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Asymmetric allylic alkylation by palladium-bisphosphinites

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Abstract—A series of new chiral palladium-bisphosphinite complexes have been prepared from readily available, naturally occurring chiral alcohols. The complexes were used to efficiently carry out catalytic allylic alkylation of 1,3-diphenylpropene-2-yl acetate with dimethyl malonate. The complexes based on derivatives of ascorbic acid carry out enantioselective alkylations, one of which showed an ee as high as 97%. Based on the structural characterization, it can be surmised that strategic placement of phenyl groups is key to higher enantioselectivities.

1. Introduction

Designing chiral ligands with variable stereochemical elements, which are suitable for use with several metal ions, is one of the challenges in the field of asymmetric catalysis. Ideally, this would result in catalysts suitable for a wide variety of reactions, having chemo-, regio-, and enantioselectivity. A test bed for such a set of ligands would be allylic substitution reactions as they are among the most extensively studied catalytic transformations. Since first reports by Tsuji[1] and Trost,[2] palladium mediated allylic carbon–carbon bond formation has been the subject of intensive investigations.[3]

The most effective chiral catalysts known to date[4,5] for allylic alkylation include the P,P-ligand[6] of Trost, the P,N-ligand[7] of Pfaltz and BINAP[8] based axially chiral ligands pioneered by Fuji. However, many of these ligands involve tedious synthesis, or resolution of enantiomers. Ligands based on the natural chiral pool, which overcome these disadvantages in synthesis have not yet been fully exploited.[9,10]

As a result, this report of palladium-bisphosphinite complexes (Fig. 1) gains importance. We have chosen naturally occurring chiral alcohols that can be transformed to different phosphinites. Some of alcohols **1**–**9** can be characterized using X-ray crystallography giving insight into the orientation of the groups on the backbone and their role in making the activated allyl moiety enantioselective.

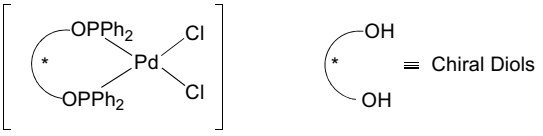
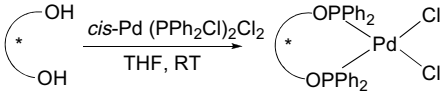


Figure 1.

2. Result and discussion

Phosphinites can be readily oxidized during their synthesis from alcohols meaning that phosphinite complexes have been studied less in comparison to phosphine complexes. We have circumvented this problem by synthesizing palladium complexes by a template synthesis[11] (see Scheme 1 and Table 1).



Scheme 1. Synthesis of palladium-bisphosphinite complexes (template procedure).

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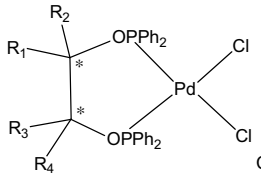
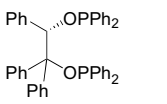
Table 1. Complexes synthesized by the template procedure

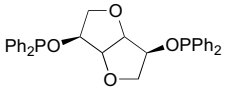


Complexes **1-5**

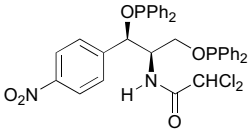
Entry	Complex ($LPdCl_2$)	R_1	R_2	R_3	R_4
1	(*R*)-**1**	H	H	H	Ph
2	(*S*)-**2**	H	H	H	Ph
3	(2*R*,3*R*)-**3**	H	COOEt	H	COOEt
4	(2*S*,3*S*)-**4**	H	COOEt	H	COOEt
5	(2*R*,3*R*)-**5**	H	Ph	H	Ph



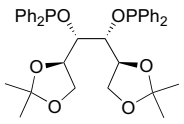
Ligand **6a**



Ligand **7a**

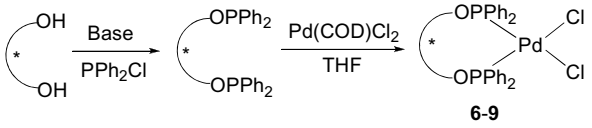


Ligand **8a**



Ligand **9a**

The more traditional synthesis of the ligands **6a**–**9a** and their reaction with the metal precursor given in Scheme 2 was necessary in a few cases (Scheme 2). All complexes have been characterized using conventional spectroscopic techniques and X-ray crystallography in cases where suitable crystals were available (Table 2).



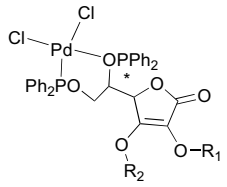
6-9

Scheme 2. Synthesis of palladium-bisphosphinite complexes via the ligands (**6a**–**9a**).

We optimized the chemical yields in the asymmetric allylic alkylation of *rac*-1,3-diphenyl-3-acetoxy-1-ene **18**, with dimethyl malonate by using 0.1 mol % of complex **1** under standard Trost conditions.[12] In comparison with the DIOP-Pd complex, which has the same ring size[13] (Scheme 3), complex **1** was more efficient.

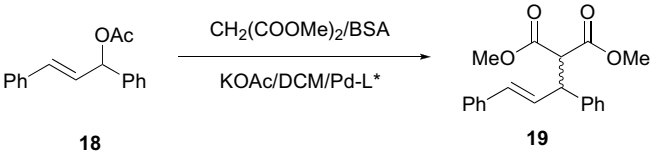
Complexes **1**–**17** were scanned for enantioselective catalysis under the optimized conditions (Table 3). The reported yields are an average of three runs. Almost all the complexes gave reasonably good chemical yields. However, the enantioselectivity varied widely among these complexes. Complexes **1**–**6**, and **9** have a similar backbone and it would be expected for them to show a predictable trend. Reaction at room temperature (Table 3) with complexes **1** and **2** gave poor selectivity. Overlaying the structures of **1** and **2** shows the flexible nature of this ring system (see Fig. 2).

Table 2. Ascorbic acid (AA) **10**–**13** and isoascorbic acid (IAA) **14**–**17** derived complexes using template procedure



Complexes **10-17**

Entry	Complex ($LPdCl_2$)	R_1	R_2
1	**10**	H	H
2	**11**	Bn	H
3	**12**	H	Bn
4	**13**	Bn	Bn
5	**14**	H	H
6	**15**	Bn	H
7	**16**	H	Bn
8	**17**	Bn	Bn



18 **19**

Scheme 3. Asymmetric allylic alkylation (AAA) of *rac*-1,3-diphenyl-3-acetoxy-1-ene by chiral palladium-bisphosphinite complexes.

