Highly Selective Halide Anion-Promoted Palladium-Catalyzed Hydroformylation of Internal Alkenes to Linear Alcohols

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Here we report on our study of the *palladium-catalyzed* hydroformylation of alkenes. A (bcope)Pd-$(OTf)_2$ complex (bcope = bis(cyclooctyl)phosphine ethane, **2**) with substoichiometrically added halide anions is a highly efficient homogeneous catalyst (precursor) to selectively convert internal linear alkenes into predominantly linear (detergent) alcohols under mild conditions. Halide anion-dependent effects on the hydroformylation reaction *rate* as well as its *chemo- and regioselectivity* are observed. Thus, the rate of hydroformylation of thermally equilibrated internal higher alkenes increases by a factor of about 6−7 with chloride/bromide and about a factor 3−4 with iodide, while the selectivity toward alcohols increases to almost 100% upon addition of a substoichiometric quantity (with respect to palladium) of the halide anion source. Curiously, the regioselectivity toward linear alcohol increases in the reverse order, i.e., iodide > bromide > chloride. From a detailed analysis of the products obtained with model substrates, it is concluded that *hydrogenolysis* of (bcope)palladium-acyl intermediates is strongly accelerated by the presence of halide anions. From a comparison of the catalytic performance with some related L_2Pd-$(OTf)_2$ complexes, in which L_2 are bidentate phosphines closely related to bcope, it also appears that the ligand plays a critical role in the promoting effect of halide anions.

Introduction

Hydroformylation of alkenes is an industrially important synthetic method for producing oxygenates, such as detergent and plasticizer alcohols, from hydrocarbons. Current commercial hydroformylation processes either use cobalt or rhodium catalysts, optionally modified by ancillary ligands.[1] The selective conversion of the less reactive internal alkenes to linear aldehydes and alcohols is a topic of current interest. So far, the Shell cobalt/phosphine catalyst system is the preferred option for the hydroformylation of straight-chain internal alkenes to give mainly linear alcohols, but has the disadvantage of producing significant amounts of alkanes (∼10%). Rhodium-phosphine catalysts are widely used for the hydroformylation of propene to produce *n*-butanal, but are generally less suitable for the hydroformylation of internal straight-chain alkenes in the detergent area. Because of their low alkene bond isomerization activity, hydroformylation of internal alkenes is a relatively slow process and shows low regioselectivity for the linear product. Recently, ligands based on the phenoxaphosphino motif[2] and 2,2′-dimethyl-1,1′-binaphthyl[3] backbones have been developed, and this has allowed the Rh-catalyzed hydroformylation of, for example, *trans*-2-octene with moderate to good regioselectivity (l/b ≈ 2−20) and moderate activity (∼60−150 mol mol^{-1} h^{-1}). However, hydroformylation of a *thermodynamically equilibrated* internal olefin mixture to produce (mainly) linear product with good rate still presents a great challenge. Moreover, Rh catalysts produce aldehydes only as the final hydroformylation product and thus require an additional hydrogenation process step to produce alcohols.

Cationic palladium cis-chelating diphosphine complexes (P_2-PdX_2) are highly versatile catalyst precursors for a wide range of industrially important carbonylation reactions. Their use as alkene and alkyne carbonylation catalysts has been recently reviewed.[4] By modifying the diphosphine ligands, the coordination strength of the anions, and the reaction conditions, (hydro)-carbonylation reaction products can be switched from high molecular weight polyketones to monomeric esters, aldehydes, alcohols, or ketones.[5]

In the present paper, we focus on the catalytic activity of complexes comprising a cationic palladium center modified by bis-dialkylphosphines, in particular C_2-bridged ligands containing the bis(9-phosphabicylo[3.3.1]nonyl) moiety, also known as phobane. These are able to efficiently convert *an equilibrated mixture of internal alkenes* with CO/H_2 (syngas) to mainly linear alcohols via a highly selective *isomerization−hydroformylation−hydrogenation* tandem reaction.[6] Whereas cationic palladium catalysts in general are severely poisoned by halide anions, presumably due to their strong coordination at the palladium center, it is a most surprising feature of the present catalysts that they are strongly *promoted* by halide anions, added *in substoichiometric* quantities with respect to palladium. A brief account of this discovery was recently disclosed in the open literature.[7]

The present work was undertaken to outline some of the basic characteristics of halide anion promotion and its interplay with

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the nature of the bidentate phosphine ligand in hydroformylation of alkenes with the above-mentioned catalyst systems.

Results and Discussion

Hydrocarbonylation of Higher Alkenes with Cationic Pd Complexes. The catalyst systems were all preformed in sulfolane solvent by combination of the appropriate amounts of palladium(II) acetate, the bidentate ligand (L−L), and HOTf (trifluoromethanesulfonic acid) via a ligand complexation and anion displacement reaction sequence (see Experimental Section):

$$Pd(OAc)_2 + L{-}L \rightarrow (L{-}L)Pd(OAc)_2 \qquad (1a)$$

$$(L{-}L)Pd(OAc)_2 + 2\ HOTf \rightarrow (L{-}L)Pd\ (OTf)_2 + 2\ HOAc \qquad (1b)$$

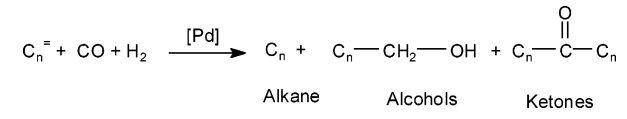
This catalyst solution was injected into an autoclave containing the appropriate alkenes dissolved in 2-ethylhexanol (2-EHA). Sulfolane has the rather unique property of being poorly soluble in higher alcohols and alkenes at room temperature but highly soluble at reaction temperature (about 100 °C). This enabled us to combine the benefits of homogeneous catalysis with an easy catalyst separation and recovery. At reaction temperature, the reaction system consisted of a single liquid phase, while after the conversion of alkenes to alkanols and cooling to room temperature, two liquid layers rapidly developed: a lower sulfolane layer containing the catalyst and very minor quantities of product, and an upper layer consisting mainly of the product alcohol and about 5−10 wt % sulfolane. The distribution ratio of the palladium catalyst in sulfolane:product was around 100:1 at room temperature. Thus, a staged operation combined with back-washing of sulfolane from the product with minimal amounts of water allowed complete catalyst−product separation.

We first tested the catalytic performance of $Pd(OTf)_2$ complexes, respectively modified with the 1,2-bis(di-*sec*-butylphosphine)ethane (BDsBPE, **1**) or bis(9-phosphabicylo-[3.3.1]nonyl)ethane (BCOPE, **2**) ligand in the hydrocarbonylation of alkenes. Their activity and selectivity toward 1-octene and a thermally equilibrated mixture of internal $C_8{-}C_{10}$ alkenes (*i*-$C_8{-}C_{10}$, see Experimental Section), respectively, is compared in Table 1.

When ligand **1** was used in combination with *noncoordinating* triflate anions, a very low selectivity for hydroformylation products (∼4%) was observed; instead saturated ketones were produced with good selectivity (88%, of which about 85% was the head-to-tail C_{17}-ketone isomer). Some alkanes (∼7%) were also coproduced. Changing to commercially interesting internal $C_8{-}C_{10}$ olefins cut as substrate (*i*-C_8-C_{10}), derived from the Shell Higher Olefin Process, led to a very low rate and conversion (Table 1, entry 2). After 5 h only traces of products were obtained.

