Tandem Palladium-Catalyzed Cyclocarbonylation of Isolimonene: A Mechanistic Investigation and Theoretical Calculations on the Fully Diastereoselective Step

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Cyclocarbonylation of isolimonene catalyzed by complexes of the type $[HPd(SnCl_3)L_2]$ provides two cyclopentanone isomers (**2a** and **2b**) containing two new stereogenic centers with a good diastereomeric excess (up to 69 % with L_2 = dppf). These results show that chiral phosphane ligands are not necessary to ensure asymmetric induction. The diastereomeric excess is due, in fact, to the substrate itself, assisted by the steric hindrance of the diphosphanes. A full characterization of the two isomers by ^1H, ^{13}C and DPFGSE NOE NMR spectroscopy gives all the signal assignations and all the positions of the substituents of interest on the chiral carbon atoms. In order to have a better understanding of the catalytic process, we also present a density functional study of the crucial intermediate species **4** involved in the proposed catalytic cycle. Our calculations show that there is no coordination of the C=C bond in an *exo* mode. Conversely, we have found a pentacoordinate species with a trigonal bipyramidal geometry in which the C=C bond is coordinated in an *endo* mode. Selected bond lengths and bond orders are reported. The calculated net charge distribution supports the cyclization process, which proceeds through a C–C(O) and a C–Pd coupling. A β-hydride elimination reaction of **4** provides the two **2a** and **2b** isomers.

Introduction

Carbon monoxide is a very powerful building block in organic synthesis, provided it can be inserted into a framework with high selectivity. For several years we have used this strategy to functionalize monoterpenes.[1] Particularly interesting are the tandem reactions in which functionality already present on the terpene reacts with an active intermediate resulting from the insertion of carbon monoxide.[2] Recently, we have specially focused our attention on the cyclocarbonylation of isolimonene, where the endocyclic carbon-carbon double bond is involved in the process; preliminary results have been reported.[3] Rhodium and palladium play a central role in such carbonylation reactions and many papers have reported the catalytic activity of complexes such as $[HRh(CO)L_3]$ or $[PdCl_2L_2]$.[4] Palladium complexes, often with $SnCl_2$ as co-catalyst, are active in the alkoxycarbonylation of alkenes.[5] During the nineties, great effort went into developing enantio- or diastereoselective catalysts by introduction of chiral ligands into the coordination sphere of a metal.[6] Our studies on the carbonylation of (1*R*,2*S*,5*R*)-isopulegol, to provide the corresponding lactone, and our preliminary results on the carbonylation of (1*R*,4*R*)-isolimonene [(3*R*,6*R*)-3-isopropenyl-6-methylcyclohexene] have shown that the introduction of a chiral diphosphane ligand does not influence the diastereoselectivity of the two cyclocarbonylation reactions of interest.[2,3] Thus, the enantiofacial selectivity should be induced by the chiral substrate itself. The situation of isolimonene appeared to us particularly interesting because, of the three chiral centers present in the resulting product, two of them (C1 and C5 in Scheme 1) are obtained with exclusively one configuration (1*R* and 5*S*). Thus, the diastereomeric excess results in fact from an enantiomeric excess at C4 to provide **2a** and **2b** of Scheme 1.

In order to understand why the cyclization reaction catalyzed by palladium occurs exclusively at the C2 atom of isolimonene (which becomes C1 in the resulting product, see Scheme 1) and provides only the *R* configuration, we have performed quantum chemical calculations using the density functional theory (DFT) on the main intermediate which would give the enantioselective cyclization step.

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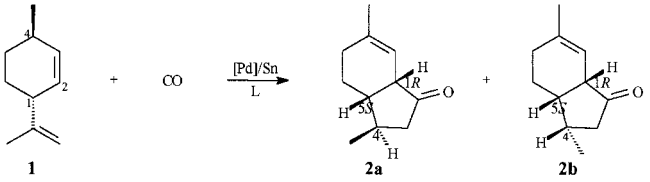
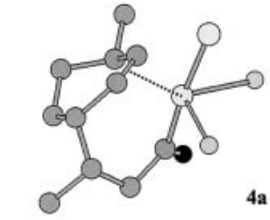
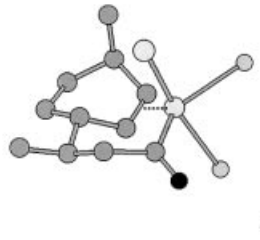


