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# Calix[4]arene based monophosphites, identification of three conformations and their use in the rhodium-catalysed hydroformylation of 1-octene

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Eight monodentate phosphites (**2**–**9**) based on the calix[4]arene backbone were synthesised following two synthetic routes. Out of six conformations only three were actually formed under the applied reaction conditions. X-Ray analysis of two conformers (**4** and **5**) provided insight into the 3-dimensional structure of two of these conformations. The three conformations were characterised by $^{1}H$, $^{13}C$ and $^{31}P$ NMR spectroscopy. NMR experiments showed that several of the phosphites are flexible showing fluxional behaviour of the molecular backbone in solution, but no interconversion between the different conformers was observed. The conformation of the product in the phosphite synthesis is determined at the point where the phosphorus atom is linked to two hydroxyl groups of the calix[4]arene (phosphorus amidite). Such an intermediate phosphorus amidite (**12**) was isolated in the synthesis of **4** and **5**. Phosphites **3**–**6**, **8** and **9** were tested in rhodium-catalysed hydroformylation. Differences in rate can be correlated to the conformation of the ligand.

## Introduction

The field of calix[4]arene chemistry is still growing rapidly and new methods of functionalisation are being discovered at a tremendous pace. The attractiveness of calix[4]arenes lies in the combination of a well defined structure, their ability to adopt several discrete conformations and the large variety of functional groups that can be attached to the upper and lower rim of the arene rings. Numerous functionalities have been attached to the calix[4]arene backbone leading to very selective complexating agents of alkaline (earth) metal ions and organic molecules depending on which conformer is formed.[1,2]

Functionalisation of calix[4]arenes often involves the introduction of hard donor atoms like oxygen and nitrogen. In the past decade, however, softer donor atoms like phosphorus, sulfur and arsenic have been attached to the calix[4]arene backbone as well.[3–7] Recently an excellent review appeared on this subject.[8] Most of these transition metal complexating ligands are based on ligating moieties containing phosphorus. Loeber *et al.* synthesised several bidentate and tetradentate phosphine ligands based on calix[4]arenes in which the phosphines are attached to the lower rim. They report on the palladium, rhodium, gold and platinum complexes based on these ligands which have very interesting properties.[9–11] Floriani *et al.* synthesised several lower rim, tetra substituted phosphinite calix[4]arenes that proved to be very efficient ligands for several transition metals.[5,12,13] The main body of complexes they produced were homo dimetallic compounds but a hetero dimetallic species was also prepared. Phosphine ligands have also been attached to the calix[4]arene upper rim and thus a tetradentate ligand was synthesised but the different conformers were not resolved. An interesting class of phosphorus containing ligands was prepared by reacting calix[4]resorcinarenes with several chlorophosphorus compounds. The availability of eight hydroxyl groups in the calix[4]resorcinarene was utilised to make both rigid tetradentate ligands and less rigid octadentate compounds. In this way phosphinites, phosphonites, phosphites, phosphorus amidites and phosphates were prepared and their complexation behaviour towards several transition metals was studied.[14–17] Another class of interesting compounds are the calix[4]arene diphosphites in which the phosphorus atoms are attached to two *cis* positioned oxygen atoms on the calix[4]arene backbone. These ligands were developed and patented by BASF together with several calix[6]arene phosphites. The calix[4]arene based ligands were tested in rhodium-catalysed hydroformylation and proved to give moderate selectivities.[18] Another possibility is to connect three oxygen atoms of the calix[4]arene to one phosphorus atom. Several reports by the group of Lattman have appeared over the years in which several intermediates leading to the calix[4]arene monophosphite were described. The ligand was synthesised in high yield and the complexation behaviour towards iron pentacarbonyl was studied.[19] This group also reported the coupling of arsenic to the calix[4]arene backbone.[7] In both the calix[4]arene phosphite and arsenite the fourth hydroxyl group on the calix[4]arene backbone was unsubstituted.

In this report we show that calix[4]arene monophosphites exist in at least three different conformations. The fourth hydroxyl group on the calix[4]arene can be functionalised by alkylation and acylation. We thus obtained several substituted calix[4]arene monophosphites. These different calix[4]arene monophosphites were tested in rhodium-catalysed hydroformylation (see Scheme 1) and the influence of the conformation and steric bulk on catalytic performance (rate and selectivity) was determined.

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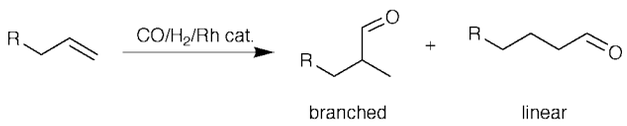



**Scheme 1** The hydroformylation reaction.

## Results and discussion

### Synthesis

Two possible routes can be followed to synthesise *O*-alkylated and *O*-acylated calix[4]arene phosphites of the type depicted in Scheme 2. Method A is based on the synthesis of the phosphite and subsequent *O*-alkylation(acylation). In method B this sequence is reversed.

Calix[4]arene phosphite (**1**) was reported by Khasnis *et al.* in 1990, and was synthesised from calix[4]arene and HMPT (hexamethylphosphorus triamide).[20] In the synthesis of **1** from its precursor **11**, trifluoroacetic acid is used. Under these conditions an undesired side product is sometimes formed that can be present in up to 60 mol%. We identified the side product as compound **13**, an H-phosphonate that is formed from **1** *via* acid hydrolysis. Compound **1** was used as the starting compound for the synthesis of monoacylated phosphites using method A. In the presence of amine bases **1** was allowed to react with acylating reagents. Acylation took place on the fourth oxygen atom in the calix[4]arene without affecting the phosphite. The reaction of **1** with an acylating agent resulted in each case in only one product judging from the signals in the $^{31}$P NMR spectrum. The chemical shifts of the phosphites fall in the range $\delta$ 114–116. Phosphites **8** and **9** were prepared using method A.

Alkylation of **1** using method A was not successful. On one occasion, using benzyl bromide as an alkylating agent, compound **5** was obtained but this phosphite could not be isolated. Unsuccessful attempts were also undertaken to alkylate the intermediate hexacoordinate phosphorus species (**11**) that is formed in the synthesis of phosphite **1**.[20] As a consequence method B was used to synthesise alkylated calix[4]arene phosphites. Mono-*O*-alkylated calix[4]arenes were synthesised *via* a literature procedure.[21,22] The phosphite was subsequently synthesised by reacting the backbone with HMPT in the presence of a mild acid like tetrazole. $PCl_3$ can also be used in combination with amine bases. The method using HMPT is preferred over the method using $PCl_3$ because calix[4]arenes are known to complex ammonium salts.[23,24] The product mixture obtained in the reaction of a mono-O-alkylated calix[4]arene with HMPT or $PCl_3$ always contained two compounds that gave rise to signals in the phosphite region in the $^{31}$P NMR spectra ($\delta \approx 106$, 116). These two products were present in different ratios depending on the applied reaction conditions. For instance if a solution of the mono-*O*-alkylated calix[4]arene is added to a warm (50 °C) solution of HMPT/tetrazole the compound at $\delta \approx 106$ is produced in excess. A reversal of this procedure leads to the formation of an excess of the phosphite with $\delta \approx 116$. Using method B phosphites **2**–**7** were synthesised. The phosphorus chemical shifts of **2**, **4**, **6** and **7** were found around $\delta$ 106, those of compounds **3** and **5** around $\delta$ 116.