Surprisingly different results were obtained when ligand **2**, very much related to ligand **1**, was applied (Table 1, entries 3 and 4). With both 1-octene and *i*-$C_8{-}C_{10}$, a considerably higher reaction rate was observed. More importantly, selectivity was now dramatically altered toward alcohols (up to almost 90%) instead of ketones. The observation of a very similar rate and product selectivity with 1-octene and a mixture of internal $C_8{-}C_{10}$ alkenes (TOFs 130−150)[8] leads us to conclude that this catalyst, in contrast to the catalyst containing ligand **1**, must be very effective in alkene double-bond isomerization under syngas. Sampling at the initial stage of the reaction supports this conclusion, as complete isomerization of 1-octene to equilibrated internal octenes occurred within the first hour at reaction temperature. This means that alkene double-bond isomerization is at least an order of magnitude faster than conversion to hydrocarbonylation products.

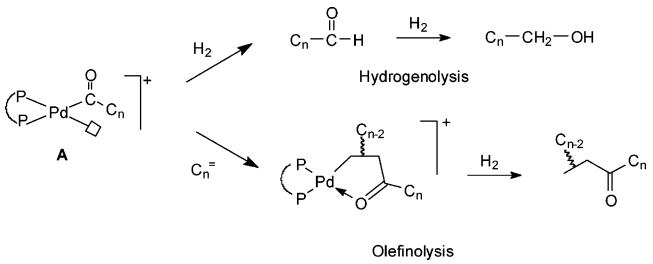
Table 1. Effect of Ligand Structure on (P−P)Pd(OTf)$_2$-Catalyzed Hydrocarbonylation of Higher Alkenes[a]



				product selectivity (% mol)[b]		
expt	P−P	substrate	rate (mol/mol h)	alkanes	alcohols (lin %)[c]	ketones ((h−t)[d] %)
1	**1**	1-octene	40	7	4 (51)	88 (85)
2	**1**	*i*-$C_8{-}C_{10}$ [e]	<10			
3	**2**	1-octene	130	2	88 (68)	10 (∼80)
4	**2**	*i*-$C_8{-}C_{10}$ [e]	150	8	89 (65)	3 (nd)

[a] Conditions: $T = 105$ °C, CO:H_2 (1:2), $P = 60$ bar, [Pd] = 0.25 mmol, L/Pd = 1.4. [b] Product selectivity defined as the percentage of alkene converted to respective product. [c] Linearity of alcohols defined as the fraction of linear alcohol in total alcohol product. [d] h−t, head-to-tail isomer. [e] *i*-$C_8{-}C_{10}$ is an equilibrated mixture of internal $C_8{-}C_{10}$ alkenes (12% C_8, 44% C_9, and 44% C_{10}).

Scheme 1. Reactions of the Pd−Acyl Intermediate to Produce Alcohols and Ketones



The selectivity to aldehydes (alcohols) and ketones is determined by the fate of the Pd−acyl intermediate **A** (Scheme 1).[5] Reaction of **A** with hydrogen (hydrogenolysis) will produce an aldehyde, which is subsequently hydrogenated to the corresponding alcohol. Alkene insertion into **A** ("olefinolysis") gives a Pd−alkyl complex and ultimately leads to a saturated ketone.

Clearly, when the ligand **1** is used, even the high H_2/CO ratio of 2 is an insufficient condition to favor hydrogenolysis over olefinolysis of the intermediate Pd−acyl species.[5] The low activity observed when using internal alkenes as substrate may be rationalized either by a low rate of formation of Pd−acyl and/or by a very low rate of hydrogenolysis of the Pd−acyl, together with the expected low rate of insertion of *internal* alkenes into it. Additionally, the rate of alkene double-bond isomerization with this catalyst must be low.

For the catalyst bearing ligand **2**, the distinctly higher ketone production rate observed with 1-octene (∼10%) compared with a mixture of internal $C_8{-}C_{10}$ alkenes (∼3%) can be seen as a consequence of the initially high concentration of 1-octene,

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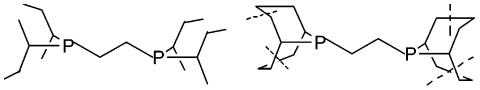
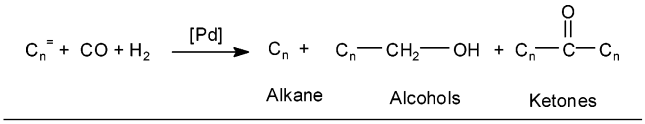
(8) The lower molecular weight of 1-octene relative to the average molecular weight of *i*-$C_8{-}C_{10}$ causes an approximately 12% higher molecular concentration of the first as both substrates were used on an equal volumetric basis (20 mL). Kinetic measurements have shown the rate to be first-order in alkene.

Scheme 2. Structural Relation between Ligands 1 and 2[a]



[a] The dotted lines represent the bonds that have been formally "cut" to form ligand 1 from ligand 2.

Table 2. Effects of Chloride Addition on (P−P)Pd(OTf)$_2$-Catalyzed Hydrocarbonylation of Higher Alkenes[a]



				product selectivity (% mol)[b]		
expt	P−P	substrate	rate (mol/mol h)	alkane (%)	alcohols (lin %)[c]	ketones ((h−t)[d] %)
1a	**1**	1-octene	40	7	7 (55)	86 (85)
2a	**1**	*i*-C_8−C_{10} [e]	<10			
3a	**2**	1-octene	1000	1	95 (79)	4 (∼80)
4a	**2**	*i*-C_8−C_{10} [e]	1000	<1	99 (72)	<1 (nd)

[a] Conditions: T = 105 °C, CO:H_2 (1:2), P = 60 bar, [Pd] = 0.25 mmol, L/Pd = 1.4. Cl/Pd = 0.4. [b] Product selectivity defined as the percentage of alkene converted to respective product. [c] Linearity of alcohols defined as the fraction of linear alcohol in total alcohol product. [d] h−t, head-to-tail isomer. [e] *i*-C_8−C_{10} is an equilibrated mixture of internal C_8−C_{10} alkenes (12% C_8, 44% C_9, and 44% C_{10}).

leading to an initially relatively high competitive rate of 1-octene insertion into the Pd−acyl over hydrogenolysis.

We thus may conclude that the cationic Pd catalyst based on the ligand **2** differs in two important catalytic performance aspects from an analogous catalyst based on the seemingly much related ligand **1**: *first*, with respect to the ease of hydrogenolysis of Pd−acyl species leading to the alcohol product, and *second*, with respect to the capability of rapidly catalyzing double-bond isomerization. It is clear that this difference must somehow be traced back to the structural differences between the two ligands (see Scheme 2).

Effects of Halides on Hydrocarbonylation of Higher Alkenes with Cationic Pd Complexes. We now turn to the dramatic influence of the presence of added halide anions on catalyst performance, which was serendipitously discovered in a study aimed at further improving the rate and selectivity of hydroformylation of internal alkenes by cationic Pd(BCOPE)-(OTf)$_2$ complexes.[6]

To systematically study the effect of the addition of halide anions on the various indicators of catalytic performance (activity, chemo- and regioselectivity), we repeated the experiments previously described, now with the addition of *substoichiometric* amounts of NaCl (Cl/Pd = 0.4). The results are shown in Table 2.