Table 3. Asymmetric allylic alkylation of *rac*-1,3-diphenyl-3-acetoxy-1-ene with various palladium-bisphosphinite complexes (room temperature)

Entry[a]	Complex	Time (h)	Yield[b] (%)	ee[c] (%)
1	**1**	9	84	12 (*R*)
2	**2**	8	92	10 (*S*)
3	**3**	5	90	5 (*S*)
4	**4**	7	92	Nil
5	**5**	16	89	Nil
6	**6**	25	86	18 (*S*)
7	**7**	10	92	37 (*S*)
8	**8**	36	72	27 (*R*)
9	**9**	3	96	Nil
10	**10**	14	75	2 (*R*)
11	**11**	5	84	91 (*R*)
12	**12**	4	90	20 (*R*)
13	**13**	7	85	69 (*R*)
14	**14**	18	69	5 (*R*)
15	**15**	15	92	22 (*S*)
16	**16**	9	84	7 (*S*)
17	**17**	8	80	20 (*S*)

[a] Molar ratio for entries: Pd-cat. (0.001 equiv), dimethyl malonate (3 equiv), *N*,*O*-bis(trimethylsilyl)acetamide (3 equiv) and KOAc (3 equiv).
[b] Isolated yield.
[c] Determined by HPLC analysis using Diacel Chiralcel OD column.

The addition of an extra phenyl group on backbone **6** improves the enantioselectivity. The extra phenyl group clearly enforces the different orientations of the Ph group on the P atom and increases the rigidity of the backbone.

The ligands based on the readily available tartaric acid esters and derivatives gave complexes **3**, **4**, and **9**.

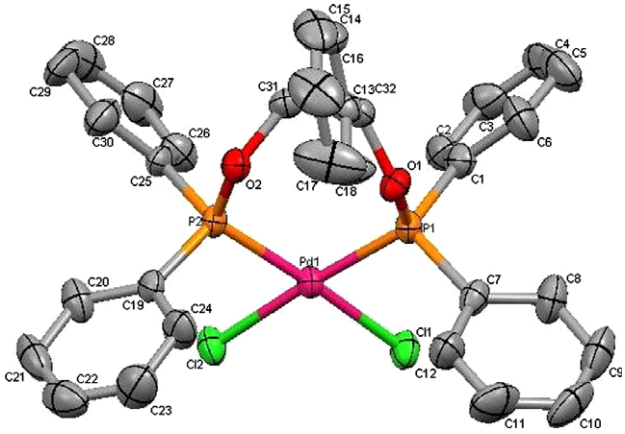


Figure 2. X-ray crystal structure of complex **1**. Ellipsoid set to 40% probability. Hydrogen atoms are omitted for clarity.

Unfortunately, all of them exhibited very poor enantioselectivity in this reaction. Replacing phenyl groups with flexible groups such as carboethoxy group resulted in very poor enantioselectivity. The role of phenyl groups in improving rigidity in chiral systems has already been pointed out[14] (see Figs. 3–6).

Among the other complexes we tested, **7** and **8** were noteworthy. Complex **7** has a very rigid framework, and the differential orientation of the PPh_2 units is recognizable in the crystal structure.[15] Surprisingly, **7** gave poor enantioselectivity. Complex **8** also gave poor enantioselectivity although the analogous Pt compound gave excellent selectivity for the asymmetric allylation of aldehydes.[16]

In comparison, ascorbic acid and isoascorbic acid based complexes gave better enantioselectivities. This was a welcome result as the five-membered ring attached to the chiral carbon on ascorbic acid has substituents which could be

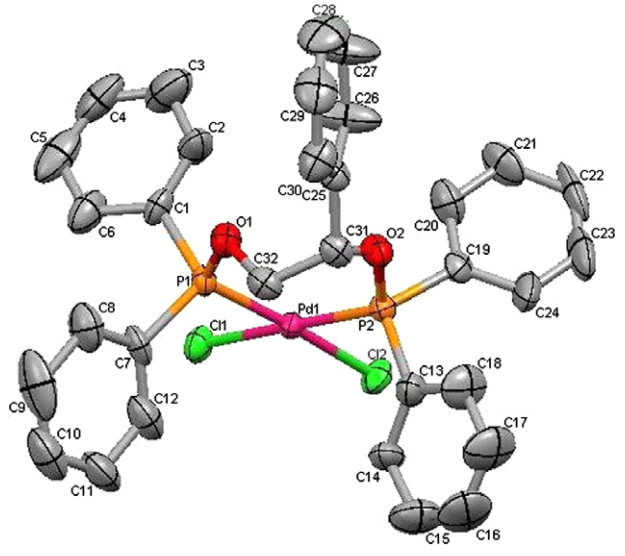


Figure 3. X-ray crystal structure of complex **2**. Ellipsoid set to 40% probability. Hydrogen atoms are omitted for clarity.

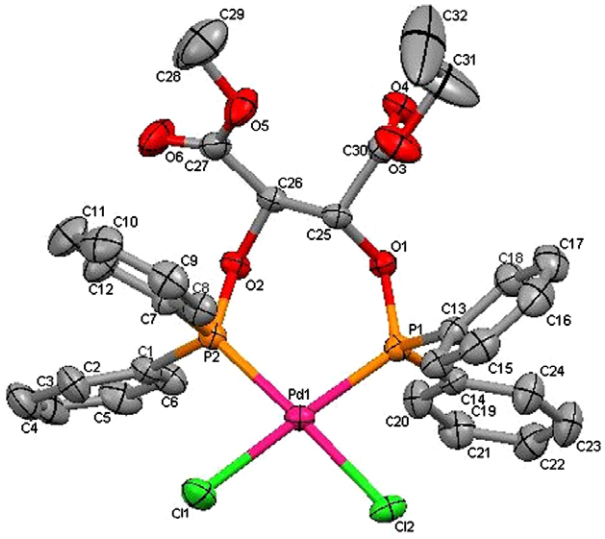


Figure 4. X-ray crystal structure of complex **3**. Ellipsoid set to 40% probability. Hydrogen atoms are omitted for clarity.

