DOI: 10.1002/chem.200903158

Phosphine Ligands in the Palladium-Catalysed Methoxycarbonylation of Ethene: Insights into the Catalytic Cycle through an HP NMR Spectroscopic Study

Verónica de la Fuente,[a] Mark Waugh,[b] Graham R. Eastham,*[b] Jonathan A. Iggo,*[c] Sergio Castillón,[d] and Carmen Claver*[a]

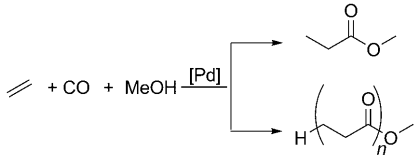
Abstract: Novel *cis*-1,2-bis(di-*tert*-butyl-phosphinomethyl) carbocyclic ligands **6**–**9** have been prepared and the corresponding palladium complexes $[Pd(O_3SCH_3)(L\text{-}L)][O_3SCH_3]$ (L-L = diphosphine) **32**–**35** synthesised and characterised by NMR spectroscopy and X-ray diffraction. These diphosphine ligands give very active catalysts for the palladium-catalysed methoxycarbonylation of ethene. The activity varies with the size of the carbocyclic backbone, ligands **7** and **9**, containing four- and six-membered ring backbones giving more active systems. The acid used as co-catalyst has a strong influence on the activity, with excess trifluoroacetic acid affording the highest conversion, whereas excess methyl sulfonic acid inhibits the catalytic system. An in operando NMR spectroscopic mechanistic study has established the catalytic cycle and resting state of the catalyst under operating reaction conditions. Although the catalysis follows the hydride pathway, the resting state is shown to be the hydride precursor complex $[Pd(O_3SCH_3)(L\text{-}L)][O_3SCH_3]$, which demonstrates that an isolable/detectable hydride complex is not a prerequisite for this mechanism.

Keywords: hydroesterification · methoxycarbonylation · NMR spectroscopy · palladium · X-ray diffraction

Introduction

Alkoxycarbonylation reactions are one of the most important industrial processes using homogeneous transition-metal catalysts.[1–16] In these reactions, a low-cost substrate is transformed into compounds of industrial interest by using a palladium catalyst. Phosphine ligands and the presence of acid are required to stabilize the palladium intermediates in the reaction.[13]

In the case of ethene, polyketones and/or low boiling liquids, such as methyl propanoate ($n = 1$) can be obtained (Scheme 1),[9,17] the selectivity of the reaction showing a marked dependence on the nature of the phosphine ligand employed. There have been many experimental[11–12,18–49] and theoretical studies of the reaction.[50–52] Initially, it was concluded that monodentate phosphines favour hydroesterification of ethene to give methyl propanoate, whereas bidentate phosphines lead to polyketones.[9] Subsequently, van Leeuwen showed that the chemoselectivity of the reaction can be



Scheme 1. Methoxycarbonylation versus copolymerisation of ethene.

[a] Dipl.-Chem. V. de la Fuente, Prof. Dr. C. Claver
Departament de Química Física i Inorgànica
Universitat Rovira i Virgili, C/Marcel·lí Domingo s/n
43007 Tarragona (Spain)
Fax: (+34) 97-755-9563
E-mail: carmen.claver@urv.cat

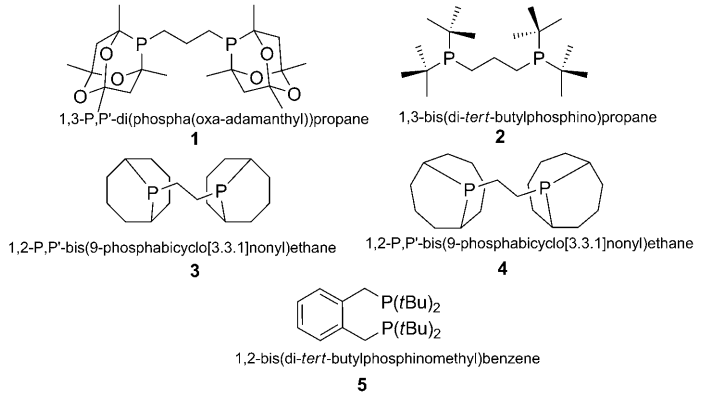
[b] Dr. M. Waugh, Dr. G. R. Eastham
Lucite International, Technology Centre
PO Box 90, Wilton, Middlesborough
Cleveland, TS68 JE (UK)

[c] Dr. J. A. Iggo
Department of Chemistry, University of Liverpool
Oxford Street, Liverpool, L69 7ZD (UK)

[d] Prof. Dr. S. Castillón
Departament de Química Analítica i Orgànica
Universitat Rovira i Virgili, C/Marcel·lí Domingo s/n
43007 Tarragona (Spain)

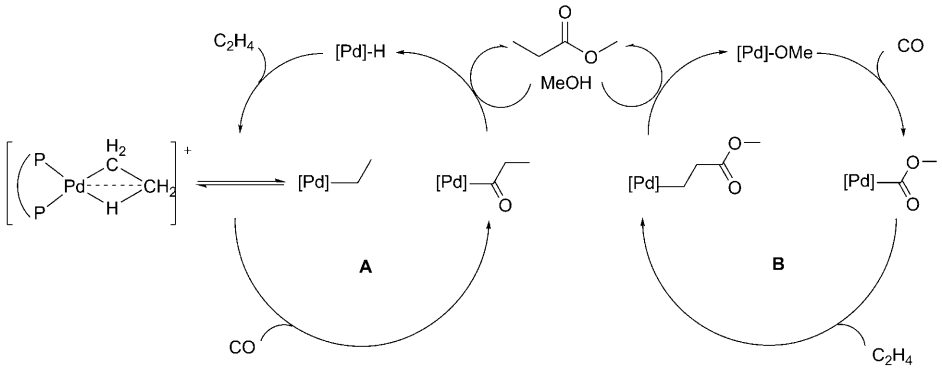
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.200903158.

controlled by the appropriate choice of the diphosphine ligand, methoxycarbonylation being favoured by sterically hindered diphosphines.[50] Recent computational studies also concluded that sterically bulky diphosphine ligands strongly favour ester formation over polymerisation.[51] Extensive screening of monodentate and bidentate ligands has shown[17,53] that trialkyl phosphine ligands, such as P(nBu$_3$), are more effective than aryl monodentate phosphines, for example, PPh$_3$, in the methoxycarbonylation of olefins with [Pd(OAc)$_2$L$_2$/L] catalysts. Similarly, alkyl diphosphine ligands containing bulky end groups (**1**–**4**) are preferred, affording methyl propanoate with 98% selectivity.[53]



In the 1990s, ICI developed a highly active and selective catalyst for the formation of methyl propanoate by the palladium-catalysed methoxycarbonylation of ethene.[2] This process similarly uses sterically bulky diphosphine ligands in the methoxycarbonylation of ethene giving methyl propanoate with > 99.9% selectivity with a turnover frequency of 50000 mol product per mol of palladium per hour, under very mild conditions (353 K and 10 atm. pressure of CO–C_2H_4).[3,13] This technology has been commercialised as the Lucite ALPHA process.[4] The catalyst is generated in situ from [Pd$_2$(dba)$_3$] (dba = dibenzylideneacetone), 1,2-bis(di-*tert*-butylphosphinomethyl)benzene (**5**, ALPHA), and methanesulfonic acid.

The mechanism of palladium-catalysed methoxycarbonylation of ethene has been studied by using NMR and IR spectroscopic techniques, and it has been shown that the reaction can occur through two different pathways (Scheme 2).[43,45,54–55]

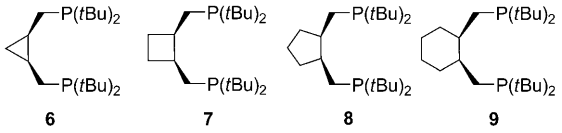


Scheme 2. Proposed mechanisms for the methoxycarbonylation of ethene: A = hydride cycle, B = methoxycarbonyl cycle (□ indicates different groups coordinated to palladium along the catalytic cycle.).

The hydride mechanism (A) starts with the formation of a palladium hydride complex.[43] Coordination of ethene, followed by insertion into the Pd–H bond then affords a Pd–alkyl complex, which is transformed into an acyl complex by the migratory insertion of CO.[45] Inter- or intramolecular nucleophilic attack of methanol on the acyl carbonyl leads to the formation of methyl propanoate and reformation of the palladium hydride species, completing the catalytic cycle.[11,41,47] The methoxycarbonyl mechanism (B) starts with a Pd–OMe complex[1,40] Then, the insertion of CO into the Pd–OMe bond leads to the formation of a methoxycarbonyl complex. Coordination and insertion of ethene followed by methanolysis then occurs to give the product and regenerate the catalyst.[40]

There is a lot of evidence and general agreement that systems affording ester product operate exclusively by the hydride catalytic cycle,[45] and that both cycles operate in copolymerisation catalysis.[40]

In the light of the known influence of ligand structure on the catalysis, and particularly the influence of alkyl substituents, we have prepared the novel diphosphine ligands **6**–**9**



that are related to **5**, but have saturated cycloalkyl backbones, which confers flexibility on the ligand backbone. We have also prepared and characterized by X-ray diffraction, the corresponding palladium(II) phosphine complexes and compared the structural features of the complexes. The performance of these ligands/complexes in the Pd-catalysed methoxycarbonylation of ethene has been determined and an in operando mechanistic study performed.

Results and Discussion

Synthesis of the phosphine ligands: The bidentate phosphine ligands **6**–**9** with a saturated alkyl ring backbone containing

three, four, five and six carbon atoms, respectively, were synthesised from the diols **10–13** in a three-step synthesis (Scheme 3).

The diol *cis*-1,2-cyclohexanedimethanol (**13**) is commercially available, whereas the diols **10**[56,57] and **11**[56,57] were prepared by reduction of dimethyl *cis*-cyclopropane-1,2-dicarboxylate (**18**) and *cis*-cyclobutane-1,2-dicarboxylic acid (**19**), respectively, with lithium aluminium hydride (Scheme 4a). *cis*-Cyclopentane-1,2-dimethanol (**12**)[57,58] was prepared in three steps from ethyl 2-oxocyclohexanecarboxylate (**20**) by bromination to give compound **21**, followed by treatment in a basic medium to induce a Favorskii[59] rearrangement affording the diacid **22** and finally reduction with lithium aluminium hydride (Scheme 4b).

The diols **10–13** were then converted in high yield to the dibromo compounds **14–17** by reaction with in situ prepared PPh_3Br_2.[60] The dibromides are easily separated from the triphenylphosphine oxide by-product by extraction into pentane (Scheme 3).

Reaction of the dibromides **14–17** with the lithium salt of the boron-protected secondary phosphine $tBu_2PH{\cdot}BH_3$ (**27**) gave the boron-protected bidentate phosphine ligands **23–26**.[61,62] Deboronation of the phosphines **23–26** was achieved by the addition of an excess of tetrafluoroboric acid to give an in situ prepared phosphonium salt that was then reduced to the desired phosphine by the addition of potassium hydroxide.[61] $^{31}P\{^1H\}$ NMR spectroscopic data for the four novel diphosphine ligands **6**, **7**, **8** and **9** are given in Table 1.

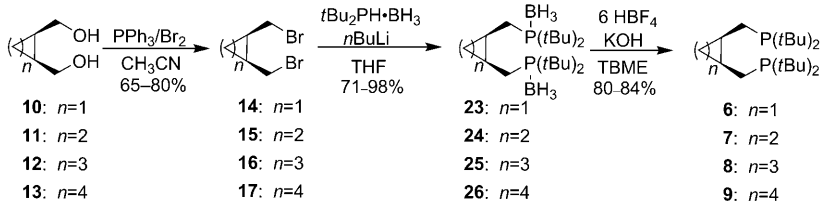
We have also prepared the phosphine diselenides of ligands **5–9** to establish any differences in the electronic properties and basicity of the ligands by the ^{31}P–^{77}Se coupling constant (Table 1). The variation in $J(^{31}P$–$^{77}Se)$ between **5–9** is small compared with the range of values for ^{31}P–^{77}Se couplings reported previously for other phosphine selenides,[63,64] thus we conclude that all the diphosphines used in this study should have comparable electronic properties. However, a titrimetric study of the protonation of diphosphines **5–9** indicated that the basicity of the cycloalkyl diphosphines is significantly greater than that of ligand **5** (Table 2, see also the Supporting Information). Thus, Table 2 reveals that diprotonation of the cycloalkyl ligands

Table 1. $^{31}P\{^1H\}$ NMR spectroscopic data for **5–9** and for the corresponding diselenides.

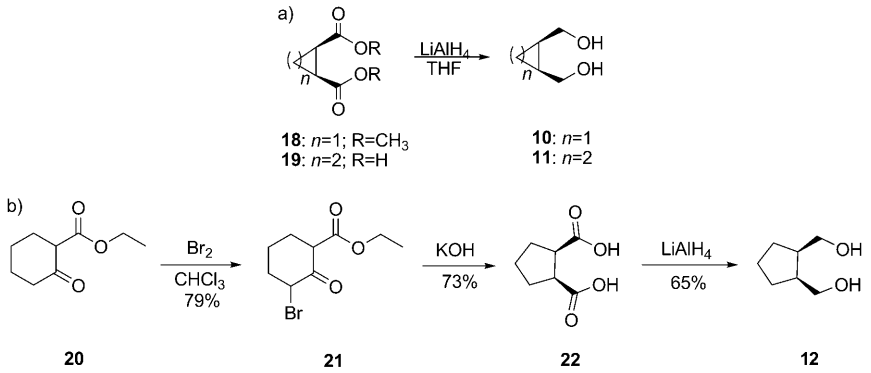
Entry	Ligand	Ligand backbone	$\delta(^{31}P)$ [ppm]	Diselenide	
				$\delta(^{31}P)$ [ppm]	J_{P-Se} [Hz]
1	**5**	xylene	25.3	77.4	695
2	**6**	cyclopropane	30.0	77.5	691
3	**7**	cyclobutane	20.9	74.7	687
4	**8**	cyclopentane	24.3	80.3	688
5	**9**	cyclohexane	24.7	81.3	689

Table 2. Equilibrium constants for protonation of the ligands **5–9**.