One conclusion from comparison of the results given in Table 2 with those in Table 1 is that substoichiometric addition of chloride exerted *no significant effect* on the Pd catalyst bearing ligand **1**, with respect to both activity and selectivity, regardless of whether 1-octene or a mixture of internal C_8−C_{10} alkenes was used as the substrate. It is noteworthy that ketones remain by far the dominant products (86%).

On the contrary, a *very strong promoting* effect on the rate and selectivity of hydroformylation was observed with the Pd catalyst bearing ligand **2**. Hydroformylation rates were increased by about a factor of 7, while selectivity to alcohol approached 100% with internal C_8−C_{10} alkenes. When 1-octene was used as the substrate, however, a small amount of ketones (∼4%) was still produced, which we again attribute to competing olefinolysis of Pd−acyl with 1-octene in the very early stage of the reaction. With this substrate, ketone formation decreased by a factor of only 2.5, whereas the competing hydroformylation rate increased by a factor of about 7 with chloride addition. This suggests that halides could have a slightly *inhibiting*, rather than promoting effect on alkene double-bond isomerization. In any case, alkene isomerization must still be a fast reaction with the catalyst based on ligand **2**, since the hydroformylation of 1-octene and an equilibrated mixture of internal C_8−C_{10} alkenes proceeded at a very similar rate. Also noteworthy was the strong decrease in alkane production (to ≲1%).

As already noted, with ligand **1** hardly any effect of the same concentration of chloride was observed. Likewise, further experiments have shown that ligand **1** is exemplary for a series of bis(dialkylphosphine)alkanes, such as 1,2-bis(di-*n*-butylphosphine)ethane, 1,2-bis(dicyclohexylphosphine)ethane, and 1,3-bis(dicyclohexylphosphine)propane. No promoting effects were observed with any of these simple dialkyl phosphine ligands. Rather, an inhibiting effect was evident, certainly at Cl/Pd ratios approaching unity. It seems clear that the phobane moiety confers the ligand *and* the Pd catalyst based on it some very unique properties!

Control experiments have shown that the promoting effects are independent of the chloride source. For example, experiment 4a in Table 2 was repeated using HCl and $MePPh_3Cl$ as halide source. The reaction rates were the same, within experimental error (±10%), while both the chemo- and regioselectivity were indistinguishable from those obtained with NaCl. Thus, the observed promoting effects can be safely attributed to the presence of the halide anion.

To determine the influence of the amount and type of halide anions on the (BCOPE)Pd(OTf)$_2$ catalyst performance, the reaction rate was measured in a series of hydroformylation experiments with *i*-C_8−C_{10} alkenes as substrate. The results are summarized in Figure 1.

It appeared that the rate-promoting effect depends on both the quantity and the type of halide used. With respect to the quantity of halide, volcano-shaped promotion curves were observed. This effect was more pronounced for chloride and bromide (with 6−7-fold increase at the maximum), while for iodide a less pronounced (and broader) maximum was observed (3−4-fold rate increase) around Hal/Pd ≈ 0.5. The volcano shape must arise from two opposite effects: a strong rate-promoting effect occurs in the lower halide concentration range, while at the higher concentration a gradual poisoning effect takes over, already significantly before a stoichiometric quantity (Hal/Pd = 2) is reached. It is well known that halide anions are relatively strongly coordinating anions to Pd^{2+}, forming "neutral" Pd halide compounds, and thus we attribute the observed poisoning effect to blocking of coordination sites, making the Pd center less accessible (or inaccessible) for substrate molecules. Apparently, the strong promoting effect can exist only if a *relatively small fraction* of the Pd is coordinated to halide, while the rest (major fraction) should be present as cationic Pd species. This suggests that the halide-promoting effect operates only at one (or a few) specific step(s) in the catalytic cycle and most certainly at the rate-determining step. The coordination strength of the anions can be strongly modified by the polarity of the reaction medium, and it has been observed that the magnitude of the rate promotion and the position and width of the volcano curves are significantly influenced by small amounts of water. Under low water conditions (≲0.5 wt %) the maximum is located at significantly lower Hal/Pd ratio, while the volcano

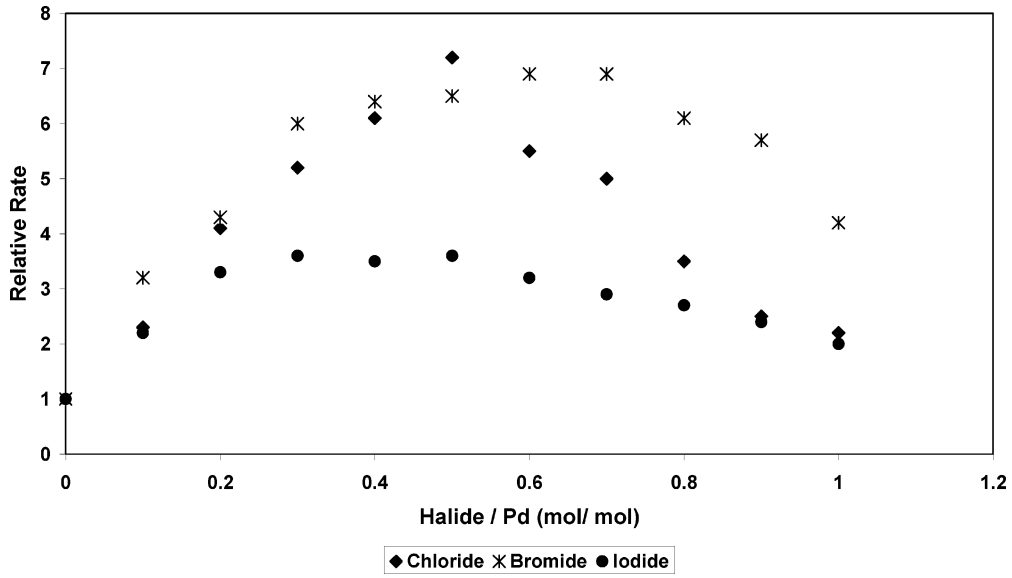


Figure 1. Relative reaction rate for the hydroformylation of a mixture of internal C_8-C_{10} alkenes as a function of type and concentration of halide. Catalyst: (BCOPE)Pd(OTf)$_2$ (0.25 mmol) in sulfolane/water (1.6%), all halides added as Na salts. $P = 60$ bar (Co:H$_2$ = 1:2), $T = 105$ °C.

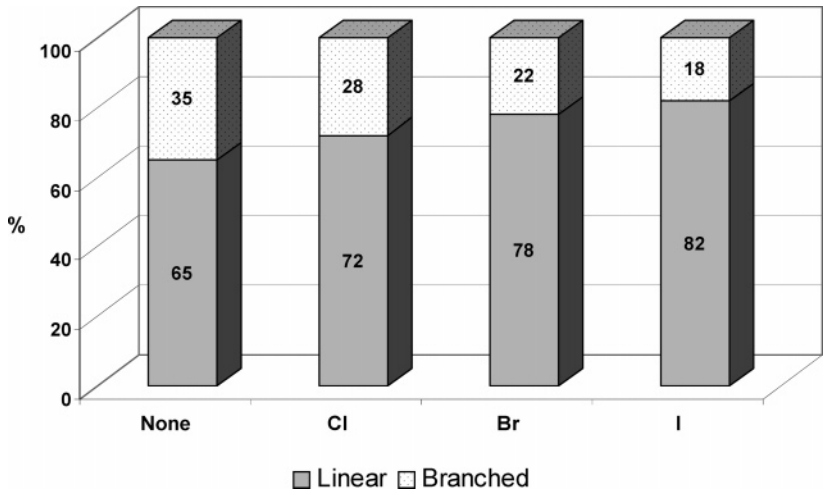


Figure 2. Halide effect on the regioselectivity of the (BCOPE)Pd(OTf)$_2$-catalyzed hydroformylation of an equilibrated mixture of internal C_8-C_{10} alkenes. Reaction conditions as stated in Table 2. Hal/Pd = 0.4

curve sharpens. The opposite occurs at higher water concentration (~2 wt %). The results shown in Figure 1 were determined at a water concentration of 1.6 wt %. We also believe that the broader volcano curves observed with iodide (and bromide) relative to chloride reflect the somewhat weaker intrinsic coordination strength of the former anions toward Pd^{2+}. Further experiments have also shown that fluoride anions do not show any significant promoting effect,[9] in line with their low coordination strength to Pd^{2+}.