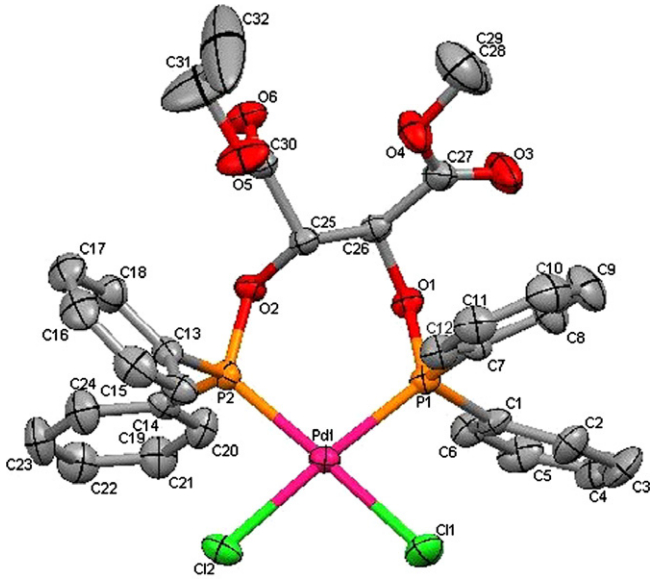


Figure 5. X-ray crystal structure of complex **4**. Ellipsoid set to 40% probability. Hydrogen atoms are omitted for clarity.

selectively altered to bear phenyl groups. We attached benzyl moieties to the OH groups. Complexes **10**–**13** are derived from ascorbic acid and gave the (*R*)-isomer. Complexes **15**–**17** derived from isoascorbic acid gave the (*S*)-isomer albeit with consistently poorer enantioselectivities in comparison with complexes **10**–**13**. Complex **14** made from isoascorbic acid is the only exception and gave the (*R*)-isomer, such as the complexes made from ascorbic acid (see Fig. 7).

In both ascorbic and isoascorbic series, a benzyl group at R_1 and H at R_2 produce the maximum enantioselectivity. The opposite arrangement leads to the least enantioselectivity. Surprisingly, adding a benzyl group to both OH groups leads to intermediate selectivity. Apparently, it is

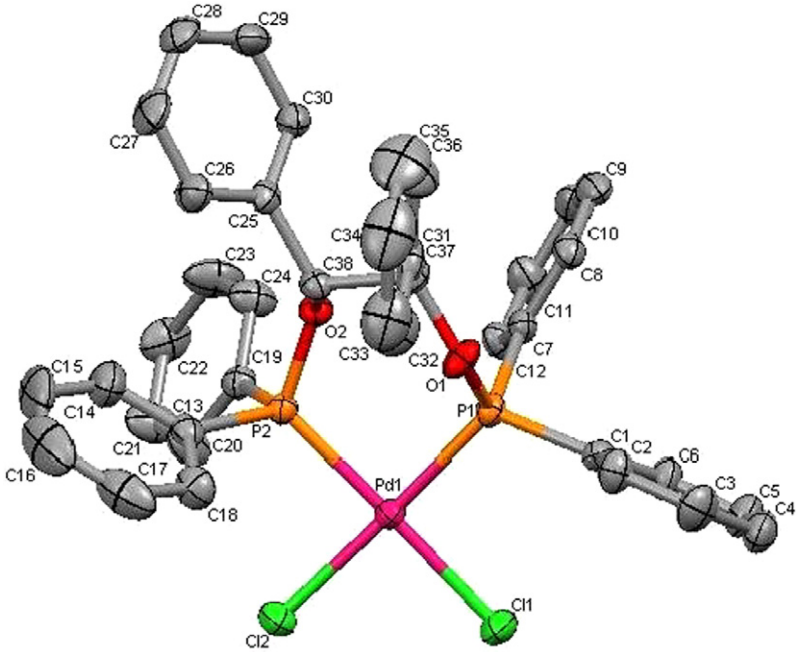


Figure 6. X-ray crystal structure of complex **5**. Ellipsoid set to 40% probability. Hydrogen atoms are omitted for clarity.

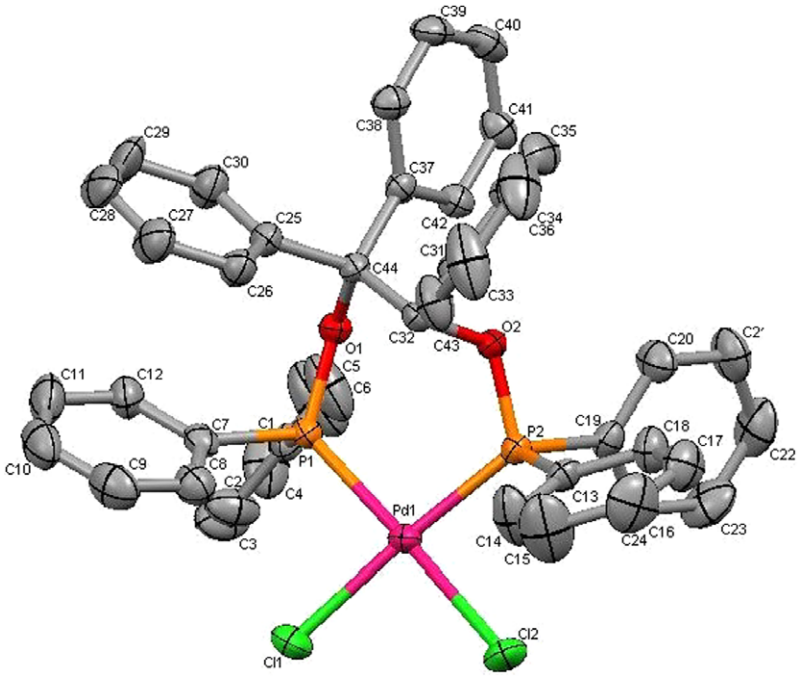


Figure 7. X-ray crystal structure of complex **6**. Ellipsoid set to 40% probability. Hydrogen atoms are omitted for clarity.

important to selectively add a phenyl group to the OH that is closer to the metal. The effect of selective hydrogen bonding is an alternative explanation and has been known to improve enantioselectivity.[17] However, the fact that complexes **10** and **14** having no benzyl groups give zero enantioselectivity suggests that the benzyl group has greater influence in directing the incoming group (see Figs. 8–10).

Complexes, which give good enantioselectivity, were selected for further investigations at lower temperatures. Improved enantioselectivities were obtained; although longer reaction times were needed, there was no significant reduction in chemical yield (Table 4; complexes **11** and **13**).