### Conformations

Calix[4]arene phosphites can exist in six different conformations. Fig. 1 shows these conformations (**a**–**f**) and a short-hand notation for every one of them.[25] In this case the 'up-down' notation is used, taking the arene ring that is not connected to the phosphorus atom as a reference (printed in bold). Molecular modeling calculations showed that conformations **e** and **f** are relatively unfavourable, but **a**–**d** were found to be of comparable energy.[26] Surprisingly, up to now only conformations **b** and **e** are known for calix[4]arene monophosphate and calix[4]arene monoarsenite, showing an *exo* orientation for the P=O moiety and an *endo* orientation for the arsenic lone pair.[7,19,27] The *exo* orientation was also found for the P=O moiety and phosphorus lone pair in calix[6]arene diphosphate and diphosphite.[28,29] X-Ray analyses of phosphites **4** and **5** (see Fig. 2) show that **4** adopts conformation **a** and **5** adopts conformation **e**. All other phosphites synthesised using method B also adopt either conformation **a** or **e**. This was proven *via* NMR spectroscopy and these data are discussed below. Although we have no crystallographic proof we conclude that **8** and **9** adopt a conformation different from the two described for compounds **4** and **5**. We base this on NMR data (*vide infra*).

We assume that **8** and **9** adopt the same conformation as calix[4]arene phosphate (**10**), *i.e.* conformation **b**, according to a crystal structure of **10** which was published by Khasnis *et al.*[27] Phosphate **10** and phosphites **8** and **9** were synthesised directly from phosphite **1**. Because we observed no change in conformation of **1** in a high temperature $^1$H NMR and $^{31}$P NMR experiment (toluene-$d_8$, 90 °C) we conlude that **1** is conformationally rigid. Therefore it is most likely that all of its derivatives (*viz.* **8**, **9** and **10**) will have conformation **b**.

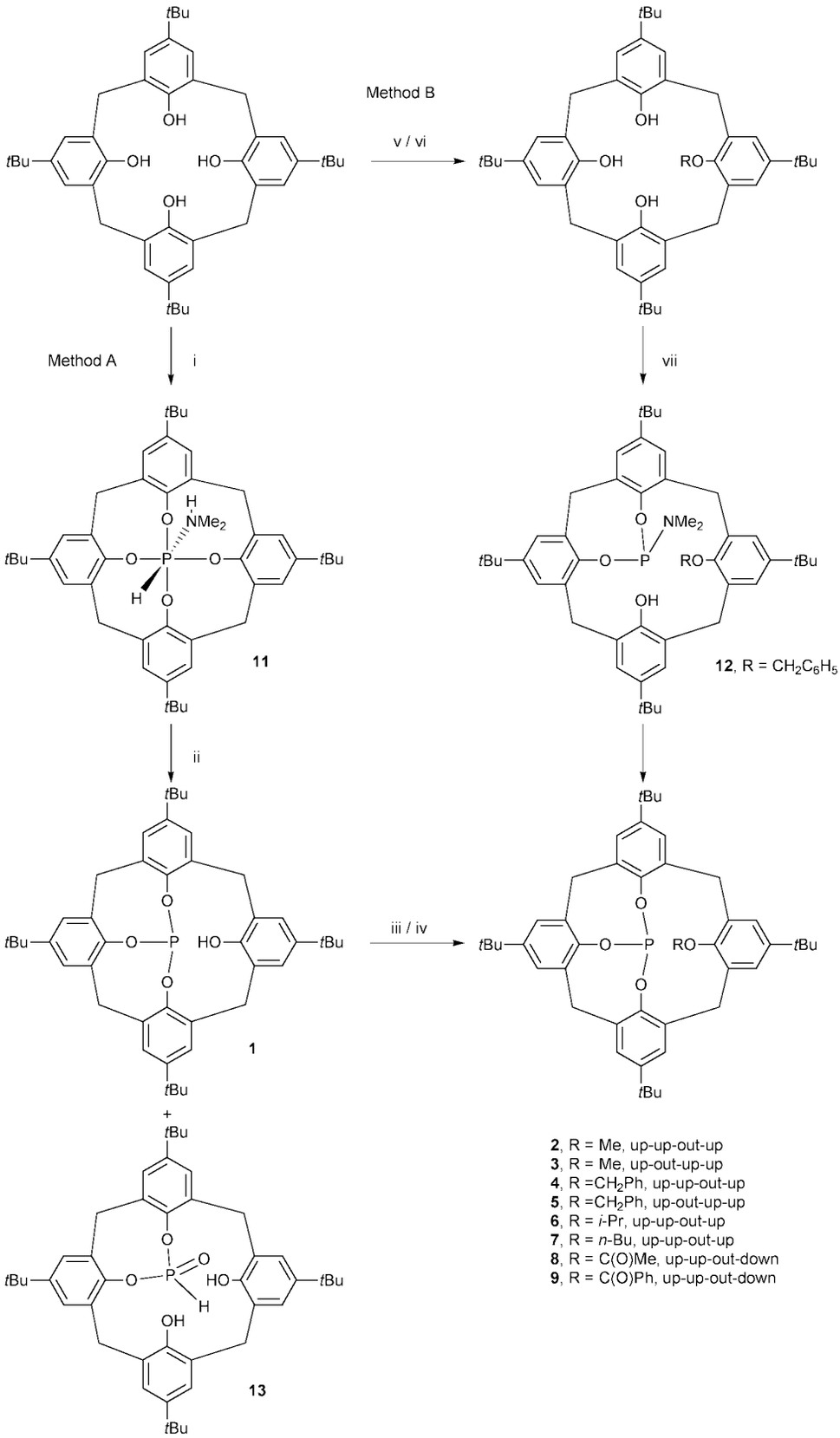
### Description of the structures of 4 and 5

The most noticeable feature of compound **4** is the conformation of the backbone. Three phenyl rings are pointing towards the same side of the molecule ('up'), while the fourth ring is in an "out" position. The benzyl group is situated in the vicinity of the phosphorus lone pair that has an *exo* orientation with respect to the cavity of the calix[4]arene. The molecular symmetry of **4** in the crystal structure is $C_1$ and therefore the compound is chiral. The spacegroup is centrosymmetric and therefore the crystal is racemic. Selected bond angles and distances are presented in Table 1. The P–O bond distances are within the usual range. Furthermore O–P–O angles are in the normal range for phosphites, except for P(1)–O(2)–C(26) which is rather large indicating there is some strain in the molecule. On the basis of NMR data we assign the same structure as that found for **4** to **2**, **6** and **7** (*vide infra*).

The crystal structure of compound **5** shows the molecule in conformation **e** (Fig. 1). The same conformation was found for the solid state structure of calix[4]arene monoarsenite.[7,19,27] The time-averaged $C_s$ symmetry found in the NMR (*vide infra*) is not retained in the crystal. The phenyl rings attached to oxygen atoms O(2) and O(4) occupy equivalent positions that are symmetry related by a mirror plane containing the phosphorus atom P(1). In contrast to the structure of **4** the orientation of the phosphorus lone pair is *endo* with respect to the cavity of the calix[4]arene. Furthermore the benzyl group on the fourth arene ring and the phosphorus atom are now located on opposite sides of the molecule. As a consequence the *tert*-butyl group at C(23) of the fourth arene ring is situated in the vicinity of the phosphorus lone pair. Bond lengths and angles are normal and so **5** seems less strained than **4**. We assign the same structure as that of **5** to compound **3** on the basis of NMR data (*vide infra*).

### NMR studies, fluxional behaviour

The $^1$H NMR spectrum of phosphites **1**–**9** shows three different peaks in the *tert*-butyl region with a relative intensity of 1 : 1 : 2 together with two AB patterns arising from the methylene bridges in a ratio 1 : 1. These data suggest that the phosphites are all $C_s$ symmetric with a mirror plane containing the phosphorus atom. For the phosphates derived from **1** and **4** the $C_1$ symmetry is proven, which is also found in the solid state.[19,27] This implies that phosphites **1** and **4** show fluxional behaviour in solution at room temperature. We propose that the arene rings connected to O(2) and O(4) of **4** are in fast exchange




**Scheme 2** Synthetic routes to calix[4]arene based monophosphites. i) HMPT, ii) $CF_3CO_2H$, iii) KO*t*-Bu, iv) R′C(O)Cl, v) 2 eq. $RX/K_2CO_3$, vi) $(CH_3)_3SiI$, vii) HMPT/tetrazole.

between an up and out position and therefore an average signal is obtained for both. The process is depicted in Fig. 3.