The regioselectivity of the hydroformylation (toward linear/branched product) was also clearly affected by adding halide promoters, with the magnitude of this effect dependent on both the type and the quantity of the halide used. If no halide was used, only 65% of linear alcohol was obtained. As can be seen from Figure 2, the highest regioselectivity to linear alcohols was achieved by using iodide (82%), followed by bromide and chloride (78% and 72%, respectively).

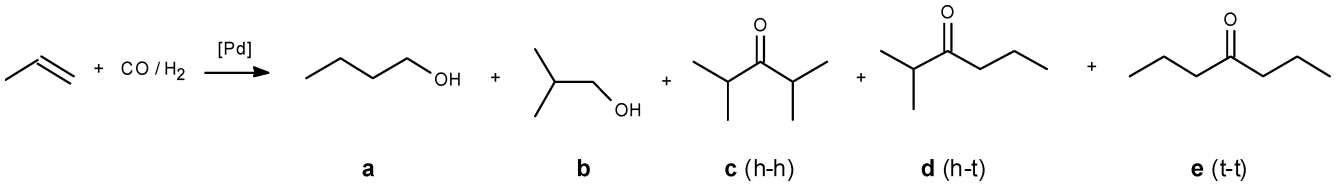
Hydrocarbonylation of Propene. To examine the possibility that the observed halide-promoting effects are intertwined with alkene double-bond isomerization, we also investigated the catalytic *hydrocarbonylation of propene* by (BCOPE)Pd(OTf)$_2$. The results are summarized in Table 3.

In the absence of chloride, only a very small amount of alcohol (~10%) was formed. By far the main products are C_7-ketones apparently formed through selective olefinolysis of the Pd−acyl intermediate (Scheme 1). The main product is 2-methylhexane-3-one, indicating that head-to-tail enchainment of C_3 units is dominant. Very similar results were observed with cationic Pd complexes bearing bis(dialkylphoshine) ligands, such as **1**.[5]

The addition of chloride anions to a (BCOPE)Pd(OTf)$_2$ catalyst again promoted the rate of hydrocarbonylation, but more importantly, very drastically changed the product structure from ketones to predominantly alcohols. Apparently, the chloride anion functions as a "switch" between olefinolysis and hydrogenolysis of Pd−acyl intermediates. A relatively high concentration of chloride was needed with propene to achieve a high selectivity to alcohols. The maximum *selectivity* to alcohol (85%) was now obtained at Cl/Pd = 1.2, while the maximum *activity* was reached at a Cl/Pd = 0.4 (TOF = 1000 mol/mol

(9) Drent, E.; Jager, W. W. Unpublished results, Shell Research and Technology Centre, Amsterdam.

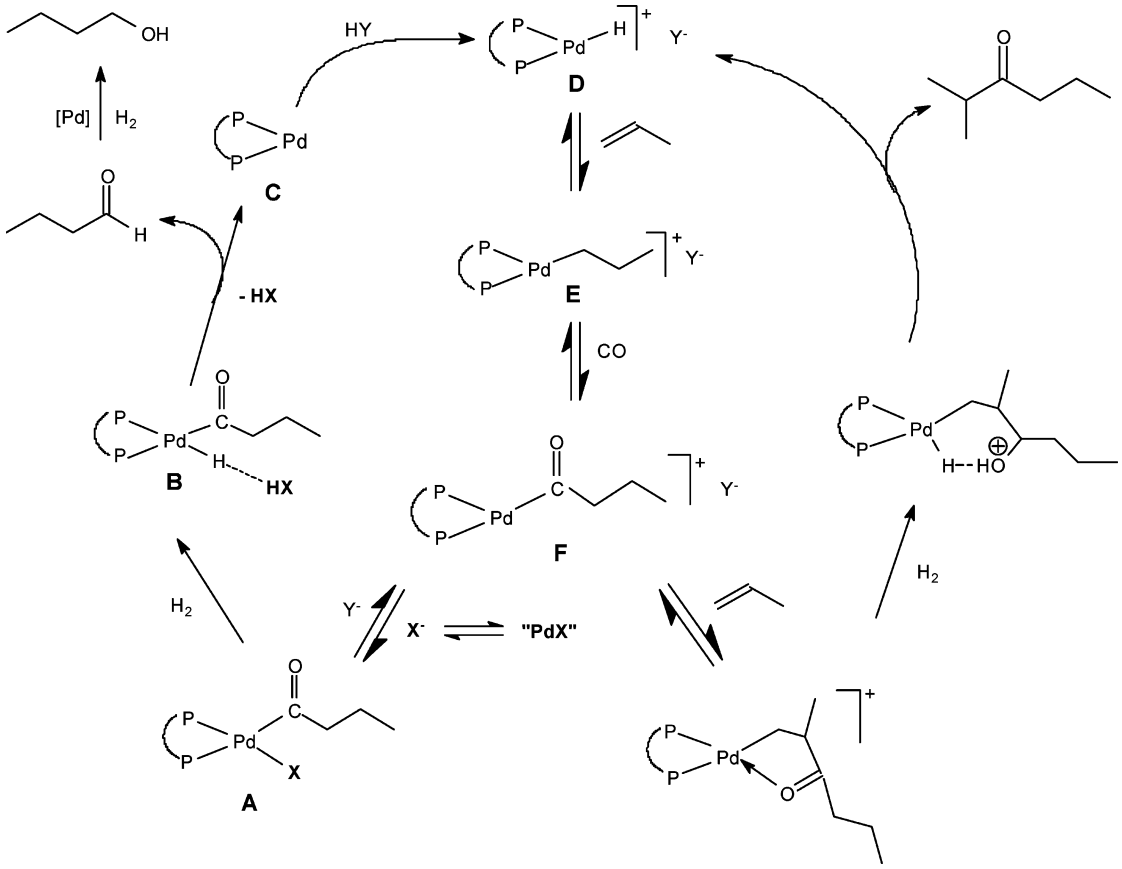
Table 3. Product Distribution for the (BCOPE)Pd(OTf)$_2$-Catalyzed Hydrocarbonylation of Propene[a]



	product selectivity (%)				
Cl/Pd ratio (mol/mol)	1-butanol (**a**)	2-methyl-1-propanol (**b**)	2,4-dimethyl-pentan-3-one (**c**)	5-methylhexan-4-one (**d**)	heptan-4-one (**e**)
0	6.8	5.7	24.0	56.5	7.0
0.4	50.1	18.1	8.3	20.9	2.6
0.8	59.9	21.8	4.0	11	3.3
1.2	62.9	21.9	4.0	10.4	0.8

[a] Conditions: 5 g of propene, $T = 105$ °C, CO:H_2 (1:2), $P = 60$ bar, [Pd] = 0.25 mmol, L/Pd = 1.4. Chloride introduced as NaCl.