Indeed complexes **10**, **14**, **15**, and **16** gave better selectivities at lower temperatures. Surprisingly complex **12** showed a decrease in enantioselectivity at lower temperatures. No significant effect of temperature could be observed with complex **7**. Clearly ascorbic acid based ligands have very good potential for use in reactions requiring editable

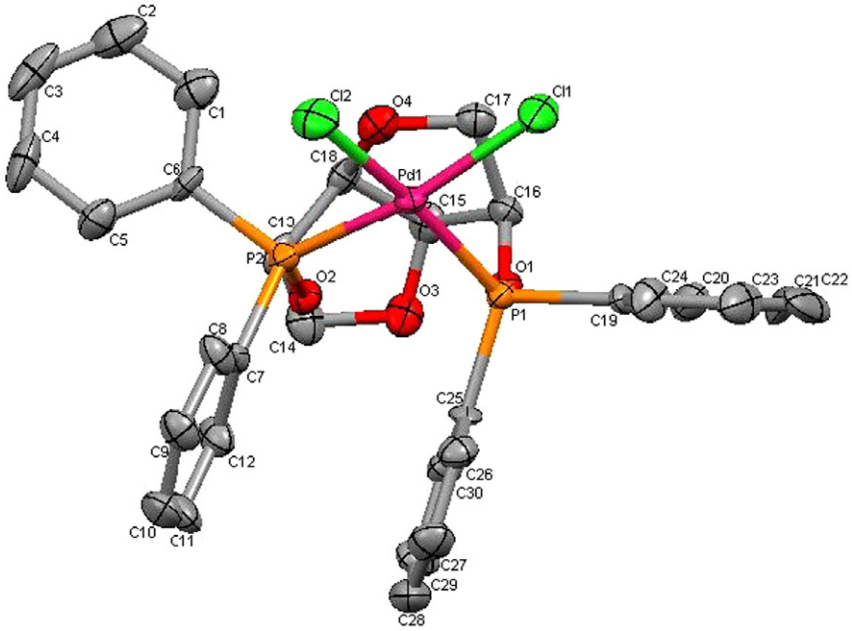


Figure 8. X-ray crystal structure of complex **7**. Ellipsoid set to 40% probability. Hydrogen atoms are omitted for clarity.

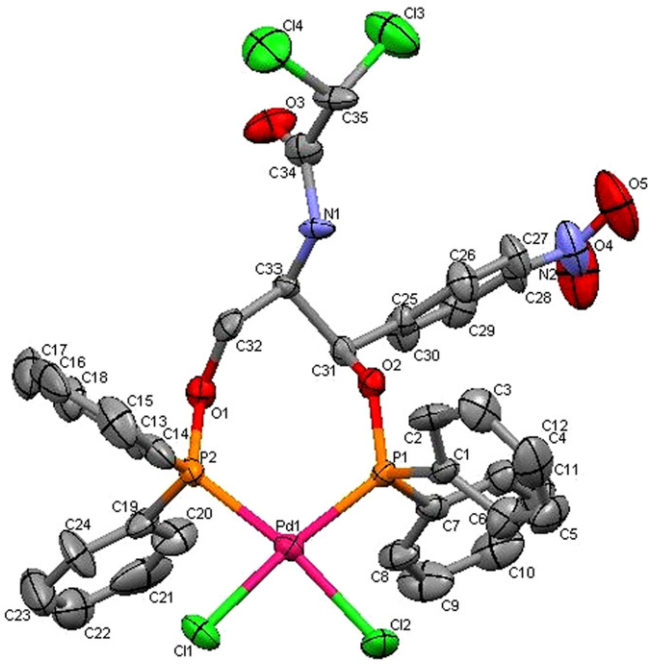


Figure 9. X-ray crystal structure of complex **8**. Ellipsoid set to 40% probability. Hydrogen atoms are omitted for clarity.

directing groups, such as the asymmetric allylic alkylation reaction.

3. Conclusion

In conclusion, new chiral palladium-bisphosphinite complexes have been synthesized and have good potential for enantioselective catalysis. Ascorbic acid based ligands are advantageous since they can be selectively functionalized. An opportunity for editing the stereochemical elements is provided by the two hydroxy groups which can be easily changed to benzyl groups. The excellent enantioselectivity for the allylic alkylation of *rac*-1,3-diphenyl-3-acetoxy-1-ene in the case of complex **11** warrants this conclusion and should encourage more investigations with ascorbic acid based ligands.

4. Experimental

4.1. General methods

All reactions were carried out in oven-dried glassware under an inert nitrogen atmosphere. Tetrahydrofuran and diethyl ether were doubly distilled over sodium/benzophenone and $LiAlH_4$. Dichloromethane was purified by distillation from P_2O_5. Triethylamine was distilled over KOH followed by $LiAlH_4$. Diphenylphosphine chloride was purified by distillation under nitrogen prior to use. Analytical thin layer chromatography (TLC) was performed using Merck 60 F_{254} pre-coated silica gel plate (0.2 mm thickness). Subsequent to elution, plates were visualized using UV radiation (254 nm). Further visualization was possible by staining with iodine or a basic solution of potassium permanganate, followed by heating on a hot plate. Column chromatography was performed using Merck silica gel 60–120 with freshly distilled solvents. Columns were typically packed as slurry and equilibrated with the appropriate solvent system prior to use.

^1H NMR and ^{31}P NMR spectra were recorded on Bruker AMX 400 spectrometers operating at 400 MHz for ^1H and 162.02 MHz for ^{31}P at 298 K. Proton chemical shifts were internally referenced to the residual solvent proton

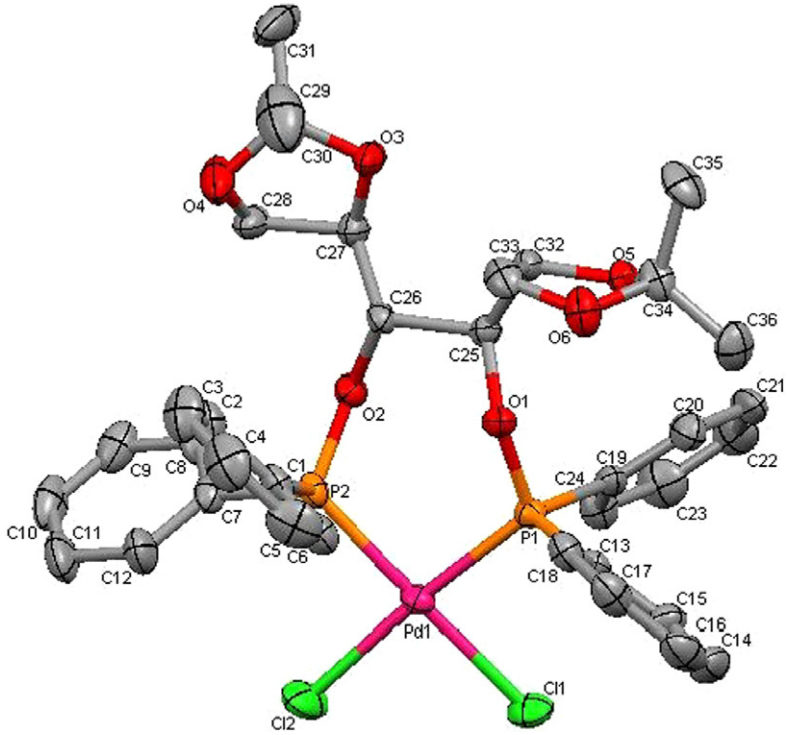


Figure 10. X-ray crystal structure of complex **9**. Ellipsoid set to 40% probability. Hydrogen atoms are omitted for clarity.