This kind of motion has already been reported by Grynszpan *et al.* for calix[6]arene diphosphate and we observed this phenomena in calix[6]arene diphosphite as well.[28–30] The exchange process is very facile with a low activation energy since cooling down a sample of either **1** or **4** to 203 K did not result in coalescence of the *tert*-butyl signals or methylene AB patterns. Only a slight broadening was observed for **4**. The $^1H$ NMR spectrum of **5** at room temperature is in accordance with the crystal structure obtained for this compound. Moreover we have evidence that **5** is more rigid than either **1** or **4** and shows only the expected time-averaged $C_s$ symmetry of conformation **e** in solution (*vide infra*).

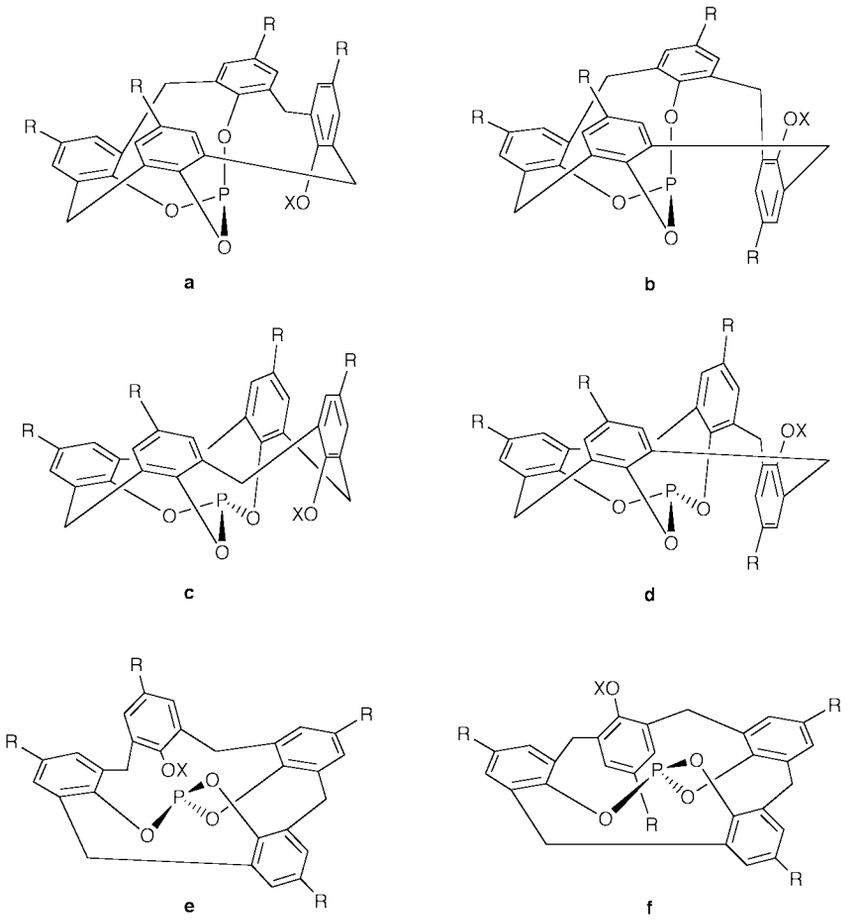


**Fig. 1** Six conformations of calix[4]arene based monophosphites ([**a**]u-u-o-**u**, [**b**]u-u-o-**d**, [**c**]u-u-u-**u**, [**d**]u-u-u-**d**, [**e**]u-o-u-**u**, [**f**]u-o-u-**d**).

## NMR studies, conformational analysis

Jaime *et al.* introduced $^{13}C$ NMR spectroscopy as a tool to assign the conformation of a calix[4]arene backbone.[31] They found that the methylene carbon chemical shifts are an indication for the relative orientation of the two phenyl rings attached to it. The two orientations, *syn* and *anti* are shown below.

Methylene carbon chemical shifts were found in the $\delta$ 31–33 and the $\delta$ 37–38 intervals of the spectrum for a *syn* and *anti* orientation respectively. The carbon chemical shifts we obtained for phosphites **1**–**9** are given in Table 2 together with relevant $^{1}H$ and $^{31}P$ NMR data.

Three important observations can be made inspecting the data in Table 2; 1) the methylene carbon chemical shifts are generally outside the regions specified by Jaime *et al.*, 2) the geminal coupling constants of the methylene protons correlate with the phosphite chemical shift, 3) the chemical shift of one *tert*-butyl signal in the $^{1}H$ NMR is correlated to the chemical shift of the phosphite.

The first observation is not very surprising, as Jaime *et al.* studied calix[4]arenes that contained arene rings with distinct up or down orientations whereas we studied compounds whose rings adopt intermediate orientations as a consequence of the conformational constraints imposed by the phosphorus atom. Therefore compounds like **2**, **4** and **6** always contain two *syn* oriented and two up-out oriented pairs of phenyl rings. The methylene carbon chemical shifts for these compounds are just outside the $\delta$ 31–33 and $\delta$ 37–38 regions. Compounds **3** and **5** always contain real *syn* and *anti* orientations and as a consequence their chemical shifts correspond to the literature values. Two intermediate values are obtained for **8** and **9** which indicates that no pair of phenyl rings adopts a true *syn* or *anti* orientation.

The second observation roughly follows the trend observed for the methylene carbon atom chemical shifts. It is known from the literature that the geminal proton coupling $^{2}J_{HH}$ becomes smaller when the H–C–H angle opens.[32] In our case the H–C–H angle depends on the orientation of the phenyl rings on one methylene carbon atom. It was shown by Jaime *et al.* that a *syn* orientation leads to a small C($sp^2$)–C($sp^3$)–C($sp^2$) angle and therefore a large H–C–H angle and *vice versa*. Compounds **2**, **4**, **6** and **7** show two relatively small $^{2}J_{HH}$ values, indicating all phenyl rings are in a more or less *syn* orientation. The values obtained for **1**, **3** and **5** show that two pairs of phenyl rings are in *syn* and the other two pairs in *anti* orientation. Furthermore data of **8** and **9** show two intermediate $^{1}J_{HH}$ values, and so the phenyl rings in these compounds are neither in a *syn* nor an *anti* orientation.

Both observed trends discussed above confirm the structure of **4** and **5** in the solid state and in solution if the fluxional behaviour of **4** is considered as well. From similarities in the NMR data we conclude therefore that **2**, **4**, **6** and **7** adopt the same conformation, as do **3** and **5** and the couple **8** and **9**. It is remarkable though that on the basis of $^{1}H$ and $^{13}C$ NMR spectra a distinction can be made between the phosphites that adopt conformation **b** (**8** and **9**) and those that adopt conformation **e** (**3**, **5**) since the phosphorus chemical shifts are so similar.

The third observation can now be understood as well. The *tert*-butyl group that is most sensitive to a conformational change is the one that experiences the presence or absence of the phosphorus lone pair *viz.* the *tert*-butyl group on the arene ring that is not attached to the phosphorus atom. A low field shift indicates that the *tert*-butyl group and the lone pair are on the same side of the molecule whereas a high field shift shows they are located on opposite sides of the molecule.