Scheme 3. Proposed Catalytic Cycle for Halide-Promoted Pd-Catalyzed Hydrocarbonylation of 1-Alkenes (using propene as example), Schematically Illustrating the Role of Noncoordinating and Halide Anions[a]



[a] Y^- represents noncoordinating triflate anion, whereas X^- represents halide anion and "PdX" represents any Pd-halide complex present in solution. For clarity, the formation of only one regioisomer is shown.

h). The maximum rate is of similar magnitude to that observed with higher internal alkenes and is indicative of a similar, alkene size independent, rate-determining step. The *lower chemoselectivity* observed with propene relative to that obtained with higher (internal) alkenes (~99%) is remarkable. However, insertion of propene into the Pd−acyl species is much more facile than insertion of the much bulkier internal C_8−C_{10} alkenes. Hence, the insertion of propene can compete better with the hydrogenolysis of Pd−acyl.

The selectivity switch obtained by addition of halide in (BCOPE)Pd(OTf)$_2$-catalyzed hydrocarbonylation of propene most clearly supports the conclusion that halide anions exert their promoting effect at the rate-determining Pd−acyl hydrogenolysis step of the hydrocarbonylation catalytic cycle at the cost of the olefinolysis of the same intermediate.

Mechanistic Proposal for Halide Anion-Promoted Pd−Acyl Hydrogenolysis. One of the most remarkable aspects of the strong promoting effect of halide anions on (BCOPE)Pd-catalyzed hydroformylation is that it operates *only* at a *substoichiometric ratio of halide anions* on Pd. This means that only a *relatively small fraction* of the Pd can be coordinated to halide, while the major fraction should still be present as cationic Pd species. As shown in the previous section on propene hydrocarbonylation, the halide-promoting effect operates at the rate-determining Pd−acyl hydrogenolysis step in the catalytic cycle. The counterion of the majority of cationic Pd species at any

moment is the noncoordinating triflate anion. It is likely that these are the species involved in the efficient generation of Pd−acyl intermediates, via alkene binding and insertion into Pd−H, and subsequent CO binding and insertion into the Pd−alkyl (Scheme 3, steps D → E → F). At higher halide concentrations progressively more coordination sites of these species will become blocked by coordination of halide anions until the promoting effect on hydrogenolysis of Pd−acyl species becomes overwhelmed by inhibition of their formation, leading to the volcano type shape of Figure 1.

The *mechanism* of Pd−acyl hydrogenolysis is not known, but it is reasonable to expect that it requires the *electrophilic* activation of dihydrogen at the Pd center. One limiting factor for dihydrogen to approach the Pd center may be (strong) coordination of neutral substrate molecules, CO, and/or alkenes as, for instance, evidenced by the formation of ketones rather than hydroformylation products. The switch in selectivity from ketone formation to hydroformylation of propene and the very significant increase in the rate of hydroformylation of internal higher alkenes observed on addition of halide anions to a (BCOPE)Pd(OTf)$_2$ catalyst point to an *active role* of anions in the Pd−acyl hydrogenolysis reaction. The halide anion-dependent effects, both on catalyst activity as well as on *chemo- and regio*selectivity, strongly suggest that the halide anion really needs to *penetrate into* the coordination sphere and subsequently *coordinate* to the Pd−acyl to promote hydrogenolysis. It is suggested that *close proximity* of the halide anion and the cationic Pd center is required for the *heterolytic* dissociation of H_2, possibly bound at the fifth coordination site. By temporarily binding a proton, the halide anion would facilitate this process, leading to a Pd(hydride)(acyl) complex (**B**) that would subsequently eliminate aldehyde to produce (P−P)Pd (**C**), which in turn reacts with H^+ to regenerate a palladium hydride (**D**).

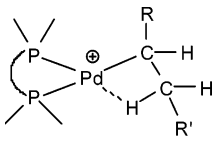
Noncoordinating anions, such as triflate, could also play this role in heterolytic H_2 dissociation, but these are thought not to be efficient, not only because of their low affinity to protons but also because they do not stay close enough to the cationic Pd−acyl complex, instead being easily displaced by neutral coordinating molecules such as CO and/or alkenes.

The halide anion dependence of *regioselectivity* in (internal) alkene hydroformylation and the predominantly linear alcohol product formed in all cases suggest that promotion of Pd−acyl hydrogenolysis depends on the space available for coordination of the halide anion. Kinetic displacement of neutral substrate molecules by halide anions will depend on the steric hindrance at the Pd−acyl center. This makes it plausible that the hydrogenolysis of a Pd−*n*-acyl is more efficiently promoted than that of a bulkier Pd−*iso*-acyl species, thus affording predominantly the linear alcohol product, under the reasonable assumption that steps **D** ↔ **E** and **E** ↔ **F** (Scheme 3) are fast and reversible.

Likewise, it is tempting to speculate that it is the *size of the halide-promoter anion* that can also play a role in affecting product linearity, as depicted in Figure 2. It seems plausible that the larger the anion, the better it discriminates between a Pd−*n*-acyl and Pd−*iso*-acyl species, and thus will lead to a higher (I^- > Br^- > Cl^-) *regioselectivity* toward the linear product.

It is, however, unlikely that free halide anions can exist in the catalytic system. Instead, it is much more likely that they are present as anions bound to a variety of Pd species (schematically indicated as "PdX" in Scheme 3). These halide anions probably exchange between all the Pd species present in the catalytic cycle and in the resting states, i.e., all the complexes that together constitute the "catalyst". In any case, these halide anions must not be *too strongly* coordinated to any non-Pd−acyl intermediates so that they are able to coordinate to the Pd−acyl species and promote hydrogenolysis. Halide transfer between the Pd species probably occurs via an intermediary halide-bridged Pd-dimer.[10] Alternatively, it is possible that the halide anions have a stronger affinity for the Pd−acyl species than for other Pd species. The observed very significant *decrease* in paraffin selectivity (cf. Tables 1 and 2) upon addition of halide anions would support the hypothesis of *selective* binding of halide anions to Pd−acyl species, as hydrogenation of the Pd−alkyl intermediate is not promoted but rather retarded.

An intriguing question remains: why does the catalytic performance of Pd complexes bearing ligand **1** differ so dramatically from those bearing ligand **2**? Not only is (BCOPE)-Pd(OTf)$_2$ much more active at isomerizing internal alkenes and eventually producing linear alcohols, but also the promoting effect of halide anions takes place only with this catalyst system (cf. Tables 1 and 2). Although the symmetric phosphacyclic phobane structure induces a different hybridization of the phosphorus atoms in BCOPE compared to that in a noncyclic tertiary phosphine,[11] we expect both ligands to be electronically rather similar. Indeed, the CO stretching frequency for [(BCOPE)-Ni(CO)$_2$] (νCO = 1980−1985 cm^{-1}) falls within the range of frequencies observed for analogous Ni complexes with 1,2-di-sec-alkyldiphosphines.[12] The Tolman cone angle at P for the phobane group is rigid and relatively small (about 120−130°),[13] whereas the more dynamic cone angle of the P(*sec*-butyl)$_2$ moiety (due to the rotational freedom of *sec*-butyl groups) can undergo considerable variation in time (∼130−170°). On average, it is expected to be considerably larger than that of a rigid and symmetric phobane moiety.[14] We tentatively put forward the following hypothesis: Rapid double-bond alkene isomerization requires a low energy barrier between all intermediate Pd(*sec*-)alkyl and Pd(H)(int-alkene) species along the linear alkyl chain of the alkene, and we expect small cone angle ligands, such as **2**, to provide sufficient coordination freedom of *sec*-alkyl groups at the square-planar Pd coordination sites. The electrophilic affinity toward the β-H atoms of *sec*-alkyl groups makes a low energy transition state, involving a significant agostic interaction between the β-hydrogens and the cationic Pd center, easily accessible (**G**).



