2CH_2Cl_2$	$C_{46}H_{60}P_2PtS_2$·$^1/_2CH_2Cl_2$
fw	887.86	976.55
cryst size (mm^3)	0.1 × 0.1 × 0.1	0.3 × 0.4 × 0.4
cryst color	yellow	yellow
temp (K)	153(2)	153(2)
cryst syst	monoclinic	monoclinic
space group	*C*2 (No. 5)	*C*2 (No. 5)
a (Å)	22.9498(11)	22.8698(5)
b (Å)	9.5115(4)	9.5592(2)
c (Å)	20.3401(8)	20.3273(5)
β (deg)	90.216(3)	90.1930(10)
V (Å^3)	4439.9(3)	4443.87(17)
Z	4	4
ρ (g/cm^3)	1.328	1.460
μ (mm^{-1})	0.675	3.415
$((\sin\theta)/\lambda)_{max}$ (Å^{-1})	0.735	0.736
no. of rflns measd	33 581	34 459
no. of unique rflns	13 964 (R_{int} = 0.0825)	13 710 (R_{int} = 0.0722)
abs cor	SADABS (Bruker-AXS)	SADABS (Bruker-AXS)
transmissn min/max	0.5868/1.0000	0.4562/1.0000
no. of params	493	495
R1/wR2 ($I > 2\sigma(I)$)	0.0642/0.1664	0.0351/0.0912
R1/wR2 (all data)	0.0675/0.1683	0.0368/0.0927
goodness of fit on F^2	1.239	1.069
largest diff peak, hole (e/Å^3)	2.093, −2.858	1.397, −3.087
absolute structure param	0.03(3)	−0.006(4)

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Table 2. Selected Distances (Å) and Angles (deg) for $5\cdot{}^1/_2CH_2Cl_2$ and $6\cdot{}^1/_2CH_2Cl_2$

	$5\cdot{}^1/_2CH_2Cl_2$	$6\cdot{}^1/_2CH_2Cl_2$
M−P1	2.2702(12)	2.2620(9)
M−P2	2.2866(12)	2.2787(9)
M−S1	2.3116(14)	2.3138(9)
M−S2	2.3347(13)	2.3386(9)
S1−C14	1.843(5)	1.856(4)
P1−C13	1.840(5)	1.836(4)
P2−C36	1.821(5)	1.833(4)
S2−C37	1.853(5)	1.853(4)
C13−C14	1.521(7)	1.541(5)
C14−C15	1.556(7)	1.558(6)
C14−C19	1.557(8)	1.533(7)
C36−C37	1.545(7)	1.536(5)
C37−C42	1.529(7)	1.537(5)
C37−C38	1.552(7)	1.561(5)
P1−M−P2	178.75(5)	178.35(4)
P1−M−S1	86.08(5)	86.37(3)
P2−M−S1	93.80(5)	93.88(3)
P1−M−S2	94.21(4)	93.88(3)
P2−M−S2	85.95(4)	85.94(3)
S1−M−S2	178.13(6)	177.72(5)
C14−S1−M	107.4(2)	107.0(2)
C13−P1−M	107.4(2)	107.6(2)
C36−P2−M	107.5(2)	107.6(2)
C37−S2−M	102.4(2)	102.3(2)
C14−C13−P1	111.1(3)	110.7(3)
C13−C14−C15	112.4(4)	111.8(3)
C13−C14−C19	111.4(4)	112.2(3)
C13−C14−S1	109.5(3)	108.4(3)
C15−C14−S1	107.2(4)	106.8(3)
C19−C14−S1	108.6(3)	109.1(3)
C37−C36−P2	111.0(3)	110.6(3)
C42−C37−C36	111.3(4)	112.2(3)
C42−C37−C38	108.9(4)	108.5(3)
C36−C37−C38	112.2(4)	112.0(3)
C36−C37−S2	106.8(3)	107.1(3)
C38−C37−S2	109.2(3)	108.9(2)