Table 4. Asymmetric allylic alkylation of *rac*-1,3-diphenyl-3-acetoxy-1-ene with various palladium-bisphosphinite complexes (lower temperature)

Entry[a]	Complex	Temp (°C)	Time (h)	Yield (%)	ee (%)
1	**7**	0	18	85	35 (*S*)
2		−40	36	90	40 (*S*)
3	**10**	0	28	77	25 (*R*)
4		−40		NR	
5	**11**	0	13	86	97 (*R*)
6		−40	20	89	97 (*R*)
7	**12**	0	15	78	3 (*R*)
8		−40	35	71	Nil
9	**13**	0	19	87	68 (*R*)
10		−40	28	94	95 (*R*)
11	**14**	0	33	70	12 (*S*)
12		−40		NR	
13	**15**	0	15	92	21 (*S*)
14		−40	26	82	49 (*S*)
15	**16**	0	20	77	11 (*S*)
16		−40	26	73	8 (*S*)
17	**17**	0	16	85	25 (*S*)
18		−40	30	90	51 (*S*)

[a] The reaction conditions and analysis are similar to Table 3.

resonance ($CHCl_3$, δ 7.26) and splitting patterns were designated as s = singlet, d = doublet, t = triplet, quartet = q, and m = multiplet. The number of protons (*n*) for a given resonance is indicated by *n*H. Coupling constants are reported in Hertz. Phosphorus nuclear magnetic resonance spectra (^{31}P NMR) are reported as δ in units of parts per million (ppm) relative to external H_3PO_4 (δ 0.0). HPLC analysis was performed using Chiralcel OD column from DAICEL. Elemental analyses (C, H, N) were performed using Thermo Finnigan FLASH EA 1112 analyzer.

Literature methods were used for the preparation of [$PdCl_2$(1,5-COD)],[18] derivatives of ascorbic and isoascorbic acid: 3-(benzyloxy)-5-(1,2-dihydroxyethyl)-4-hydroxyfuran-2(5*H*)-one,[19] 4-(benzyloxy)-5-(1,2-dihydroxyethyl)-3-hydroxyfuran-2(5*H*)-one,[20] 3,4-bis(benzyloxy)-5-(1,2-dihydroxyethyl) furan-2(5*H*)-one,[20] complexes **1**–**2**,[11] and **6a**–**9a**.[16]

4.2. Synthesis of complexes 3–5 and 10–17[11]

4.2.1. [(2*R*,3*R*)-Diethyl 2,3-bis(diphenylphosphinooxy) succinate $PdCl_2$] 3. Light yellow crystals, yield 68%, $[\alpha]_D^{25} = +59.2$ (*c* 1.0, $CHCl_3$); ^{1}H NMR δ 7.77–7.85 (m, 8H, H_{arom}) 7.51–7.54 (m, 4H, H_{arom}) 7.38–7.42 (m, 8H, H_{arom}) 5.27 (s, 2H, C*H*OP) 3.96 (m, 4H, CH_2CH_3) 1.13 (t, $J = 7.6$, 6.8 Hz, 6H, CH_2CH_3). ^{31}P NMR δ 122.0 (s). Anal. Calcd for $C_{32}H_{32}P_2O_6PdCl_2$: C, 51.12; H, 4.29. Found: C, 51.08; H, 4.35.

4.2.2. [(2*S*,3*S*)-Diethyl 2,3-bis(diphenylphosphinooxy) succinate $PdCl_2$] 4. Yellow crystals, yield 71%, $[\alpha]_D^{25} = -52.9$ (*c* 1.0, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77–7.88 (m, 8H, H_{arom}) 7.51–7.54 (m, 4H, H_{arom}) 7.40–7.42 (m, 8H, H_{arom}) 5.26 (s, 2H, C*H*OP) 3.95 (m, 4H, CH_2CH_3) 1.14 (t, $J = 7.2$ Hz, 7.2 Hz, 6H, CH_2CH_3). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 122.0 (s). Anal. Calcd for $C_{32}H_{32}P_2O_6PdCl_2$: C, 51.12; H, 4.29. Found: C, 50.94; H, 4.36.

4.2.3. [(1*R*,2*R*)-1,2-Bis(diphenylphosphinooxy)-1,2-diphenylethane $PdCl_2$] 5. Colorless crystals, yield 88%, $[\alpha]_D^{25} = -9.9$ (*c* 2.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61–7.74 (m, 30H, H_{arom}) 5.10 (t, $J = 6.0$ Hz, 5.2 Hz,

1H, C*H*OP) ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 127.1 (s) Anal. Calcd for $C_{38}H_{32}P_2O_2PdCl_2{\cdot}CHCl_3$: C, 53.27; H, 3.78. Found: C, 53.19; H, 3.89.

4.3. General procedure for the synthesis of bisphosphinite complexes 6–9

4.3.1. [(*S*)-1,2-Bis(diphenylphosphinooxy)-1,1,2-triphenylethane PdCl$_2$] 6. The bisphosphinite ligand **6a** (0.157 mmol) was dissolved in 1 mL of dry THF and added to THF (5 mL) containing Pd(COD)Cl_2 (0.157 mmol) under dry nitrogen. The solution was stirred till it became a clear yellow solution (5 h). After 2 h, a yellow precipitate appeared which was filtered and washed with cold THF (5 mL) and diethyl ether (5 mL) to give a light yellow powder **6**, yield 77%. $[\alpha]_D^{25} = +12.8$ (*c* 2.0, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82–6.53 (m, 35H, Ph) 6.38 (d, $J = 16.0$ Hz 1H, C*H*OP). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 138.1 (d) $J_{PP} = 38.8$ Hz and 112.1 (d) $J_{PP} = 42.0$ Hz. Anal. Calcd for $C_{44}H_{36}P_2O_2PdCl_2$: C, 63.21; H, 4.34. Found: C, 63.16; H, 4.37.

4.3.2. [(3*S*,6*S*)-3,6-Bis(diphenylphosphinooxy)-hexahydrofuro[3,2-*b*]furan PdCl$_2$] 7. Yellow crystalline solid, yield 81%, $[\alpha]_D^{25} = +28.2$ (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93–7.23 (m, 20H, H_{arom}) 5.30 (d, $J = 12.0$ Hz, 2H, C*H*OP) 4.58 (s, 2H, C*H*OC) 3.97 (d, $J = 9.2$ Hz, 4H, CH_2O). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 104.0 (s). Anal. Calcd for $C_{30}H_{28}P_2O_4PdCl_2$: C, 52.08; H, 4.07. Found: C, 52.16; H, 4.27.