G

With—on average—larger cone angle ligands, such as **1**, the formation of low-energy transition states, such as **G**, may be

(10) Ex-situ NMR spectroscopic studies of catalyst solutions have identified various chloride-bridged Pd-dimer species (Mul, P. W.; et al. Unpublished results, Shell Research and Technology Centre, Amsterdam).

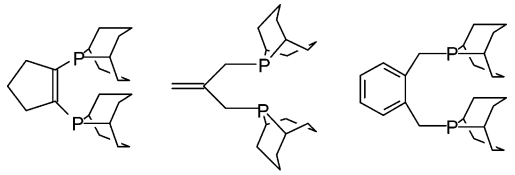
(11) Gallagher, M. J. In *Phosphorous-31 Spectroscopy in Stereochemical Analysis*; Verkade, J. G., Quin, L. D., Eds.; VCH Verlagsgessellschaft mbH: Weinheim, 1987; Vol. 8.

(12) Mul, P. W.; Buijink, J. F. K. Unpublished results, Shell Research and Technology Centre, Amsterdam. (b) Pugh, R. I. Ph.D. Thesis, University of Bristol, 2000.

(13) Marsh, P. S. Ph.D. Thesis, University of Bristol, 2003. Cone angles were calculated from X-ray crystal structures of (diphosphine)PdCl$_2$ complexes.

(14) Crabtree, R. H. *The Organometallic Chemistry of Transition Metals*, 2nd ed.; John Wiley & Sons: New York, 1994; Chapter 4.

Scheme 4. Biscyclo-octyl Phosphine Ligands Studied



3 **4** **5**

unfavorable due to insufficient coordination space. This will cause relatively higher average barriers for the interconversion between Pd−(*sec*-)alkyl and Pd(H)(int-alkene) species along the alkyl chain and thus lead to inefficient alkene double-bond isomerization.

The absence of any significant halide effect on the predominant formation of ketones with catalysts bearing ligand **1** (see in particular experiments with 1-octene as substrate, Table 1, expt 1 and Table 2, expt 1a) may be attributed to inefficient transfer of halide anions to Pd−acyl. A larger cone angle ligand such as **1** could present too much steric congestion at the coordination sites around Pd (as suggested above for alkene double-bond isomerization) to obtain efficient transfer of halide anions between *all* the various intermediate Pd complexes. This in turn will lead to the inability to pass on the halide anion efficiently to the right intermediate, i.e., the Pd−acyl, for its promoting effect to be exerted. Alternatively, it is also possible that certain (**1**)Pd species, other than (**1**)Pd−acyl, have a very high binding affinity toward halide anions and thus prevent transfer. In either case it seems more surprising that halide promotion *does occur* (with ligand **2**, where halide exchange between *all* Pd species must be efficient) than that it *does not* occur (as with all catalysts studied bearing a variety of bis-(dialkylphosphines), such as the exemplary ligand **1**). It would indeed seem that the odds of achieving efficient halide anion exchange among all possible Pd species are minimal.

Influence of Backbone Structure of Bis(cyclo-octylphosphine) Ligands. As shown, ligand **2** provides cationic (P−P)-$Pd(OTf)_2$ complexes with a set of unique catalytic properties, such as rapid double-bond alkene isomerization and strongly halide anion-promoted hydroformylation. We suggested that the rigid low-cone angle structure of the 9-phosphabicylo[3.3.1]-nonyl (phobane) group could be an important attribute for the catalytic performance of these catalysts.

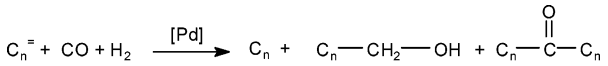
We wanted to address the question whether these properties are solely imposed by the two cis-chelating phobane groups or whether the backbone, i.e., the bite angle of the bidentate ligand, is a critical parameter too. To investigate this, a variety of bis-(cyclo-octylphosphine) ligands with some specific bridge structures were synthesized (Scheme 4) and tested in the Pd-catalyzed hydrocarbonylation of a mixture of internal C_8−C_{10} alkenes. The results are summarized in Table 4.

With these ligands a relatively low rate was observed (TOF $\approx$ 20−50) in the absence of halide. Nevertheless, C_2-bridged ligand **3** (and also ligand **2** in Tables 1, 2) afforded considerably more active catalysts than analogous C_3 and C_4 bidentate ligands (**4** and **5**, respectively).

Clearly, chloride anions exert a much stronger promoting effect for C_2 and C_3 backbones than for the C_4-bridge ligand. It is also apparent that the relationship between the rate enhancement and the length of the phosphine backbone is not a linear one: $r_{C2} > r_{C3} \gg r_{C4}$, with TOF of 800, 300, and 40, respectively. Competing ketone formation shows a reverse trend.

When 1-octene is used as substrate, ketone formation became the main hydrocarbonylation reaction in the absence of chloride

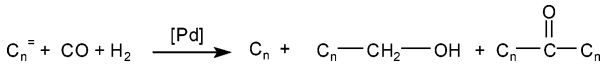
Table 4. Influence of Backbone Structure of Bisphobane Ligands on the Hydrocarbonylation of *i*-C_8−C_{10} Alkenes[a]



			product selectivity (mol %)[b]		
ligand	Cl/Pd	rate (mol/mol h)	alkane	alcohols (lin %)[c]	ketones
3	0	50	9	83 (66)	7
	0.4	800	2	96 (81)	1
4	0	~20[d]	20	40 (nd)[e]	40
	0.4	300	1	96 (84)	2
5	0	~20[d]	10	20 (63)	70
	0.4	40	5	60 (75)	35

[a] Conditions: T = 105 °C, CO:H_2 (1:2), P = 60 bar, [Pd] = 0.25 mmol, L/Pd = 1.4. [b] Product selectivity defined as the percentage of alkene converted to respective product. [c] lin % = % linear product alcohols in total alcohol product. [d] Low-activity catalysts: conversion after 5 h ~10−15%. [e] nd = not determined.

