Selective hydroformylation of internal alkenes to linear aldehydes - Novel phosphacyclic diphosphines and their applications

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Citation for published version (APA):
Bronger, R. P. J. (2004). Selective hydroformylation of internal alkenes to linear aldehydes - Novel phosphacyclic diphosphines and their applications
The Immobilisation of Phenoxaphosphine-Modified Xanthene-type Ligand on Polysiloxane Support and Application thereof in the Hydroformylation Reaction

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Abstract.

For the first time a phenoxaphosphino-modified Xantphos-type ligand (1) has been covalently anchored to polysiloxane support (Silica-1 and Sol-gel-1). The use of these heterogenised ligands in the rhodium catalysed hydroformylation of 1-octene gives a system that is competitive with systems employing Xantphos (9) as ligand, but with the added advantages of immobilised systems, like facile catalyst recycling and facile product-catalyst separation. During the recycle experiments no rhodium leaching was detected by ICP analysis (< 0.2% Rh-leaching of initial intake) when either Silica-1 or Sol-gel-1 were used.

The application of Sol-gel-1 for the hydroformylation of trans-2-octene resulted in an active and regio-selective catalyst, but under forced reaction conditions (T = 393 K, p(CO/H₂) = 3.6 bar) significant catalyst deterioration was detected.

The use of supercritical carbon dioxide as reaction medium in a continuous-flow set-up resulted in similar activities, but slightly lower regio-selectivities compared to batch-wise hydroformylation reactions in toluene. In this medium the catalyst can withstand high temperatures and low pressures, but shows no activity for the hydroformylation of trans-2-octene.
Introduction.

Nowadays, many industrial processes use homogeneous catalysts for the production of bulk chemicals, e.g. hydroformylation, the Monsanto and BP acetic acid processes, Wacker oxidation process, terephthalic acid process,\(^1\) and for the production of many important fine chemicals, e.g. Ibuprofen and Naproxen.\(^2\) A key issue in these processes remains the separation of the catalyst from the products, especially for the fine chemical industry; important factors to consider are catalyst costs, added value, and toxicity of the metal. Thus in the past decades intensive research has been devoted to facilitate product-catalyst separation for a number of catalytic reactions.\(^3\) Distillation, liquid-liquid separation or extraction, catalyst destruction and crystallisation are all applied in bulk chemical industry. Often the catalyst cannot be reused easily and therefore many different methods for catalyst recycling have been studied.\(^4\) Successful approaches in the laboratory include the attachment of homogeneous catalysts to polymeric or dendrimeric support,\(^5-9\) aqueous biphasic catalysis,\(^10-11\) fluorous catalysis,\(^12-15\) the use of supercritical fluids\(^16-17\) and ionic liquids\(^18-22\) or combinations thereof.\(^23-26\) Unfortunately there is no general methodology that overcomes all of the problems often encountered with these systems, like loss of activity, catalyst instability, metal leaching and problems concerning the solubility of the different components. For example inorganic materials such as silica are particularly suited for the preparation of heterogenised homogeneous catalysts because of their high physical strength and chemical inertness, but the activity is in general lower compared to the homogeneous system. One of the problems of immobilisation on soluble polymers is caused by the limited availability of proper membrane materials that are compatible with the reaction conditions, while aqueous phase catalysis is limited to substrates that are soluble in water.

Previous studies in which Nixantphos was heterogenised on silica support (Silica-\(^6\)-27 and Sol-gel-\(^6\)-28) showed that high regio-selectivities, moderate activities and highly stable catalysts for the rhodium catalysed hydroformylation can be obtained. Substitution of the diphenylphosphino-moieties by phenoxyphosphino-moieties could give some additional advantages, like improved activity and the possibility of selective hydroformylation of internal olefins, while a high regio-selectivity and good recyclability are retained.\(^29-32\)

Here we report the synthesis of a new phenoxyphosphino-modified ligand (1) that was prepared via a route comparable to the synthesis of a dicationic ligand for the hydroformylation of 1-octene in ionic liquids,\(^33\) and for the use as recyclable non-covalently bound ligand (Silica-7).\(^34\) Thus, small and facile modifications in the generic backbone (4) allow a rapid screening of this type of ligands under many different reaction conditions.
Here we further extend the general use of these type of ligands by covalently anchoring the ligand on polysiloxane support for the use in the rhodium catalysed hydroformylation of 1-octene in toluene and in supercritical carbon dioxide (scCO₂).

Results and discussion.

Synthesis.