deviation from the best plane 0.0259 Å for **5** and 0.0326 Å for **6**), owing most probably to packing forces in the solid state. For complex **5** the Pd−S and Pd−P distances are in the range observed for other bis(phosphinothiolate)palladium(II) complexes.[4,8,9] Complex **6** represents, to the best of our knowledge, the first example of a structurally characterized mononuclear bis(phosphinothiolate)platinum(II) complex. The Pt−S and Pt−P bond lengths are similar to those observed for the related polymeric bimetallic complex *catena-trans*-[AgPt(μ-$SCH_2CH_2PEt_2$)$_2$]NO_3[11] and for other trans-bis-chelate Pt(II) complexes with anionic P,S-donor ligands such as the 2-(dicyclohexylphosphino)-*N*-phenylthioacetamidocarboxylate[12] and smaller than those described for *trans*-dithiolatebis(triphenylphosphine)platinum(II) complexes,[13] due to the chelate effect. The menthane cycle presents the chair conformation in **5** and **6**, as it does in **1**, with the (diphenylphosphino)methyl group in an axial position. The chelate rings adopt the λ conformation in order to place the tertiary carbons C15 and C38, which incorporate the most voluminous substituent of the menthane cycle (isopropyl), in equatorial positions. The stereoelectronic preference of the chelate rings to adopt the λ conformation, together with the intrinsic chirality of the ligand, forces both menthane cycles to

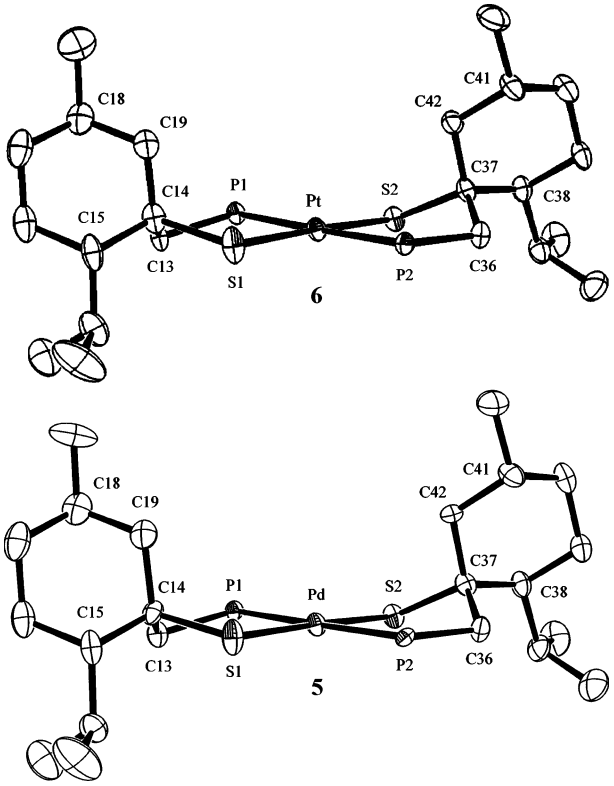

Figure 3. ORTEP plots (50%) of complexes **5** and **6**. Hydrogen atoms and aryl rings have been omitted for the sake of clarity. Selected distances and angles are given in Table 2.

be placed on the same side of the metal coordination plane. On the other hand, in this arrangement, the pseudo-axial phenyl rings are located almost parallel and very close to the menthane cycles, and this forces them to hold conformations practically face to face to the menthane backbone (Figure 4). Thus, as we have previously suggested, owing to the menthane ring interferences the phenyl groups cannot rotate freely (at least the pseudo-axial phenyl groups) and this most probably prevents a conformation compatible with the cis geometry, forcing **5** and **6** to exist only in the trans-P,P form. Finally, it should be noted that the XRD analysis of both complexes has clearly established the absolute configuration of the ligand, with Flack parameters of 0.03(3) for **5** and −0.006(4) for **6**; the stereochemistries are C14 (*R*), C15 (*S*), C18 (*R*), C37 (*R*), C38 (*S*), and C41 (*R*).