4.3.3. [*N*-((1*R*,2*R*)-1,3-Bis(benzhydryloxy)-1-(4-nitrophenyl)-propan-2-yl)-2,2-dichloroacetamide PdCl$_2$] 8. Yellow crystalline solid, yield 71%, $[\alpha]_D^{25} = +57.3$ (*c* 1.0, DMSO); ^{1}H NMR (400 MHz, $CDCl_3$+DMSO-d_6) δ 8.08–7.12 (m, 24H, H_{arom}) 6.37 (s, 1H, C*H*Cl$_2$) 5.54 (d, 1H, $J = 6.4$ Hz, C*H*OP) 4.31 (m, 2H, CH_2OP) 3.73 (m, 1H, C*H*N). ^{31}P NMR (162.02 MHz, $CDCl_3$+DMSO-d_6) δ 123.1 (d) and 121.8 (d) $J_{PP} = 38.8$ Hz. Anal. Calcd for $C_{35}H_{30}P_2N_2O_5PdCl_4$: C, 48.38; H, 3.48; N, 3.22. Found: C, 48.32; H, 3.52; N, 3.19.

4.3.4. [(*S*)-4-((1*R*,2*S*)-2-((*R*)-2,2-Dimethyl-1,3-dioxolan-4-yl)-1,2-bis(diphenylphosphinooxy)ethyl)-2,2-dimethyl-1,3-dioxolane PdCl$_2$] 9. Colorless crystalline solid, yield 65%, $[\alpha]_D^{25} = +28.4$ (*c* 0.5, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.99–7.34 (m, 20H, H_{arom}) 4.13 (d, 1H, $J = 5.2$ Hz, C*H*HC) 4.01 (d, 1H, $J = 4.8$ Hz, CH*H*C) 3.69 (dd, 1H, $J = 6.8$, 8.4 Hz, C*H*OC) 3.56 (dd, 2H, $J = 5.6$, 8.4 Hz, 2H, C*H*OP) 1.18 (s, 3H, CH_3) 1.03 (s, 3H, CH_3). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 125 (s). Anal. Calcd for $C_{36}H_{40}P_2O_6PdCl_2$: C, 53.51; H, 4.99. Found: C, 56.54; H, 5.16.

4.4. Synthesis of bisphosphinite complexes derived from ascorbic and isoascorbic acid

4.4.1. [(*R*)-5-((*S*)-1,2-Bis(diphenylphosphinooxy)ethyl)-3,4-dihydroxyfuran-2(5*H*)-one PdCl$_2$] 10. L-Ascorbic acid (0.012 g, 0.070 mmol) was dissolved in dry degassed THF (2 ml) containing DMF (0.1 mL) and HMPA (0.01 mL), and added dropwise to a stirred solution of [Pd(PPh$_2$Cl)$_2$Cl$_2$] (0.071 mmol) under nitrogen for 48 h at room temperature. The solvent was removed under vacuum and ether (10 mL) added to the residue which resulted in a gummy solid. The addition of chloroform gave a hazy solution that gradually precipitated the complex. The precipitate was filtered and washed with cold chloroform to give an off white powder **10**, 0.016 g, yield 32%, $[\alpha]_D^{25} = +21.2$ (*c* 1.0, DMSO); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87–7.35 (m, 20H, H_{arom}) 4.97 (br s, 1H, C*H*OP) 4.63 (s, 1H, C*H*OC) 4.38 (m, 1H, C*H*HOP) 4.06 (m, 1H, CH*H*OP) ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 120.5 (d) and 116.1 (d) $J = 27.5$ Hz. Anal. Calcd for $C_{30}H_{26}P_2O_6PdCl_2$: C, 49.92; H, 3.63. Found: C, 49.96; H, 3.68.

4.4.2. [(*R*)-5-((*S*)-1,2-Bis(diphenylphosphinooxy)ethyl)-3-(benzyloxy)-4-hydroxyfuran-2(5*H*)-one PdCl$_2$] 11. White powder, yield 61%, $[\alpha]_D^{25} = +19.9$ (*c* 1.6, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89–7.31 (m, 25H, H_{arom}) 5.46 (br s, 1H, C*H*OP) 4.83 (d, $J = 11.2$ Hz, 1H, C*H*OC) 4.70 (d, $J = 11.6$ Hz, 2H, CH_2Ph) 4.39 (m, 1H, C*H*HOP) 3.84 (m, 1H, CH*H*OP). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 123.6 (d) and 112.5 (d) $J_{PP} = 29.1$ Hz. Anal. Calcd for $C_{37}H_{32}P_2O_6PdCl_2{\cdot}CH_2Cl_2$: C, 54.73; H, 3.97. Found: C, 54.79; H, 3.92.

4.4.3. [(*R*)-5-((*S*)-1,2-Bis(diphenylphosphinooxy)ethyl)-4-(benzyloxy)-4-hydroxyfuran-2(5*H*)-one PdCl$_2$] 12. White powder, yield 58%, $[\alpha]_D^{25} = +31.2$ (*c* 1.8, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91–7.13 (m, 25H, H_{arom}) 5.35 (d, $J = 12$ Hz, 1H, C*H*HOPh) 5.21 (d, $J = 11.6$ Hz, 1H, CH*H*OPh) 4.57 (m, 1H, C*H*OP) 4.50 (m, 1H, C*H*OC) 4.27 (m, 1H, C*H*HOP) 4.22 (m, 1H, CH*H*OP). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 121.7 (d) and 121.2 (d) $J = 35.6$ Hz. Anal. Calcd for $C_{37}H_{32}P_2O_6PdCl_2$: C, 54.73; H, 3.97. Found: C, 54.70; H, 4.00.

4.4.4. [(*S*)-5-((*R*)-1,2-Bis(diphenylphosphinooxy)ethyl)-3,4-bis(benzyloxy)furan-2(5*H*)-one PdCl$_2$] 13. Off white powder, yield 77%, $[\alpha]_D^{25} = +42.1$ (*c* 1.4, $CHCl_3$); ^{1}H NMR δ 7.90–7.12 (m, 30H, H_{arom}) 5.15 (d, $J = 11.6$ Hz, 1H, C*H*HOPh) 5.06 (m, 2H, CH_2OPh) 4.76 (d, $J = 11.2$ Hz, 1H, CH*H*OPh) 4.54 (m, 1H, C*H*OP) 4.49 (s, 1H, C*H*OC) 4.19 (m, 2H, CH_2OP). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 122.0 (d) $J_{PP} = 34.0$ Hz and 121.3 (d) $J_{PP} = 35.6$ Hz. Anal. Calcd for $C_{44}H_{38}P_2O_6PdCl_2$: C, 58.59; H, 4.25. Found: C, 58.54; H, 4.44.