Ligand 1 was prepared via a multistep procedure (Scheme 1). Friedel-Crafts acylation of 9,9-dimethylxanthene with 5-bromovaleryl chloride and hexanoylchloride followed by an indium(III)chloride catalysed reduction35 gives 2 in a good yield (~86 % on the basis of the amount of 9,9-dimethylxanthene). Selective mono-functionalisation of the 9,9-dimethylxanthene backbone is possible since the introduction of the first acyl-group deactivates 9,9-dimethylxanthene for electrophilic substitution to such an extent that only after complete mono-substitution of 9,9-dimethylxanthene a second electrophilic attack takes place and only on the aromatic ring that is non-substituted. We chose to put only one single functional group on the backbone in order to retain optimal fluxional structure.

Scheme 1 Synthesis of Silica-1 and Sol-gel-1 (yields between parenthesis) i) a) 1 eq. hexanoyl chloride / 1 eq. AlCl₃, b) 1 eq. 5-bromovalericacid chloride / 1 eq. AlCl₃ (86%), c) InCl₃ / chlorodimethylsilane (86%), ii) Br₂ (83%), iii) a) n-BuLi, -80 °C, 30 min., b) 10-chloro-2,8-dimethylphenoxyphosphine (53%), iv) NH₃ (l), 70 °C (89%), v) 1.1 eq. triethoxysilane-n-propylisocyanate (95%), vi) Silica-1: Silica, 70 °C; Sol-gel-1: TMOS / H₂O / THF, Rh(CO)₂(acac).
and contact to the solution. Effectively, the ligand can move from the polysiloxane support and thereby the final catalyst will resemble more the homogeneous analogue. Next the 4, and 5 positions of the xanthene backbone were brominated. Subsequent lithiation with n-butyllithium at -80 °C and reaction with 2,8-dimethyl-10-chlorophenoxaphosphine yielded 4. Compound 5 was obtained by the reaction of 4 with ammonia at 70 °C. Next the amine was reacted with triethoxysilane-n-propylisocyanate to give 1 in a moderate overall yield (32%, based on 9,9-dimethylxanthene). Anchoring of 1 on commercially available silica (particle size 200 - 500 µm) took place by the condensation reaction between the triethoxysilane groups of the ligand and free silanol groups of silica at 70 °C to yield Silica-1. The catalyst precursor was prepared by adding 0.1 equivalent of Rh(CO)₂(acac) to a mechanically stirred suspension of Silica-1 in a 5:1 THF : Et₃N mixture.²⁷

The sol-gel procedure involved the immobilisation of a 10:1 mixture of 1 and Rh(CO)₂(acac) in THF using tetramethyloctasilicat e (TMOS), MeOH and H₂O.²⁸ Gelation started after a few hours and was continued for 36 hours. The resulting gel was carefully dried and crushed into free flowing silica to yield the pink-red Sol-gel 1.

**Batch-wise hydroformylation recycling experiments.**

The catalytic performance and recyclability of Silica-1 and Sol-gel-1 in the hydroformylation of 1-octene was studied by performing a series of consecutive catalytic experiments in a batch-wise process. The results are compared with Silica-6,²⁷ Sol-gel-6,²⁸ Silica-7,³⁴ 8³⁹ and Xantphos (9)³⁶,³⁷ ((Figure 1 and Table 1).

Compared to Silica-6, Sol-gel-6 and Silica-7, both Silica-1 and Sol-gel-1 show a higher activity under similar reaction conditions. In addition, Sol-gel-1 shows a slight increase in regio-selectivity compared to the homogeneous system (8), but with more isomerisation, and Silica-1 shows a similar regio-selectivity, while immobilisation of the diphenylphosphino-modified ligands²⁸,³⁹,³⁴ resulted in a decrease in regio-selectivity. It has been observed before that changes in catalyst environment have less effect on regio-selectivity when phenoxyphosphino-modified ligands are used.³³ The increase in regio-selectivity for Sol-gel-1 compared to 8 is in part attributed to an increase in isomerisation activity as isomerisation offers an 'escape route' of the branched alkyl rhodium species, but the overall selectivity toward the linear aldehyde has decreased. Compared to catalysis in presence of 8 a large decrease in hydroformylation activity was observed, which is commonly encountered for heterogenised systems. On the other hand both activity and selectivity with Silica-1 and Sol-gel-1 are very competitive with the results obtained for Xantphos (9) under identical reaction conditions. It must be noted, though, that the amount of isomerisation is much higher in the immobilised systems and therefore the selectivity toward the linear aldehyde is much lower.
Table 1 Results of the hydroformylation of trans 1-octene in subsequent cycles.