Entry	Ligand	pK		Equilibrium constant	
		pk_1	pk_2	K_1	K_2
1	**5**	1.12	0.56	0.075	0.275
2	**6**	–	1.01	–	0.098
3	**7**	–	1.21	–	0.062
4	**8**	1.51	1.12	0.031	0.075
5	**9**	0.98	0.77	0.105	0.170



Scheme 3. Synthesis of phosphines **6–9** from diols **10–13**.



Scheme 4. Synthesis of diols **10–12**.

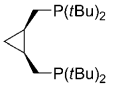
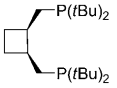
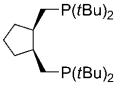
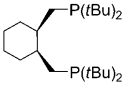
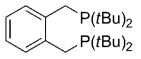
6–9 occurs at a higher pH than for ligand **5**, and that diprotonation of ligands **6** and **7** is strongly favoured compared to diprotonation of ligand **5**.

We show below that the bite angle of the cycloalkyl ligands **6–9** and ligand **5** are practically identical (see Table 3), differences in catalytic activity between **5** and **6–9** should, therefore, reflect the differences in basicity of the ligands and, possibly, the flexibility of the ligand backbone.

Synthesis and characterization of cationic palladium complexes $[Pd(O_3SCH_3)(L\text{-}L)]^+$

Synthesis of cationic complexes: The palladium complexes **32–35** containing ligands **6–9** have been prepared and the X-ray

Table 3. Selected X-ray data of complexes **32**–**36**.

Complex		$[Pd(O_3SCH_3)(\mathbf{6})]^+$ (**32**)	$[Pd(O_3SCH_3)(\mathbf{7})]^+$ (**33**)	$[Pd(O_3SCH_3)(\mathbf{8})]^+$ (**34**)		$[Pd(O_3SCH_3)(\mathbf{9})]^+$ (**35**)	$[Pd(O_3SCH_3)(\mathbf{5})]^+$ (**36**)
(L-L)							
ligand bite angle		101.2	100.6	99.4		100.9	100.6
bond lengths	a	2.272(4)	2.262(10)	2.285(9)	2.267(8)	2.285(9)	2.273(8)
	b	2.276(4)	2.266(11)	2.283(10)	2.273(66)	2.283(10)	2.268(8)
	c	2.182(11)	2.194(3)	2.184(2)	2.172(80)	2.184(2)	2.174(2)
	d	2.197(11)	2.194(2)	2.187(2)	2.188(38)	2.187(2)	2.199(3)
bond angles	a–b	100.55(16)	99.09(4)	100.94(3)	100.58(7)	100.94(3)	101.23(3)
	a–c	160.57(3)	162.93(7)	161.97(6)	160.99(13)	161.97(6)	162.79(7)
	a–d	95.61(3)	97.83(7)	96.97(6)	95.82(13)	96.97(6)	97.29(7)
	b–c	98.48(3)	97.96(7)	97.08(6)	98.19(13)	97.08(6)	95.86(7)
	b–d	163.84(3)	163.05(7)	162.09(6)	163.21(14)	162.09(6)	161.21(7)
	c–d	65.38(4)	65.11(9)	65.01(8)	65.68(17)	65.01(8)	65.53(9)

crystal structures of the complexes determined to compare the structural features of these complexes with those of the palladium complex of the reference ligand **5**, with the aim of establishing structure–catalytic performance correlations.

Direct reaction of diphosphines **6**–**9** with $[Pd_2(dba)_3]$ affords the [Pd(dba)(diphosphine)] complexes **28**–**31**. These complexes can then be oxidized (without prior isolation) in the presence of traces of O_2 to give the palladium(II) complexes[43] **32**–**35** by the addition of two equivalents of methanesulfonic acid (Scheme 5).

*X-ray crystal structures of cationic palladium complexes **32**–**35***: Single crystals suitable for X-ray crystal structure determinations were obtained by slow diffusion of diethyl ether (**32**, **33** and **35**) or *tert*-butyl methyl ether (**34**) into tetrahydrofuran solutions of the complexes.

In the X-ray structure of the complexes **32**–**35**, two sulfonate ions (one coordinated and the other as the counterion) and one molecule of sulfonic acid are present. During the formation of the single crystals, some palladium black precipitated, probably as a result of decoordination of sulfonate, which provides the additional sulfonic acid molecule that was observed in the crystal structure.

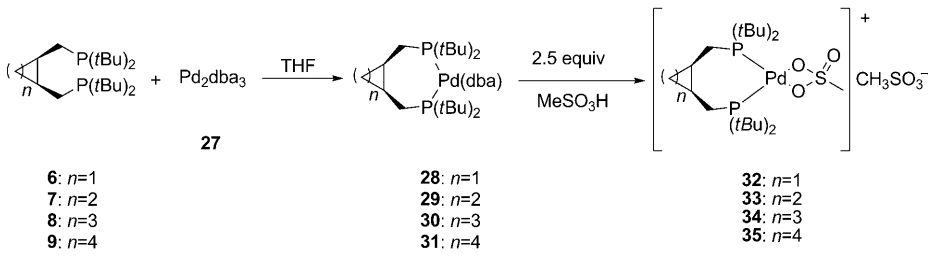
$[Pd(O_3SCH_3)(\mathbf{6})][O_3SCH_3]$ (**32**) crystallizes in a monoclinic space group with unit cell parameters $a=9.8572(14)$, $b=12.8636(18)$, $c=26.605(4)$ Å and $V=3326.6(8)$ Å^3. The structure was solved in space group $P2_1/c$. The $R1$ value is 0.0449.

The asymmetric unit of the structure contains one cation (with a single bidentate sulfonate ligand), one sulfonate anion and one sulfonic acid molecule (Figure 1). The palladium atom is coordinated in a square-planar geometry. There is disorder in the coordinated sulfonate and in what is presumed to be the sulfonic acid molecule for which the acid H atom was not located and the assignment of oxygen and methyl was based on interatomic distances.

$[Pd(O_3SCH_3)(\mathbf{7})][O_3SCH_3]$ (**33**) crystallizes in a triclinic space group with $a=11.2245(12)$, $b=13.0794(14)$, $c=16.0019(17)$ Å and $V=2113.4(4)$ Å^3. The structure was solved in space group $P\bar{1}$. The $R1$ value is 0.0233. The asymmetric unit of the structure contains one cation (with a single bidentate sulfonate ligand), one sulfonate anion, one sulfonic acid molecule (hydrogen bonded to the sulfonate anion, with an essentially symmetrical hydrogen bond) and two molecules of THF (Figure 1). The palladium atom is coordinated in a square-planar geometry. There is no disorder in the structure. Hydrogen atoms are omitted in this figure, except for the one involved in the hydrogen bond.

Compound $[Pd(O_3SCH_3)(\mathbf{8})]O_3SCH_3$ (**34**) crystallizes in a triclinic space group with $a=10.8149(13)$, $b=11.278(2)$, $c=31.700(5)$ Å and $V=3376.7(9)$ Å^3. The structure was solved in space group $P\bar{1}$. The $R1$ value is 0.0396. The asymmetric unit contains two cations, two uncoordinated anions (one of which is disordered, the second component is not shown in the figure), a sulfonic acid molecule and a water molecule (these form hydrogen bonds). The palladium atom is coordinated in a square-planar geometry. The five-membered ring has an envelope conformation (Figure 1).

Compound $[Pd(O_3SCH_3)(\mathbf{9})][O_3SCH_3]$ (**35**) crystallizes in a monoclinic space group with $a=20.680(4)$, $b=11.156(2)$, $c=32.862(7)$ Å and $V=7397(3)$ Å^3. The structure was solved in

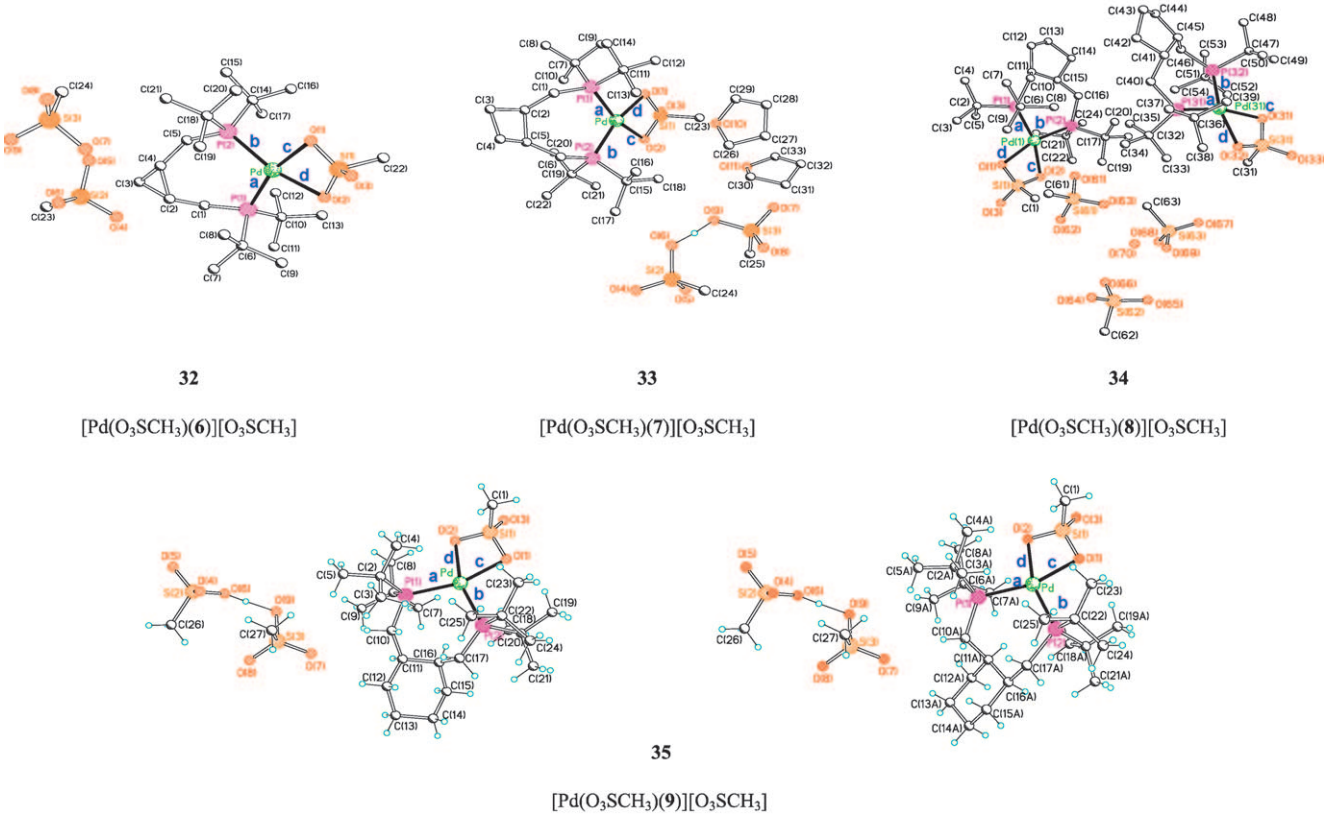


6: *n*=1
7: *n*=2
8: *n*=3
9: *n*=4

28: *n*=1
29: *n*=2
30: *n*=3
31: *n*=4

32: *n*=1
33: *n*=2
34: *n*=3
35: *n*=4

Scheme 5. Synthesis of Pd^{II} complexes **32**–**35**.



32

$[Pd(O_3SCH_3)(\mathbf{6})][O_3SCH_3]$

33

$[Pd(O_3SCH_3)(\mathbf{7})][O_3SCH_3]$

34

$[Pd(O_3SCH_3)(\mathbf{8})][O_3SCH_3]$

35

$[Pd(O_3SCH_3)(\mathbf{9})][O_3SCH_3]$

Figure 1. X-ray crystal structure of complexes **32**–**35**.

space group *C*2/*c*. The *R*1 value is 0.0353. The palladium atom is coordinated in a square-planar geometry. The six-membered ring has two disordered conformations in the structure, which represent the chair and boat conformations of the ligand (Figure 1). Only C and H atoms are affected, and the metal coordination remains the same. The uncoordinated anion and acid molecule are hydrogen bonded together. Table 3 compares the bond lengths, and interbond angles in **32**–**35** with those of the [1,2-bis(di-*tert*-butylphosphinomethyl)benzene] palladium(II) complex (**36**).[55] Bond lengths and angles are broadly comparable across the five complexes. The (P-Pd-P) bite angles of the ligand in **32**, **33** and **35** are 101.23, 100.55 and 100.94°, respectively, and in **34**, in which two cations are present, the bite angles are 99.09 and 99.42°. The palladium(II) complex of the cyclopentane-based phosphine (**8**) has the smallest bite angle of the four cycloalkyl phosphines at (av. 99.25°), whereas the palladium(II) complex of the cyclopropane-based phosphine (**6**) has the largest bite angle at (101.2°). The bite angle of the cyclobutane-based phosphine (**7**) in **33** is similar to that of 1,2-bis(di-*tert*-butylphosphinomethyl)benzene in **36**. We conclude that all these palladium complexes might be expected to show a similar catalytic performance (vide infra) if this is determined by ligand bite angle.[65]

Methoxycarbonylation of ethene: Table 4 reports the catalyst performance for the diphosphines **6**–**9** in the palladium-catalysed methoxycarbonylation of ethene to methyl propanoate (Scheme 1). The catalytic systems were prepared in situ by adding the diphosphine ligand (**5**–**9**) to a solution of $Pd(OAc)_2$ in MeOH/methyl propanoate to form the complexes **37**–**41** followed by the addition of methanesulfonic acid to give the catalyst precursors **32**–**36**. The catalytic solutions were introduced into the autoclave under vacuum, which was then charged with 20 bar of ethene and 45 bar of carbon monoxide. The overall ratio Pd/L/$MeSO_3H$ was 1:3:2.5.