## Conformational stability

To test the influence of the conformation of the calix[4]arene phosphites on catalytic performance at 80 °C we studied the

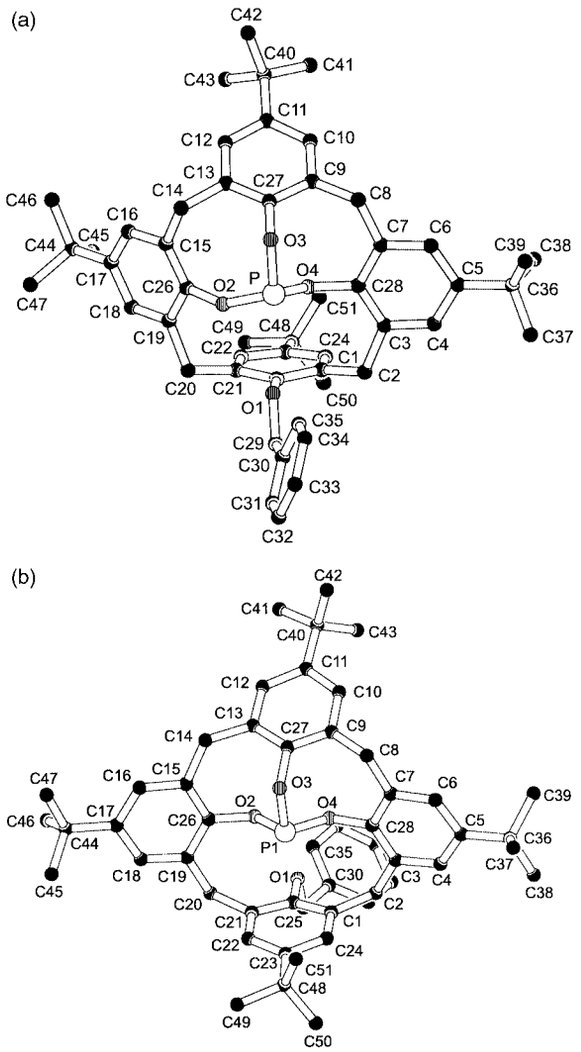



**Fig. 2** (a) Crystal structure of compound **4**. (b) Crystal structure of compound **5**.

**Table 1** Selected bond lengths (Å) and angles (°) of compounds **4** and **5**

| **4** | | **5** | |
|---|---|---|---|
| P(1)–O(2) | 1.614(3) | P(1)–O(2) | 1.640(4) |
| P(1)–O(3) | 1.628(4) | P(1)–O(3) | 1.640(5) |
| P(1)–O(4) | 1.649(3) | P(1)–O(4) | 1.635(4) |
| O(1)–C(25) | 1.390(4) | O(1)–C(25) | 1.386(9) |
| O(1)–C(29) | 1.425(7) | O(1)–C(29) | 1.428(8) |
| O(2)–C(26) | 1.412(4) | O(2)–C(26) | 1.399(8) |
| O(3)–C(27) | 1.402(5) | O(3)–C(27) | 1.417(8) |
| O(4)–C(28) | 1.418(4) | O(4)–C(28) | 1.397(8) |
| C(1)–C(2) | 1.516(6) | C(1)–C(2) | 1.522(10) |
| C(2)–C(3) | 1.513(8) | C(2)–C(3) | 1.524(10) |
| C(7)–C(8) | 1.521(8) | C(7)–C(8) | 1.502(9) |
| C(8)–C(9) | 1.502(6) | C(8)–C(9) | 1.505(10) |
| C(13)–C(14) | 1.510(5) | C(13)–C(14) | 1.519(10) |
| C(14)–C(15) | 1.510(7) | C(14)–C(15) | 1.530(10) |
| C(19)–C(20) | 1.504(7) | C(19)–C(20) | 1.518(9) |
| C(20)–C(21) | 1.515(5) | C(20)–C(21) | 1.531(10) |
| O(2)–P(1)–O(3) | 104.7(2) | O(2)–P(1)–O(3) | 100.7(2) |
| O(2)–P(1)–O(4) | 101.4(1) | O(2)–P(1)–O(4) | 89.2(2) |
| O(3)–P(1)–O(4) | 99.7(2) | O(3)–P(1)–O(4) | 101.3(2) |
| P(1)–O(2)–C(26) | 147.5(3) | P(1)–O(2)–C(26) | 116.4(4) |
| P(1)–O(3)–C(27) | 122.0(3) | P(1)–O(3)–C(27) | 114.6(4) |
| P(1)–O(4)–C(28) | 120.4(2) | P(1)–O(4)–C(28) | 123.2(4) |
| C(25)–O(1)–C(29) | 112.6(4) | C(25)–O(1)–C(29) | 110.6(5) |
| C(1)–C(2)–C(3) | 117.1(4) | C(1)–C(2)–C(3) | 115.6(6) |
| C(7)–C(8)–C(9) | 121.2(5) | C(7)–C(8)–C(9) | 120.5(6) |
| C(13)–C(14)–C(15) | 111.0(3) | C(13)–C(14)–C(15) | 124.2(6) |
| C(19)–C(20)–C(21) | 110.7(4) | C(19)–C(20)–C(21) | 116.0(6) |

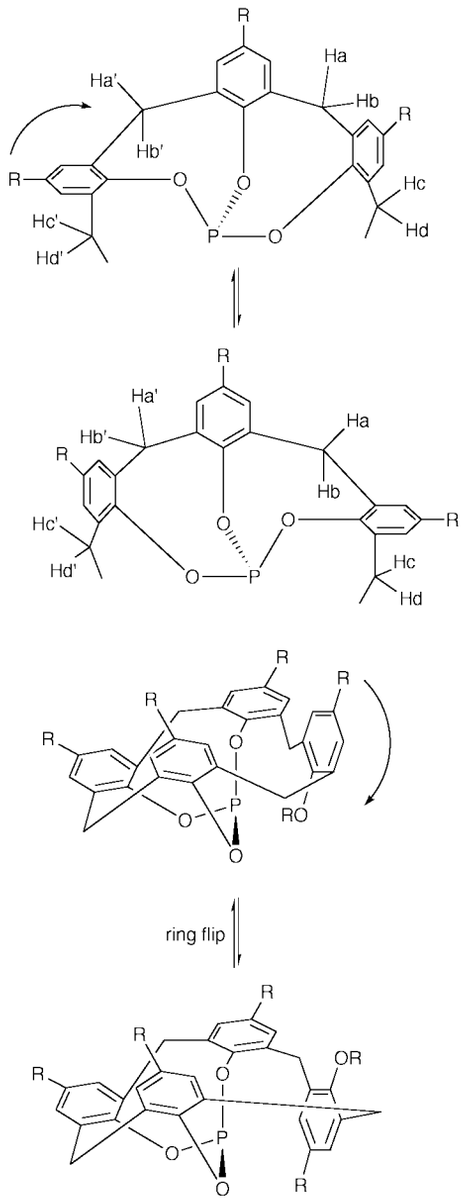



**Fig. 3** Fluxional process in the calix[4]arene backbone.

conformational stability at this temperature. To this end we performed high temperature NMR experiments with compounds **1** and **3**. The other phosphites were not examined as it is well known that *O*-alkyl groups larger than ethyl groups cannot rotate through the annulus of the calix[4]arene and inversion of the phosphorus configuration requires very high temperatures. Spectra of both **1** and **3** showed no additional peaks or line broadening in either $^{1}H$ or $^{31}P$ spectra as a consequence of heating the sample to 90 °C in toluene-$d_8$. Based on these results our conclusion is that none of the phosphites **1**–**9** is capable of rotating the substituted phenyl ring from an up to a down position or *vice versa*.

