weeks did not affect the *ee* value for the reduction of **1a**, neither did deliberate addition of water to the reaction (one equivalent per Ga, to simulate impure "wet" ketones).

The enantioselectivity in the reduction of **1a** shows an unusual temperature dependence: a maximum *ee* value is attained at $-20$ to $-15\,^{\circ}C$, both the chemical yield and *ee* value decrease steadily at temperatures below this range. At $-78\,^{\circ}C$ an 18% yield of racemic alcohol is realized. One explanation of this behavior is that transmetalation of **4** to **3** (X = MTB dianion) is slow below $-20\,^{\circ}C$ and that an achiral catalytic process begins to compete. Support for this hypothesis comes from the observation that added lithium alkoxides do catalyze catecholborane reduction of **1a** via the borate **6**.[8] The use of the MTB ligand is vital to the reaction; $LiGaH_4$ with either 1,1′-bi(2-naphthol) or 1,1′-bi(2-thionaphthol) leads to low selectivities (3–34% *ee*). The probable causes are decomplexation of the chiral ligand by catecholborane and poor lithium coordination. Both the presence of **6** and removal of the chiral ligand may account, in part, for the lower enantioselectivities encountered in some recent titanium work.[9]

The solid-state structure of the pre-catalyst **5**[7] is not retained in solution during the catalysis. The new species formed are currently still under investigation. However, the absence of a nonlinear effect[10] in the reduction of **1a** by **5** suggests that a mononuclear catalyst with a single active MTB ligand is responsible for the enantioselection. In Noyori's BINAL reagent[3] the ($R_a$)-ligand gives the (*R*)-alcohol because of repulsion between the n electrons of the reagent and the π electrons of the substrate. The similarity in the *ee* value for the reduction of **1a–d** suggests a related electronic control with **5**, but steric factors cannot be ruled out.

*Experimental Section*

All operations were performed under argon. A solution of MTB (15 mg, 0.05 mmol) in THF (5 mL) was treated with $LiGaH_4$ (100 μL of a 0.25 M solution in $Et_2O$) and the mixture stirred (20 °C, 25 min). The reaction was cooled to $-20\,^{\circ}C$ and catecholborane (1.1 mL of a 1 M THF solution, 1.1 mmol) and ketone (1.0 mmol) were added. The solution was stirred at $-20\,^{\circ}C$ for 18 h (method A), or sealed and stored at $-20\,^{\circ}C$ (method B; $-15\,^{\circ}C$ and 4 mol% catalyst for **1d**). Alternatively, the catecholborane and ketone were added at $-78\,^{\circ}C$ and the reaction mixture stirred as it warmed to room temperature overnight (method C). Normal workup procedures afforded the alcohols **2** as essentially single products (the *ee* values were determined by gas chromatography on a chiral column (LIPODEX A or CYCLODEX B) or the α-methoxy-α-(trifluoromethyl)phenyl acetate analyzed for the alcohol of **1h**).

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## Hydroformylation of Internal Olefins to Linear Aldehydes with Novel Rhodium Catalysts**

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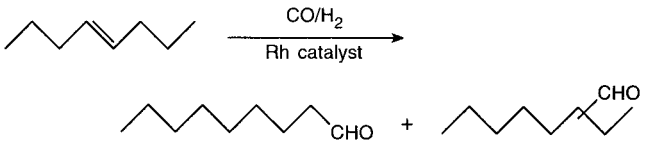
Hydroformylation is one of the world's largest homogeneously catalyzed processes in industry, which produces more than six million tons of aldehydes and alcohols annually.[1] Since linear aldehydes are the most desired products a key issue in this process is the control of regiochemistry. High selectivities in the hydroformylation of terminal alkenes have been reported for both diphosphites and diphosphanes.[2] Selective hydroformylation of internal alkenes, which is of great interest in industry and in synthetic organic chemistry, on the other hand is still a relatively unexplored terrain (Scheme 1).




Scheme 1. The hydroformylation of *trans*-4-octene to linear and branched aldehydes.