Table 4. Palladium-catalysed methoxycarbonylation of ethene by using diphosphines **5**–**9**.[a]

Entry	Ligand	X [g][b]	TON[c]	Average rate[d]
1	**5**	21.1	630	315
2	**6**	21.6	646	323
3	**7**	33.4	997	499
4	**8**	8.2	245	123
5	**9**	25.4	758	379

[a] Pd/L/$MeSO_3H$ 1:3:2.5; substrate/Pd 1079; $Pd(OAc)_2$ (5.98×10^{-4} mol), $MeSO_3H$ (1.50×10^{-3} mol), ethene (0.65 mol); $P_{ethene}=20$ bar, $P_{CO}=45$ bar; methyl propanoate (180 mL), MeOH (120 mL); $T=100$ °C. [b] Grams of methyl propionate produced during the reaction. [c] Turnover number. [d] Average rate during the catalytic reaction [s^{-1}].

Ligands **6**–**9** vary both in the size of the cyclic backbone, and consequently the conformational freedom of the ligand, and in relative basicity (vide supra). The catalytic systems

incorporating ligands **6**, **7** and **9**, with three-, four- and six-membered rings in the ligand backbone, were all more active than the catalytic system with ligand **5** albeit with ligand **6** only marginally more active (compare Table 4, entries 2, 3 and 5 with 1). The catalytic systems incorporating ligands **6**, **7** and **9** are all significantly more active than that with ligand **8** containing a five-membered ring (entry 4). There is, thus, no clear correlation between flexibility in the chelate ring and catalyst performance. However, in contrast to the commercialized system incorporating ligand **5**, for which higher turnover numbers are obtained on increasing the amount of acid present,[56–57] we find that the $Pd(OAc)_2$/**6–9** systems are deactivated by an excess of methanesulfonic acid. Thus, on changing the acid to palladium ratio from 2.5:1 to 12.5:1, low yields of methyl propanoate, and large amounts of palladium black are observed. We attribute this to the protonation of the more basic cycloalkyl ligands (Table 2). Thus, in NMR spectroscopic experiments in which 12.5 equivalents of methanesulfonic acid were added to solutions containing **37–40** in methanol, immediate formation of the protonated phosphines (**42–45**) and Pd metal was observed (Scheme 6c). However, when the protonated diphosphines **42–45**, obtained by adding 3.3 equivalents of methanesulfonic acid to ligands **6–9**, were allowed to react with $Pd(OAc)_2$, the catalyst precursors **32–35** were formed (Scheme 6d). This is consistent with the redistribution of the various equilibria involving protonated phosphine, free acid and palladium coordinated phosphine, the differing basicities of **5** versus **6–9** resulting in differing concentration effects on the position of the equilibrium. When excess methanesulfonic acid is present, the more basic ligands **6–9** remain protonated, and thus unable to complex Pd, whereas the less basic ligand **5** is deprotonated in the presence of palladium acetate leading to complex formation. However, when no excess of acid over ligand is present, protonated phosphines can be deprotonated by the acetate ion, leading to complexes **32–35**.

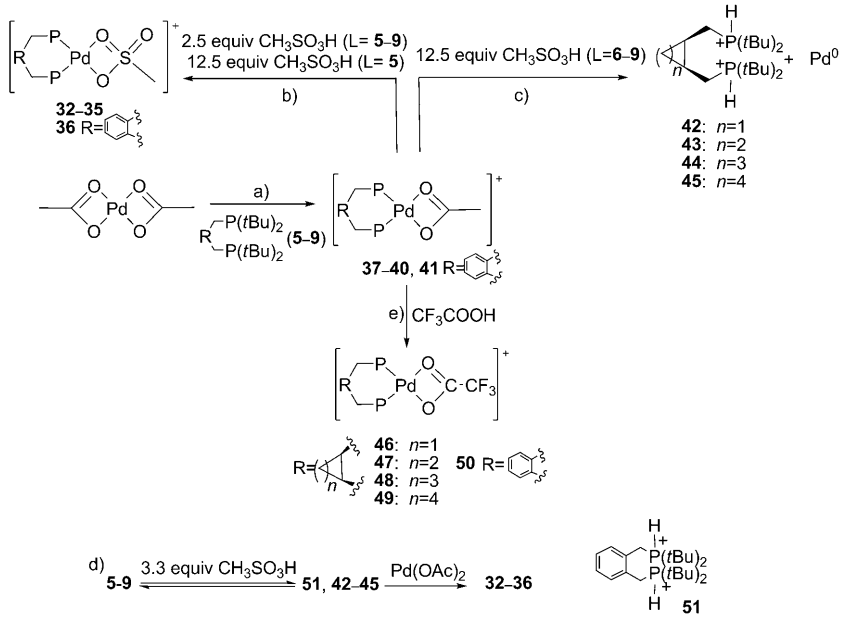
Consistent with this hypothesis, good catalytic results were obtained upon using a large excess of the weaker acid, trifluroacetic acid ($pK_a = 0.5$). Under these conditions, the catalytic activity of the system $Pd(OAc)_2$/**5**/TFA is similar to that obtained in the presence of $MeSO_3H$ (cf. Tables 4 and 5, entry 1). The systems with cycloalkyl ligands **7** and **9** are again slightly more active than the system with ligand **5** (Tables 4 and 5, entries 3 and 5 vs. 1). However, ligand **8** affords significantly higher (Tables 4 and 5, entry 4) and ligand **6** significantly lower (Tables 4 and 5, entry 2) activity. These results illustrate the complexity of homogeneous catalysis and the dependence of each catalyst system on several factors.

Table 5. Palladium-catalysed methoxycarbonylation of ethene by using diphosphines **5–9** and trifluoroacetic acid.[a]

Entry	Ligand	X [g][b]	TON[c]	Average rate[d]
1	**5**	20.2	603	302
2	**6**	13.1	392	196
3	**7**	28.1	839	420
4	**8**	27.9	834	417
5	**9**	28.8	860	430

[a] Pd/L/CF_3CO_2H 1:3:125; $Pd(OAc)_2$ (5.98×10^{-4} mol), CF_3CO_2H (8.5 mol); $P_{ethene} = 20$ bar, $P_{CO} = 45$ bar; methyl propionate (180 mL), MeOH (120 mL); $T = 100\,^{\circ}C$. [b] Grams of methyl propionate produced during the reaction. [c] Turnover number. [d] Average rate during the catalytic reaction [s^{-1}].

As was mentioned before, catalyst systems based on the more basic ligands (**6–9**) are inactive when run in the presence of excess methanesulfonic acid (as the typically used commercial operation). For these ligands, good activity in the presence of excess acid is only possible when an acid of lower pK_a is employed. Drent and Pugh have previously noted the complex influence of ligand basicity and acid strength on catalyst selectivity in palladium–diphosphine carbonylation catalysis.[7] Further studies are required to fully understand the relationship between acid pK_a, ligand basicity and catalyst activity (Scheme 6).



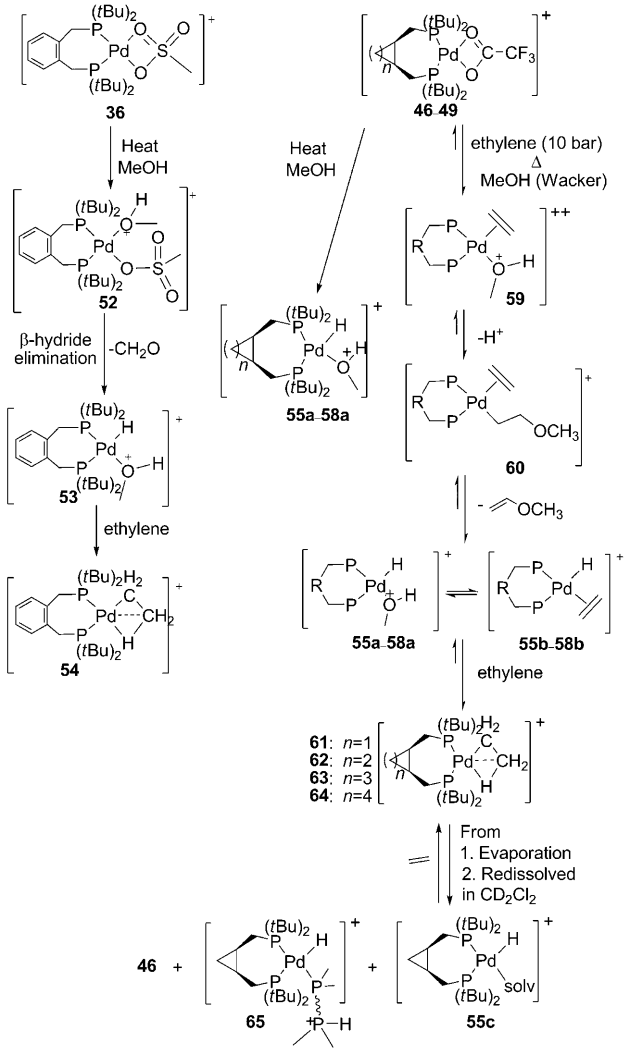
Scheme 6. Influence of acid on the formation of the catalyst precursors.

High-pressure NMR spectroscopic study: As noted above, Pd-catalysed alkoxycarbonylation reactions normally show an acceleration of reaction rate on increasing the amount of strong acid present, which is attributed

to the formation of the catalytically active Pd–H species being favoured.[66,67] In contrast, we observe the opposite trend for catalyst systems based on ligands **6–9**, which are deactivated by an excess of strong acid. We have, therefore, performed a mechanistic study by NMR and HP NMR spectroscopy to establish if the hydride mechanism is indeed operating in this catalytic system.

*Attempted preparation of palladium–carbomethoxy or palladium–hydride initiators from [Pd(O_2CCF_3)(**6–9**)]$^+$ (**46–49**)*: No reaction was observed on heating a methanolic solution of $Pd(OAc)_2$/**9**/TFA with CO in a sapphire NMR tube (353 K, 20 bar CO), which indicated that the catalysis does not proceed by a carbomethoxy complex (Scheme 2b).

Consistent with the report of Heaton and co-workers,[43] who found that [Pd(O_3SCH_3)(**5**)]$^+$ (**36**), is converted under catalytic conditions to the hydride complex [Pd(H)(MeOH)(**5**)]$^+$ (**53**) at 353 K (Scheme 7),[55] we find that [Pd(O_2CCF_3)(**5**)]$^+$ (**50**) is transformed into **53** on heating in a methanol solution to 353 K in a sapphire NMR tube. However, we find that starting from either the isolated complexes [Pd(O_2CCF_3)(L-L)]$^+$ (L-L = **6–9**) (**46–49**) or from (**46–49**) prepared in situ, the trifluoroacetate complexes (**46–49**) are recovered unchanged following heating in methanol to 353 K, in the presence of a stoichiometric amount or with an excess of acid (see Figures 18–21 in the Supporting Information; a slight decomposition of the ligand is observed), with no evidence for the formation of the hydride complexes [Pd(H)(MeOH)(**6–9**)]$^+$ (**55–58**) required for a hydride mechanism (Scheme 2a).



Scheme 7. Formation the palladium–hydride and palladium–ethyl complexes.

Reaction of [Pd(O_2CCF_3)(6–9)]$^+$ (46–49) with ethene (10 bar): We next studied the direct reaction of the trifluoroacetate complexes [Pd(O_2CCF_3)(**6–9**)]$^+$ (**46–49**) with ethene in methanol and successfully generated the Pd–ethyl complexes required by the hydride pathway. Thus, on heating methanolic solutions of **46–48** in a sapphire NMR tube in the presence of an excess of trifluoroacetic acid and ethene (10 bar) at 353 K for 20 min, followed by cooling to 193 K, the $^{31}P\{^1H\}$ NMR spectra showed the presence of two new doublets that can be assigned (vide infra) to [Pd(**6–8**)(CH_2CH_3)]$^+$ (**61–63**) (Table 6, Scheme 7). When the experiment was repeated with complex **49**, two sets of doublets were observed corresponding to two conformers of the ethyl complex **64** (vide infra).

Table 6. Selected $^{31}P\{^1H\}$ NMR spectroscopic data for **61–64**.