Addition of 1 equiv of ligand **4** to a solution of [$PdCl_2$(PPh_3)$_2$] at room temperature in the absence of base produced the corresponding complex chloro[(1*R*,2*S*,5*R*)-1-((diphenylphosphino)methyl)-2-isopropyl-5-methylcyclohexanethiolate](triphenylphosphine)palladium(II) (**7**) (Scheme 3). Unlike bis-chelate **5**, chloro complex **7** exhibits a chemical equilibrium between the cis-P,P and trans-P,P geometries in solution, strongly displaced toward the trans-P,P form (95%), as can be seen in the $^{31}P\{^1H\}$ NMR (Figure 5). Freshly prepared CD_2Cl_2 solutions of **7** have one set of sharp signals only, at δ_P 52.2 (−PPh_2) and 24.2 (PPh_3), with the coupling constant $^2J_{PP}$ = 465 Hz typical of a trans-P,P arrangement. Aged solutions of **7** develop new low-intensity signals in the phosphorus NMR at the displaced positions of δ 60.6 (−PPh_2) and 22.7 (PPh_3) with a coupling constant

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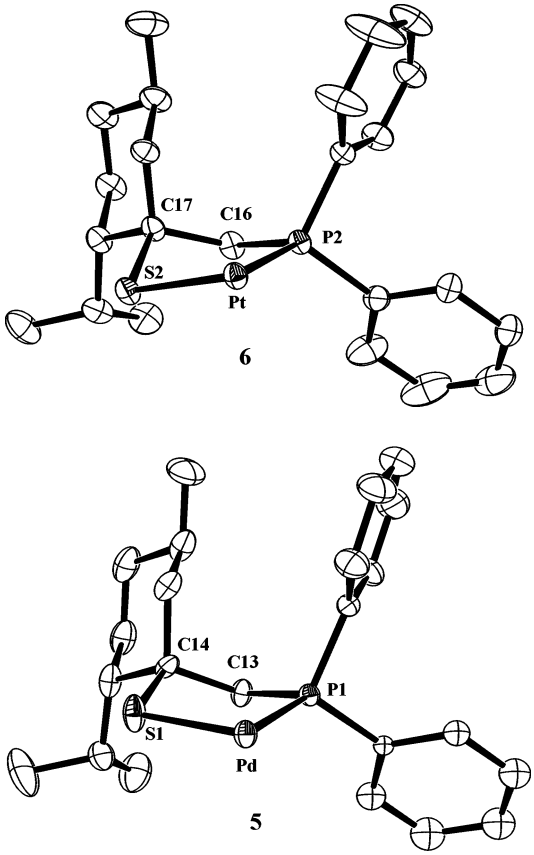
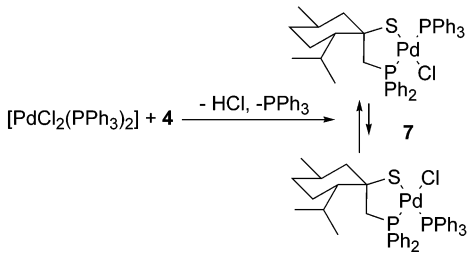


Figure 4. ORTEP plots (50%) of bis-chelates **5** and **6**, with only one of the phosphinothiolate ligands having been drawn to show the relative positions of the menthane cycle and the pseudo-axial phenyl ring.

Scheme 3. Base-Free Addition of 1 Equiv of Ligand 4 to a Solution of $[PdCl_2(PPh_3)_2]$, Giving the Chloro(phosphinothiolato)(triphenylphosphine)palladium(II) Complex 7, Which Exists as a Mixture of Cis- and Trans-P,P Isomers in Solution



$^2J_{PP} = 13$ Hz indicative of a cis-P,P configuration, which places the bulky groups close to each other. The free rotation of PPh_3 allows in this case the placement of five phenyl rings on the same side of this minor, less sterically stable cis isomer. This dynamic process can be avoided by cooling the freshly prepared solutions of **7** to −22 °C. It is also interesting that crystallization of the *cis*-P,P-**7**-containing solutions yields only the original *trans*-P,P-**7** isomer. Presumably, lower solubility and greater concentration cause the crystallization of *trans*-P,P-**7** exclusively.

Conclusions

The development of practical methodologies that can be generalized to prepare new, highly enantiopure bulky phosphinothiol ligands from easily available, inexpensive ketones from the chiral pool, such as in this example, should facilitate the practical applications of these ligands, which, compared to phosphines and diphosphines, are still poorly understood. The introduction of enantiopure and bulky cyclic systems into the chelate backbones of these ligands allows us to control the ligand-based stereoelectronic effects that determine the coordination conformations around the metal. It has been evidenced that high rigidity is necessary to prevent the formation in solution of the presumably more electronically stable cis-P,P isomers: in the case of **7**, with just one rigid chelate ligand, the cis-P,P complex was observed in solution, although only in small amounts.