<table>
<thead>
<tr>
<th>Ligand</th>
<th>cycle</th>
<th>Conv. (%)</th>
<th>% isom. (%)</th>
<th>TOF</th>
<th>l/b</th>
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<td>7</td>
<td>22.2</td>
<td>8.3</td>
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</table>

Conditions: $p(\text{CO}/\text{H}_2) (1:1) = 20 \text{ bar}$, ligand/Rh = 10, Substrate/Rh = 640, $T = 80^\circ\text{C}$, Initial TOF determined and averaged over indicated conversion. Average turnover frequencies were calculated as (mol aldehyde)/(mol catalyst)$^\text{a}$ at indicated conversion. For the immobilized systems much scatter was observed, but with different catalyst batches gave TOF-values within the same range. Linear to branched ratio. Substrate = trans-2-octene, $p(\text{CO}/\text{H}_2) (1:1) = 3.2 \text{ bar}$, $T = 120^\circ\text{C}$.
In contrast to the system where Silica-6 and Sol-gel-6 were employed no hydrogenation activity was observed when Silica-1 or Sol-gel-1 were used. The hydrogenation activity in presence of Silica-6 and Sol-gel-6 were attributed to the formation of $[\text{Rh}(\text{diphosphine})(\text{CO})]^{+}$ species having a siloxate as its counterion. The absence of any hydrogenation activity gives a strong indication that a similar cationic species is not formed when phenoxaphosphino-substituted ligands are used. The steric shielding of the phenoxaphosphino-moieties might hamper the formation of such a species under the applied catalysis conditions.

The high isomerisation activity and the high regio-selectivity obtained with Sol-gel-1, prompted us to test this system for the hydroformylation of trans-2-octene. Despite the promising initial results, the catalyst was not stable under typical hydroformylation conditions for internal alkenes (high temperature, low pressure ($T = 120^\circ\text{C}$, $p(\text{CO}/\text{H}_2) = 3.2 \text{ bar}$)). Severe catalyst deterioration was observed in consecutive recycling experiments using 1-octene as substrate (Table 1, Sol-gel-1, cycle 7 and 8).

**Continuous hydroformylation in scCO$_2$.**

An elegant approach toward catalyst recycling involves the use of supercritical carbon dioxide (scCO$_2$; $T_c = 31^\circ\text{C}$, $p_c = 73.75$ bar, $d_c = 0.468$ g.mL$^{-1}$). This environmentally benign medium has a few advantages over conventional solvents: it is highly miscible with gases, there exists no liquid-gas boundary, and it has a high compressibility. Previous studies using Silica-6 in scCO$_2$ resulted in a large increase in hydroformylation activity. This effect was mainly attributed to increased mass-transfer. Therefore, Silica-1 was tested in scCO$_2$ using a continuous flow reactor. In addition we tested the influence of various reaction parameters on catalytic performance.

In contrast to our expectations, the use of Silica-1 did not show an improvement in hydroformylation activity. Thus, Silica-1 behaves differently in scCO$_2$ than Silica-6. Additionally, the regio-selectivity decreased compared to the results obtained in toluene. This drop in regio-selectivity is ascribed to an

<table>
<thead>
<tr>
<th>Entry</th>
<th>$p\text{CO}_2$ (bar)</th>
<th>CO$_2$-flowrateb (L.min$^{-1}$)</th>
<th>1-octene-flowrateb (mL.min$^{-1}$)</th>
<th>Conv. (%)</th>
<th>TOF</th>
<th>l/b$^d$</th>
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<td>52.7</td>
<td>18.7</td>
</tr>
<tr>
<td>6</td>
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<td>0.03</td>
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<td>7</td>
<td>120</td>
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<td>0.10</td>
<td>0.32</td>
<td>27.3</td>
<td>19.0</td>
</tr>
</tbody>
</table>

*a* Ligand: Rh ratio is 10:1. catalysis performed at 80 °C, substrate:syngas = 1:5. No accurate data on the extent of isomerisation can be provided due to the low conversions. *b* Flowrates at 20 °C, 1 atm. *c* Average turnover frequencies were calculated as (mol aldehyde).(mol catalyst)$^{-1}$.h$^{-1}$ at indicated conversion. *d* linear to branched ratio.

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enhanced rate of CO-insertion in the secondary alkyl rhodium intermediate. This should be reflected in the amount of isomerisation, but since we operated under very low conversion levels, no accurate measurement of the amount of isomerisation could be accomplished. Nevertheless, it is assumed that the rate of isomerisation is suppressed considerably taking into consideration the results during the hydroformylation of trans-2-octene (vide infra).

Variation of the CO$_2$ pressure between 80 bar and 160 bar shows an optimum around 120 bar. A decrease in activity upon increasing the CO$_2$ pressure has been observed previously by Cole-Hamilton et al.,\textsuperscript{38} but they could not provide a satisfactorily explanation. We also cannot explain the initial increase in activity and this requires further investigations. For example the change in density of the reaction mixture could play an important role.