Entry	Complex	δ P_1/P_2 [ppm]	J_{PP} [Hz]
1	**61**	67.9/50.3	24.3
2	**62**	63.4/41.2	23.1
3	**63**	77.3/47.0	23.0
4	**64**	major: 87.8/38.6	22.4
		minor: 64.3/58.4	22.4

Attempts to isolate **62–64** were unsuccessful, thus on removal of methanol at a reduced pressure and redissolution of the resulting residue in deuterated dichloromethane, the $^{31}P\{^1H\}$ NMR spectra revealed only the presence of the precursors **47–49**. However, for complex **61**, the $^{31}P\{^1H\}$ NMR spectrum showed, in addition to **46**, the presence of a new complex containing two broad resonances at $\delta = 70.4$ and 37.9 ppm that can be assigned as the hydride–solvento complex **55** (Scheme 7, Figure 2b).

Thus, in the proton-coupled ^{31}P NMR spectrum, recorded at 193 K, the signal at $\delta = 70.4$ ppm becomes a broadened doublet ($^2J_{PP} = 19.4$ Hz), whereas the signal at $\delta = 37.9$ ppm shows an additional coupling due to a *trans* disposed hydride, (doublet of doublets, $^2J_{PP} = 19.4$ and $^2J_{P^bH} = 193.8$ Hz; Figure 2a). The resonance of the hydride ligand occurs in the ^1H NMR spectrum, recorded at 193 K, at $\delta = -10.69$ ppm (dd, $^2J_{P^aH} = 13.6$, $^2J_{P^bH} = 193.8$ Hz) (Figure 3). The resonances of a second, minor hydride complex can be seen at $\delta = -10.47$ ppm (ddd, $^2J_{P^aH} = 22.4$, $^2J_{P^cH} = 36.0$ and $^2J_{P^bH} = 188.4$ Hz). The resonances of this new complex are

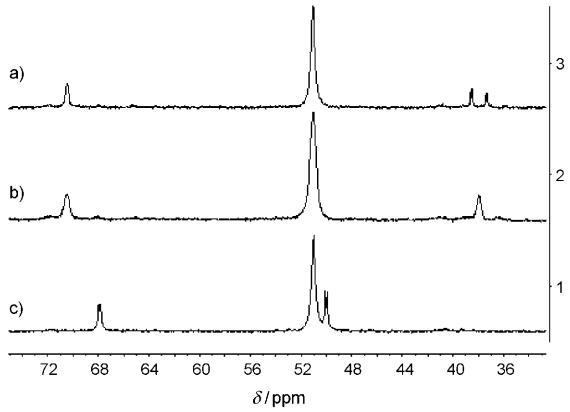


Figure 2. a) ^{31}P NMR spectra of a mixture of complexes [Pd(O_2CCF_3)(**6**)]$^+$ (**46**) and [Pd(H)(MeOH)(**6**)]$^+$ (**55**) at 193 K, b) ^{31}P{^{1}H} NMR spectra of complexes [Pd(O_2CCF_3)(**6**)]$^+$ (**46**) and [Pd(H)(MeOH)(**6**)]$^+$ (**55**) at 193 K, c) ^{31}P{^{1}H} NMR spectra of complexes [Pd(O_2CCF_3)(**6**)]$^+$ (**46**) and [Pd(**6**)(CH_2CH_3)]$^+$ (**61**).

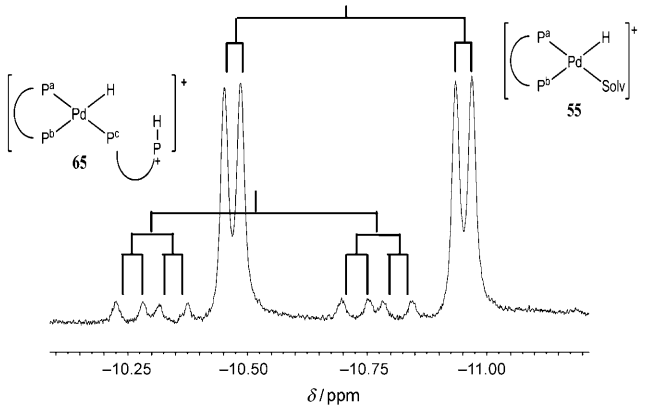


Figure 3. Selected region of the ^{1}H NMR spectra of [Pd(H)(MeOH)(**6**)]$^+$ (**55**).

not resolved in the ^{31}P{^{1}H} NMR spectrum making assignment of its structure problematic; we tentatively propose the structure **65** for this complex, consistent with the presence of an additional P–H coupling (Scheme 7). According to the law of microscopic reversibility, the forward reaction must go by insertion of ethylene into the Pd–H bond. On pressurization of this solution with ethene at room temperature and cooling to 193 K, the ^{31}P{^{1}H} NMR spectrum showed the disappearance of the resonances of the hydride complex and the appearance of the resonances attributed to the ethyl complex [Pd(**6**)(CH_2CH_3)]$^+$ (**61**) (Figure 2c). We conclude that on heating methanolic solutions of [Pd(O_2CCF_3)(**6**)]$^+$ (**46**) in the presence of ethene, traces of the hydride complex [Pd(H)(MeOH)(**6**)]$^+$ (**55**) are formed. This complex reacts with ethene to give the ethyl complex [Pd(**6**)(CH_2CH_3)]$^+$ (**61**). However, in contrast to [Pd(**5**)(CH_2CH_3)]$^+$ insertion of ethene is readily reversible, giving the hydride complex **55** transiently on removal of ethene from solution. Complex **55** itself is unstable and returns to the precursor complex [Pd(O_2CCF_3)(**6**)]$^+$ (**46**) (Scheme 7).

Conformational dynamic process in [Pd(9)(CH_2CH_3)]$^+$ (64): We noted above that two conformers exist for the ethyl complex [Pd(**9**)(CH_2CH_3)]$^+$ (**64**). Thus, at 193 K two pairs of doublets are observed in the ^{31}P{^{1}H} NMR spectrum. Those of the major isomer occur at $\delta = 87.8$ (d, $^2J_{PP} = 22.4$ Hz; P^{1A}) and 38.6 ppm (d, $^2J_{PP} = 22.4$; P^{1B}), values similar to those of [Pd(**5**)(CH_2CH_3)]$^+$ (**54**) ($\delta = 67.7$, 36.3 ppm ($^2J_{PP} =$ 31 Hz)).[54–55] The resonances of the minor conformer occur at $\delta = 64.3$ (d; P^{2A}) and 58.4 ppm (d, $^2J_{PP} = 22.4$ Hz; P^{2B}). The two isomers occur in the ratio 2.2:1. These conformers are in dynamic equilibrium.[16] Figure 4 shows the variable-temperature (VT) ^{31}P{^{1}H} NMR spectra of **64**, together with simulations performed by using gNMR5. The simulations reveal that concerted intermolecular equivalencing of P^{1A} with P^{2A} and P^{1B} with P^{2B} occurs, as would be expected for a chair-to-boat conformational flip. Intramolecular exchange

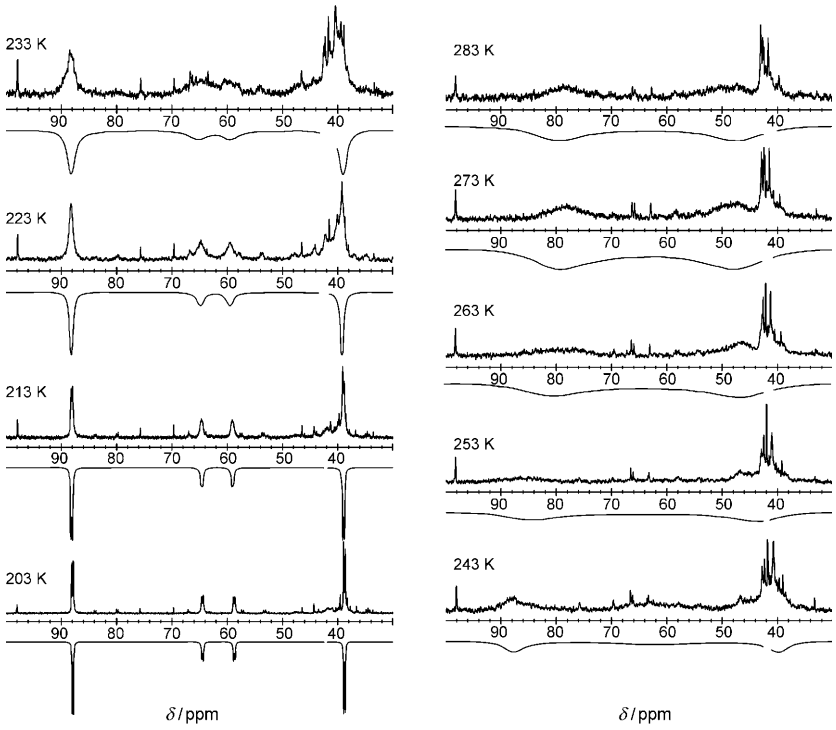


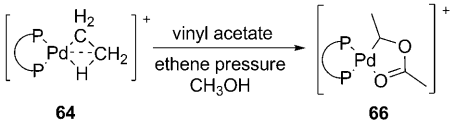
Figure 4. ^{31}P{^{1}H} NMR spectra and simulations at VT of the [Pd(**9**)(CH_2CH_3)]$^+$ (**64**).

of P^{1A} with P^{1B} and of P^{2A} with P^{2B} also occurs but at a slower rate and at different rates for the two isomers. The uncertainty in the exchange rate constants derived from the simulations is high, resulting in large uncertainties in the activation enthalpies and entropies obtained (see the Supporting Information). Both processes appear to have similar activation enthalpies of 45 kJ mol^{-1} and activation entropies close to 0 J mol^{-1} K^{-1} as might reasonably be expected for the proposed exchanges.

Zacchini has previously reported that a rapid insertion–deinsertion fluxional process occurs in **54** in which the inequivalent phosphorus donors remain distinct. These donors are then equivalenced by a much slower fluxional process, in accord with our results.[54]

The chair and boat conformations of the ethyl complex **64** have been simulated in ArgusLab to determine the energy of each conformer. We find that the complex in which the ligand adopts the chair conformation is approximately 38 kJ mol^{-1} lower in energy than the boat conformer. Chair and boat conformers are also observed in the X-ray crystal structures of the precursor complex **35** (Figure 1).

Reaction of complex [Pd(9)(CH$_2$CH$_3$)]$^+$ in methanol in the presence of vinyl acetate: Due to the difficulty in isolating the hydride complexes **55**–**58** and ethyl complexes **61**–**64** we turned our attention to the vinyl acetate (VAM) insertion complex **66** since the β-chelate complex formed is more easily handled. Thus, the ethyl complex **64** was synthesised, and a solution of vinyl acetate in methanol was added under an ethene atmosphere to prevent back reaction to the trifluoroacetate complex **49**. Complex **66** was obtained as a mixture of two conformers (Scheme 8) presumably by an



64 66

Scheme 8. Synthesis of [Pd(**9**)(CH$_2$CH$_2$OC(O)CH$_3$)]$^+$ (**66**).

alkene exchange reaction that proceeds through β-hydride elimination, and decoordination of ethene, followed by VAM coordination and 2,1-insertion into the Pd–H bond.

Complex **66** was fully characterized by NMR spectroscopy. The ^{31}P{^{1}H} NMR spectrum, acquired at 193 K, (Figure 5a) shows two sets of signals, at $\delta = 52.5$ and 51.3 ppm ($^2J_{PP} = 29.7$ Hz) and at $\delta = 70.2$ and 30.5 ppm ($^2J_{PP} = 27.7$ Hz) (relative intensity of 4:1). When ^{13}C-labelled vinyl acetate was used, additional couplings are seen in the ^{31}P{^{1}H} NMR spectrum, the resonances at $\delta = 52.5$ and 30.5 ppm appearing as doublets of doublets ($^2J_{PC} = 95.6$, $J_{PP} = 30.5$ Hz and $^2J_{PC} = 97.7$, $J_{PP} = 30.5$ Hz, respectively) (Figure 5b), values of $^2J_{PC}$ are consistent with the proposed β-chelate structure.[68]

The resonances of C^a and C^b of the major isomer occur at $\delta = 23.9$ (d, $J_{CC} = 32.5$ Hz) and 96.2 ppm (dd, $J_{CC} = 32.6$, $J_{PC} = 94.7$ Hz) in the ^{13}C{^{1}H} NMR spectrum (Figure 6b). The resonance of C^a shows an additional quartet coupling ($J_{CH} = 127.9$ Hz) in the proton-coupled ^{13}C NMR spectrum confirming its identity as a CH_3 group, whereas the resonance of C^b becomes a complex multiplet as expected for a methine carbon atom (Figure 6c). The methine resonance of the minor isomer is seen at $\delta = 93.9$ ppm (dd, $J_{CC} = 31.2$, $J_{PC} = 94.3$ Hz) in the ^{13}C{^{1}H} NMR spectrum and a poorly resolved doublet around $\delta = 27.5$ ppm may be assigned to the methyl carbon atom of the minor isomer (Figure 6b).

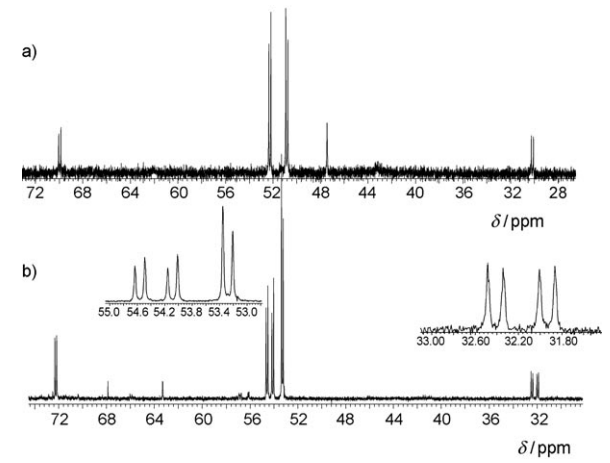


Figure 5. ^{31}P{^{1}H} NMR spectra. a) Complex [Pd(**9**)(CH$_2$CH$_3$)]$^+$ (**64**) and vinyl acetate in methanol at 193 K. b) Complex [Pd(**9**)(CH$_2$CH$_3$)]$^+$ (**64**) and vinyl-$^{13}C_2$ acetate in methanol at 193 K.