Scheme 1. Cyclocarbonylation of (1*R*,4*R*)-isolimonene (**1**) catalyzed by palladium

This paper deals with the complete identification of the two diastereomers **2a** and **2b** resulting from the carbonylation of (1*R*,4*R*)-isolimonene (**1**) based on DPFGSE NOE experiments[7] as well as the configuration at all the chiral carbon atoms. The analysis of the structure of these two isomers leads us to confirm that the active species contains a palladium-hydride bond. Calculations have been carried out on the two isomers **4a** and **4b**, and the two other possible diastereomers. DFT computations have been done on the crucial intermediate species, which contains an acyl group, and the fate of the endocyclic carbon-carbon double bond and the palladium center either in an *endo* or in an *exo* mode (Scheme 2); such calculations show that an enantioselective C1−C2 coupling in the *endo* mode is the only one possible. Finally, the full mechanism of the tandem carbonylation reaction is considered.





Scheme 2. Representation of two conceivable intermediates, **2a** resulting from an *endo* coordination mode and **2b** from an *exo* mode

Method of Calculation

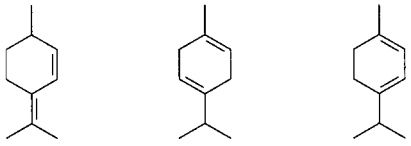
As the complex $[PdCl_2(PPh_3)_2]$ reacts to give the same products in catalysis as $[PdCl(SnCl_3)(PPh_3)_2]$, although somewhat more slowly, we chose to model the species $[PdCl_2(PH_3)_2]$ in which PPh_3 has been replaced by the PH_3 ligand, as is normal in these types of calculations. The system contains a palladium atom, which is a transition metal and thus has strongly correlated *d* electrons. Consequently, we chose to carry out our study by using the density functional approach, which is well adapted to this type of problem.[8,9]

All structures presented here were fully optimized using conjugate gradient methods without constraints at the density functional theory (DFT) level with the Gaussian 98 software package release A.3.[10] The method has been described extensively elsewhere.[11−13] We used the B3LYP hybrid functional.[14,15] For all optimizations a valence basis-set of double-ξ quality was employed and relativistic effects were addressed implicitly by the use of relativistic effective core potentials for Pd, P and Cl.[16−18] For H, C and O the standard Dunning−Hay D95V basis was used.[19] A Mulliken population analysis, together with significant Mayer bond orders between palladium and its neighbors were thus determined. Finally, the charge-transfer effects arising between the metal atom and the ligands were examined.

Results and Discussion

Catalytic Experiments

Carbonylation of (1*R*,4*R*)-isolimonene (**1**; Scheme 1) at 40 bar (4 MPa) catalyzed by $[PdCl_2(PPh_3)_2]$ in the presence of $SnCl_2{\cdot}2H_2O$ and a slight excess of PPh_3, leads to a mixture of the two cyclopentanones **2a** and **2b** with good selectivity. These two products have been shown by mass spectrometry to contain a C11 framework and a ketone function; further strong evidence for the presence of a CO group results from the ν_{CO} band at 1740 cm^{-1} in the IR spectrum of both products. The mixture was enriched in one product to reach a **2a**/**2b** ratio of 90:10 by column chromatography on silica. ^1H and ^{13}C NMR characterizations confirmed that **2a** and **2b** are two diastereomers, and a complete assignment of the various configurations at the carbon atoms was obtained by NOE experiments, as discussed later.



Scheme 3. Isomers of **1**

From Table 1 it can be seen that a 95 % conversion of the starting material can be obtained in 18 hours, giving a selectivity in **2a**+**2b** of 84 %, operating with a substrate-to-catalyst ratio of 50. The other products, which account for 16 %, were identified by GC-MS as isomers of **1**, the most abundant of which are shown in Scheme 3.

Addition of more substrate, as in runs 2 and 3, decreases the conversion but does not affect significantly the selectivity in **2**. The **2a**/**2b** ratio gives rise to a diastereomeric excess of 12 % in the three experiments.

We then introduced the classical chiral ligand (+)-DIOP into the coordination sphere of palladium and prepared the catalyst precursor $[PdCl_2\{(+)\text{-DIOP}\}]$ to carry out run 4.