4.4.5. (*R*)-5-((*R*)-1,2-Bis(diphenylphosphinooxy)ethyl)-3,4-dihydroxyfuran-2(5*H*)-one PdCl$_2$] 14. Procedure was similar to **10** (in place of HMPA, DBU was used), light yellow powder, yield 34%, $[\alpha]_D^{25} = -18.6$ (*c* 0.6, DMSO); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90–7.23 (m, 20H, H_{arom}) 5.39 (br s, 1H, C*H*OP) 4.91 (s, 1H, C*H*OC) 4.25 (m, 1H, C*H*HOP) 3.73 (m, 1H, CH*H*OP). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 120.5 (d) and 116.1 (d) $J_{PP} = 27.5$ Hz. Anal. Calcd for $C_{30}H_{26}P_2O_6PdCl_2$: C, 49.92; H, 3.63. Found: C, 49.89; H, 3.66.

4.4.6. [(*R*)-5-((*R*)-1,2-Bis(diphenylphosphinooxy)ethyl)-3-(benzyloxy)-4-hydroxyfuran-2(5*H*)-one PdCl$_2$] 15. Light yellow powder, yield 61%, $[\alpha]_D^{25} = -23.6$ (*c* 1.1, $CHCl_3$);

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.78–7.04 (m, 25H, H_{arom}) 5.93 (br s, 1H, C*H*OP) 5.39 (s, 1H, C*H*OC) 5.06 (d, $J = 12.4$ Hz, 1H, C*H*HPh) 4.96 (d, $J = 11.6$ Hz, 1H, CH*H*Ph) 3.81 (m, 1H, C*H*HOP) 3.21 (d, $J = 12$ Hz, 1H, CH*H*OP). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 125.1 (d) and 109.1 (d) $J_{PP} = 25.9$ Hz. Anal. Calcd for $C_{37}H_{32}P_2O_6PdCl_2$: C, 54.73; H, 3.97. Found: C, 54.70; H, 4.01.

4.4.7. [(*R*)-5-((*R*)-1,2-Bis(diphenylphosphinooxy)ethyl)-4-(benzyloxy)-4-hydroxyfuran-2(5*H*)-one $PdCl_2$] 16. Off white powder, yield 55%, $[\alpha]_D^{25} = -37.3$ (*c* 1.8, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43–7.19 (m, 25H, H_{arom}) 5.33 (d, $J = 11.6$ Hz, 1H, C*H*HOP) 5.25 (d, 1H, CH*H*OP) 4.67 (m, 1H, C*H*OP) 4.57 (d, $J = 4.0$ Hz, 1H, C*H*OC) 4.13 (m, 1H, C*H*HOP) 3.96 (m, 1H, CH*H*OP). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 123.3 (d) $J_{PP} = 35.6$ Hz and 119.2 (d) $J_{PP} = 37.2$ Hz. Anal. Calcd for $C_{37}H_{32}P_2O_6PdCl_2$: C, 54.73; H, 3.97. Found: C, 54.80; H, 3.93.

4.4.8. [(*R*)-5-((*R*)-1,2-Bis(diphenylphosphinooxy)ethyl)-3,4-bis(benzyloxy)furan-2(5*H*)-one $PdCl_2$] 17. Off white powder, yield 75%, $[\alpha]_D^{25} = -33.9$ (*c* 2.0, $CHCl_3$); ^{1}H NMR; δ 7.90–7.03 (m, 30H, H_{arom}) 5.11–4.86 (m, 4H, 2CH_2OPh) 4.79 (m, 1H, C*H*OP) 4.55 (d, $J = 3.6$ Hz, 1H, C*H*OP) 4.07 (m, 1H, C*H*HOP) 3.69 (m, 1H, CH*H*OP). ^{31}P NMR (162.02 MHz, $CDCl_3$) δ 124.6 (d) and 117.2 (d) $J_{PP} = 35.6$ Hz. Anal. Calcd for $C_{44}H_{38}P_2O_6PdCl_2$: C, 58.59; H, 4.25. Found: C, 58.63; H, 4.29.

4.5. (*E*)-Dimethyl 2-(1,3-diphenylallyl)malonate 19

A mixture of complex **1** (0.05 mg, 0.079 μmol) and acetate **18** (20 mg, 0.079 mmol) was stirred in 0.5 mL of dichloromethane at room temperature for 30 min to give a clear light yellow solution. Potassium acetate (23.2 mg, 0.237 mmol) was added and stirred for 5 min. To this solution a mixture of *N*,*O*-bis(trimethylsilyl)acetamide (BSA) (48.1 mg, 0.0586 mL, 0.237 mmol) and dimethyl malonate (DMM) (31.3 mg, 0.0272 mL, 0.237 mmol) in 0.5 mL of dichloromethane was added and stirred at room temperature for 9 h. The reaction was monitored by TLC (5% ether in hexane), product $R_f = 0.46$. The reaction was quenched with saturated NH_4Cl and extracted with CH_2Cl_2 (3×10 mL). The organic layer was washed with brine, water and dried over Na_2SO_4. The solvent was evaporated under reduced pressure. The crude mixture was purified by column chromatography (AcOEt/petroleum ether 1/9) to afford a colorless oil **19** that solidified on standing. Yield 0.021 g, 84%, 12% ee (*R*). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29–7.20 (m, 10H, H_{arom}) 6.48 (d, $J = 15.6$ Hz, 1H, CH) 6.32 (dd, $J = 8.4$, 15.6 Hz, 1H, CH) 4.27 (dd, $J = 8.8$, 10.4 Hz, 1H, CH) 3.95 (d, $J = 10.8$ Hz, 1H, CH) 3.70 (s, 3H, Me) 3.52 (s, 3H, Me). The enantiomeric excess was determined by Chiral HPLC analysis (eluent: *n*-hexane/*i*-propanol = 98/02) flow rate: 0.5 mL/min, retention times: 16.8 min (*R*) and 17.9 (*S*). It has been established that the (*R*)-enantiomer elutes first.[21]

4.6. Crystal data

Suitable single crystals were mounted and X-ray diffraction data were collected on a SMART APEX CCD diffractometer (graphite-monochromated Mo-Kα radiation, Π–ω-scan technique, $\lambda = 0.71073$ Å). The intensity data were integrated by means of the SAINT program.[22] SADABS[23] was used to perform area-detector scaling and absorption corrections. The structures were solved by direct methods and were refined against F^2 using all reflections with the aid of the SHELXTL package.[24] All non-hydrogen atoms were refined anisotropically. The H atoms were included in the calculated positions with isotropic thermal parameters related to those of the supporting carbon atoms, but were not included in the refinement. All non-hydrogen atoms were found from the different Fourier syntheses. All calculations were performed using the BRUKER SMART program.