### Reaction mechanism leading to phosphites 4 and 5

The syntheses of phosphites according to method B often gives compounds that have resonances at *ca.* $\delta = 138$–$145$ in the $^{31}P$ NMR spectrum. Usually these signals did not disappear after prolonged reaction time. The corresponding compounds were identified as phosphorus amidites which are intermediates in phosphite synthesis using HMPT. In the synthesis of **4** and **5** we isolated the intermediate resonating at $\delta = 138$ and it was identified as compound **12** (see also Scheme 2). Considering the conformational stability of compound **1** and **3** at 363 K it is

**Table 2** NMR data on phosphites **1**–**9** ($^2J_{HH}$ in Hz in parentheses)

| | $^{31}$P | $^{13}$C | | $^1$H | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $CH_2$ | $CH_2$ | *t*Bu | $CH_2$ ax | $CH_2$ ax | $CH_2$ eq | $CH_2$ eq |
| **1**[a] | 113 | 33.8 | 36.9 | 1.20 | 4.29(17) | 4.49(15) | 3.62(15) | 3.71(17) |
| **2** | 107 | 32.5 | 35.5 | 0.98 | 4.40(14.4) | 4.62(14.2) | 3.45(14.4) | 3.55(14.2) |
| **3** | 116 | 33.1 | 37.3 | 1.17 | 4.30(16.9) | 4.57(14.4) | 3.60(14.4) | 3.70(16.9) |
| **4** | 107 | 33.5 | 36.4 | 0.99 | 4.40(14.4) | 4.64(14.2) | 3.44(14.4) | 3.50(14.2) |
| **5** | 116 | 33.4 | 37.2 | 1.16 | 4.29(16.9) | 4.45(14.6) | 3.33(14.6) | 3.68(16.9) |
| **6** | 105 | 34.0 | 36.3 | 0.83 | 4.63(14) | 4.94(14) | 3.39(14) | 3.59(13) |
| **7** | 106 | — | — | 0.99 | 4.41(14) | 4.61(14) | 3.44(14) | 3.50(14) |
| **8** | 116 | 34.3 | 36.9 | 1.20 | 4.09(15) | 4.32(16.4) | 3.63(15) | 3.65(16.4) |
| **9** | 114 | 35.0 | 36.6 | 1.26 | 4.09(15.4) | 4.38(16) | 3.64(16) | 3.66(15.4) |

[a] $CD_2Cl_2$.[6]

**Table 3** Calix[4]arene phosphites **3**–**6**, **8** and **9** in hydroformylation of 1-octene

| | | | Selectivity | | | | |
|---|---|---|---|---|---|---|---|
| Entry | Ligand | Conversion (%) | Linear (%) | Branched (%) | Isomerisation (%) | L/B | T.O.F.[a] |
| 1 | **3** | 78 | 45 | 23 | 32 | 2.0 | 1900 |
| 2 | **3** | 89 | 47 | 24 | 29 | 2.0 | 1800 |
| 3 | **3** | 53 | 48 | 25 | 28 | 1.9 | 1700 |
| 4[b] | **3** | 55 | 47 | 25 | 29 | 1.9 | 1600 |
| 5 | **4** | 92 | 51 | 40 | 9 | 1.3 | 7200 |
| 6 | **4** | 97 | 52 | 40 | 8 | 1.3 | 7600 |
| 7 | **5** | 71 | 45 | 31 | 24 | 1.4 | 1800 |
| 8 | **5** | 79 | 45 | 30 | 25 | 1.5 | 1900 |
| 9 | **5** | 77 | 46 | 32 | 21 | 1.4 | 1800 |
| 10[b] | **5** | 74 | 46 | 32 | 22 | 1.4 | 1800 |
| 11[c] | **5** | 91 | 39 | 20 | 41 | 2.1 | 2200 |
| 12 | **6** | 98 | 54 | 40 | 5 | 1.4 | 8100 |
| 13 | **6** | 96 | 54 | 40 | 6 | 1.4 | 7300 |
| 14 | **8** | 97 | 50 | 32 | 19 | 1.6 | 4400 |
| 15 | **8** | 97 | 50 | 31 | 19 | 1.6 | 4700 |
| 16 | **8** | 98 | 48 | 31 | 22 | 1.5 | 4100 |
| 17[b] | **8** | 96 | 47 | 29 | 24 | 1.6 | 4200 |
| 18 | **9** | 97 | 46 | 40 | 15 | 1.2 | 5000 |
| 19 | **9** | 98 | 47 | 40 | 13 | 1.2 | 5600 |

Conditions: [Rh] = 0.1 mM, L/Rh = 20, S/Rh = 6370, $T$ = 80 °C, $p$ = 20 bar $CO/H_2$ (1/1), incubation overnight (17 h). [a] Measured as an average over time in the linear part of the graph (typically conversion < 50%). [b] Quenched with $(n\text{-}C_4H_9O)_3P$. [c] L/Rh = 3.

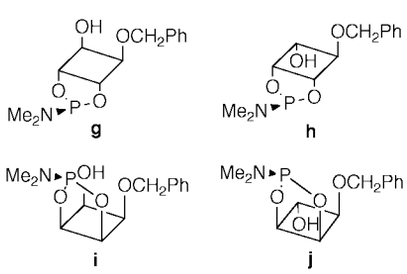



**Fig. 4** Four conformers of **12**.

likely that **12** exists in several non-interconvertible conformers. Four possibilities are depicted in Fig. 4.

It seems reasonable that only those conformers having both the hydroxyl group and the phosphorus amidite moiety on one side of the calix[4]arene, *viz.* conformations **h** and **i**, will lead to the formation of phosphites. As a consequence the ratio of conformers that are formed during the reaction is determined by the ratio of conformers **g**–**j** of **12**. The exact influence of solvent (polarity) and reaction temperature is not clear at present.

### Hydroformylation using calix[4]arene phosphites

In order to examine the effect of the different conformers of calix[4]arene phosphites on catalyst performance, several hydroformylation experiments using **3**–**6**, **8** and **9** were performed. The data obtained from these experiments using 1-octene as a substrate are presented in Table 3 and Fig. 5.

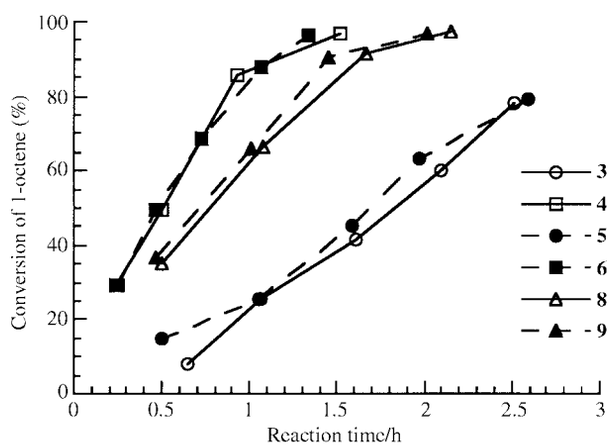



**Fig. 5** Conversion of 1-octene as a function of time using ligands **3**–**6**, **8** and **9**.

Fig. 5 shows an interesting phenomenon. The three classes of conformers of calix[4]arene phosphites show totally different rates in catalysis although all are fast. The ligands that form the slowest catalyst are those that have an **e** conformation (**3** and **5**). The conversion of 1-octene against time using **3** and **5** as modifying ligand shows an almost straight line with a slight

increase in reaction rate at higher conversions. This suggests that the catalyst concentration is increasing slowly towards the end of the reaction. In compounds **3** and **5** the phosphorus lone pair is more or less embedded in the cavity of the calix[4]arene and is pointed towards the fourth phenol ring and the *tert*-butyl group attached to it. It is clear that the environment of the lone pair is sterically congested. This will hamper coordination to the metal centre and as a result catalyst formation is probably slow. Moreover, steric hindrance in the complex will impede substrate coordination slowing down the reaction. A higher selectivity towards the branched product at the expense of isomerisation was observed comparing **3** and **5**. This cannot be caused directly by the bulk of the alkyl group on the fourth phenyl ring as this is not positioned in the vicinity of the phosphorus lone pair.

Compounds **4** and **6** afford the fastest catalysts in this series and they are also very active catalysts compared to other phosphite based hydroformylation catalysts. The crystal structure of **4** shows that the phosphorus lone pair of this conformer suffers the least from steric crowding as the benzyl group on the fourth oxygen atom can easily move away from it. As a consequence catalyst formation is fast and the catalyst is easily accessible for the alkene substrate. The character of the alkyl group did not affect the selectivity. This also indicates that the alkyl group is not in the vicinity of the rhodium centre.