Table 1. Cyclocarbonylation reactions of (1*R*,4*R*)-isolimonene (**1**)[a]

	Catalytic precursor	Substrate/catalyst	Conversion (%)	Selectivity (%)	**2a/2b**[b]	*de*[b] (%)
1	$[PdCl_2(PPh_3)_2]$	50	95	84	56:44	12
2	$[PdCl_2(PPh_3)_2]$	80	78	80	55:45	10
3	$[PdCl_2(PPh_3)_2]$	100	62	82	56:44	12
4	$[PdCl_2\{(+)\text{-DIOP}\}]$	100	75	52	85:15	70
5	$[PdCl_2\{(-)\text{-DIOP}\}]$	100	75	52	85:15	70
6	$[PdCl_2(dppb)]$[c]	100	75	65	82:18	64
7	$[PdCl_2(dppf)]$[c]	100	71	68	84.5:15.5	69

[a] General conditions: Catalytic precursor = 1 mmol, $SnCl_2{\cdot}2H_2O$ = 2.5 mmol, P/Pd = 4, toluene = 25 mL, temp. = 70 °C, p_{CO} = 40 bar, t = 18 h. [b] Determined by GC. [c] Temp. = 97 °C.

Under the same catalytic conditions as in run 3, a 75 % conversion of **1** and a 52 % selectivity in **2** were observed. However, a diastereomeric excess of 70 % was calculated from the relative amounts of **2a** and **2b**. A similar experiment carried out with $[PdCl_2\{(-)\text{-DIOP}\}]$ led to the same results, especially the **2a**/**2b** ratio, which is still 85:15 and not the reverse. Therefore, whatever the configurations of the two chiral carbons of the diphosphane ligand, they have no influence on the diastereoselectivity and we suspected that the reaction could be governed by the chirality of the substrate itself.

Various experiments, not reported here, showed that a change in the temperature, pressure, or L*/Pd ratio did not affect significantly these performances, except maybe a higher pressure, which improved the conversion somewhat; for instance, at 80 bar, the yield is 82 %.

For this reason we have prepared two catalyst precursors containing the classical diphosphane ligands bis(diphenylphosphanyl)butane (dppb) and bis(diphenylphosphanyl)ferrocene (dppf). Runs 6 and 7 show that the performances of these two non-chiral catalysts are essentially the same as those of the DIOP-containing catalysts: the two diastereomeric excess values are 64 % and 69 % respectively. In experiments not described here, we also checked that shorter carbon chains in the ligands, like bis(diphenylphosphanyl)ethane and -propane, did not lead to any catalytic activity.[20] It can therefore be concluded that simple diphosphane ligands can play an important role, and thus assist the asymmetric catalysis, presumably through their electronic effects during the various steps of the catalytic cycle, but also thanks to their bulkiness during the asymmetric induction.

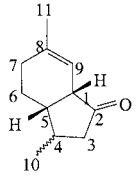
Stereochemistry Determination of 2a and 2b by NMR Spectroscopy

In previous studies, due to the isolation in the solid state of one isomer of the lactone obtained by cyclocarbonylation of (1*R*,2*S*,5*R*)-isopulegol and solved by an X-ray crystal structure, we have been able to determine all the configurations of the chiral centers present in the molecule and its diastereoisomers by NMR spectroscopy.[2d,3] With this knowledge, we have used NOE experiments to assign the positions of the various substituents of interest in **2a** and **2b**. NMR spectroscopic data for the two diastereomers **2a** and **2b** are displayed in Table 2, with the numbering system shown in Scheme 4, which differs from normal terpene nomenclature. These data were obtained from 1D ^1H and ^{13}C NMR spectra and COSY (^1H,^1H), HMQC (^1H,^{13}C) ^1J (see Figure 1) as well as long-range experiments. Due to the presence of a five-membered cycle and an endocyclic carbon-carbon double bond, most of the substituents are labeled as pseudo-equatorial in Schemes 5 and 6.