A lower CO$_2$ pressure resulted in a higher regio-selectivity, thus at a CO$_2$ pressure of 80 bar regio-selectivities that resemble more the homogeneous system were obtained.

The CO$_2$ flow-rate effectively influences the residence time of the substrate in the medium. A decrease in CO$_2$ flow-rate leads to an increased contact time of the substrate with the catalyst, and could in theory lead to a higher conversion compared to catalysis at higher CO$_2$ flow rates. Surprisingly, decreasing the CO$_2$ flow-rate from 0.65 L.min$^{-1}$ to 0.33 L.min$^{-1}$ did not lead to an increase in conversion, but to a slight decrease in conversion. Increasing the flow-rate to 1.4 L.min$^{-1}$ did show the expected effect as the conversion dropped. The regio-selectivity increased by decreasing the CO$_2$ flow-rate. Similar effects were expected and observed by changing the substrate flow-rate. For the regio-selectivity, however, a minimum was found at a substrate flow-rate of 0.05 mL.min$^{-1}$ at a CO$_2$ flow rate of 0.65 L.min$^{-1}$ (pCO$_2$ = 120 bar).

It is important to note that we did not investigate whether or not we preserved single-phase conditions while studying the effect of the different reaction parameters. Thus, while the influence of the different reactions parameters are not fully understood it is likely that by changing one parameter the system is affected in many different ways.

When trans-2-octene was used as substrate (at an increased temperature of 120 °C and syngas/substrate = 2.5) no hydroformylation took place, which is potentially the result of decreased rate of isomerisation. However, under these conditions the catalyst remains stable as no rhodium leaching (< 0.2% of initial Rh-intake as determined by ICP analysis) was detected and the activity was restored when the initial reaction conditions were applied (substrate = 1-octene, T = 80 °C, syngas/substrate = 5).

Conclusions.

In conclusion we have prepared a new highly stable heterogenised catalysts that shows enhanced activities when used for the hydroformylation of terminal olefins. Although the catalyst obtained from
Sol-gel-1 and Rh(CO)$_2$(acac) is very selective and moderately active for the hydroformylation of internal olefins, with regard to stability the system has to be improved considerably.

Although the use of scCO$_2$ does not lead to improved activity, it does offer a more facile separation of substrate from the reaction medium. Additionally the stability is enhanced considerably since under forced reaction conditions the catalyst retained its activity and selectivity. The influence of most reaction parameters is still unclear and needs further exploration.

Experimental.

General procedure. All air- or water-sensitive reactions were performed using standard Schlenk techniques under an atmosphere of purified argon. Toluene was distilled from sodium, THF from sodium/benzophenone, and hexanes from sodium/benzophenone/triglyme. Isopropanol and dichloromethane from CaH$_2$. Chemicals were purchased from Acros Chimica, and Aldrich Chemical Co. Silica gel 60 (230-400 mesh) purchased from Merck was used for column chromatography. Silica 100 (0.2 – 0.5 mm), BET: 300 – 400 m$^2$.g$^{-1}$, porevolume 0.9 – 1.2 mL.g$^{-1}$ (N$_2$-isotherm) was purchased from Merck. Melting points were determined on a Gallenkamp MFB-595 melting point apparatus in open capillaries and are reported uncorrected. NMR spectra were recorded on a Varian Mercury 300 or Inova 500 spectrometer. $^{31}$P and $^{13}$C spectra were measured $^1$H decoupled. TMS was used as a standard for $^1$H and $^{13}$C NMR and 85% of H$_3$PO$_4$ in H$_2$O for $^{31}$P NMR. Infrared spectra were recorded on a Nicolet 510 FT-IR spectrophotometer. Batch-wise hydroformylation reactions were carried out in a 200 mL home-made stainless steel autoclave. The continuous hydroformylation experiments were carried out in a flow-reactor assembled from commercially available units: scCO$_2$ pump PM101, CO/H$_2$ compressor CU105 and Expansion Module PE103 (all from NWA gmbH, Lörrach, Germany), a high pressure mixer (Medimix) and a Gilson 305 pump (for the substrate). The alkene was filtered over neutral activated alumina to remove peroxide impurities. Synthesis gas (CO/H$_2$, 1:1, 99.9%) was purchased from Air Liquide. Gas chromatographic analysis were run on an Interscience HR GC Mega 2 apparatus (split/splitless injector, J&W Scientific, DB-1 30m column, film thickness 3.0 mm, carrier gas 70 kPa He, FID detector) equipped with a Hewlett Packard Data system (Chrom-Card) using decane as an internal standard.