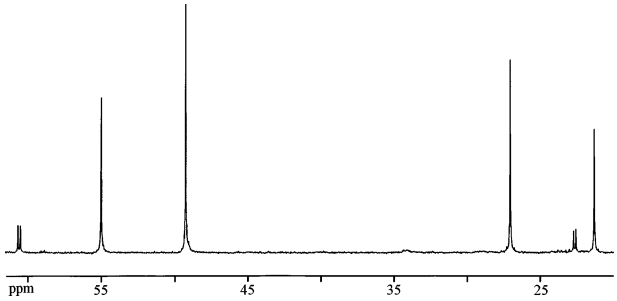


Figure 5. $^{31}P\{^1H\}$ NMR (CD_2Cl_2) of complex **7**. The equilibrium between the cis and trans isomers is strongly displaced toward the less sterically encumbered trans-P,P isomer.

Experimental Section

General Procedures. All complexes were synthesized using standard Schlenk techniques under a nitrogen atmosphere. Solvents were dried by standard methods and distilled and deoxygenated before use. Complexes $Pd(PPh_3)_4$ and $PdCl_2(PPh_3)_2$ were prepared as previously reported.[14] The C, H, and S analyses were carried out using a Carlo Erba microanalyzer. Infrared spectra (range 4000−400 cm^{-1}) were recorded on a Nicolet 205 spectrophotometer. Deuterated solvents for NMR measurements were dried over molecular sieves. Proton NMR spectra were recorded at 200.13 MHz on a Bruker DPX-200 spectrometer. Peak positions are relative to tetramethylsilane as internal reference. $^{31}P\{^1H\}$ NMR spectra were recorded on the same instrument operating at 81.0 MHz. Chemical shifts are relative to external 85% H_3PO_4, with downfield values reported as positive. $^{13}C\{^1H\}$ NMR spectra were recorded on the same instrument operating at 50.3 MHz. Chemical shifts are relative to tetramethylsilane as internal reference. ^{195}Pt NMR spectra were recorded on a Bruker DRX-400 operating at 85.6 MHz and are referenced to Na_2PtCl_6. Gas chromatography analyses were performed on a Shimatzu GC-17A in a TRB-2 column (30 m × 0.25 mm diameter), incorporating an FID detector, and also on a Thermo Quest Trace GC 2000 in a J&W Scientific DB-5 capillary column (30 m × 0.25 mm diameter), incorporating an MS detector. Optical rotations of products in CH_2Cl_2 solution were measured on a Krüss P3002 electronic polarimeter equipped with a sodium bulb light (589 nm). Flash chromatography was performed on silica gel 60 A CC. Solvents for chromatography were distilled at atmospheric pressure prior to use. Microdistillation procedures were performed on a Buchi GK-R-51 instrument.

Preparation of (1*R*,2*S*,5*R*)-1-((Diphenylphosphino)-methyl)-2-isopropyl-5-methylcyclohexanethiol (4). Step

(14) Colquhoun, H. N.; Holton, J.; Thompson, D. J.; Twigg, M. V. *New Pathways for Organic Synthesis*; Plenum Press: New York, 1984; pp 383−384.