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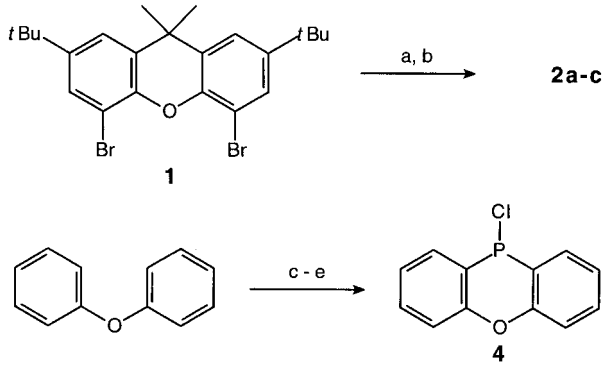
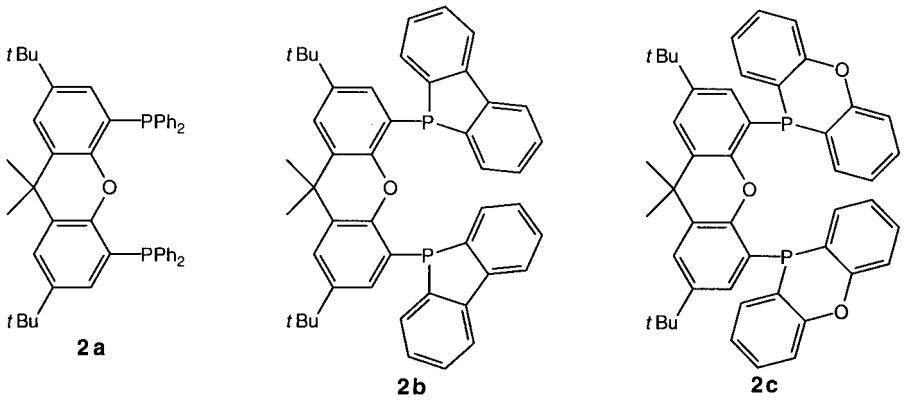
Very few rhodium catalysts have been reported that will hydroformylate internal alkenes at acceptable rates, and even fewer that will produce linear aldehydes preferentially.[3] Considerable progress in this field has been made by using bulky diphosphites as modifying ligands.[4] However, because of the intrinsicly low long-term stability of phosphites the development of new efficient catalysts for the hydroformylation of internal alkenes continues to be an important goal.

In our effort to develop ligands that induce high regioselectivity in the rhodium-catalyzed hydroformylation, we have reported on new diphosphanes with large bite angles.[2f] This work and studies done by Casey and co-workers[2c, 5] showed that high selectivities towards linear aldehydes can be obtained with rigid diphosphanes with chelate bite angles close to 120°. Herein we describe the synthesis of new dibenzophospholyl- and phenoxaphosphanyl-substituted xanthene ligands **2b** and **2c**, and their high activity and selectivity in the rhodium-catalyzed hydroformylation of 1-octene. More importantly, **2b** and **2c** exhibit an unprecedented high activity and selectivity in the hydroformylation of *trans*-2- and -4-octene to linear nonanal. To the best of our knowledge diphosphanes **2b** and **2c** constitute the first rhodium catalysts with modified phosphane groups for the selective linear hydroformylation of internal olefins.




Scheme 2. Synthesis of diphosphanes **2a–c** and the monophosphane **4**. a) *n*BuLi, THF, 1 h at −60 °C; b) $Ph_2PCl$, **3** or **4**, THF, 1 h at −60 °C then 16 h at 20 °C, 81 % (**2a**), 67 % (**2b**), or 75 % (**2c**); c) *n*BuLi, TMEDA, $Et_2O$/hexanes (1/2), 1 h at 0 °C then 16 h at 20 °C; d) $iPr_2NPCl_2$, hexanes, 1 h at −60 °C then 16 h at 20 °C; e) $PCl_3$, 16 h at reflux, 54 %.




The diphosphanes **2a–c** were synthesized by dilithiation of 4,5-dibromo-2,7-di-*tert*-butyl-9,9-dimethylxanthene **1** with *n*-butyllithium in THF at −60 °C, followed by reaction with the corresponding chlorophosphane (Scheme 2).[6] The natural bite angles of **2a–c** are 110, 120, and 119°, respectively.[7] 9-Chlorodibenzo[*b*, *d*]phosphole (**3**) was prepared from a literature procedure.[8] 10-Chlorophenoxaphosphane (**4**) was obtained in 54 % yield by dilithiation of diphenyl ether with *n*-butyllithium and *N*,*N*,*N*′,*N*′-tetramethylethylenediamine (TMEDA) in diethyl ether/hexanes (1/1) at room temperature, followed by reaction with diisopropylphosphoramidous dichloride at −60 °C, and refluxing the resulting 10-(diisopropylamino)phenoxaphosphane in phosphorus trichloride.

The activity and selectivity of ligands **2a–c** were first tested in the hydroformylation of 1-octene (Table 1). Under mild reaction conditions the diphosphanes **2b** and **2c** both showed a higher activity and a higher linear:branched (l:b) ratio compared to the parent diphosphane **2a**. The extraordinary high activity of **2c** places it among the most active diphosphanes known. Since large steric differences in the catalyst complexes of the ligands **2b** and **2c** are not anticipated, the higher activity of **2c** relative to **2b** might be ascribed to very subtle effects in the bite angle or electronic characteristics of the phosphorus heterocycles.

Although the high l:b ratios of ligands **2b** and **2c** are in good agreement with our earlier observations that diphosphanes with natural bite angles close to 120° give very selective catalysts,[2f] the selectivity for the formation of the linear aldehyde of both **2b** and **2c** is considerably lower than that of **2a**. This is a consequence of a dramatic increase in the rate of isomerization of 1-octene to form internal alkenes, which are not hydroformylated as long as 1-octene is present. The reason why **2b** and **2c** display such a high isomerization activity relative to **2a** is not completely clear yet, but we speculate that it could be caused by the higher rigidity and the larger bite angles of the former ligands.