2-hexanoyl-9,9-dimethylxanthen\m_\n
At 0 °C 8.32 g of AlCl$_3$ (62.4 mmol) was added slowly to a stirred solution of 13.1 g of 9,9-dimethylxanthen (62.4 mmol) and 8.8 mL of hexanoylchloreide (62.4 mmol) in 200 mL of CH$_2$Cl$_2$. The mixture was warmed to room temperature and was stirred overnight. Next, the mixture was poured on 300 ml ice and extracted with 3x 100 ml CH$_2$Cl$_2$. The combined extracts were washed with 150 ml of a 10% NaHCO$_3$ solution and washed with dichloromethane. The organic layer
was dried over MgSO₄ and the solvent was removed *in vacuo*. Crude yield: 17.6 g (57 mmol, 91%) of a yellow/brown solid that was used without any further purification. \(^1\)H NMR (CDCl₃): δ = 8.10 (d, \(^1\)J(H,H) = 2.1 Hz, 1H), 7.81 (dd, \(^3\)J(H,H) = 8.7 Hz, \(^4\)J(H,H) = 2.4 Hz, 1H), 7.42 (dd, \(^3\)J(H,H) = 5.7, \(^4\)J(H,H) = 1.5 Hz, 1H), 7.22 (td, \(^4\)J(H,H) = 7.8 Hz, \(^4\)J(H,H) = 1.5 Hz, 1H), 7.14 (td, \(^3\)J(H,H) = 7.5, \(^4\)J(H,H) = 1.5 Hz, 1H), 7.08 (d, \(^3\)J(H,H) = 8.5, 1H), 7.05 (dd, \(^3\)J(H,H) = 7.5, \(^4\)J(H,H) = 1.5 Hz, 1H), 2.94 (t, \(^3\)J(H,H) = 7.8 Hz, 2H), 1.66 (m, 8H), 1.37 (m, 4H), 0.92 (t, 3H).

\(^1\)3C \(^1\)H NMR (CDCl₃): 5 = 199.46 (s), 198.57 (s), 153.54 (s), 153.32 (s), 133.25 (s), 132.93 (s), 130.20 (s), 130.02 (s), 128.30 (s), 128.33 (s), 127.33 (s), 127.32 (s), 116.87 (s), 116.78 (s), 38.58 (s), 37.43 (s), 33.52 (s), 33.05 (s), 32.41 (s), 32.04 (s), 24.43 (s), 23.11 (s), 22.73 (s), 14.15 (s).

2-(5-bromopentanoyl)-7-hexanoyl-9,9-dimethylxanthene (2) To a stirred suspension of 470 mg of AlCl₃ (2.1 mmol) and 11.2 mL of chlorodimethylsilane (4.8 eq., 102.7 mmol) in 80 mL of CH₂Cl₂ was added 10.0 g of 2-(5-bromopentanoyl)-7-hexanoyl-9,9-dimethylxanthene (20 mmol) in 80 mL of CH₂Cl₂. The reaction was quenched after complete reduction of the ketone functionalities by addition of 100 mL of water (~4 h reaction time). Next, the mixture is extracted with 3 x 80 mL of CH₂Cl₂. The organic layer was dried over MgSO₄ and the solvent was removed *in vacuo*. The resulting solid was purified by flash column chromatography (eluent: hexanes). Yield: 7.6 g (17 mmol, 86%) of a slightly yellow compound that was used without further purification. \(^1\)H NMR (CDCl₃): 7.20 (s, 2H), 7.01 (d, \(^3\)J(H,H) = 8.1 Hz, 2H), 6.96 (d, \(^3\)J(H,H) = 8.7 Hz, 2H), 3.55 (t, \(^3\)J(H,H) = 6.6 Hz, 0.9H), 3.42 (t, \(^3\)J(H,H) = 6.6 Hz, 1.1H), 2.62 (t, \(^3\)J(H,H) = 6.9 Hz, 2H), 2.60 (t, \(^3\)J(H,H) = 7.2 Hz, 2H), 1.9 – 1.1 (m, 14H), 1.64 (s, 6H), 1.0 – 0.8 (m, 3H). \(^1\)3C \(^1\)H NMR (CDCl₃): δ = 149.01 (s), 148.82 (s), 137.51 (s), 136.79 (s).
130.06 (s), 129.85 (s), 127.47 (s), 127.41 (s), 126.03 (s), 126.01 (s), 116.34 (s), 116.23 (s), 35.82 (s), 35.57 (s), 34.28 (s), 34.06 (s), 32.95 (s), 32.60 (s), 31.99 (s), 31.97 (s), 31.10 (s), 29.25 (s), 28.07 (s), 22.90 (s), 14.37. GC-MS (m/z, rel. intensity): 444 / 446 (M+, 6), 429 / 431 (100), 349 (29), 307 (7), 294 (10), 236 (7), 223 (13), 207 (10).