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1. A mixture of 0.92 g (21.0 mmol) of NaH (55%) and 4.62 g (21.0 mmol) of $(CH_3)_3SOI$ in 15 mL of anhydrous DMSO, under a nitrogen atmosphere, was vigorously stirred at room temperature for 2 h and placed in an ice bath. A solution of (−)-menthone (3.84 mL, 20.0 mmol) in 5 mL of anhydrous DMSO was gradually added over 10 min. The reaction mixture was then protected from light and stirred at room temperature for 24 h. The reaction mixture was poured on ice−water (80 mL), and the aqueous phase was extracted with diethyl ether (3 × 40 mL). The organic phase was washed with water (2 × 20 mL), dried with magnesium sulfate, filtered, evaporated to dryness, and distilled (70−75 °C, 0.1 Torr) to yield (1*S*,4*S*,7*R*)-4-isopropyl-7-methyl-1-oxaspiro[2.5]octane (**2**) of purity >97% by GLC (2.69 g, 80%). ^{1}H NMR ($CDCl_3$ solution): δ 0.80 (d, 3H, H_{10}, ^3J = 6.8 Hz); 0.90 (d, 3H, H_{11}, ^3J = 6.8 Hz); 0.91 (d, 3H, H_9, ^3J = 6.5 Hz); 1.0−1.9 (m, 9H, H_3−H_8); 2.47 (d, 1H, H_1, ^2J = 4.5 Hz); 2.90 (d, 1H, $H_{1'}$, ^2J = 4.5 Hz). ^{13}C{^{1}H} NMR ($CDCl_3$ solution): δ 18.61 (s, C_9); 21.83 (s, C_{10}); 22.31 (s, CH_{11}); 24.38 (s, C_5); 25.88 (s, C_8); 30.61 (s, C_4); 33.94 (s, C_6); 43.41 (s, C_3); 44.81 (s, C_7); 51.88 (s, C_1); 61.05 (s, C_2). MS: *m/e* 168 (M^+, 5%); 153 (M^+ − 15, 100%); 125 (M^+ − 43, 65%); 95 (75%); 81 (85%). $[\alpha]^{20}_D$ = +7.7°.

Step 2. Potassium thiocyanate (194.36 mg, 14.26 mmol), (1*S*,4*S*,7*R*)-4-isopropyl-7-methyl-1-oxaspiro[2.5]octane (**2**; 1.0 g, 5.94 mmol), water (0.3 mL), and ethanol (3.0 mL) were introduced into a reactor and vigorously stirred at room temperature for 9 days. Water (10 mL) was added to the reaction mixture. The aqueous phase was extracted with diethyl ether (3 × 10 mL). The organic phase was washed with water (10 mL), dried with magnesium sulfate, filtered, and evaporated to dryness. Purification of the crude product by flash chromatography (hexane−ethyl acetate, 9.5/0.5) afforded (1*R*,4*S*,7*R*)-4-isopropyl-7-methyl-1-thiaspiro[2.5]octane (**3**) of purity >93% by NMR (383 mg, 35%). ^{1}H NMR ($CDCl_3$ solution): δ 0.78 (d, 3H, H_{10}, ^3J = 6.8 Hz); 0.90 (d, 3H, H_{11}, ^3J = 6.8 Hz); 0.96 (d, 3H, H_9, ^3J = 6.2 Hz); 1.0−1.9 (m, 9H, H_3−H_8); 2.22 (br s, 1H, H_1); 2.46 (br s, 1H, $H_{1'}$). ^{13}C{^{1}H} NMR ($CDCl_3$ solution): δ 19.75 (s, C_9); 21.58 (s, C_{10}); 23.76 (s, CH_{11}); 25.51 (s, C_8); 26.77 (s, C_5); 30.70 (s, C_6); 33.06 (s, C_3); 33.47 (s, C_4); 48.49 (s, C_7); 48.46 (s, C_1); 51.98 (s, C_2). MS: *m/e* 184 (M^+, 50%); 169 (M^+ − 15, 50%); 137 (M^+ − 47, 70%); 109 (100%); 95 (85%); 81 (80%). $[\alpha]^{20}_D$ = −33.0°.