Table 5. Influence of Backbone Structure on the Hydrocarbonylation of 1-Octene[a]



			product selectivity (mol %)[b]		
ligand	Cl/Pd	rate (mol/mol h)	alkanes	alcohols (lin %)[c]	ketones
3	0	50	6	41 (69)	53
	0.4	900	2	95 (81)	3
4	0	30	15	23 (66)	62
	0.4	200	1	87 (84)	11
5	0	30	12	8 (57)	81
	0.4	50	4	50 (71)	46

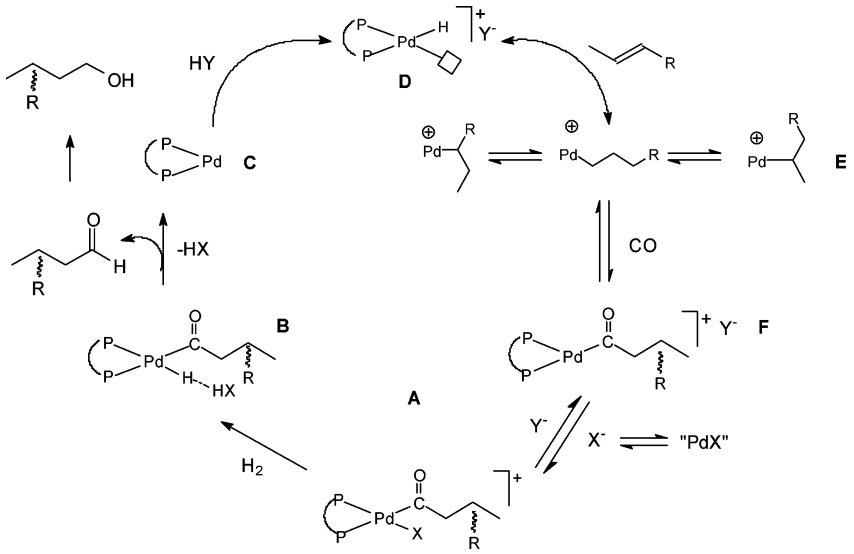
[a] Conditions: T = 105 °C, CO:H_2 (1:2), P = 60 bar, [Pd] = 0.25 mmol, L/Pd = 1.4. [b] Product selectivity defined as the percentage of alkene converted to respective product. [c] lin % = % linear product alcohols in total alcohol product.

(Table 5). Addition of chloride again shifts the selectivity to hydroformylation in all cases, with an increase of conversion rate, which is, however much more pronounced with the C_2 ligand **3** than with the C_3 ligand **4** and only small with the C_4 ligand **5**.

The results indicate that the hydrogenolysis step of Pd−acyl proceeds far less efficiently with catalysts containing the larger bite angle C_4 ligands. The chloride-promoting effect observed with these ligands is too weak, so that a high hydrogenolysis rate cannot be achieved.

Given the above proposed model for the rate-determining heterolytic dissociation of H_2 as the crucial step in hydrogenolysis, we can rationalize a bite angle dependence as follows: a chelating ligand with larger bite angle causes more steric crowding at the remaining two coordination sites of the square-planar Pd^{2+}. As suggested before, halide promotion requires the anion to penetrate into the coordination sphere of Pd−acyl to allow for efficient heterolytic activation and dissociation of H_2 and subsequent formation of hydroformylation products. Less space at the two substrate-binding sites in C_4 ligand chelated Pd species may have a negative effect on the ease of exchange of halide anions (via proposed intermediate halide-bridged Pd dimer species) between the various palladium complexes and thus will have a negative effect on passing the halide to the Pd−acyl for exerting its promoting effect.

Scheme 5. Proposed Mechanism of the Pd-Catalyzed Hydroformylation of Alkenes



Summary and Conclusions

We have discussed the remarkable performance of (BCOPE)-$Pd(OTf)_2$ as catalyst precursor for the selective hydroformylation of internal olefins to linear alcohols. Both activity and selectivity show a huge improvement when sources of halide anions are added in *substoichiometric* amounts with respect to Pd. The best activity is obtained by using chloride or bromide anions, while iodide is the best choice for improving regioselectivity. Furthermore, this halide anion-promoting effect appears to occur by far most effectively with ligands containing phobane substituents, while being much more pronounced for C_2-bridged diphosphines than for chelating ligands with larger bite angles containing C_3 and C_4 backbone structures. All results indicate that the halide anions strongly influence the fate of the Pd−acyl species and that this is both the rate- and selectivity-determining step of the hydroformylation catalytic cycle. We propose that the halide anion assists the heterolytic splitting of dihydrogen in the Pd−acyl and, thus, favors its hydrogenolysis over the olefinolysis pathway.

A further remarkable property of the (BCOPE)$Pd(OTf)_2$-based catalyst is its ability to efficiently catalyze alkene double-bond isomerization, which leads to the observation that a significantly higher (chemo)selectivity in hydroformylation can be achieved with higher internal linear alkenes (∼99%) than with 1-alkenes, such as propene (∼85%). This is attributed to more effective competition of propene insertion into the Pd−acyl versus hydrogenolysis, compared with bulky internal higher alkenes. Both the efficient alkene double-bond isomerization and the strong halide anion-promoting effect observed with catalysts based on BCOPE are a result of two combined attributes of the ligand, i.e., a small rigid cone angle at phosphorus with a small bite angle of the C_2-bridged bisphobane ligand BCOPE. The proposed mechanism for halide-promoted (BCOPE)$Pd(OTf)_2$-catalyzed hydroformylation of higher olefins, including alkene double-bond isomerization, is summarized in Scheme 5.

A surprising feature of the catalysts is also the fact that no ester products are formed,[15] given the fact that 2-ethylhexanol is used as cosolvent, and toward the end of the reaction linear primary alcohols are the main component of the reaction mixture. Apparently, alcoholysis of the Pd−acyl intermediates does not occur. It remains intriguing why activation and presumed heterolytic dissociation of dihydrogen and reaction with Pd−acyl proceeds much faster than reaction with an already preionized alcohol molecule. It is interesting to note that similar palladium catalysts bearing chelating ligands, such as **4** and **5**, but with a bulky di-*tert*-butylphosphine group instead of the phobane group, are highly efficient for hydrolysis or alcoholysis of Pd−acyl species, producing carboxylic acids or esters with high rates.[16] It serves as an illustration of the subtle interplay between the structure of the neutral ligand and the coordinating abilities of the anionic ligands, controlling which of the various substrate molecules, e.g., alkene, hydrogen, or alcohol, is more reactive toward, for instance, Pd−acyl intermediates.

We rationalized most of the observed phenomena in a qualitative way, but it is clear that further detailed studies of the elementary steps involved in the palladium-catalyzed hydrocarbonylation of alkenes are required to gain full insight into factors controlling activity and selectivity of the catalysts.

Experimental Section

General Remarks. Product analysis of reaction mixtures was performed by gas−liquid chromatography (GLC) on a Perkin-Elmer 8500 GC equipped with two capillary columns, Chrompack 50 m CP-sil-5 and 50 m FFAP. Structural analysis was performed with GLC-mass spectroscopic (GC/MS) analysis on a Finnigan-9610 gas chromatograph fitted with the CP-sil-5 column and coupled to a Finnigan-4000 triple-stage mass spectrometer using electron-impact ionization. ^1H (chemical shifts relative to residual solvent) and $^{31}P\{H\}$ (chemical shifts to high frequency of H_3PO_4) NMR spectra were recorded on either a Varian Mercury 300 MHz or Varian Inova 400 MHz spectrometer at 298 K.

Materials. Palladium acetate, trifluoromethane sulfonic acid, and the halide sources (alkali halide salts) were obtained from Aldrich and used as received. The sulfolane was topped and tailed before use. The BCOPE and BDsBPE ligands and 9-phosphabicyclononane

(15) Pd catalysts based on BCOPE and coordinating carboxylate anions are effective in the methoxycarbonylation of alkenes and even of ethene (to produce carboxylic acid esters in high selectivity). Drent, E.; Pello, D. H. L.; Hasselaar, M. (Shell Oil Co) U.S. patent 5436356, 1994.