Table 2. NMR spectroscopic data for diastereomers **2a** and **2b** in $CDCl_3$

Atom	**2a**				**2b**			
	$\delta(^1H)$[a]	$^2J_{H,H}$[b]	$^3J_{H,H}$[b]	$\delta(^{13}C)$	$\delta(^1H)$[a]	$^2J_{H,H}$[b]	$^3J_{H,H}$[b]	$\delta(^{13}C)$
1	2.45 (dd)			49.3	2.35 (dd)			52.0
2				217.7				218.0
3pa	2.04 (dd)	18.3 (3pe)	6.8 (4)	45.0	1.92 (dd)	18 (3pe)	6 (4)	41.9
3pe	1.52 (dd)	18.3 (3pa)	8.1 (4)		1.52 (dd)			
4	1.70 (m)			31.0	2.00 (m)			31.4
5	1.70 (m)			41.1	1.90 (m)			38.2
6pa	1.54 (m)			21.8	1.55 (m)			19.8
6pe	1.35 (m)				1.35 (m)			
7pa	1.54 (m)			26.9	1.55 (m)			29.0
7pe	1.35 (m)				1.35 (m)			
8				135.6				135.7
9	4.90 (d)		1.4 (1)	116.1	5.16 (d)		1.5 (1)	116.4
10	0.76 (d)		6.4 (4)	18.7	0.76 (d)		6.4 (4)	15.1
11	1.30 (s)			23.6	1.30 (s)			23.2

[a] Resonance multiplicities in parentheses. [b] Coupled partners in parentheses.



Scheme 4. Compound **2** (with IUPAC nomenclature)

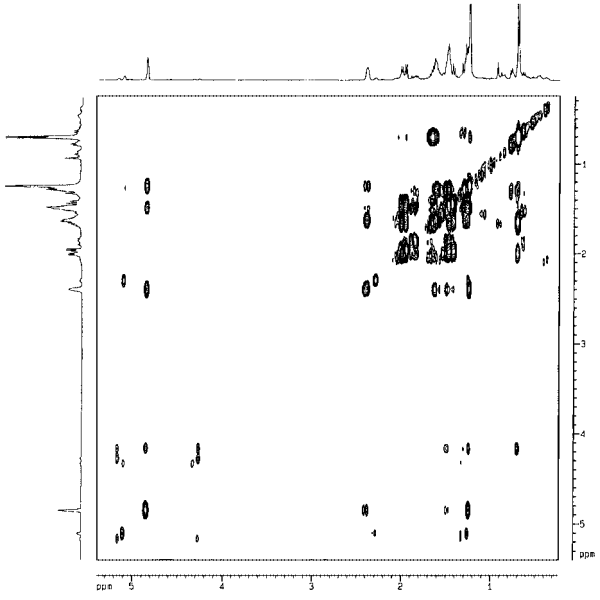
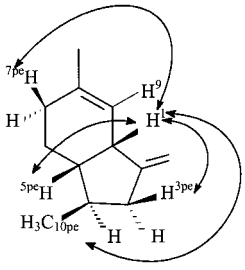
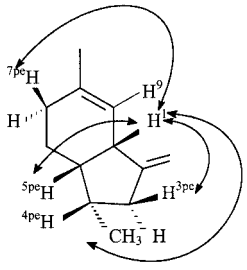


Figure 1. 2D COSY.DQF.GE ($^1H,^1H$) spectrum (400 MHz) of mixture of diastereomers **2a** and **2b** at 298 K in $CDCl_3$



Scheme 5. Interactions observed for H1 in **2a**



Scheme 6. Interactions observed for H1 in **2b**

The measurement of NOE effects by a 1D DPFGSE method appears to be much more selective for resonances that are not well resolved, especially when this is due to the overlap of several signals. As the spatial arrangement at C5 does not change during the reaction [C1 (*R*) in isolimonene becomes C5 (*S*) in cyclopentanone], irradiation of H1 on C1 in **2a** (Figure 2) allowed us to detect interactions with H9, H7 in a pseudo-equatorial position (pe), H5pe, H10pe, H11pe and H3pe (Scheme 5) indicating that all these atoms or groups are in the up position. Thus, C1 presents an *R* configuration, and C4 an *R* one.