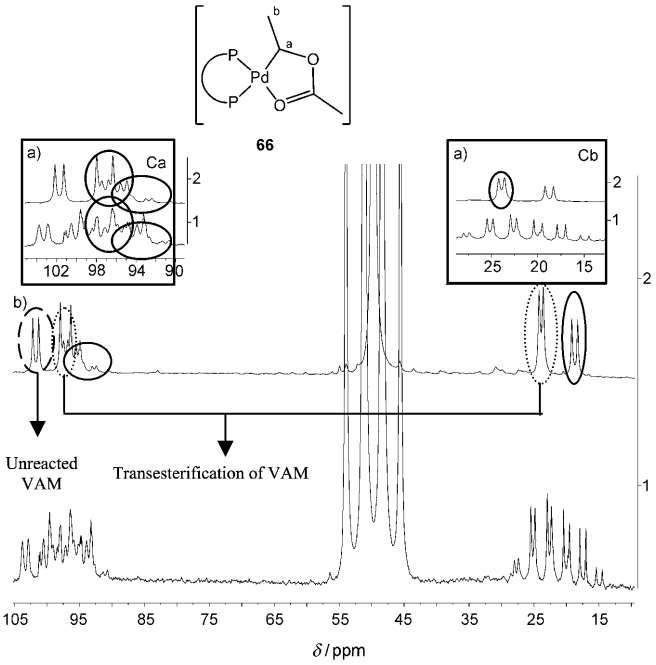


Figure 6. Spectrum of [Pd(**9**)(^{13}CH$_2$^{13}CH$_2$OC(O)CH$_3$)]$^+$ (**66**) obtained by treating [Pd(**9**)(CH$_2$CH$_3$)]$^+$ (**64**) with vinyl-$^{13}C_2$ acetate in methanol at 193 K. a) Spectra b) and c) expanded. b) ^{13}C-{^{1}H} NMR spectra. c) ^{13}C NMR spectra.

Finally, a $^{31}P\{^{1}H\}$–$^{13}C\{^{1}H\}$ HMQC correlation spectrum was obtained and shows correlations between the ^{31}P signals at $\delta = 23.9$ and 52.5 ppm and ^{13}C signals at $\delta = 93.9$ and 96.2 ppm, respectively (Figure 7). Thus, we can confidently

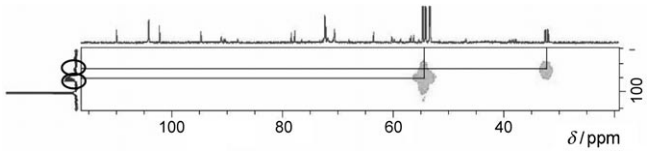


Figure 7. $^{31}P\{^{1}H\}$–$^{13}C\{^{1}H\}$ NMR correlation spectra of complex $[Pd(\mathbf{9})(^{13}CH_2{}^{13}CH_2OC(O)CH_3)]^+$ (**66**).

assign **66** as two conformers or two diastereoisomers of the β-chelate complex resulting from the 2,1-insertion of VAM into the Pd–H bond of **57**. The two conformers or two diastereoisomers are proposed to arise from different conformations adopted by the backbone of the ligand, as previously observed. The Pd–H must originate by β-hydride elimination of ethene from the alkyl complex **64**.

Conclusion

Four novel bidentate bis(*tert*-butylphosphine) ligands (**6–9**) with saturated cycloalkyl rings of different ring size have been synthesised in high yield. These ligands have been used in the synthesis of the palladium complexes **32–35** and in the palladium-catalysed methoxycarbonylation of ethene. The synthesis of the palladium(II) phosphine complexes and their subsequent crystallisation allowed the determination of the geometries of the molecules and of the bite angles of the ligands that are very similar for all complexes. Differences in the catalytic performance of the ligands cannot, therefore, be attributed to differences in ligand bite angle or to differences in the rigidity of the ligand backbone. Thus, catalytic systems containing ligands with high-conformational mobility (**8**) or with a rigid backbone (**6**) afford catalytic systems of lower performance. The combination of the basicity of the ligand and the strength of the acid used, however, is important in determining catalyst performance. Thus, the Pd/**6–9** catalytic systems were activated by weaker acids and were strongly inhibited by the strong acid required to activate the Pd/**5** catalytic system.

The catalytic cycle when using ligands **6–9** follows a hydride pathway, similar to that proposed by Heaton et al. However, in contrast to the ALPHA/triflic acid system studied by Heaton, in which the hydride complex [Pd(ALPHA)H(MeOH)][OTf] could be isolated, in the case of ligands **6–9**, the equilibrium between the trifluoroacetate (**46–49**) and hydride (**54–57**) complexes is strongly shifted in favour of the trifluoroacetate complexes. In further contrast to the ALPHA/triflic acid system, the ethyl complexes **61–64** are only stable in the presence of an overpressure of ethene. In situ NMR spectroscopic studies confirm the presence of the ethyl complexes in the absence of CO; however, the resting state of the operando catalyst is the trifluoroacetate **46–49** (Scheme 8, Figure 2).

Two important conclusions follow from these observations: 1) although the hydride pathway is shown to be dominant in palladium-catalysed hydroesterification of alkenes when using the ligands described here, the existence or not of a stable palladium-hydride catalyst precursor is no indication of the activity of the catalyst system and 2) detection and characterization of the catalytic intermediates can be successfully performed in situ, indeed isolation and conventional characterization of such intermediates may not be possible, particularly if the resting state of the catalyst lies outside the catalytic cycle, as here.

Experimental Section

General methods: All experiments were performed under an atmosphere of nitrogen by using standard Schlenk line, cannula and glovebox techniques. All chemicals were obtained from Aldrich and used as supplied without further purification: (1*R*,2*S*)-cyclopropane-1,2-dicarboxylate, *cis*-cyclobutane-1,2-dicarboxylic acid, *cis*-cyclohexanedimethanol and ethyl 2-oxocyclohexanecarboxylate. NMR spectra were recorded by using a Varian Mercury Spectrometer (400 MHz) or Bruker Avance DPX400. H NMR spectra were recorded on a Bruker AMX-II 200 spectrometer. The chemical shifts (δ) were reported in ppm and they are referenced to tetramethylsilane (TMS). Methoxycarbonylation reactions were carried out in a 1 L stainless steel autoclave.

***cis*-(1,2-Dibromomethyl)cycloalkyl (general procedure)**: A solution of triphenyldibromophosphorane was prepared by adding bromine (141 mmol) dropwise to an ice-water-cooled solution of triphenylphosphine (141 mmol) in dry acetonitrile (200 mL). A solution of *cis*-1,2-cycloalkyldimethanol (70 mmol) in dry acetonitrile (100 mL) was added to the reaction mixture, which was then stirred under nitrogen overnight. The solvent was evaporated to yield an orange oil. The solid was finely dispersed in pentane (2×250 mL) and filtered to remove the triphenylphosphine oxide. The pentane solution was dried under vacuum to give the desired compound.

***cis*-1,2-(Dibromomethyl)cyclopropane (10)**: The synthesis of **10** was carried out in accordance with the general procedure. The product was isolated as a colourless oil. Yield: 18.59 g, 80%; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 3.47$ (m, 4H; CH_2), 1.61 (m, 2H; CH*cy*), 1.13 (m, 1H; CH*cy*), 0.39 ppm (m, 1H; CH*cy*).

***cis*-1,2-(Dibromomethyl)cyclobutane (11)**: The synthesis of **11** was completed according to the general procedure previously described. The product was isolated as a colourless oil. Yield: 6.68 g, 80%; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 3.63$ (m, 2H; CH_2); 3.45 (m, 2H; CH_2), 2.88 (m, 2H; CH), 2.15 (m, 2H; CH_2); 1.76 ppm (m, 2H; CH_2); ^{13}C NMR (100.6 MHz, $CDCl_3$,): $\delta = 39.8$ (s, CH*cy*), 34.0 (s, CH_2), 24.1 ppm (s, CH_2*cy*).

***cis*-(1,2-Dibromomethyl)cyclopentane (12)**: By following the general procedure, compound **12** was obtained as a colourless oil. Yield: 23 g, 80%; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 3.52$- 3.41 (m, 2H; CH_2), 3.29 (m, 2H; CH_2), 2.46 (m, 2H; CH*cy*), 2.09–1.85 (m, 4H; CH_2*cy*), 1.63–1.44 ppm (m, 2H; CH_2*cy*).

***cis*-(1,2-Dibromomethyl)cyclohexane (13)**: The synthesis of **13** was completed according to the general procedure previously described. The product was isolated as a colourless oil. Yield: 11.81 g, 63%; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 3.41$ (m, 4H; CH_2), 2.20 (m, 4H; CH_2*eq*), 1.64 (m, 2H; CH), 1.56 ppm (m, 4H; CH_2*ax*); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta =$ 33.7 (s; CH*cy*), 32.8 (s; CH_2*cy*), 31.3 (s; *C*(CH_3)), 29.7 (s; CH_3), 26.1 (s; CH_2*cy*), 17.5 ppm (s; CH_2).

Di-*tert*-butylphosphine borane (27): Di-*tert*-butylphosphine chloride (34 g, 188.41 mmol) was added to a schlenk flask followed by diethyl ether (200 mL). The ether solution was cooled in a cold water bath and $LiAlH_4$ (1 M in diethyl ether, 100 mL, 100 mmol) was added slowly. This gave a yellow suspension that was allowed to stir at room temperature overnight. The suspension was quenched by the addition of water (50 mL, degassed with nitrogen for 20 min). This gave a biphasic solution. The upper (organic layer) was cannula transferred into a clean schlenk flask and the aqueous residues washed with a further 100 mL of ether. The ether extracts were combined and dried with sodium sulfate. The ether extracts were then cannula transferred into a clean schlenk and the ether removed by distillation. This gave a colourless oil. The colourless oil was then diluted with THF (200 mL) and cooled to 0 °C; to this was added BH_3 in THF (1 M solution, 250 mL, 250 mmol). The resultant solution was then stirred at room temperature overnight. The solvent was then removed under vacuum to give a white crystalline solid that was isolated in the glovebox. Yield: 22.1 g, 73% yield; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.9 (dq, ^1J(H,P) = 345, ^3J(H,H) = 6 Hz; 1H), 1.2 (d, ^3J(H,P) = 13.5 Hz, 18H; CH_3), 0.4 ppm (br m, 3H; BH_3); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 38.2 (d, ^1J(C,P) = 29 Hz; *C*(CH_3)), 29.1 ppm (d, ^2J(C,P) = 1.6 Hz; CH_3); ^{31}P{^{1}H} NMR (80 MHz, $CDCl_3$): δ = 49.23 ppm (m); ^{13}B NMR (128.4 MHz, $CDCl_3$,): δ = −43.7 ppm (d, ^1J = 51.1 Hz).

Boron-protected bidentate phosphine (general procedure): *t*$Bu_2PH{\cdot}BH_3$ (**27**) (179 mmol) was dissolved in THF (200 mL). The solution was then cooled. *n*BuLi (2.5 M in hexanes, 179 mmol) was added to this solution. The resultant solution was stirred at room temperature for 1 h. This mixture was then added dropwise to a solution of the corresponding *cis*-1,2-(dibromomethyl)cycloalkyl (82 mmol) in THF (200 mL). The resultant solution was then stirred overnight at room temperature. The solution was dried under vacuum and the residue suspended in diethyl ether (400 mL). Water was added to give a biphasic mixture. The organic layer was collected by separation and the aqueous layer washed with diethyl ether (2 × 100 mL). The organic layers were then combined and washed with water (3 × 150 mL) and brine solution (3 × 100 mL). The organic layer was dried over Na_2SO_4 and filtered. The solution was evaporated under reduced pressure to give the desired compound.

Boron-protected bidentate phosphine (23): The synthesis of **23** was completed according to the general procedure previously described. The product was isolated as a white solid. Yield: 22.17 g, 71%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.99 (m, 2H; CH_2), 1.56 (s, 6H; BH_3), 1.43 (m, 2H; CH_2), 1.31 (d, ^3J(H,P) = 17 Hz, 36H; CH_3), 1.24 (m, 2H; CH*Hcy*), 1.08 (m, 1H; CH*Hcy*), 0.08 ppm (m, 1H; CH*Hcy*); ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 46.6 ppm (m); HRMS (ESI-TOF): *m*/*z*: calcd: 387.3652 $[M]^+$; found: 387.3634; elemental analysis calcd (%) for $C_{21}H_{50}B_2P_2$: C 65.31, H 13.05, B 5.60, P 16.04; found: C 65.29, H 13.09.