Phosphites **8** and **9** exist as a conformer in which the phosphorus lone pair is in the vicinity of the fourth phenol ring (and the *tert*-butyl group attached to it) but is not pointing directly towards it. The ligands are sterically less demanding than **3** and **5** and as a consequence catalysis is faster. The character of the acyl group attached to the fourth phenol group does have an effect on the selectivity of the catalyst, *viz.* the larger aryl group leads to less isomerisation and more branched aldehyde while the selectivity towards the linear product does not change. This cannot be a direct effect of the steric bulk of the acyl group because it is not in the vicinity of the phosphorus lone pair; the size of the acyl group can have a small if distinct influence on the exact ligand structure. The results of Pringle *et al*. using calix[4]arene having an unsubstituted hydroxy group confirm that the substituent can have a large effect on the catalytic reaction.[33]

## Concluding remarks

We have been able to synthesise eight calix[4]arenes with three different conformations. Furthermore we have been able to establish a correlation between the conformation of the calixarene backbone and the phosphite chemical shifts, chemical shifts of the methylene carbon atoms and the geminal coupling constants of the methylene protons. This can be a useful tool in future investigations. NMR experiments have proven that conformers of the same calix[4]arene phosphite are not interconvertible. Therefore we conclude that the rate in the rhodium-catalysed hydroformylation is mainly determined by the conformation of the calix[4]arene phosphite that is used. This effect was never clearly demonstrated before as most phosphites are flexible. The rates in hydroformylation of the tested ligands lie in between the very fast bulky phosphites (tris(*o*-*tert*-butyl-*p*-methylphenyl) phosphite) and the relatively small triphenyl phosphite which leads to catalytically inactive $L_4RhH$ species. The substituent on the fourth arene ring of the calix[4]arene plays an indirect role in the selectivity of the reaction, but this effect is not well understood yet.

## Experimental

### Chemicals

All preparations were carried out under an inert atmosphere of dinitrogen or argon using standard Schlenk techniques unless stated otherwise. Toluene, benzene, THF, diethyl ether, pentane and hexane were distilled from sodium/benzophenone. Chlorinated solvents, acetonitrile, triethylamine and pyridine were distilled from $CaH_2$. Synthesis gas ($CO/H_2$ 1/1) was obtained from Air Liquide and was used without purification. *p-tert*-Butylphenol, $PCl_3$, HMPT (85%) and tetrazole were purchased from Aldrich. Formaldehyde was used as a 37% solution in water purchased from Janssen Chimica. NaOH was purchased from Riedel de Haen and used without further purification. $Rh(CO)_2(acac)$ was purchased from Degussa/Merck. A 0.1 mM solution of this metal complex was prepared by dissolving 12.9 mg of $Rh(CO)_2(acac)$ in 50 ml of toluene which was stored in a Schlenk vessel under an argon atmosphere at −20 °C. The solution was allowed to warm to room temperature 30 minutes before use. The silica gel used for column chromatography (Kieselgel 60, 70–230 mesh ASTM) was purchased from Merck.

### Apparatus

Melting points (uncorrected) were determined on a Gallenkamp MFB 595 melting point apparatus. NMR measurements ($^1H$ NMR (300.1 MHz), $^{13}C\{^1H\}$ NMR (75.5 MHz), $^{31}P\{^1H\}$ NMR (121.5 MHz)) were performed on a Bruker AMX 300 spectrometer. Chemical shifts are given in ppm using $SiMe_4$ or $H_3PO_4$ as a standard reference. NMR spectra were measured in chloroform-$d_1$ at 25 °C unless stated otherwise. IR spectra were taken on a Nicolet 510 FT-IR spectrophotometer. Mass spectrometric measurements were performed at the Institute for Mass Spectrometry of the University of Amsterdam. Elemental analyses were performed in our own laboratory on an Elementar Vario EL Apparatus (Foss Electric) or they were performed in the Micro Analytical Department of the University of Groningen. Gas-chromatographic analyses were performed on a HRGC-MEGA 2 series (Interscience) apparatus equipped with a 30 m DB-1 dimethyl siloxane cross-linked phase column (inner diameter 0.32 mm, film thickness 3.0 μm) and a FID detector. The hydroformylation experiments were performed in a stainless steel (SS 316) 180 ml autoclave, equipped with a glass liner, a gas inlet, a thermocouple, an external heating mantle and a magnetic stirrer.

### Hydroformylation experiments

In a typical experiment the autoclave was charged with 2 ml of a 1 mM toluene solution of $Rh(CO)_2(acac)$, 20 equivalents of ligand (0.04 mmol) and 13 ml of toluene. The autoclave was closed and flushed thrice with syngas ($CO/H_2$ 1/1 v/v). It was then pressurised with 12 bar of syngas and heated overnight at 80 °C to preform the catalyst. At this point a mixture of substrate (1-octene, 2 ml), internal standard (decane, 1 ml) and toluene (2 ml) was added to the catalyst mixture under pressure and the total pressure was raised to 20 bar. The reaction was monitored by the decrease of the pressure. At several points in time a sample was taken that was diluted with ethanol and analysed with gas-chromatography.

### Syntheses

***p-tert*-Butyl-calix[4]arene.** This compound was synthesised following a literature procedure.[34]

***p-tert*-Butyl-calix[4]arene phosphite (1).** This compound was synthesised following a literature procedure.[20]

**Compounds 2–9, 12 and 13.** *Method A: starting from p-tert-butyl-calix[4]arene phosphite.* 0.5 mmol (0.34 g) of calix[4]arene phosphite (**1**) was dried azeotropically with dry toluene and then dissolved in 20 ml of dry toluene. 5 mmol of distilled pyridine (0.4 ml) was added and the solution was stirred for 5 minutes. Then a ten-fold excess of the acid chloride was added and the solution was stirred at room temperature under

an argon atmosphere for 5 days. The solution was washed twice with water, dried over $MgSO_4$, filtered and the solvent evaporated. The crude mixture was purified by column chromatography with toluene/light petroleum (PE, bp 40–60 °C) as eluent.

*Method B: starting from monoalkylated p-tert-butyl-calix-[4]arenes.* 2.5 mmol of the calix[4]arene was azeotropically dried twice with dry toluene (5 ml) and dissolved in 30 ml of dry toluene. This solution was dropwise added to a solution of 3 mmol of HMPT (0.64 ml) and a catalytic amount of 1*H*-tetrazole in 25 ml of dry toluene under an argon atmosphere at 50 °C and under stirring. After a night of stirring at 50 °C the temperature was raised to reflux temperature and heated for 20 hours. Toluene and excess of HMPT were evaporated under vacuum and the resulting solid was subjected to column chromatography. An excess of phosphite with conformation **a** was produced in this way. Addition of the HMPT and 1*H*-tetrazole to a solution of the monoalkylated calix[4]arene at 50 °C resulted in the formation of an excess of phosphite with conformation **e**.

*Method B′: synthesis with $PCl_3$.* 0.5 mmol of the monoalkylated calix[4]arene phosphite was azeotropically dried with dry toluene and then dissolved in 30 ml of dry THF. Distilled triethylamine was added and the solution was cooled to −78 °C in an acetone/dry ice bath. 0.5 mmol $PCl_3$, dissolved in 10 ml of dry THF, was then added dropwise and the solution was allowed to come to room temperature whilst stirring under an argon atmosphere. The solid pyridine salts were removed by filtration and the solvent was evaporated. The resulting solid was seperated by column chromatography over silica with $CH_2Cl_2$/PE (ratio 1/2) as eluent.