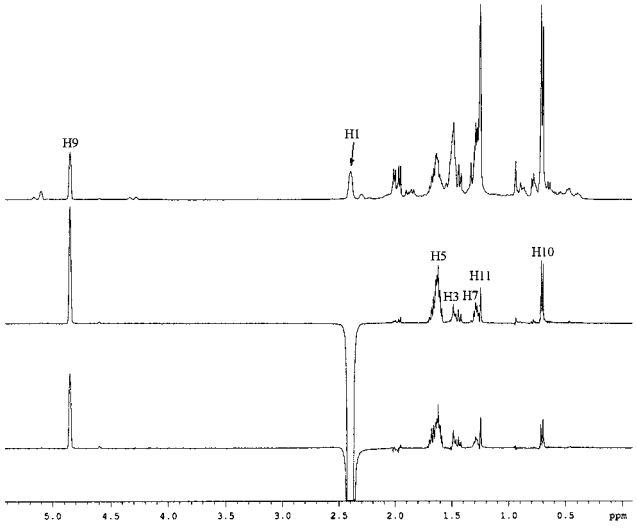


Figure 2. 1D NOESY-DPFGSE spectrum (400 MHz; irradiation of H1 on C1 in **2a**) of mixture of diastereomers **2a** and **2b** at 298 K in $CDCl_3$; top: full spectrum; middle: mixing time 800 ms; bottom: mixing time 400 ms

In the same 90:10 mixture of **2a**/**2b**, irradiation of H1 in **2b** (Figure 3) led us to assign the configurations C1 (*R*) and C4 (*S*; Scheme 6).

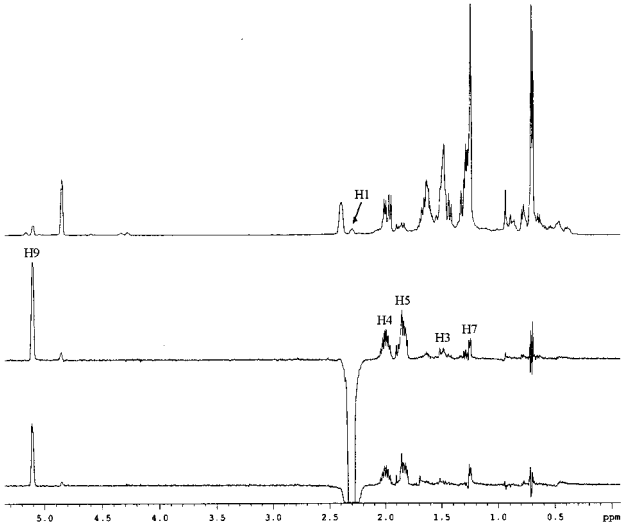
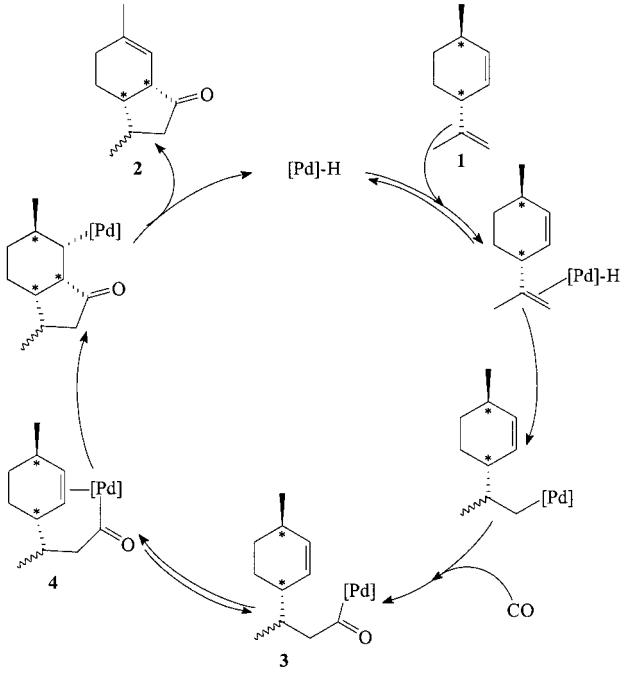


Figure 3. 1D NOESY-DPFGSE spectrum (400 MHz; irradiation of H1 on C1 in **2b**) of mixture of diastereomers **2a** and **2b** at 298 K in $CDCl_3$; top: full spectrum; middle: mixing time 800 ms; bottom: mixing time 400 ms

This NMR study shows that in the two products obtained in the cyclocarbonylation reaction, the stereochemistry of C1 is unchanged in both isomers. The diastereomeric excess of 70 % results in fact from the two (*S* and *R*) configurations at the C4 atom (*R*/*S* = 85:15).