4,5-dibromo-2-(5-bromopentyl)-7-hexyl-9,9-dimethylxanthenee (3) To an ice-cooled solution of 1.97 g 2-(5-bromopentyl)-7-hexyl-9,9-dimethylxanthen (4.4 mmol) in 30 mL of CH₂Cl₂ was added dropwise 0.81 mL of Br₂ (3.6 eq., 16.7 mmol) in 2 mL of hexanes. The reaction mixture was warmed to room temperature and stirred overnight. Next the excess of Br₂ is quenched with 20 mL of an aqueous NaSO₃ solution, the mixture is extracted with 3 x 20 mL of CH₂Cl₂. Subsequently, the organic layer was dried over MgSO₄. The solvents were removed in vacuo and the resulting solid was purified by flash column chromatography (eluent: CH₂Cl₂). Yield: 2.2 g (3.7 mmol, 83%) of a yellow solid that was used without further purification. ¹H NMR (CDCl₃): 7.29 (d, 4J(H,H) = 1.5 Hz, 2H), 7.11 (d, 4J(H,H) = 1.8 Hz, 2H), 3.55 (t, 3J(H,H) = 6.3 Hz, 0.9H), 3.40 (t, 3J(H,H) = 6.3 Hz, 1.1H), 2.58 (t, 3J(H,H) = 7.5 Hz, 2H), 2.55 (t, 3J(H,H) = 7.8 Hz, 2H), 1.93 (quintet, 3J(H,H) = 7.1 Hz, 2H), 1.7 – 1.55 (m, 4H), 1.59 (s, 6H), 1.6 – 1.4 (m, 2H), 1.4 – 1.25 (m, 6H), 0.88 (t, 3J(H,H) = 6.6 Hz, 3H). ¹³C {¹H} NMR (CDCl₃): δ = 145.92 (s), 145.71 (s), 139.27 (s), 138.54 (s), 131.86 (s), 131.66 (s), 131.28 (s), 131.22 (s), 124.92 (s), 124.91 (s), 110.92 (s), 110.80 (s), 35.66 (s), 35.54 (s), 35.29 (s), 33.99 (s), 32.82 (s), 32.04 (s), 31.91 (s), 31.70 (s), 30.84 (s), 29.11 (s), 27.94 (s), 22.85 (s), 14.34 (s).

2-(5-bromopentyl)-7-hexyl-9,9-dimethyl-4,5-bis(2,8-dimethyl-10-phenoxaphosphino)xanthenee (4) At -78 °C 3.2 mL of n-butyllithium (2.5 M in hexanes, 7.9 mmol) was added to a stirred solution of 2.2 g 4,5-dibromo-2-(5-bromopentyl)-7-hexyl-9,9-dimethyl-xanthen (3.6 mmol) in 75 mL of Et₂O. The resulting solution was stirred for 30 min. at -78 °C. Subsequently, a suspension of 2.4 g of 2,8-dimethyl-10-chloro-phenoxaphosphine (9.3 mmol) in 20 mL of toluene was added dropwise. The reaction mixture was slowly warmed to room temperature and stirred overnight. Next the diethylether was removed in vacuo and the mixture was diluted with 50 mL of CH₂Cl₂ and hydrolyzed with 50 mL of a 10% aqueous HCl solution. The water layer was removed and the organic layer was dried over MgSO₄. The solvents were removed in vacuo and the resulting yellow/white solid was crystallized from 2-propanol/toluene. Yield: 1.7 g of white crystals (1.9 mmol, 53%). ¹H NMR (CDCl₃): 7.93 (d, 3J(P,H) = 6 Hz, 4H), 7.16 (m, 4H), 7.11 (m, 4H), 7.06 (m, 2H), 6.50 (m, 2H), 3.34 (t, 3J(H,H) = 7.0 Hz, 2H), 2.4 – 2.3 (m, 4H), 2.34 (s, 12H), 1.79 (quintet, 3J(H,H) = 7.0 Hz, 1.1H), 1.70 (quintet, 3J(H,H) = 7.5 Hz, 0.9H), 1.50 (s, 6H), 1.4 (m, 4H), 1.31 (t, 3J(H,H) = 7.0 Hz, 2H), 1.2 (m, 8H), 0.87 (t, 3J(H,H) = 7.5 Hz, 3H). ¹³C {¹H} NMR (CDCl₃): δ = 154.36 (s), 154.29 (s), 150.82 (t, 17.6 Hz), 137.58 (s), 136.86 (s), 136.83
The Immobilisation of Phenoxyphosphine-Modified Xanthene-type Ligand on Polysiloxane Support and Application thereof