## Characterisation

***p-tert*-Butyl-calix[4]arene-25-methoxy-26,27,28-phosphite (up-up-out-up) (2).** Method B. Yield 0.06 g (0.087 mmol, 17%); because the product contained 1–2% of the intermediate phosphorus amidite **12** no correct microanalytical data could be obtained; mp = 310 °C; $^1$H NMR: $\delta$ = 0.98 (s, 9H; *t*-Bu), 1.19 (s, 9H; *t*-Bu), 1.36 (s, 18H; *t*-Bu), 3.45 (d, $^2J_{HH}$ = 14.4 Hz, 2H; $CH_2$ eq), 3.55 (d, $^2J_{HH}$ = 14.2 Hz, 2H; $CH_2$ eq), 3.82 (s, 3H; $OCH_3$), 4.40 (d, $^2J_{HH}$ = 14.4 Hz, 2H; $CH_2$ ax), 4.62 (d, $^2J_{HH}$ = 14.2 Hz, 2H; $CH_2$ ax), 6.80 (s, 2H; ArH), 7.06 (s, 2H; ArH), 7.11 (d, $^2J_{HH}$ = 2.3 Hz, 2H; ArH), 7.18 (d, $J_{HH}$ = 2.3 Hz, 2H; ArH); $^{13}$C NMR: $\delta$ = 30.1, 30.4 (s; *C*$H_3$), 32.5, 35.5 (s; *C*$H_2$), 32.9, 33.0, 33.2 (s; *C*$(CH_3)_3$), 61.1 (s; O*C*$H_3$), 123.5, 123.6, 125.1, 125.6 (s; Ar*C*H), 129.0, 131.4 (d, $J_{PC}$ = 2.3 Hz; Ar*C*), 131.3 (d, $J_{PC}$ = 3.0 Hz; Ar*C*), 130.8, 143.8, 143.8, 144.8, 145.4, 146.2, 146.7, 146.9, 152.6 (s; Ar*C*); $^{31}$P NMR: $\delta$ = 107 (s, 1P; $P(OR)_3$); IR(KBr): $\nu$(cm$^{-1}$) 3051 (C–H arom.); 2962, 2906, 2868 (C–H aliph.); 1480, 1465 (C=C); 1212, 1173 (C–O–P); 1108 (C–O); FAB: *m*/*z* (%) 57(100) [$C(CH_3)_3$], 691(78) [$MH^+$].

***p-tert*-Butyl-calix[4]arene-25-methoxy-26,27,28-phosphite (up-out-up-up) (3).** Method B. Yield 0.83 g (1.2 mmol, 10%); mp = 325 °C; $^1$H NMR: $\delta$ = 1.17 (s, 9H; *t*-Bu), 1.28 (s, 9H; *t*-Bu), 1.39 (s, 18H; *t*-Bu), 3.60 (d, $^2J_{HH}$ = 14.4 Hz, 2H; $CH_2$ eq), 3.70 (d, $^2J_{HH}$ = 16.9 Hz, 2H; $CH_2$ eq), 3.71 (s, 3H; $OCH_3$), 4.30 (d, $^2J_{HH}$ = 16.9 Hz, 2H; $CH_2$ ax), 4.57 (d, $^2J_{HH}$ = 14.4 Hz, 2H; $CH_2$ ax), 7.06 (s, 2H; ArH), 7.14 (d, $^4J_{HH}$ = 2.3 Hz, 2H; ArH), 7.16 (s, 2H; ArH), 7.21 (d, $^4J_{HH}$ =2.3 Hz, 2H; ArH); $^{13}$C NMR: $\delta$ = 31.2, 31.3, 31.5 (s; *C*$H_3$), 33.1, 37.3 (s; *C*$H_2$), 34.0, 34.1, 34.1 (s; *C*$(CH_3)_3$), 61.9 (s; O*C*$H_3$), 125.9, 126.2, 126.2 (s; Ar*C*H), 129.9, 130.0, 132.7, 132.7, 133.2, 133.2, 134.7, 134.7, 144.0, 145.0, 145.1, 146.2, 146.4, 147.2 (s; Ar*C*); $^{31}$P NMR: $\delta$ = 116 (s, 1P; $P(OR)_3$); IR(KBr): $\nu$(cm$^{-1}$) 3040 (C–H arom.); 2962, 2904, 2867 (C–H aliph.); 1478 (C=C); 1290, 1183 (C–O–P); 1113, 1100 (C–O); FAB: *m*/*z* (%) 57(100) [$C(CH_3)_3$], 691(35) [$MH^+$]; Anal. Calcd. for $C_{45}H_{55}O_4P{\cdot}1.5H_2O$: C, 75.29; H, 8.14. Found: C, 75.36; H, 8.10%.

***p-tert*-Butyl-calix[4]arene-25-benzyloxy-26,27,28-phosphite (up-up-out-up) (4).** Method B and B′. Crystals suitable for X-ray analysis were grown from a $CH_2Cl_2$/pentane solution. Yield 0.11 g (0.14 mmol, 29%); mp = 265 °C; $^1$H NMR: $\delta$ = 0.99 (s, 9H; *t*-Bu), 1.20 (s, 9H; *t*-Bu), 1.36 (s, 18H; *t*-Bu), 3.44 (d, $^2J_{HH}$ = 14.4 Hz, 2H; $CH_2$ eq), 3.50 (d, $^2J_{HH}$ = 14.2 Hz, 2H; $CH_2$ eq), 4.40 (d, $^2J_{HH}$ = 14.4 Hz, 2H; $CH_2$ ax), 4.64 (d, $^2J_{HH}$ = 14.2 Hz, 2H; $CH_2$ ax), 4.95 (s, 2H; $OCH_2Ph$), 6.81 (s, 2H; ArH), 7.06 (s, 2H; ArH), 7.10 (d, $^4J_{HH}$ = 2.3 Hz, 2H; ArH), 7.15 (d, $^4J_{HH}$ = 2.3 Hz, 2H; ArH), 7.38 (m, 4H; ArH), 7.57 (d, $J_{HH}$ = 7 Hz, 1H; ArH); $^{13}$C NMR: $\delta$ = 31.0, 31.3 (s; *C*$H_3$), 33.5, 36.4 (s; *C*$H_2$), 33.5, 33.9, 34.1 (s; *C*$(CH_3)_3$), 76.6 (s; O*C*$H_2C_6H_5$), 124.3, 124.4, 126.0, 126.5, 126.9, 127.3, 128.1 (s; Ar*C*H), 129.8, 131.9, 132.2, 133.8, 133.8, 137.8, 144.7, 144.7, 145.7, 146.5, 147.1, 147.7, 147.9, 152.1 (s; Ar*C*); $^{31}$P NMR: $\delta$ = 107 (s, 1P; $P(OR)_3$); IR(KBr): $\nu$(cm$^{-1}$) >3000 (C–H arom.); 2961, 2869 (C–H aliph.); 1486, 1465 (C=C); 1207, 1193.94, 1173 (C–O–P); 1106 (C–O); FAB: *m*/*z* (%) 767(100) [$MH^+$]; Anal. Calcd. for $C_{51}H_{59}O_4P{\cdot}1.5H_2O$: C, 77.15; H, 7.87. Found: C, 77.60; H, 7.80%.