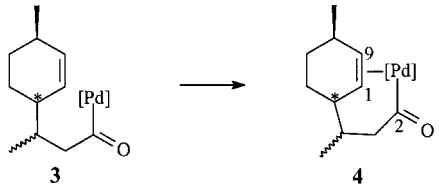
DFT Calculations

The shift of the endocyclic C=C bond from the substrate **1** to the resulting cyclopentanone **2** (Scheme 7) is indicative of a β-hydride elimination in an intermediate which affords a palladium hydride species. Thus, we have supposed the following sequence for the early steps of the catalytic cycle: formation of an alkylpalladium species by hydride transfer to the exocyclic C=C bond, and CO migratory insertion to afford the acyl intermediate **3**. During the cyclization process, which involves the carbon−carbon coupling of the two C1 and C2 atoms, we have considered that the stereoselectivity results from one privileged approach of the palladium center toward the endocyclic C=C bond in species **4** (Scheme 8). As the full system involves 39 atoms the potential hypersurface is rather complex, therefore we calculated only certain regions of this hypersurface, taking into account the classical geometries for d^8 complexes.



Scheme 7. Catalytic cycle of cyclocarbonylation of **1**

Our calculations show that there is no coordination of the C=C bond in an *exo* mode and we found two species with the C=C bond not coordinated to the metal center, which adopts a square-planar environment, at all (d_{Pd-C} = 4.75 and 5.63 Å for the more stable and 3.69 and 4.66 Å for the second one, which is 3 kcal·mol^{-1} higher in energy, as shown in Table 3). Moreover, we found a pentacoordinate species with a trigonal bipyramidal (TBP) geometry in which the C=C bond is coordinated in an *endo* mode (Scheme 9). Indeed, the two palladium−carbon bond lengths are 2.31 and 2.35 Å, corresponding to Mayer bond-orders of 0.36 and 0.31, respectively; in addition, the C−C bond length is 1.40 Å and its bond order is 1.53 (see Table 3). Among the various axial and/or equatorial positions for the ligands, the calculations seem to slightly favor (1.3 kcal·mol^{-1}) the Cl and CO-acyl ligands in the two axial positions.



Scheme 8. Coordination of the endocyclic C=C bond of **1** to the palladium center

Concerning the Mulliken population analysis, our results show clearly that there are no significant differences between the net charges on each atom in both species.

Proposed Catalytic Cycle

Our calculations give strong evidence that the TBP intermediate in which the (*endo*)C=C double bond and the CO-acyl are in close vicinity allows the next step in the catalytic cycle. Indeed, the C2−C1 distance is 2.97 Å, whereas it is 3.58 and 4.41 Å in the less- and more-stable square-planar palladium species. The resulting C1 configuration is thus 100 % *R*.

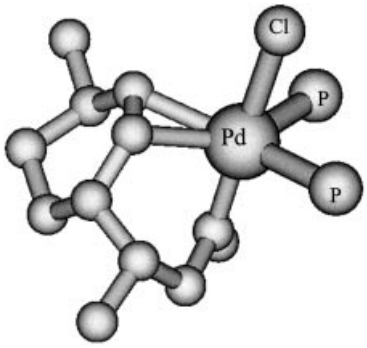
A further analysis of the mechanism shows that the new intermediate **5**, in which the cyclopentanone has been formed and the palladium atom is still bonded to C9, presents the two palladium and H8 hydrogen atoms in mutual *cis* positions. Thus, a β-hydride elimination reaction, which re-forms the active palladium hydride species, is possible. In addition, the H1 atom is *trans* to Pd and cannot provide the β-H elimination required for the further step. Moreover, it is worth mentioning that a possible intermediate resulting from the coordination of the C=C bond in the *exo* mode would provide the two H1 and H8 hydrogen atoms in *trans* positions to the palladium atom; such a situation, in which no β-H elimination can occur, precludes any catalytic reaction. We did not detect these two isomers. Scheme 7 shows the catalytic cycle that we propose.

Conclusion

The main point of this study is related to an asymmetric induction that is caused by the substrate itself so that chiral ancillary phosphane ligands are not necessary in the catalytic reaction. Moreover, the steric hindrance of the diphosphane ligands plays an essential role in obtaining a large diastereomeric excess.