(16) Drent, E.; Jager W. W. (Shell Oil Co.) U.S. patent 6706912, 2001. Drent, E. (Shell Oil Co.) U.S. patent 6639091, 2002. Van Leeuwen, P. W. N. M.; Zuideveld, M. A.; Swennenhuis, B. H. G.; Freixa, Z.; Kamer, P. C. J.; Goubitz, K.; Fraanje, J.; Lutz, M.; Spek, A. J. *J. Am. Chem. Soc.* **2003**, *125*, 5523. Clegg, W.; Eastman, G. R.; Elsegood, M. R. J.; Tooze, R. P.; Wang, X. L.; Whiston, K. *Chem. Commun.* **1999**, 1877−1878. Eastman, G. R.; Tooze, R. P.; Wang, X. L.; Whiston, K. (ICI) WO96/19434, 1996. Drent, E.; Kragtwijk, E. (Shell) EP495548, 1992.

(phobane, mixture of *as* and *sym* isomers) were obtained from CYTEC. The symmetric and asymmetric phobanes were separated as reported in the literature[17] and the *sym*-isomer was used for ligand synthesis. Purity of the phosphines was always higher than 95%, measured by ^{1}H NMR and ^{31}P spectroscopy; phosphine oxides were found as main impurities.

The mixture of thermally equilibrated internal C_8-C_{10} alkenes from the Shell Higher Olefins Process (12% C_8, 44% C_9, and 44% C_{10}) was obtained from in-house sources, while 1-octene was obtained from Merck. Alkenes were treated over an alumina bed to remove peroxides and stored under nitrogen. Propene was polymer grade and was obtained from in-house sources.

Synthesis of the Ligands. 1,2-Bis(cyclo-octyl)phosphinocyclopentenylidene (3). 1,2-Dibromocyclopentene (5 g, 22 mmol), phobane (9 g, 57 mmol, 90% *sym*), and DABCO (9 g, 80 mmol) were dissolved in 60 mL of degassed xylene. After addition of 1.15 g (1 mmol) of $Pd(PPh_3)_4$, the reaction mixture was stirred overnight at 140 °C and filtered while hot. Upon cooling to room temperature, a fluffy precipitate appeared. The mixture was further cooled to −35 °C and filtered under vacuum. The solid was recrystallized twice from MeOH (50 mL). Yield: 4.3 g (12.4 mmol, 56%). ^{1}H NMR (CD_2Cl_2): 1.41−2.12 (m, 26H,CH_2 phobane, CH_2 cyclopentene); 2.28 (br, 4H, CH_2 cyclopentene); 2.58 (m, 4H, CH phobane). ^{31}P{^{1}H} NMR: −25.8 ppm.

1,3-Bis(cyclo-octyl)phosphinoisobutenylidene (4). 3-Chloro-2-chloromethylpropene (2.5 g, 20 mmol) and 7 g of *sym*-phobane (50 mmol) were dissolved in acetonitrile. The phobane is insoluble at room temperature but dissolves completely at 80 °C. After 15 min at this temperature a precipitate appears. After 3 h reflux the reaction mixture is cooled to room temperature and filtered under vacuum. The crude product was dissolved in 30 mL of toluene, and the organic phase was extracted with 20 mL of water and 10 mL of $HNEt_2$. The water layer was separated, and the organic phase was washed with 20 mL of water. The toluene was evaporated under vacuum, and the product was recrystallized from MeOH (30 mL). Yield: 2.8 g (8.3 mmol, 36%). ^{1}H NMR (C_6D_6): 1.4−2.2 (m, 28H, phobane); 2.7 (s, 4H, CH_2); 4.9 (s, 2H, CH). ^{31}P{^{1}H} NMR: −36.5 ppm.

1,2-Bis(cyclo-octyl)phosphinoxylene (5). 1,1′-Dibromo-*o*-xylene (6.6 g, 25 mmol) and 7.1 g (50 mmol) of *sym*-phobane were mixed in 30 mL of acetonitrile. After a few minutes an exothermic reaction starts with formation of a precipitate. The reaction mixture was stirred for 16 h at room temperature. After addition of 100 mL of water and 50 mL of toluene all the solid dissolved. A solution of 10% NaOH was slowly added until the water phase was basic. Then 10 mL of EtOH was added, and the solution was warmed until two clear phases were formed. The water phase was separated and the toluene was washed one more time with 50 mL of water. The toluene was removed under vacuum, and the solid was recrystallized from MeOH. Yield: 6.2 g (16 mmol, 65%). ^{1}H NMR (CD_2Cl_2): 1.75 (m, 12H, CH_2 phobane); 2.15 (m, 12H, CH_2 phobane); 2.4 (m, 4H, CH phobane); 3.1 (s, 4H, CH_2); 7.1(m, 4H, Ar). ^{31}P{^{1}H} NMR: −30.5 ppm.

Procedures. All hydroformylation experiments were carried out in a 250 mL magnetically stirred, electronically heated Hastelloy C autoclave. The catalyst solution was prepared in a sampling vessel as follows: 0.25 mmol of $Pd(OAc)_2$ (56.1 mg), 0.35 mmol (1.4 equiv) of the corresponding bisphosphine ligand, and 9.6 mL of sulfolane/water (99:1) were mixed and magnetically stirred for 4−5 h,[18] followed by addition of 0.5 mmol (45 μL) of HOTf to the orange solution. After addition of 0.4 mL of water containing the appropriate type and quantity of halide source, the solution immediately became yellow (NaCl), yellow-brown (NaBr), or red (NaI).

The autoclave was charged with 30 mL of 2-ethylhexanol and 20 mL of an equilibrated mixture of linear internal C_8-C_{10} alkenes, 20 mL of α-octene, or 5 g of propene, depending on the specific experiment. The autoclave was closed and evacuated (in the case of propene evacuation occurred before pumping in propene), and it was pressurized with 18 bar of CO and 40 bar of H_2 and heated to 105 °C. The preformed catalyst solution was placed under a CO atmosphere in an injector tube. When the temperature was stabilized, the catalyst solution was rapidly injected with CO pressure. The pressure was continuously recorded by using a Transamerica Instruments pressure transducer, Series 2000. After a reaction time of 1−5 h, the autoclave was allowed to cool to room temperature, depressurized, and opened. After settling, the reaction mixture separated in two layers, an upper one containing product alcohol and a lower one containing sulfolane and the catalyst. Activity data during the experiment were calculated from the pressure decrease in time; selectivity data were obtained from standard analysis by GLC of the product layer. Product identification was accomplished by GC/MS analysis. The rate data in the tables are initial rates, averaged over a period corresponding to <30% conversion.

Acknowledgment. We gratefully acknowledge the technical assistance of Willem Jager, Roel van Ginkel, and Rene Ernst. We wish to thank Shell Global Solutions B.V. and the European Union (HYDROCHEM, contract no. HPRN-CT-2002-001766) for financial support.

OM0601293

(17) Eberhard, M. P. Ph.D. Thesis, University of Bristol, 2000. *sym*-Phobane is 9-phosphabicyclo[3.3.1]nonane and the *as* isomer is 9-phosphabicyclo[4.2.1]nonane.

(18) Marson, A.; van Oort, A. B.; Mul, W. P. *Eur. J. Inorg. Chem*. **2002**, 3028.