Table 1. Hydroformylation of 1-octene.[a]

| Ligand | Isomerization [%][b] | l:b[b,c] | Selectivity [%][b,d] | TOF[e] |
|---|---|---|---|---|
| $PPh_3$ | 1.2 | 3.1 | 74 | 1880 |
| **2a** | 3.9 | 49 | 94 | 250 |
| **2b** | 16 | 65 | 83 | 360 |
| **2c** | 13 | 68 | 86 | 1100 |

[a] Reactions were carried in a 180 mL stainless steel autoclave in toluene at 80 °C under an atmosphere of $CO/H_2$ (1:1) with an initial pressure of 20 bar, catalyst precursor: [$Rh(CO)_2$(dipivaloylmethanoate)], [Rh] = 1.0 mM, Rh:P:1-octene = 1:10:673. [b] Determined by GC with decane as the internal standard. [c] l:b ratio includes all branched aldehydes. [d] Selectivity for the linear aldehyde. [e] Turnover frequencies (TOF) were calculated as (mol aldehyde)(mol catalyst)$^{-1}h^{-1}$ at 20–30 % conversion.

The high activity of diphosphanes **2b** and **2c**, combined with the very high l:b ratio and rate of isomerization that leads to the internal olefins, prompted us also to test the ligands in

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the hydroformylation of simple internal alkenes of low reactivity. A relatively high temperature and low pressure were used to enhance the rate of isomerization and to prevent hydroformylation of the internal alkenes. In the hydroformylation of *trans*-2-octene both ligands **2b** and **2c** showed a high activity and selectivity towards the formation of linear nonanal (Table 2). The hydroformylation of 1-octene formed

Table 2. Hydroformylation of *trans*-2- and -4-octene.[a]

| Ligand | Substrate | *t* [h] | Conversion [%][b] | l:b[d] | 1-Nonanal [%][c] | TOF[d] |
|---|---|---|---|---|---|---|
| $PPh_3$ | 2-octene | 1.0 | 8.5 | 0.9 | 46 | 39 |
| **2b** | 2-octene | 1.0 | 10 | 9.5 | 90 | 65 |
| **2c** | 2-octene | 1.0 | 22 | 9.2 | 90 | 112 |
| $PPh_3$ | 4-octene | 17 | 9.0 | 0.3 | 23 | 2.4 |
| **2b** | 4-octene | 17 | 54 | 6.1 | 86 | 15 |
| **2c** | 4-octene | 17 | 67 | 4.4 | 81 | 20 |

[a] As Table 1, but at 120 °C and with an initial pressure of $CO/H_2$ (1/1) of 2 bar. [b] Determined by GC with decane as an internal standard. [c] Percentage of linear nonanal in all products other than octenes. [d] See Table 1.

in situ by isomerization was highly favored over the hydroformylation of the large excess of 2-octene, and no hydrogenation was observed. The high selectivity of ligands **2b** and **2c** was even more pronounced in the hydroformylation of *trans*-4-octene; selectivities in the formation of linear nonanal still exceeded 80 % although three consecutive double bond isomerizations had to precede hydroformylation. From these remarkable results it can be concluded that diphosphane rhodium complexes can be very efficient for the selective linear hydroformylation of internal alkenes, an area that seemed hardly accessible. The high activity and selectivity of diphosphanes **2b** and **2c** may open up a new range of applications for hydroformylation catalyzed by diphosphane rhodium complexes. One of the possible interesting industrial applications could be the linear hydroformylation of "Raffinate 2", a mixture of butenes that originates from steam crackers.[1d]

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## $\alpha$-Chloroalkylmagnesium Reagents of $>90\,\%$ *ee* by Sulfoxide/Magnesium Exchange**

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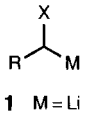
$\alpha$-Heterosubstituted organometallic reagents such as **1** are attractive chiral $d^1$-synthons[1] provided that they have sufficient configurational stability and that they can be generated in high stereochemical purity (Scheme 1). The ($\alpha$-alkoxy)-




**1** M = Li
**2** M = MgX

**a**: X = OR **e**: X = SR
**b**: X = $OCONR_2$ **f**: X = $SiR_3$
**c**: X = $NR_2$ **g**: X = Cl
**d**: X = NRBoc **h**: X = I

Scheme 1. The organolithium compounds **1a – h** and the Grignard reagents **2a – h**. Boc = *tert*-butoxycarbonyl.

alkyllithium reagents **1a**,**b**[2] and ($\alpha$-amino)alkyllithium reagents **1c, d**[3] are prominent examples. Reagents **1**, in which X is a heteroatom of the second row of the periodic table (see **1e**,**f**) have much lower barriers to racemization.[4] Their diminished configurational stability limits their use in stereoselective synthesis. Higher configurational stability may be expected for the corresponding magnesium reagents **2**, since previous studies[5, 6] indicated compounds of the type **2h** to be configurationally stable on a macroscopic time scale at or above $-78\,^\circ C$. We have therefore explored diastereoselective and enantioselective routes to reagents of the type **2**. We

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