Boron-protected bidentate phosphine (24): The synthesis of **24** was completed according to the general procedure previously described. The product was isolated as a white solid. Yield: 10.93 g, 98%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.85 (m, 6H; BH_3); 2.19 (m, 2H; CH_2); 1.99 (m, 2H; CH_2); 1.79 (m, 2H; CH*cy*); 1.61 (m, 2H; CH_2*cy*); 1.49 (m, 2H; CH_2*cy*); 1.30 (d, ^3J(H,P) = 27 Hz, 18H; *CH*$_3$); 1.26 ppm (d, ^3J(H,P) = 27 Hz, 18H; CH_3); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 34.6 (d, ^2J(C,P) = 7.64 Hz; CH*cy*), 27.8 (d, ^2J(C,P) = 3.82; CH_3), 27.4 (d, ^2J(C,P) = 3.82 Hz; CH_2*cy*), 18.9 (s), 18.7 ppm (s); ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 44.3 ppm (m); HRMS (ESI-TOF): *m*/*z*: calcd: 401.3809 $[M]^+$; found: 401.3814; elemental analysis calcd (%) for $C_{22}H_{52}B_2P_2$: C 66.02, H 13.10, B 5.40, P 15.48; found: C 66.02, H 13.15.

Boron-protected bidentate phosphine (25): The synthesis of boron-protected bidentate phosphine **25** was completed according to the general procedure previously described. The product was isolated as a white solid. Yield: 27.9 g, 75%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.30 (m, 2H; *CH*$_2$), 2.02 (m, 2H; *CH*$_2$), 1.97 (m, 2H; *CHcy*), 1.69–1.59 (m, 4H, *CH*$_2$*cy*), 1.43–1.36 (m, 2H, CH_2*cy*), 1.27 (d, ^3J(H,P) = 26 Hz, 18H; CH_3), 1.21 ppm (d, ^3J(H,P) = 23 Hz, 18H; CH_3); ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 45.92 ppm (m); HRMS (ESI-TOF): *m*/*z*: calcd: 415.3965 $[M]^+$; found: 415.3889; elemental analysis calcd (%) for $C_{23}H_{54}B_2P_2$: C 66.69, H 13.14, B 5.22, P 14.95; found: C 66.69, H 13.14.

Boron-protected bidentate phosphine (26): By following the general procedure, the product **26** was obtained as a white solid. Yield: 18.29 g, 97%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.95 (s, 3H; BH_3), 2.88 (s, 3H; BH_3), 1.81 (m, 4H; CH_2), 1.78 (m, 4H; CH_2*eq*); 1.66 (m, 2H; CH); 1.45 (m, 4H; CH_2*ax*); 1.30 (d, ^3J(H,P) = 24 Hz, 18H; CH_3), 1.23 ppm (d, ^3J(H,P) = 24 Hz, 18H; CH_3); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 33.4 (s; CH*cy*), 33.1 (s; CH_2*cy*), 30.5 (s; CH_2*cy*), 29.1 (br s; *C*(CH_3)$_3$), 28.5 (d, ^2J(C,P) = 6.84 Hz; CH_3), 28.1 ppm (s; CH_2); ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 46.71 ppm (m); HRMS (ESI-TOF): *m*/*z*: calcd: 429.4122 $[M]^+$; found: 429.4096; elemental analysis calcd (%) for $C_{24}H_{56}B_2P_2$: C 67.31, H 13.18, B 5.05, P 14.46; found: C 67.26, H 13.20.

***cis*-1,2-Bis(di-*tert*-butylphosphinomethyl)cycloalkyl (general procedure)**: The corresponding boron-protected bidentate phosphine (42 mmol) was suspended in *tert*-butyl methyl ether (TBME; 300 mL) and to this was added tetrafluoroboric acid (54% in diethyl ether, 260 mmol). This gave a rapid gas evolution and the solution was heated to reflux overnight under nitrogen. The solvent was then removed under vacuum and the residue quenched with a solution (degassed with N_2 for 20 min) of potassium hydroxide in water (21 g, 200 mL, 651 mmol). The potassium hydroxide solution was added dropwise to the phosphine residue. This gave heat evolution and a white suspension. Pentane (2 × 250 mL) was added. The organic layers were removed by cannula to a separate schlenk flask. The organic extracts were then dried over Na_2SO_4 and filtered. The solution was dried under vacuum to give the desired compound in good yields.

***cis*-1,2-Bis(di-*tert*-butylphosphinomethyl)cyclopropane (6)**: By following the general procedure, product **6** was obtained as a colourless oil. Yield = 17.23 g, 84%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.61 (m, 2H; CH_2), 1.50 (m, 2H; CH_2), 1.14 (d, ^3J(H,P) = 21 Hz, 36H; CH_3), 1.05 (m, 2H; CH*cy*), 0.88 (m, 1H; CHH*cy*), 0.05 ppm (m, 1H; CHH *cy*); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 36.2 (d, ^1J(C,P) = = 7.8 Hz; *C*(CH_3)$_3$), 35.6 (d, ^1J(C,P) = 7.8 Hz; *C*(CH_3)$_3$), 29.8 (br s; CH*cy*), 27.2 (br s; CH_3), 26.9 (br s; CH_3), 24.8 (m; CH_2*cy*), 11.3 ppm (m; CH_2); ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 30.0 ppm (s); HRMS (ESI-TOF): *m*/*z*: calcd: 358.2918 $[M]^+$; found: 357.2085.

***cis*-1,2-Bis(di-*tert*-butylphosphinomethyl)cyclobutane (7)**: The synthesis of **7** was completed according to the general procedure previously described. The product was isolated as a colourless oil. Yield = 8.5 g, 83%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.50 (m, 2H; CH_2*cy*), 1.93 (m, 2H; CH_2*cy*), 1.70 (m, 2H; CH*cy*), 1.42 (m, 2H; CH_2), 1.24 (m, 2H; CH_2), 1.15 ppm (d, ^3J(H,P) = 27 Hz, 32H; CH_3); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 37.6 (dd, ^1J(C,P) = 21.08, ^3J(C,P) = 9.4 Hz; *C*(CH_3)$_3$), 30.0 (d, ^2J(C,P) = 6.8 Hz; CH_3), 29.9 (d, ^2J(C,P) = 6.8 Hz; CH_3), 26.9 (s; CH_2*cy*), 25.5 (d, ^2J(C,P) = 11.5 Hz; CH), 22.1 ppm (d, ^1J(C,P) = 20.6 Hz; CH_2); ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 20.9 ppm (s); HRMS (ESI-TOF): *m*/*z*: calcd: 373.3153 $[M+H]^+$; found: 373.3137.

***cis*-1,2-Bis(di-*tert*-butylphosphinomethyl)cyclopentane (8)**: The synthesis of **8** was completed according to the general procedure previously described. The product was isolated as a yellow oil. Yield: 20.8 g, 80%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.99 (m, 2H; CH_2*cy*), 1.83 (m, 2H; CH_2*cy*), 1.64 (m, 2H; CH_2*cy*), 1.60 (m, 2H; CH*cy*), 1.57–1.54 (m, 4H; CH_2), 1.12 ppm (d, ^3J(H,P) = 26 Hz, 36H; CH_3); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 43.9 (dd, ^1J(C,P) = 19.1, ^3J(C,P) = 8.3 Hz; *C*(CH_3)$_3$), 32.1 (d, ^2J(C,P) = 22.1 Hz; CH), 31.5 (d, ^3J(C,P) = 9.9 Hz; CH_2*cy*), 30.2 (d, ^2J(C,P) = 6.4 Hz; CH_3), 30.1 (d, ^2J(C,P) = 6.4 Hz; CH_3), 22.4 (s; CH_2*cy*); 21.6 ppm (d, ^1J(C,P) = 21.3 Hz; CH_2); ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 24.33 ppm (s); HRMS (ESI-TOF): *m*/*z*: calcd: 387.3309 $[M+H]^+$; found: 387.3310.

***cis*-1,2-Bis(di-*tert*-butylphosphinomethyl)cyclohexane (9)**: According to the general procedure, product **9** was obtained as a yellow oil. Yield = 14.37 g, 82%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.77 (m, 4H; CH*eq*), 1.61 (m, 4H; CH_2*ax*), 1.51 (m, 2H; CH), 1.35 (m, 4H; CH_2), 1.14 (d, ^3J(H,P) = 18 Hz, 18H; CH_3), 1.12 ppm (d, ^3J(H,P) = 18 Hz, 18H; CH_3); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 41.0 (dd, ^1J(C,P) = 21.2, ^3J(C,P) = 7.8 Hz; C(CH_3)$_3$), 31.9 (d, ^2J(C,P) = 21.4 Hz; CH), 31.3 (d, ^3J(C,P) = 19.1 Hz; CH_2*cy*), 30.0 (d, ^2J(C,P) = 1.5 Hz; CH_3), 30.0 (d, ^2J(C,P) = 1.5 Hz; CH_3), 29.9 (d, ^4J(C,P) = 28.7 Hz; CH_2*cy*), 23.7 ppm (br s; CH_2);

$^{31}P\{^1H\}$ NMR (161.97 MHz, $CDCl_3$): $\delta =$ 24.7 ppm (s); HRMS (ESI-TOF): *m/z*: calcd: 401.3466 $[M+H]^+$; found: 401.3469.

Palladium(II) complexes $[Pd(L\text{-}L)O_3SCH_3]O_3SCH_3$ (general procedure): Bidentate phosphine ligand (1.30 mmol) and $[Pd_2(dba)_3]$ (1.30 mmol) were combined in a schlenk flask. THF (50 mL) was then added and the resultant solution was stirred overnight at room temperature. Methanesulfonic acid was added and the mixture reaction was stirred for 2 h. The solution was filtered under nitrogen and then dried under vacuum.

***cis*-1,2-Bis(di-*tert*-butylphosphinomethyl)cyclopropane palladium(II) complex (32)**: The synthesis of complex **(32)** was completed according to the general procedure previously described (yield: 313 mg, 43%). The crystals were obtained after purification by the elimination of dba with diethyl ether (3×50 mL) and the solid was dissolved in THF (10 mL). Then, 3 mL of this solution were put in a layer tub and diethyl ether was added carefully (20 mL) to form a biphasic solution. The solution was left to stand for 3 days, after which time, the formation of crystals was observed. ^1H NMR (400 MHz, $CDCl_3$): $\delta = 2.91$ (s; CH_3), 2.80 (m, 2H; CH*cy*), 2.60–1.78 (m, 6H; CH_2*cy*, CH), 1.55–1.17 ppm (m, 38H; CH_3, CH_2); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta = 39.7$ (s; CH_3), 36.7 (m; *C*-$(CH_3)_3$), 28.9 (brs; CH_2*cy*), 26.4 (m; CH*cy*), 23.7 ppm (d, $^1J(C,P) = 8.2$ Hz; CH_2); $^{31}P\{^1H\}$ NMR (161.97 MHz, $CDCl_3$): $\delta = 77.64$ ppm (s); HRMS (ESI-TOF): calcd: 465.2043 $[M-CH_3SO_3+H]^+$; found: 465.2051; elemental analysis calcd (%) for $C_{23}H_{50}O_6P_2PdS_2$: C 42.17, H 7.69, O 14.65, P 9.46, Pd 16.24, S 9.79; found: C 42.05, H 7.74, S 9.67.

***cis*-1,2-Bis(di-*tert*-butylphosphinomethyl)cyclobutane palladium(II) complex (33)**: The synthesis of complex **(33)** was completed according to the general procedure previously described (yield: 350 mg, 47%). The crystals were obtained after purification by the elimination of dba with diethyl ether (3×50 mL) and the solid was dissolved in THF (10 mL). Then, 3 mL of this solution was put in a layer tube and diethyl ether was added carefully (20 mL) to form a biphasic solution. The solution was left to stand for 3 days, after which time, the formation of crystals was observed. ^1H NMR (400 MHz, $CDCl_3$): $\delta = 2.90$ (s; CH_3), 2.80 (m, 2H; CH*cy*), 2.05–1.59 (m, 4H; CH_2*cy*), 1.55–1.17 ppm (m, 40H; CH_3, CH_2); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta = 40.8$ (dd, $^1J(C,P) = 18.8$, $^3J(C,P) = 5.2$ Hz; *C*-$(CH_3)_3$), 39.7 (s; CH_3), 31.7 (brs; CH_3), 30.5 (brs; CH_3), 29.5 (brs; CH*cy*), 26.6 (m; CH_2*cy*), 25.7 ppm (d, $^1J(C,P) = 10.8$ Hz; CH_2); $^{31}P\{^1H\}$ NMR (161.97 MHz, $CDCl_3$): $\delta = 73.3$ ppm (s); HRMS (ESI-TOF): *m/z*: calcd: 479.2188 $[M-CH_3SO_3+H]^+$; found: 479.2147; elemental analysis calcd (%) for $C_{24}H_{52}O_6P_2PdS_2$: C 43.08, H 7.83, O 14.35, P 9.26, Pd 15.90, S 9.58; found: C 43.02, H 7.86, S 9.53.