Table 3. Absolute energies, representative bond lengths, selected Mayer bond orders and Mulliken net charges distribution in the intermediate species **4**

Complexes	Absolute energy (Hartree)	Distances (Å)	Bond order	Net charges
C=C uncoordinated species	−662.862124	Pd−C9: 5.63	Pd−C9: 0.00	Pd: −0.17
		Pd−C1: 4.75	Pd−C1: 0.00	C1: −0.25
		C1−C9: 1.35	C1−C9: 1.95	C9: −0.23
	−662.857868	Pd−C9: 4.66	Pd−C9: 0.00	Pd: −0.17
		Pd−C1: 3.69	Pd−C1: 0.00	C1: −0.26
		C1−C9: 1.35	C1−C9: 1.90	C9: −0.18
C=C coordinated species	−662.856565	Pd−C9: 2.35	Pd−C9: 0.31	Pd: −0.14
		Pd−C1: 2.31	Pd−C1: 0.36	C1: −0.23
		C1−C9: 1.40	C1−C9: 1.53	C9: −0.20



Scheme 9. Compound **4** (C=C *endo* coordination mode)

Experimental Section

Materials: Solvents with high purity, as well as (1*R*,4*R*)-isolimonene, were used as received from Dérivés Résiniques et Terpéniques (DRT SA). $SnCl_2{\cdot}2H_2O$ (Prolabo 98 %), triphenylphosphane (Aldrich 99 %), 1,4-bis(diphenylphosphanyl)butane (dppb) (Acros 98 %), 1,1′-bis(diphenylphosphanyl)ferrocene (dppf) (Aldrich 97 %), (−)-2,3-*O*-isopropylidene-2,3-dihydroxy-1,4-bis(diphosphanyl)butane [(−)-DIOP] and (+)-2,3-*O*-isopropylidene-2,3-dihydroxy-1,4-bis(diphosphanyl)butane [(+)-DIOP] (Janssen 98 %). Column chromatography was performed with SiO_2 (Merck).

Instrumentation: The ^1H, ^{13}C and ^{31}P NMR spectra were recorded with $CDCl_3$ solutions containing TMS as internal standard on a Bruker AMX 400 spectrometer operating at 400.13 MHz (^1H) and 100.62 MHz (^{13}C), and a Bruker AM 250 spectrometer operating at 250.13 MHz, 62.90 MHz and 101.26 MHz, respectively. Data are reported as follows: chemical shift in ppm (δ), multiplicity (s = singlet, d = doublet, t = triplet, q = quadruplet and m = multiplet), coupling constant (*J*) in Hz (n.d. = no determined), integration, and assignment (pa = pseudo-axial and pe = pseudo-equatorial). IR spectra were obtained on a Perkin−Elmer 1710 spectrometer; absorptions are reported in cm^{-1}. Analytical GC was carried out on a Carlo Erba MFC 500 apparatus equipped with a Econo-Cap FFAP (30 m; 0.53 mm; 1.2 μm) capillary column and a flame ionization detector. Products were identified by GC/MS on a Perkin−Elmer QMass 910 Mass Spectrometer with ionization voltage of 70 eV, with a Crompack CP WAX 52 CB (50 m; 0.32 mm; 0.2 μm) polar column.

General Procedure: A mixture of dichlorobis(triphenylphosphane)-palladium(II) (0.702 g, 1 mmol), hydrated tin(II) chloride (0.474 g, 2.5 mmol) and triphenylphosphane (0.524 g, 2 mmol) was introduced into a 250 mL stainless steel autoclave with mechanical stirring. A nitrogen-saturated mixture of isolimonene (13.624 g, 100 mmol) in toluene (25 mL) was introduced into the evacuated autoclave by aspiration. It was heated to 70 °C under 40 bar pressure of carbon monoxide at constant pressure. After 18 h, the autoclave was cooled and then slowly depressurized. The yellow-orange reaction mixture was analyzed by gas chromatography. The same procedure was followed for other ligands maintaining the P/Pd ratio at 4.

After the catalytic reaction, the organometallic compounds and the excess phosphane were separated from the crude solution by washing with CCl_4. The deeply colored oily layer was decanted. After concentration by rotary evaporation, the oily residue was purified by column chromatography on silica gel (petroleum ether/dichloromethane/ethyl acetate, 70:24:6).