2-(5-aminopentyl)-7-hexyl-9,9-dimethyl-4,5-bis(2,8-dimethyl-10-phenoxyphosphino)xanthene (5)

A homemade 100 ml hastelloy autoclave was equipped with a stirring bean and filled with approximately 60 mL of NH$_3$(l). To this was added a solution of 420 mg of 2-(5-bromopentyl)-7-hexyl-9,9-dimethyl-4,5-bis(2,8-dimethyl-10-phenoxyphosphino)-xanthene in 10 mL of THF, that was cooled down to -80 °C. The autoclave was closed and stirred at 70 °C overnight. During heating the pressure increased to approximately 20 bars. Next, the autoclave was cooled to room temperature and slowly depressurised. The autoclave was washed several times with dichloromethane and the solvents were removed in vacuo. The solid was dissolved in dichloromethane and washed with water (3 x 20 mL). The organic layer was dried over MgSO$_4$ and the solvent was removed in vacuo. Yield: 0.35 g (89%) of a pure white solid. $^1$H NMR (CDCl$_3$): $\delta$ = 7.94 (bs, 4H), 7.16 (d, $^3$J(H,H) = 8.5 Hz, 4H), 7.10 (d, $^3$J(H,H) = 8.5 Hz, 4H), 7.05 (s, 2H), 6.49 (d, $^3$J(H,H) = 2 Hz, 2H), 5.30 (s, 2H), 2.67 (t, $^3$J(H,H) = 7.0 Hz, 2H), 2.37 (t, $^3$J(H,H) = 7 Hz, 4H), 2.33 (s, 12H), 1.53 (s, 6H), 1.41 (m, 6H), 1.22 (m, 8H), 0.86 (t, $^3$J(H,H) = 7.0 Hz, 3H). $^{13}$C $^1$H NMR (CDCl$_3$): $\delta$ = 154.14 (s), 154.08 (m), 150.55 (t, unresolved), 137.33 (s), 136.89 (s), 135.54 (m), 132.65 (d, 10.6 Hz), 132.61 (d, 11.06 Hz), 131.60 (s), 131.50 (s), 131.40 (s), 131.36 (s), 129.80 (s), 129.64 (s), 126.97 (vt, unresolved), 126.86 (s). 118.17 (t, 5.5 Hz), 117.31 (s), 41.81 (s), 35.19 (s), 35.10 (s), 34.43 (s), 32.73 (s), 31.62 (s), 30.97 (s), 30.75 (s), 28.63 (s), 26.13 (s), 22.55 (s), 20.61 (s), 14.09 (s). $^{31}$P $^1$H NMR (CDCl$_3$): $\delta$ = -70.46 (s). Anal. Calcd. for C$_{44}$H$_{59}$NO$_3$P$_2$: C, 77.95; H, 7.15; N, 1.68. Found: C, 77.76; H, 7.21; N, 1.61.

2-(5-(3-(triethoxysilyl)propylurea)pentyI)-7-hexyl-9,9-dimethyl-4,5-bis(2,8-dimethyl-10-phenoxyphosphino)xanthene (1)

A mixture of 720 mg of 2-(5-amino-pentyl)-7-hexyl-9,9-dimethyl-4,5-bis(2,8-dimethyl-10-phenoxyphosphino)xanthene (0.9 mmol) and 270 µL of triethoxysilane-η-propylisocyanate (1.1 mmol) in 15 mL of CH$_2$Cl$_2$ were stirred overnight. The resulting mixture was evaporated in vacuo to yield pure 2-(5-(3-(triethoxysilyl)propylurea)pentyI)-7-hexyl-9,9-dimethyl-4,5-bis(2,8-dimethyl-10-phenoxyphosphino)xanthene (1). Yield: 890 mg (0.8 mmol, 95%). $^1$H NMR (CDCl$_3$): $\delta$ = 7.96 (d, J = 9 Hz, 2H), 7.95 (d, J = 7.5 Hz, 2H), 7.16 (d, $^3$J(H,H) = 8.5 Hz, 4H), 7.13 (d, $^3$J(H,H) = 8.0 Hz, 4H), 7.06 (d, $^4$J(H,H) = 3 Hz, 2H), 6.50 (d, $^4$J(H,H) = 5.7 Hz, 2H), 4.42 (t, $^3$J(H,H) = 5.5 Hz, 1H), 4.24 (t, $^3$J(H,H)
\[ \text{Hz, 1H}, 3.83 \text{ (q, 3J(H,H) = 7.0 Hz, 6H), 3.18 (q, 3J(H,H) = 6.5 Hz, 2H), 3.11 (q, 3J(H,H) = 6.5 Hz, 2H), 2.39 - 2.32 (m, 4H), 2.33 (s, 12H), 1.64 (quintet, 3J(H,H) = 8.0 Hz, 2H), 1.55 (s, 6H), 1.53 (m, 2H), 1.44 - 1.37 (m, 6H), 1.24 (t, 3J(H,H) = 7.2 Hz, 9H), 1.21 (m, 6H), 0.88 (t, 3J(H,H) = 7.0 Hz, 3H), 0.66 (t, 3J(H,H) = 8.0 Hz, 2H).} \]