***cis*-(Di-*tert*-butylphosphinomethyl)cyclopentane palladium(II) complex (34)**: By following the general procedure, complex **34** is obtained (yield = 321 mg, 42%). The dba was removed by diethyl ether (3×50 mL) and the solid was dissolved in THF (10 mL). Then, 3 mL of this solution were put in a layer tube and *tert*-butyl methyl ether was added carefully (10 mL) to form a biphasic solution. The solution was left to stand for 3 days, after which time, the formation of crystals was observed. ^1H NMR (400 MHz, $CDCl_3$): $\delta = 2.93$ (s; CH_3), 2.19 (m, 2H; CH*cy*), 2.11 (m, 4H; CH_2*cy*), 1.93 (m, 2H; CH*cy*), 1.58 (d, $^3J_{H-P} = 15.2$ Hz, 18H; CH_3), 1.52 (d, $^3J_{H-P} = 15.2$ Hz, 18H; CH_3), 1.19 ppm (m, 4H; CH_2); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta = 40.9$ (dd, $^1J(C,P) = 26.1$, $^3J(C,P) = 18.0$ Hz; *C*-$(CH_3)_3$), 39.6 (s; CH_3), 35.7 (brs; CH_2*cy*), 35.6 (d, $^2J(C,P) = 3.9$ Hz; CH*cy*), 31.7 (d, $^2J(C,P) = 2.3$ Hz; CH_3), 30.4 (d, $^2J(C,P) = 2.3$ Hz; CH_3), 26.2 (m; CH_2*cy*), 23.1 ppm (dd, $^1J(C,P) = 20.3$, $^3J(C,P) = 8.1$ Hz; CH_2); $^{31}P\{^1H\}$ NMR (161.97 MHz, $CDCl_3$): $\delta = 79.5$ ppm (s); HRMS (ESI-TOF): *m/z*: calcd: 493.2344 $[M-CH_3SO_3+H]^+$; found: 493.2347; elemental analysis calcd (%) for $C_{25}H_{54}O_6P_2PdS_2$: C 43.95, H 7.97, O 14.05, P 9.07, Pd 15.58, S 9.39; found: C 43.82, H 8.06, S 9.42.

***cis*-1,2-Bis(di-*tert*-butylphosphinomethyl)cyclohexane palladium(II) complex (35)**: The synthesis of complex **(35)** was completed according to the general procedure previously described (yield = 399 mg, 51%). The crystals were obtained after purification by the elimination of dba with diethyl ether (3×50 mL and the solid was dissolved in THF (10 mL)). Then, 3 mL of this solution were put in a layer tube and diethyl ether was added carefully (20 mL) to form a biphasic solution. The solution was left to stand for 3 days, after which time, the formation of crystals was observed. ^1H NMR (400 MHz, $CDCl_3$): $\delta = 2.93$ (s; CH_3), 2.16 (brs, 2H; CH*cy*), 1.91 (m, 4H; CH_2*cy*), 1.58 (d, ^3J(H,P) = 15.2 Hz, 18H; CH_3), 1.52 (d, 15.2 Hz, 18H; CH_3), 1.34 (m, 4H; CH_2*cy*), 1.32 ppm (m, 4H; CH_2); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta = 41.5$ (d, $^1J(C,P) = 17.2$ Hz; $C(CH_3)_3$), 40.8 (d, $^1J(C,P) = 17.2$ Hz; $C(CH_3)_3$), 39.7 (s; CH_3), 34.3 (brs; CH*cy*), 31.3 (d, $^2J(C,P) = 1.6$ Hz; CH_3), 30.6 (d, $^2J(C,P) = 1.6$ Hz; CH_3), 27.4 (m; CH_2*cy*), 26.3 (d, $^4J(C,P) = 2.4$ Hz; CH_2*cy*), 23.3 (brs; CH_2); $^{31}P\{^1H\}$ NMR (161.97 MHz, $CDCl_3$, 193 K): $\delta = 94.4$ (d, $^2J_{P-P} = 4.8$ Hz), 63.3 (d, $^2J(P,P) = 4.8$ Hz); HRMS (ESI-TOF): *m/z*: calcd: 507.2501 $[M-CH_3SO_3+H]^+$; found: 507.2527; elemental analysis calcd (%) for $C_{26}H_{56}O_6P_2PdS_2$: C 44.79, H 8.10, O 13.77, P 8.88, Pd 15.26, S 9.20; found: C 44.67, H 8.21, S 9.23.

Methoxycarbonylation reactions: A 1 L stainless steel autoclave was used to run these experiments. A standard catalyst solution was comprised of palladium(II) acetate, the bidentate phosphine ligand and methane sulfonic acid in a 1 Pd:3 (L-L):2.5 $MeSO_3H$ ratio. 5.98×10^{-4} mol of palladium was used in the catalyst experiment. Palladium acetate and the bidentate phosphine ligand were weighed into a flask in a glovebox, the flask was then transferred to a schlenk line. Degassed methyl propionate (180 mL) and degassed methanol (120 mL) were then added. The reaction mixture was stirred at room temperature for twenty minutes and then methanesulfonic acid was added by syringe to give the palladium(II) complexes $[Pd(O_3SCH_3)(L\text{-}L)]O_3SCH_3$. The catalyst solution was then added to the autoclave by vacuum transfer. The autoclave is pressured with 5 bar of hydrogen, 20 bar of ethene and 40 bar of carbon monoxide. The autoclave was then heated to 100 °C. After 3 h at 100 °C, the autoclave was cooled to room temperature and the excess pressure vented. The catalyst exit solution was then collected, weighted and sampled for GC analysis.

NMR simulations of the VT $^{31}P\{^1H\}$ NMR spectra of 64: A 0.013 M solution of **64** in methanol was prepared by following the general procedure below and $^{31}P\{^1H\}$ NMR spectra recorded at 10 K increments from 193 to 293 K. NMR simulations were performed by using gNMR5. Several exchange models were tested including: intramolecular exchange of P^A and P^B in each isomer, pairwise intermolecular exchange of P^A in isomer 1 with P^A in isomer 2 and P^B in isomer 1 with P^B in isomer 2, pairwise intermolecular exchange of P^A in isomer 1 with P^B in isomer 2 and P^B in isomer 1 with P^A in isomer 2, etc. The spectra are best modelled by three independent exchange processes involving pairwise intermolecular exchange of P^A in isomer 1 with P^A in isomer 2 and P^B in isomer 1 with P^B in isomer 2, in combination with intramolecular exchange of P^A with P^B in each isomer. The simulations are relatively insensitive to the intramolecular exchange rate for isomer 2. For simplicity, therefore, the exchange rate constants of the two intramolecular exchanges were set to equal.

HP NMR spectroscopic study

General method: All reactions and manipulations were carried out under a dry oxygen-free nitrogen atmosphere by using Schlenk techniques. All solvents were carefully purified by appropriate procedures. CD_2Cl_2 and CD_3OD were subjected to three freeze pump–thaw cycles and stored over 4 Å molecular sieves under nitrogen. Air sensitive compounds were stored under nitrogen at 243 K. ^{13}CO was purchased from ISOTEK and $^{13}CH_2{=}^{13}CHOC(O)CH_3$ from Aldrich. All other chemicals were purchased from Aldrich. Bis(ditertiarybutylphosphinomethyl)benzene (DTBPMB) was donated by Lucite International. The sapphire tube was supplied by Saphikon. The recirculating pump by HiT-Hydraulik.[69]

HP NMR spectroscopic measurements: In a typical experiments, the sapphire NMR tube was charged under N_2 with a solution containing the palladium precursor (0.048 mmol), the corresponding ligand (0.144 mmol) and the corresponding acid CH_3SO_3H or CF_3CO_2H (0.12 or 6 mmol, respectively) in methanol. The tube was then pressurised with ethylene and carbon monoxide to the desired pressure. Most of the compounds reported below have not been isolated due to their instability or the reversible nature of the reaction involved. However, 1D and 2D NMR spectroscopic measurements and detailed isotopic labelling experiments allow all of these compounds to be assigned unambiguously.

$[Pd(O_2CCF_3)(L\text{-}L)]O_2CCF_3$ (46–49) (general procedure): Bidentate phosphine ligand (0.144 mmol) and $Pd(AOc)_2$ (0.140 mmol) were combined in a schlenk flask. MeOH (3 mL) was then added and the resultant solution was stirred for 2 h at room temperature. Trifluoroacetic acid was added and the reaction mixture was then stirred for 2 h. The solution was

filtered under nitrogen and then concentrated under vacuum. Diethyl ether (3 mL) was added to precipitate the corresponding complex.

[Pd(O_2CCF_3)(6)]O_2CCF_3 (46): By following the general procedure, compound **46** was obtained as a yellow powder. Yield: 56 mg, 63 %; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.67 (m, 4H; CH_2), 1.68 (d, 18H, ^3J(H,P) = 14.4 Hz; CH_3), 1.46 (d, 18H, ^3J(H,P) = 14.4 Hz; CH_3), 1.31 (m, 2H; CH_2*cy*), 1.13 (m, 1H; C*H*cy), 0.91 ppm (m, 1H; C*H*cy); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 162.9 (d, ^2J(C,F) = 39.5 Hz; *C*(CF_3)), 117.5 (d, ^1J(C,F) = 285.2 Hz; CF_3), 39.3 (dd, ^1J(C,P) = 18.4, ^3J(C,P) = 9.2 Hz; *C*-(CH_3)$_3$), 31.3 (brs; CH_3), 30.2 (brs; CH_3), 29.9 (s; CH_2*cy*), 23.5 (d, ^2J(C,P) = 20.6 Hz; C*H*cy), 17.6 ppm (m; CH_2); ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 51.0 ppm (s); HRMS *m*/*z*: (ESI-TOF): *m*/*z*: 465.2043, calcd: 465.2051 [*M*−CF_3CO_2+H]$^+$; elemental analysis calcd for $C_{25}H_{44}F_6O_4P_2Pd$: C 43.46, H 6.42, F 16.50, O 9.26, P 8.97, Pd 15.40; found: C 43.33, H 6.47.

[Pd(O_2CCF_3)(7)]O_2CCF_3 (47): Synthesis of **47** was completed according to the general procedure previously described. ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 49.0 ppm (s); HRMS (ESI-TOF): *m*/*z*: calcd: 479.2188 [*M*−CF_3CO_2+H]$^+$; found: 479.2178; elemental analysis calcd (%) for $C_{26}H_{46}F_6O_4P_2Pd$: C 44.29, H 6.58, F 16.17, O 9.08, P 8.79, Pd 15.10; found: C 44.21, H 6.61.

[Pd(O_2CCF_3)(8)]O_2CCF_3 (48): The synthesis of **47** was completed according to the general procedure previously described. ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 48.3 (s); HRMS (ESI-TOF): *m*/*z*: calcd: 493.2344 [*M*−CF_3CO_2+H]$^+$; found: 493.2341; elemental analysis calcd (%) for $C_{27}H_{48}F_6O_4P_2Pd$: C 45.10, H 6.73, F 15.85, O 8.90, P 8.62, Pd 14.80; found: C 45.02, H 6.78.

[Pd(O_2CCF_3)(9)]O_2CCF_3 (49): The synthesis of **49** was carried out in accordance with the general procedure. The product was isolated as a yellow/green solid. Yield: 148 mg, 77 %; ^{1}H NMR (400 MHz, CD_2Cl_2): δ = 1.63 (d, 18H, ^3J(H,P) = 14 Hz; CH_3), 1.54 (d, ^3J(H,P) = 14 Hz, 18H; CH_3), 1.48–1.18 ppm (m, 14H); ^{13}C NMR (CD_2Cl_2, 100.6 MHz): δ = 162.7 (d, ^2J(C,F) = 38.9 Hz; *C*(CF_3)), 116.0 (d, ^1J(C,F) = 291.4 Hz; CF_3), 41.8 (d, ^2J(C,P) = 17.5 Hz; *C*(CH_3)$_3$), 40.5 (d, ^1J(C,P) = 17.5 Hz; *C*(CH_3)$_3$), 38.2 (m; C*H*cy), 31.9 (m; CH_2*cy*), 30.3 (m; CH_3), 26.8 (m; CH_2*cy*), 16.9 ppm (d, ^1J(C,P) = 19.8; CH_2); ^{31}P{^{1}H} NMR (161.97 MHz, CD_2Cl_2, 193 K): δ = 76.2 (s), 46.9 ppm (s); HRMS (ESI-TOF): calcd: 507.2501 [*M*−CF_3CO_2+H]$^+$; found: 507.2527; elemental analysis calcd (%) for $C_{28}H_{50}F_6O_4P_2Pd$: C 45.88, H 6.87, F 15.55, O 8.73, P 8.45, Pd 14.52; found: C 45.51, H 6.96.

[Pd(6–9)(CH_2CH_3)]O_2CCF_3 (61–64) (general procedure): Bidentate phosphine ligand (0.144 mmol) and Pd(AOc)$_2$ (0.140 mmol) were combined in a schlenk flask. MeOH (3 mL) was then added and the resultant solution was stirred for 20 min at room temperature. Trifluoroacetic acid (0.480 mmol) was added and the reaction mixture was then stirred for another 20 min. The solution was then transferred into the sapphire tube and it was charged with 10 bar of ethene at 353 K for 20 min.

[Pd(6)(CH_2CH_3)]O_2CCF_3 (61): The synthesis of complex **61** was completed according to the general procedure previously described. ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 67.9 (d, ^2J(P,P) = 24.3 Hz), 50.3 ppm (d, ^2J(P,P) = 24.3 Hz).

[Pd(7)(CH_2CH_3)]O_2CCF_3 (62): The synthesis of complex **62** was completed according to the general procedure previously described. ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 63.4 (d, ^2J(P,P) = 23.1 Hz), 41.2 ppm (d, ^2J(P,P) = 23.1 Hz).

[Pd(8)(CH_2CH_3)]O_2CCF_3 (63): The synthesis of complex **63** was completed according to the general procedure previously described. ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 77.3 (d, ^2J(P,P) = 23.0 Hz), 47.0 ppm (d, ^2J(P,P) = 23.0 Hz).

[Pd(9)(CH_2CH_3)]O_2CCF_3 (64): The synthesis of complex **64** was completed according to the general procedure previously described. ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): major isomer: δ = 87.8 (d, ^2J(P,P) = 22.4 Hz), 38.6 (d, ^2J(P,P) = 22.4 Hz); minor isomer 64.3 (d, ^2J(P,P) = 22.4 Hz), 58.4 ppm (d, ^2J(P-P) = 22.4 Hz).