Step 3. (1*R*,4*S*,7*R*)-4-isopropyl-7-methyl-1-thiaspiro[2.5]-octane (**3**; 200 mg, 1.10 mmol) was slowly added to an ice-cold solution of potassium diphenylphosphide (0.5 M in tetrahydrofuran, 2.4 mL, 1.19 mmol), with stirring, under a nitrogen atmosphere. The reaction mixture was then vigorously stirred at room temperature. After 2 h, deoxygenated methanol (1 mL), deoxygenated saturated ammonium chloride aqueous solution (3 mL), and deoxygenated water (5 mL) were consecutively added to the reaction mixture. The aqueous phase was extracted with diethyl ether (3 × 15 mL). The organic phase was washed with water (15 mL), dried with magnesium sulfate, filtered, and evaporated to dryness. Purification of the crude product by flash chromatography (hexane−ethyl acetate, 8:2) afforded (1*R*,2*S*,5*R*)-1-((diphenylphosphino)methyl)-2-isopropyl-5-methylcyclohexanethiol (**4**) of purity >99% by NMR (334.7 mg, 76%). ^{1}H NMR ($CDCl_3$ solution): δ 0.47 (d, 3H, H_9, ^3J = 6.0 Hz); 0.90 (d, 3H, H_{10}, ^3J = 6.9 Hz); 0.97 (d, 3H, H_{11}, ^3J = 6.9 Hz); 0.8−2.4 (m, 10H, H_3−H_8, SH); 2.45 (d*p*st, 1H, H_1, ^2J = 14.4 Hz, ^2J = 2.2 Hz, ^3J = 2.2 Hz); 2.77 (dd, 1H, $H_{1'}$, ^2J = 14.4 Hz, ^2J = 5.3 Hz); 7.2−7.8 (m, 10H, H_{ar}). ^{13}C{^{1}H} NMR ($CDCl_3$ solution): δ 19.18 (s, C_9); 21.59 (s, C_{10}); 22.84 (s, C_5); 24.99 (s, C_{11}); 27.08 (s, C_8); 29.33 (s, C_4); 34.95 (s, C_6); 36.85 (d, C_1, ^1J = 12.5 Hz); 52.65 (d, C_3, ^3J = 12.9 Hz); 54.55 (d, C_7, ^3J = 3.9 Hz); 55.11 (d, C_2, ^2J = 16.8 Hz); 127−141 (C_{ar}). ^{31}P-{^{1}H} NMR ($CDCl_3$ solution): δ −22.75 (s). MS: *m/e* 370 (M^+, 5%); 337 (M^+ − 33, 60%); 218 (100%); 183 (60%). $[\alpha]^{20}_D$ = −79.6°.

Preparation of the Bis(phosphinothiolate)palladium-(II) Complex 5. (1*R*,2*S*,5*R*)-1-((diphenylphosphino)methyl)-2-isopropyl-5-methylcyclohexanethiol (**4**; 276 mg, 0.67 mmol) was added to a solution of the complex $[Pd(PPh_3)_4]$ (350 mg, 0.30 mmol) in anhydrous dichloromethane (25 mL) under a nitrogen atmosphere to produce an intense yellow solution. The reaction mixture was stirred at room temperature. After 3 h, the volume was reduced to 5 mL and the product was crystallized by the addition of hexane to afford the complex as orange crystals (152 mg, 60%). ^{1}H NMR (CD_2Cl_2 solution): δ 0.27 (d, 3H, H_9, ^3J = 5.7 Hz); 0.87 (d, 3H, H_{10}, ^3J = 7.1 Hz); 0.90 (d, 3H, H_{11}, ^3J = 7.1 Hz); 1.0−2.0 (m, 8H, H_3−H_6, H_8); 2.58 (dtd, 1H, H_1, ^2J = 13.5 Hz, ^2J = 6.3 Hz, ^3J = 1.5 Hz); 2.61 (m, 1H, H_7); 3.14 (dt, 1H, $H_{1'}$, ^2J = 13.5 Hz, ^2J = 6.3 Hz); 7.3−8.3 (m, 10H, H_{ar}). ^{13}C{^{1}H} NMR (CD_2Cl_2 solution): δ 20.21 (s, C_9); 22.06 (s, C_{10}); 25.66 (s, C_{11}); 27.20 (s, C_5); 27.38 (s, C_8); 31.18 (s, C_4); 36.16 (s, C_6); 39.42 (t, C_1, ^1J = 18.1 Hz); 53.98 (t, C_7, ^3J = 7.5 Hz); 56.76 (t, C_3, ^3J<3 Hz); 59.58 (t, C_2, ^2J = 9.1 Hz); 129.02 (t, C_m, ^3J = 5.4 Hz); 129.16 (t, C'_m, ^3J = 4.9 Hz); 130.61 (s, C_p); 131.50(s, C'_p); 132.59 (t, C_o, ^2J = 6.1 Hz); 133.65 (t, C_i, ^1J = 21.9 Hz); 135.42 (t, C'_i, ^1J = 21.8 Hz); 136.29 (t, C'_o, ^2J = 7.4 Hz). ^{31}P{^{1}H} NMR (CD_2Cl_2 solution): δ 50.10 (s). Anal. Found: C, 65.52; H, 7.23; S, 7.05. Calcd for $C_{46}H_{60}P_2PdS_2$: C, 65.35; H, 7.15; S, 7.52.