Complexes: $[PdCl_2(PPh_3)_2]$ was prepared according to the literature procedure.[21] Yield 95 %. $^{31}P\{^1H\}$ NMR (250 MHz, $CDCl_3$, 25 °C): δ = 23.47 (s) ppm. IR (KBr): $\tilde{\nu}$ = 1481, 1436, 1099, 746, 693 cm^{-1}. Complexes containing diphosphanes were prepared by addition of the diphosphane to $[PdCl_2(PhCN)_2]$[22] in hot acetone.
[$PdCl_2$(dppb)]: Yield 90 %. $^{31}P\{^1H\}$ NMR (250 MHz, $CDCl_3$, 25 °C): δ = 63.75 (s) ppm.
[$PdCl_2$(dppf)]: Yield 88 %. $^{31}P\{^1H\}$ NMR (250 MHz, $CDCl_3$, 25 °C): δ = 36.14 (s) ppm.
[$PdCl_2$[(+)-DIOP)] and [$PdCl_2$[(−)-DIOP)]: Yield 85 %. $^{31}P\{^1H\}$ NMR (250 MHz, $CDCl_3$, 25 °C): δ = 16.47 (s) ppm.

(1*R*,4*R*,5*S*)-4,8-Dimethylbicyclo[4.3.0]non-8-en-2-one (2a): ^1H NMR (400 MHz, $CDCl_3$, 25 °C, TMS): δ = 4.90 (d, $^3J_{H,H}$ = 1.4 Hz, 1 H, H9), 2.45 (dd, n.d., 1 H, H1), 2.04 (dd, $^3J_{H,H}$ = 18.3, 6.8 Hz, 1 H, H3pa), 1.70 (m, 2 H, H4 and H5), 1.54 (m, 2 H, H6pa and H7pa), 1.52 (dd, $^3J_{H,H}$ = 8.1, 18.3 Hz, 1 H, H3pe), 1.35 (m, 2 H, H6pe and H7pe), 1.30 (s, 3 H, CH_3 11), 0.76 (d, $^3J_{H,H}$ = 6.4 Hz, 3 H, CH_3 10) ppm $^{13}C\{^1H\}$ NMR (400 MHz, $CDCl_3$, 25 °C): δ = 217.7 (C2), 135.6 (C8), 116.1 (C9), 49.3 (C1), 45.0 (C3), 41.1 (C5), 31.0 (C4), 26.9 (C7), 23.6 (C11), 21.8 (C6), 18.7 (C10) ppm. IR (KBr): $\tilde{\nu}$ = 1740 cm^{-1} (C=O). MS (70 eV, EI): *m*/*z* (%) = 79 (100) $[C_6H_7]^+$, 94 (100) $[C_7H_{10}]$, 164 (61) [M], 165 (9) $[M - H]^+$.

(1*R*,4*S*,5*S*)-4,8-Dimethylbicyclo[4.3.0]non-8-en-2-one (2b): ^1H NMR (400 MHz, $CDCl_3$, 25 °C, TMS): δ = 5.16 (d, $^3J_{H,H}$ = 1.5 Hz, 1 H, H9), 2.35 (dd, n.d., 1 H, H1), 2.00 (m, 1 H, H4), 1.92 (dd, $^3J_{H,H}$ = 6 and 18 Hz, 1 H, H3pa), 1.90 (m, 1 H, H5), 1.55 (m, 2 H, H6pa and H7pa), 1.52 (dd, n.d., 1 H, H3pe), 1.35 (m, 2 H, H6pe and H7pa), 1.30 (s, 3 H, CH3 11), 0.76 (d, $^3J_{H,H}$ = 6.4 Hz, 3 H, CH3 10) ppm. $^{13}C\{^1H\}$ NMR (400 MHz, $CDCl_3$, 25 °C): δ = 218.0 (C2), 135.7 (C8), 116.4 (C9), 52.0 (C1), 41.9 (C3), 38.2 (C5),

31.4 (C4), 29.0 (C7), 23.2 (C11), 19.8 (C6), 15.1 (C10) ppm. IR (KBr): $\tilde{\nu}$ = 1740 cm^{-1} (C=O). MS (70 eV, EI): *m/z* (%) = 94 (100) $[C_7H_{10}]$, 79 (92) $[C_6H_7]^+$, 164 (61) [*M*], 165 (9) $[M - H]^+$.

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