\[ ^{13}C ^{1}HNMR (CDCl\textsubscript{3}); \delta = 158.32 \text{ (s), 154.38 (s), 154.29 (s), 150.68 (m, unresolved), 137.37 (s), 137.04 (s), 135.89 (t, 14.6 Hz), 135.67 (t, 14.6 Hz), 132.87 (t, 10.9 Hz), 131.82 (s), 131.64 (s), 131.59 (s), 130.06 (s), 129.86 (s), 127.09 (s), 118.41 (t, 8.7 Hz), 118.34 (t, 8.7 Hz), 117.54 (s), 117.51 (s), 58.67 (s), 43.19 (s), 40.82 (s), 35.41 (s), 35.32 (s), 34.66 (s), 32.59 (s), 31.83 (s), 31.19 (s), 30.93 (s), 30.27 (s), 28.85 (s), 26.50 (s), 23.82 (s), 22.76 (s), 20.82 (s), 18.53 (s), 14.31 (s), 7.83 (s). Anal. Calcd. for C\textsubscript{8}H\textsubscript{80}N\textsubscript{2}O\textsubscript{2}P\textsubscript{2}Si: C, 71.22; H, 7.47; N, 2.60. Found: C, 71.29; H, 7.41; N, 2.48. \]

**Synthesis of silica bound 1 (Silica-1)**

To a mechanically stirred slurry of 3.2 g of pre-dried silica (at T = 180 °C, under reduced pressure) in 40 mL of toluene was added 320 mg of 1 (0.30 mmol). The reaction mixture was stirred at 70 °C overnight. Subsequently, the silica was washed with toluene, dried under reduced pressure and stored under an inert atmosphere.

The catalyst pre-cursor (Silica-1)Rh(acac) was prepared by stirring a suspension of 2.6 mg of Rh(CO)\textsubscript{2}(acac) and 1 g Silica-1 in 5 mL of THF and 1 mL of Et\textsubscript{3}N for 30 minutes. Next, the solvent was removed and the pink-red silica was washed with toluene (3 x 10 mL) and dried in vacuo. Rhodium content: 1.10 x 10\textsuperscript{-5} mol.g\textsuperscript{-1}.

**Synthesis of Sol-gel bound 1 (Sol-gel-1)**

To a mixture of 129 mg of 1 (0.12 mmol) and 3.2 mg of Rh(CO)\textsubscript{2}(acac) (0.1 eq., 0.012 mmol) in 6 mL of THF was added 2 mL of H\textsubscript{2}O and 2 mL of tetramethylorthosilicate. After 1.5h 0.2 mL of MeOH was added and the mixture was allowed to stand for 36 h. The resulting gel was carefully dried and crushed into free flowing silica to yield the pink-red Sol-gel 1. This was subsequently washed with MeOH, THF and Et\textsubscript{2}O. Yield: 0.98 g of a pink-red silica. That was either used directly or stored under an inert atmosphere at -20 °C. Rhodium content: 1.3 x 10\textsuperscript{-5} mol.g\textsuperscript{-1}.

**Batch-wise hydroformylation.** In a typical experiment a home-made 200 mL autoclave was charged with a 1 g of Silica-1 or Sol-gel-1. Next 8.5 mL of toluene was added. The reactor was purged and pressurised to 16 bar of syngas (CO/H\textsubscript{2}, 1:1) and heated to 80 °C. After 1 hour the substrate was introduced by overpressure of 20 bar of CO/H\textsubscript{2}. The reactions were stopped by cooling on ice and venting the gases. The reaction mixture was removed from the silica by syringe and analysed by GC.
Next, the silica was washed with toluene (2 x 5 mL), and prepared for the next hydroformylation cycle. The top-layer was removed for analysis. New substrate was added, the reactor was pressurised and heated for the next hydroformylation cycle.
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