Preparation of the Bis(phosphinothiolate)platinum-(II) Complex 6. A solution of (1*R*,2*S*,5*R*)-1-((diphenylphosphino)methyl)-2-isopropyl-5-methylcyclohexanethiol (**4**; 104.2 mg, 0.28 mmol) in methanol (2 mL) was added to a solution of $K_2[PtCl_4]$ (46.7 mg, 0.11 mmol) in H_2O (2 mL). The reaction mixture was then stirred at room temperature until a yellow precipitate was formed. The reaction mixture was filtered, and the solid was washed with hexane (3 × 2 mL). Crystallization from CH_2Cl_2−hexane affords the complex as yellow crystals (56.5 mg, 55%). ^{1}H NMR ($CDCl_3$ solution): δ 0.26 (d, 3H, H_9, ^3J = 6.0 Hz); 0.85 (d, 3H, H_{10}, ^3J = 8.0 Hz); 0.89 (d, 3H, H_{11}, ^3J = 8.0 Hz); 1.0−2.0 (m, 8H, H_3−H_6, H_8); 2.39 (d*p*st, 1H, H_1, ^2J = 13.6 Hz, ^2J = 4.9 Hz); 2.70 (m, 1H, H_7); 2.93 (dt, 1H, $H_{1'}$, ^2J = 13.6 Hz, ^2J = 3.6 Hz); 7.0−8.5 (m, 10H, H_{ar}). ^{13}C{^{1}H} NMR ($CDCl_3$ solution): δ 19.73 (s, C_9); 21.48 (s, C_{10}); 24.87 (s, C_{11}); 26.33 (s, C_5); 26.85 (s, C_8); 30.22 (s, C_4); 35.32 (s, C_6); 37.02 (t, C_1, ^1J = 21.9 Hz); 53.00 (t, C_7, ^3J = 6.5 Hz); 56.76 (t, C_3, ^3J<2 Hz); 57.95 (t, C_2, ^2J = 7.7 Hz); 128.21 (t, C_m, ^3J = 5.7 Hz); 128.33 (t, C'_m, ^3J = 5.1 Hz); 129.97 (s, C_p); 130.51 (s, C'_p); 132.15 (t, C_o, ^2J = 6.2 Hz); 132.64 (t, C_i, ^1J = 27.2 Hz); 133.06 (t, C'_i, ^1J = 26.2 Hz); 135.23 (t, C'_o, ^2J = 7.0 Hz). ^{31}P{^{1}H} NMR (CD_2Cl_2 solution): δ 48.88 (*p*st, ^1J = 2785). ^{195}Pt NMR ($CDCl_3$ solution): δ −4872.66 (t*p*st, ^1J = 2785 Hz, $^3J \approx$ 66 Hz). Anal. Found: C, 56.60; H, 6.26; S, 6.46. Calcd for $C_{46}H_{60}P_2PtS_2 \cdot CH_2Cl_2$: C, 57.19; H, 6.30; S, 6.57.