4.6.1. Complex 1. (CCDC 662048): $PdCl_2(C_{32}H_{28}O_2P_2)\cdot CHCl_3$, $M = 803.15$; monoclinic, space group $P2_1$, $a = 9.437(5)$, $b = 17.574(10)$, $c = 11.074(6)$ Å, $\beta = 109.929(9)°$, $V = 1722.4(17)$ Å^3, $T = 293(2)$ K, $Z = 2$, $\mu = 1.049$ mm^{-1}, $R_{int} = 0.0154$ (for 13,666 measured reflections), $R_1 = 0.0257$ [for 6436 unique reflections with $I > 2\sigma(I)$], $wR_2 = 0.0653$ (for all 6936 unique reflections).

4.6.2. Complex 2. (CCDC 662049): $PdCl_2(C_{32}H_{28}O_2P_2)\cdot CH_2Cl_2$, $M = 768.71$; monoclinic, space group $P2_1$, $a = 9.0562(9)$, $b = 17.6441(18)$, $c = 11.2785(12)$ Å, $\beta = 109.463(2)°$, $V = 1699.2(3)$ Å^3, $T = 293(2)$ K, $Z = 2$, $\mu = 0.983$ mm^{-1}, $R_{int} = 0.0186$ (for 13,658 measured reflections), $R_1 = 0.0414$ [for 5853 unique reflections with $I > 2\sigma(I)$], $wR_2 = 0.0653$ (for all 6694 unique reflections).

4.6.3. Complex 3. (CCDC 662050): $PdCl_2(C_{32}H_{32}O_6P_2)$, $M = 751.82$; monoclinic, space group $P2_1$, $a = 20.961(5)$, $b = 10.978(2)$, $c = 14.804(3)$ Å, $\beta = 109.889(3)°$, $V = 3203.4(12)$ Å^3, $T = 293(2)$ K, $Z = 4$, $\mu = 0.889$ mm^{-1}, $R_{int} = 0.0310$ (for 18,739 measured reflections), $R_1 = 0.0357$ [for 6583 unique reflections with $I > 2\sigma(I)$], $wR_2 = 0.0713$ (for all 7464 unique reflections).

4.6.4. Complex 4. (CCDC 662051): $PdCl_2(C_{32}H_{32}O_6P_2)$, $M = 751.82$; monoclinic, space group $P2_1$, $a = 20.977(5)$, $b = 10.990(5)$, $c = 14.811(5)$ Å, $\beta = 109.859(5)°$, $V = 3211(2)$ Å^3, $T = 293(2)$ K, $Z = 4$, $\mu = 0.887$ mm^{-1}, $R_{int} = 0.0320$ (for 14,207 measured reflections), $R_1 = 0.0473$ [for 6392 unique reflections with $I > 2\sigma(I)$], $wR_2 = 0.0906$ (for all 7422 unique reflections).

4.6.5. Complex 5. (CCDC 662052): $PdCl_2(C_{38}H_{32}O_2P_2)\cdot CHCl_3$, $M = 879.24$; monoclinic, space group $P2_1$, $a = 9.859(2)$, $b = 17.537(4)$, $c = 11.239(2)$ Å, $\beta = 92.084(4)°$, $V = 1942.0(7)$ Å^3, $T = 293(2)$ K, $Z = 2$, $\mu = 0.938$ mm^{-1}, $R_{int} = 0.0458$ (for 22,769 measured reflections), $R_1 = 0.0478$ [for 7147 unique reflections with $I > 2\sigma(I)$], $wR_2 = 0.1021$ (for all 9052 unique reflections).

4.6.6. Complex 6. (CCDC 662053): $PdCl_2(C_{44}H_{36}O_2P_2)$, $M = 835.97$; orthorhombic, space group $P2_12_12_1$, $a = 12.6654(11)$, $b = 12.7093(11)$, $c = 48.957(4)$ Å, $\beta =$

90.000°, $V = 7880.4(12)$ Å^3, $T = 293(2)$ K, $Z = 8$, $\mu = 0.724$ mm^{-1}, $R_{int} = 0.0458$ (for 68,947 measured reflections), $R_1 = 0.0411$ [for 16,032 unique reflections with $I > 2\sigma(I)$], $wR_2 = 0.907$ (for all 18,515 unique reflections).

4.6.7. Complex 7. (CCDC 662054): $PdCl_2(C_{30}H_{28}O_4P_2)$, $M = 879.24$; monoclinic, space group $P2_1$, $a = 9.656(2)$, $b = 16.294(4)$, $c = 9.840(2)$ Å, $\beta = 111.811(4)°$, $V = 1437(5)$ Å^3, $T = 293(2)$ K, $Z = 2$, $\mu = 0.978$ mm^{-1}, $R_{int} = 0.0692$ (for 11,992 measured reflections), $R_1 = 0.0675$ [for 4295 unique reflections with $I > 2\sigma(I)$], $wR_2 = 0.1660$ (for all 5952 unique reflections).

4.6.8. Complex 8. (CCDC 662055): $PdCl_2(C_{35}H_{29}N_2O_5P_2)$. 9O, $M = 1011.74$; orthorhombic, space group $P2_12_12_1$, $a = 13.849(3)$, $b = 14.502(3)$, $c = 25.311(5)$ Å, $\beta = 90.000$, $V = 5083.2$ (18) Å^3, $T = 293(2)$ K, $Z = 4$, $\mu = 0.693$ mm^{-1}, $R_{int} = 0.1077$ (for 36,766 measured reflections), $R_1 = 0.1029$ [for 5985 unique reflections with $I > 2\sigma(I)$], $wR_2 = 0.2701$ (for all 8962 unique reflections).

4.6.9. Complex 9. (CCDC 662056): $PdCl_2(C_{36}H_{40}O_6P_2)$, $M = 807.92$; monoclinic, space group $P2_1$, $a = 11.246(2)$, $b = 26.679(5)$, $c = 12.173(3)$ Å, $\beta = 91.608(4)°$, $V = 3650.7(13)$ Å^3, $T = 293(2)$ K, $Z = 4$, $\mu = 0.786$ mm^{-1}, $R_{int} = 0.0332$ (for 25,984 measured reflections), $R_1 = 0.0468$ [for 10,591 unique reflections with $I > 2\sigma(I)$], $wR_2 = 0.0892$ (for all 12,311 unique reflections).

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