[Pd(9)(κ-2-CH(Me)OAc)]O_2CCF_3 (66): [Pd(**9**)(CH_2CH_3)]O_2CCF_3 (**63**) was synthesised as above. Then, CH_2=CHOC(O)CH_3 or $^{13}CH_2$=^{13}CHOC(O)CH_3 (1.5 equiv, 10 μL) was added. A mixture of **66a** and **66b** was formed immediately, as indicated by the ^{31}P{^{1}H} NMR spectrum.

*Complex **66a** (major)*: ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 96.2 (dd, J(C,C) = 32.5, J(P,C) = 94.7 Hz), 23.9 ppm (d, J(C,C) = 32.5 Hz); ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 52. 5 (dd, ^2J(P,C) = 95.6, ^2J(P,P) = 30.5 Hz), 51.3 ppm (d, ^2J(P,P) = 29.7 Hz).

*Complex **66a** (minor)*: ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 93.9 (dd, J(C,C) = 31.2, J(C,P) = 94.3 Hz), 27.5 ppm; ^{31}P{^{1}H} NMR (161.97 MHz, $CDCl_3$): δ = 70.2 (d, ^2J(P,P) = 29.7 Hz), 30.5 ppm (dd, ^2J(P,C) = 97.7, ^2J(P,P) = 30.5 Hz).

Acknowledgements

We thank the Spanish Government, Ministerio de Educación y Ciencia (CTQ2007-62288/BQU, Consolider Ingenio 2010, CSD2006-0003), Generalitat de Catalunya (distinction for Research Promotion 2003 CC, and research PhD grant for V.F. (FI program/2008FI)) and Lucite International for their financial support. J.A.I. thanks the EPSRC (EP/C005643/1) for financial support. We also thank William Clegg for elucidating the X-ray structures.

[1] K. Nozaki in *Comprehensive Asymmetric Catalysis* (Eds.: I. E. N. Jacobsen, A. Pfaltz, H. Yamamoto), Springer, Heidelberg, **1999**, p. 382.
[2] R. P. Tooze, G. R. Eastham, K. Whiston, X. L. Wang, WO/1996/019434, **1996**.
[3] R. Hadden, J. M. Pearson, WO/1998/041495, **1998**.
[4] http://www.icis.com/Articles/2009/08/10/9238750/SABIC-Mitsubishi-Rayon-in-1bn-acrylics-joint-venture.html.
[5] R. I. Pugh, E. Drent in *Catalytic Synthesis of Alkene-Carbon Monoxide Copolymers and Cooligomers, Vol. 27* (Ed.: A. Sen), Kluwer, Dordrecht, **2003**.
[6] E. Drent, W. P. Mul, P. H. M. Budzelaar, *Comments Inorg. Chem.* **2002**, *23*, 127.
[7] R. I. Pugh, E. Drent, *Adv. Synth. Catal.* **2002**, *344*, 837.
[8] E. Drent, *Abstr. Pap. Am. Chem. Soc.* **1999**, *218*, 273.
[9] E. Drent, P. H. M. Budzelaar, *Chem. Rev.* **1996**, *96*, 663.
[10] E. Drent, J. A. M. van Broekhoven, P. H. M. Budzelaar, *Recl. Trav. Chim. Pays-Bas-J. R. Neth. Chem. Soc.* **1996**, *115*, 263.
[11] C. Bianchini, A. Meli, W. Oberhauser, *Dalton Trans.* **2003**, 2627.
[12] I. del Rio, C. Claver, P. W. M. N. van Leeuwen, *Eur. J. Inorg. Chem.* **2001**, 2719.
[13] W. Clegg, G. R. Eastham, M. R. J. Elsegood, R. P. Tooze, X. L. Wang, K. Whiston, *Chem. Commun.* **1999**, 1877.
[14] A. Sen in *Catalytic Synthesis of Alkene-Carbon Monoxide Copolymers and Cooligomers, Vol. 27* (Ed.: A. Sen), Kluwer, Dordrecht, **2003**.
[15] D. Konya, K. Q. A. Lenero, E. Drent, *Organometallics* **2006**, *25*, 3166.
[16] J. G. Knight, S. Doherty, A. Harriman, E. G. Robins, M. Betham, G. R. Eastham, R. P. Tooze, M. R. J. Elsegood, P. Champkin, W. Clegg, *Organometallics* **2000**, *19*, 4957.
[17] P. W. M. N. van Leeuwen in *Catalytic Synthesis of Alkene-Carbon Monoxide Copolymers and Cooligomers* (Ed.: A. Sen), Kluwer Academic Publishers, Dordrecht, **2003**.
[18] C. Bianchini, A. Meli, W. Oberhauser, C. Claver, E. J. Garcia Suarez, *Eur. J. Inorg. Chem.* **2007**, 2702.
[19] C. Bianchini, A. Meli, W. Oberhauser, A. M. Segarra, C. Claver, E. J. G. Suarez, *J. Mol. Catal. A* **2007**, *265*, 292.
[20] C. Bianchini, A. Meli, W. Oberhauser, P. van Leeuwen, M. A. Zuideveld, Z. Freixa, P. C. J. Kamer, A. L. Spek, O. V. Gusev, A. M. Kal'sin, *Organometallics* **2003**, *22*, 2409.
[21] C. Bianchini, A. Meli, G. Muller, W. Oberhauser, E. Passaglia, *Organometallics* **2002**, *21*, 4965.
[22] C. Bianchini, A. Meli, *Coord. Chem. Rev.* **2002**, *225*, 35.

[23] O. V. Gusev, A. M. Kalsin, M. G. Peterleitner, P. V. Petrovskii, K. A. Lyssenko, N. G. Akhmedov, C. Bianchini, A. Meli, W. Oberhauser, *Organometallics* **2002**, *21*, 3637.
[24] C. Bianchini, H. M. Lee, A. Meli, S. Moneti, F. Vizza, M. Fontani, P. Zanello, *Macromolecules* **1999**, *32*, 4183.
[25] C. Bianchini, H. M. Lee, P. Barbaro, A. Meli, S. Moneti, F. Vizza, *New J. Chem.* **1999**, *23*, 929.
[26] C. Bianchini, P. Bruggeller, C. Claver, G. Czermak, A. Dumfort, A. Meli, W. Oberhauser, E. J. G. Suarez, *Dalton Trans.* **2006**, 2964.
[27] C. Bianchini, W. Oberhauser, A. Orlandini, *Organometallics* **2005**, *24*, 3692.
[28] C. Bianchini, A. Meli, W. Oberhauser, S. Parisel, E. Passaglia, F. Ciardelli, O. V. Gusev, A. M. Kal'sin, N. V. Vologdin, *Organometallics* **2005**, *24*, 1018.
[29] G. Cavinato, L. Toniolo, A. Vavasori, *J. Mol. Catal. A* **2004**, *219*, 233.
[30] G. Cavinato, L. Toniolo, *J. Organomet. Chem.* **1990**, *398*, 187.
[31] D. Fatutto, L. Toniolo, R. V. Chaudhari, *Catal. Today* **1999**, *48*, 49.
[32] S. D. Ittel, L. K. Johnson, M. Brookhart, *Chem. Rev.* **2000**, *100*, 1169.
[33] C. S. Shultz, J. Ledford, J. M. DeSimone, M. Brookhart, *J. Am. Chem. Soc.* **2000**, *122*, 6351.
[34] J. P. Dunne, S. Aiken, S. B. Duckett, D. Konya, K. Q. Almeida Lenero, E. Drent, *J. Am. Chem. Soc.* **2004**, *126*, 16708.
[35] W. P. Mul, H. Oosterbeek, G. A. Beitel, G. J. Kramer, E. Drent, *Angew. Chem. Int. Ed.* **2000**, *39*, 1848.
[36] K. Nozaki, H. Komaki, Y. Kawashima, T. Hiyama, T. Matsubara, *J. Am. Chem. Soc.* **2001**, *123*, 534.
[37] K. Nozaki, T. Hiyama, S. Kacker, I. T. Horvath, *Organometallics* **2000**, *19*, 2031.
[38] K. Nozaki, Y. Kawashima, K. Nakamoto, T. Hiyama, *Polym. J.* **1999**, *31*, 1057.
[39] J. K. Liu, B. T. Heaton, J. A. Iggo, R. Whyman, J. F. Bickley, A. Steiner, *Chem. Eur. J.* **2006**, *12*, 4417.
[40] J. K. Liu, B. T. Heaton, J. A. Iggo, R. Whyman, *Angew. Chem.* **2004**, *116*, 92; *Angew. Chem. Int. Ed.* **2004**, *43*, 90.
[41] J. Liu, B. T. Heaton, J. A. Iggo, R. Whyman, *Chem. Commun.* **2004**, 1326.
[42] J. A. Iggo, Y. Kawashima, J. Liu, T. Hiyama, K. Nozaki, *Organometallics* **2003**, *22*, 5418.
[43] W. Clegg, G. R. Eastham, M. R. J. Elsegood, B. T. Heaton, J. A. Iggo, R. P. Tooze, R. Whyman, S. Zacchini, *J. Chem. Soc. Dalton Trans.* **2002**, 3300.
[44] J. Wolowska, G. R. Eastham, B. T. Heaton, J. A. Iggo, C. Jacob, R. Whyman, *Chem. Commun.* **2002**, 2784.
[45] G. R. Eastham, B. T. Heaton, J. A. Iggo, R. P. Tooze, R. Whyman, S. Zacchini, *Chem. Commun.* **2000**, 609.
[46] Z. Freixa, P. van Leeuwen, *Dalton Trans.* **2003**, 1890.
[47] P. van Leeuwen, M. A. Zuideveld, B. H. G. Swennenhuis, Z. Freixa, P. C. J. Kamer, K. Goubitz, J. Fraanje, M. Lutz, A. L. Spek, *J. Am. Chem. Soc.* **2003**, *125*, 5523.
[48] P. van Leeuwen, M. A. Zuideveld, P. C. J. Kamer, *Abstr. Pap. Am. Chem. Soc.* **2002**, *223*, 367.
[49] M. A. Zuideveld, P. C. J. Kamer, P. W. M. N. van Leeuwen, P. A. A. Klusener, H. A. Stil, C. F. Roobeek, *J. Am. Chem. Soc.* **1998**, *120*, 7977.
[50] E. Zuidema, C. Bo, P. van Leeuwen, *J. Am. Chem. Soc.* **2007**, *129*, 3989.
[51] S. M. A. Donald, S. A. Macgregor, V. Settels, D. J. Cole-Hamilton, G. R. Eastham, *Chem. Commun.* **2007**, 562.
[52] E. Zuidema, P. van Leeuwen, C. Bo, *Organometallics* **2005**, *24*, 3703.
[53] G. Kiss, *Chem. Rev.* **2001**, *101*, 3435.
[54] W. Clegg, G. R. Eastham, M. R. J. Elsegood, B. T. Heaton, J. A. Iggo, R. P. Tooze, R. Whyman, S. Zacchini, *Organometallics* **2002**, *21*, 1832.
[55] S. Zacchini, Ph.D. Thesis, The University of Liverpool (UK), **2000**.
[56] W. T. Ashton, L. C. Meurer, C. L. Cantone, A. K. Field, J. Hannah, D. Karkas, R. Liou, G. F. Patel, H. C. Perry, A. F. Wagner, E. Walton, R. L. Tolman, *J. Med. Chem.* **1988**, *31*, 2304.
[57] M. Ito, A. Osaku, A. Shiibashi, T. Ikariya, *Org. Lett.* **2007**, *9*, 1821.
[58] A. Padwa, S. F. Hornbuckle, G. E. Fryxell, P. D. Stull, *J. Org. Chem.* **1989**, *54*, 817.
[59] A. Favorskii, *J. Russ. Phys. Chem. Soc.* **1905**, *37*, 643.
[60] V. Percec, R. Yourd, *Macromolecules* **1988**, *21*, 3379.
[61] J. J. R. Frew, K. Damian, H. Van Rensburg, A. M. Z. Slawin, R. P. Tooze, M. L. Clarke, *Chem. Eur. J.* **2009**, *15*, 10504.
[62] A. Naghipour, S. J. Sabounchei, D. Morales-Morales, S. Hernández-Ortega, C. M. Jense, *J. Organomet. Chem.* **2004**, *689*, 2494.
[63] T. Schulz, C. Torborg, B. Schäffner, J. Huang, A. Zapf, R. Kadyrov, A. Börner, N. Beller, *Angew. Chem.* **2009**, *121*, 936; *Angew. Chem. Int. Ed.* **2009**, *48*, 918.
[64] D. W. Allen, B. F. Taylor, *J. Chem. Soc. Dalton Trans.* **1982**, 51.
[65] M. Kranenburg, P. C. J. Kamer, P. W. N. M. van Leewen, D. Vogt, W. Keim, *J. Chem. Soc. Dalton Trans.* **1995**, 2177.
[66] A. Vavasori, G. Cavinato, L. Toniolo, *J. Mol. Catal. A* **2001**, *176*, 11.
[67] A. Seayad, S. Jayasree, K. Damodaran, L. Toniolo, R. V. Chaudhari, *J. Organomet. Chem.* **2000**, *601*, 100.
[68] J. Liu, P. J. Pogorzelec, J. Pelletier, E. Zuidema, C. Bo, D. Cole-Hamilton, J. A . Iggo, R. Whyman, G. R. Eastham, P. Richards, unpublished results.
[69] D. Selent, W. Baumann, A. Boerner, DE20031033143 20030717, **2005**.

Received: November 17, 2009
Published online: May 3, 2010