Preparation of the Chloro(phosphinothiolato)(triphenylphosphine)palladium(II) Complex 7. (1*R*,2*S*,5*R*)-1-((diphenylphosphino)methyl)-2-isopropyl-5-methylcyclohexanethiol (**4**; 126 mg, 0.34 mmol) was added to a solution of the complex $[PdCl_2(PPh_3)_2]$ (250.0 mg, 0.36 mmol) in anhydrous dichloromethane (25 mL) under a nitrogen atmosphere to produce a yellow solution. The reaction mixture was stirred at room temperature. After 3 h, the volume was reduced to 3 mL and the product was crystallized by adding hexane and cooling the mixture to −20 °C for 12 h. Complex **7** was obtained as orange crystals (111 mg, 40%). ^{1}H NMR (CD_2Cl_2 solution): δ 0.27 (d, 3H, H_9, ^3J = 5.8 Hz); 0.84 (d, 6H, H_{10}, H_{11}, ^3J = 7.0 Hz); 0.8−2.0 (m, 8H, H_3−H_6, H_8); 2.61 (m, 1H, H_7); 2.67 (dd, 1H, H_1, ^2J = 13.6 Hz, ^2J = 8.2 Hz); 3.03 (dd, 1H, $H_{1'}$, ^2J = 13.6 Hz, ^2J = 10.4 Hz); 7.0−8.4 (m, 10H, H_{ar}). ^{13}C{^{1}H} NMR (CD_2Cl_2 solution): δ 19.99 (s, C_9); 21.91 (s, C_{10}); 25.55 (s, C_{11}); 27.29 (s, C_5); 27.42 (s, C_8); 30.99 (s, C_4); 35.78 (s, C_6); 40.24 (d, C_1, ^1J = 35.8 Hz); 52.59 (d, C_7, ^3J = 17.8 Hz); 55.58 (d, C_3, ^3J = 6.7 Hz); 60.33 (d, C_2, ^2J = 9.4 Hz); 128−136 (C_{ar}). ^{31}P{^{1}H} NMR (CD_2Cl_2 solution): ***trans*-7**, δ 24.19 (d, PPh_3, ^2J = 465.0 Hz), 52.16 (d, $-PPh_2$, ^2J = 465.0 Hz); ***cis*-7**, δ 22.66 (d, PPh_3, ^2J = 13.0 Hz), 60.60 (d, $-PPh_2$, ^2J = 13.0 Hz). Anal. Found: C, 64.37; H, 6.05; S, 3.98. Calcd for $C_{41}H_{45}ClP_2PdS$: C, 63.65; H, 5.86; S, 4.14.

Crystal Structure Determinations. Yellow crystals of bis[(1*R*,2*S*,5*R*)-1-((diphenylphosphino)methyl)-2-isopropyl-5-methylcyclohexanethiolato]palladium(II)·$^1/_2CH_2Cl_2$ (**5**) were obtained after different trials by slow evaporation of CH_2Cl_2−hexane. Crystal structure determination for **5** was carried out using a Siemens P4 diffractometer equipped with a SMART-CCD-1000 area detector, a MACScience Co rotating anode with Mo Kα radiation, a graphite monochromator, and a Siemens LT2 low-temperature device ($T = -120$ °C). The measurements were made in the range 1.65−30.07° for θ. Full-sphere data collection was carried out with ω and φ scans. Programs used: data collection, Smart version 5.060 (BrukerAXS 1999); data reduction, Saint + version 6.02 (Bruker AXS 1999), absorption correction, SADABS (Bruker AXS 1999). After the measured crystals of **5** and **6** were indexed, identical isomorphic monoclinic cells with a β angle close to 90° were determined. After excluding a orthorhombic cell (for **5**, $R_{int} =$ 44.9% and for **6**, $R_{int} =$ 37,7%) a monoclinic *C*-centered cell with the space group *C*2 was selected for further processes. Crystal structure solution for **5** was achieved using direct methods, as implemented in SHELXTL version 5.10 (G. M. Sheldrick, Universtität Göttingen, Göttingen, Germany, 1998) and visualized using the XP program. Missing atoms were subsequently located from difference Fourier syntheses and added to the atom list. Crystal structure solution of bis[(1*R*,2*S*,5*R*)-1-((diphenylphosphino)methyl)-2-isopropyl-5-methylcyclohexanethiolate}platinum(II)·$^1/_2CH_2Cl_2$ (**6**) was obtained by molecular replacement using the structure of **5** and changing palladium by platinum for refining. Least-squares refinement on F^2 using all measured intensities was carried out using the program SHELXTL version 5.10 (G. M. Sheldrick, Universtität Göttingen, Göttingen, Germany, 1998). All non-hydrogen atoms were refined including anisotropic displacement parameters. Hydrogen atoms were invariably placed in geometrically optimized positions and forced to ride on the atom to which they are attached.

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Supporting Information Available: Tables and figures giving details of the two structure determinations, including atomic coordinates, bond lengths and angles, thermal parameters, least-squares planes, and interatomic contacts and spectra of complexes **6** and **7**. This material is available free of charge via the Internet at http://pubs.acs.org. The supplementary crystallographic data for this paper (CCDC 201836 and CCDC 213436) can also be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, U.K.; fax, +44 1223 336033; e-mail, deposit@ccdc.cam.ac.uk).

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