***p-tert*-Butyl-calix[4]arene-25-benzyloxy-26,27,28-phosphite (up-out-up-up) (5).** Method B and B′. Crystals suitable for X-ray analysis were grown from a toluene solution. Yield 1.26 g (1.6 mmol, 36%); mp = 180 °C; $^1$H NMR: $\delta$ = 1.16 (s, 9H; *t*-Bu), 1.28 (s, 9H; *t*-Bu), 1.36 (s, 18H; *t*-Bu), 3.33 (d, $^2J_{HH}$ = 14.6 Hz, 2H; $CH_2$ eq), 3.68 (d, $^2J_{HH}$ = 16.9 Hz, 2H; $CH_2$ eq), 4.29 (d, $^2J_{HH}$ = 16.9 Hz, 2H; $CH_2$ ax), 4.45 (d, $^2J_{HH}$ = 14.6 Hz, 2H; $CH_2$ ax), 4.86 (s, 2H; $OCH_2Ph$), 7.00 (s, 2H; ArH), 7.12 (s, 4H; ArH), 7.16 (s, 2H; ArH), 7.26 (m, 5H; ArH); $^{13}$C NMR: $\delta$ = 31.2, 31.3, 31.4 (s; *C*$H_3$), 33.4, 37.2 (s; *C*$H_2$), 33.9, 34.0, 34.1 (s; *C*$(CH_3)_3$), 76.4 (s; O*C*$H_2C_6H_5$), 125.7, 126.0, 126.1, 127.7, 127.9, 128.9 (s; Ar*C*H), 130.0, 133.0, 133.1, 133.1, 134.8, 134.9, 136.6, 144.0, 145.0, 145.1, 146.2, 146.5, 154.0 (s; Ar*C*); $^{31}$P NMR: $\delta$ = 116 (s, 1P; $P(OR)_3$); IR(KBr): $\nu$(cm$^{-1}$) 3038 (C–H arom.); 2963, 2907, 2865 (C–H aliph.); 1477 (C=C); 1290, 1184 (C–O–P); 1117, 1100 (C–O); FAB: *m*/*z* (%) 57(100) [$C(CH_3)_3^+$], 767(48) [$MH^+$]; Anal. Calcd. for $C_{51}H_{59}O_4P$: C, 79.86; H, 7.75. Found: C, 79.24; H, 7.90%.

***p-tert*-Butyl-calix[4]arene-25-isopropoxy-26,27,28-phosphite (up-up-out-up) (6).** Method B. Yield 0.57 g (0.80 mmol, 42%); mp = 270 °C; $^1$H NMR (benzene-$d_6$): $\delta$ = 0.83 (s, 9H; *t*-Bu), 1.01 (s, 9H; *t*-Bu), 1.37 (d, $^2J_{HH}$ = 6.1 Hz, 6H; -CH(C*H*$_3$)), 1.41 (s, 18H; *t*-Bu), 3.39 (d, $^2J_{HH}$ = 14 Hz, 2H; $CH_2$ eq), 3.59 (d, $^2J_{HH}$ = 13 Hz, 2H; $CH_2$ eq), 4.09 (septet, $^2J_{HH}$ = 6.1 Hz, 1H; C*H*$(CH_3)_2$), 4.63 (d, $^2J_{HH}$ = 14 Hz, 2H; $CH_2$ ax), 4.94 (d, $^2J_{HH}$ = 14 Hz, 2H; $CH_2$ ax), 4.95 (s, 2H; $OCH_2Ph$), 7.02 (s, 2H; ArH), 7.06 (s, 2H; ArH), 7.18 (d, $^2J_{HH}$ = 2.5 Hz, 2H; ArH), 7.34 (d, $J_{HH}$ = 2.5 Hz, 2H; ArH); $^{13}$C NMR: $\delta$ = 22.1 (s; CH(*C*$H_3$)$_2$), 31.2, 30.9 (s; C(*C*$H_3$)$_3$), 34.0, 36.3 (s; *C*$H_2$), 33.7, 33.8, 34.1 (s; *C*$(CH_3)_3$), 77.0 (s; O*C*H$(CH_3)_2$), 123.9, 124.3, 125.7, 126.3 (s; Ar*C*H), 129.9, 132.1, 132.4, 134.2, 144.8, 145.6, 147.0, 147.7, 147.9, 150.9 (s; Ar*C*); $^{31}$P NMR (benzene-$d_6$): $\delta$ = 105 (s, 1P; $P(OR)_3$); IR(KBr): $\nu$(cm$^{-1}$) >3000 (C–H arom.); 2954, 2897, 2862 (C–H aliph.); 1474 (C=C); 1275, 1154 (C–O–P); 1104 (C–O); FD: *m*/*z* (%) 718(100) [$M^+$]; Anal. Calcd. for $C_{47}H_{59}O_4P$: C, 78.52; H, 8.27. Found: C, 78.25; H, 8.35%.

***p-tert*-Butyl-calix[4]arene-25-*n*-butoxy-26,27,28-phosphite (up-up-out-up) (7).** Method B. Because the product contained up to 5% of hydrolytic side products (phosphate and $^1$H-phosphonate) no correct microanalytical data could be obtained; $^1$H NMR: $\delta$ = 0.99 (s, 9H; *t*-Bu), 0.99 (t, 3H; $CH_2$-$CH_2CH_2CH_3$), 1.20 (s, 9H; *t*-Bu), 1.36 (s, 18H; *t*-Bu), 1.63 (m, $^3J_{HH}$ = 7.7 Hz, 2H; $CH_2CH_2CH_2CH_3$), 1.85 (m, $^3J_{HH}$ = 7.7 Hz, 2H; $CH_2CH_2CH_2CH_3$), 3.44 (d, $^2J_{HH}$ = 14 Hz, 2H; $CH_2$ eq), 3.50 (d, $^2J_{HH}$ = 14 Hz, 2H; $CH_2$ eq), 3.85 (t, $^3J_{HH}$ = 6.3 Hz, 1H; $CH_2CH_2CH_2CH_3$), 4.41 (d, $^2J_{HH}$ = 14 Hz, 2H; $CH_2$ ax), 4.61 (d, $^2J_{HH}$ = 14 Hz, 2H; $CH_2$ ax), 6.80 (s, 2H; ArH), 7.06 (s, 2H;

ArH), 7.11 (d, $^4J_{HH}$ = 2.2 Hz, 2H; ArH), 7.17 (d, $^4J_{HH}$ = 2.2 Hz, 2H; ArH); $^{31}$P NMR: $\delta$ = 106 (s, 1P; P(OR)$_3$); FD: *m*/*z* (%) 732(100).

***p-tert*-Butyl-calix[4]arene-25-acetoxy-26,27,28-phosphite (up-up-out-down) (8).** Method A. Yield 1.14 g (1.59 mmol, 72%); mp = 260 °C; $^1$H NMR: $\delta$ = 1.20 (s, 9H; *t*-Bu), 1.30 (s, 9H; *t*-Bu), 1.37 (s, 18H; *t*-Bu), 2.16 (s, 3H; OC(O)CH$_3$), 3.63 (d, $^2J_{HH}$ = 15 Hz, 2H; CH$_2$ eq), 3.65 (d, $^2J_{HH}$ = 16.4 Hz, 2H; CH$_2$ eq), 4.09 (d, $^2J_{HH}$ = 15 Hz, 2H; CH$_2$ ax), 4.32 (d, $^2J_{HH}$ = 16.4 Hz, 2H; CH$_2$ ax), 7.13-7.21 (m, 8H; ArH); $^{13}$C NMR: $\delta$ = 20.8 (s; *C*H$_3$), 31.2, 31.3, 31.4 (s; C(*C*H$_3$)$_3$), 34.1, 34.1, 34.2 (s; *C*(CH$_3$)$_3$), 34.3, 36.9 (s; *C*H$_2$), 125.1, 125.4, 125.9, 126.1, 126.3, 126.5, 128.0, 128.8 (s; Ar*C*H), 129.8, 131.9, 149.0 (3 × d, $J_{PC}$ = 2.3 Hz; Ar*C*), 133.2, 145.6 (2 × d, $J_{PC}$ = 3.0 Hz; Ar*C*), 133.7, 146.0 (2 × d, $J_{PC}$ = 3.8 Hz; Ar*C*), 146.4, 146.7 (s; Ar*C*), 169.9 (s; O*C*(O)CH$_3$); $^{31}$P NMR: $\delta$ = 116 (s, 1P; P(OR)$_3$); IR(KBr): $\nu$(cm$^{-1}$) 3024 (C–H arom.); 2962, 2904, 2869 (C–H aliph.); 1754 (C=O); 1478 (C=C); 1227, 1170 (C–O–P); 1116, 1097 (C–O); FD: *m*/*z* (%) 718(100) [M$^+$]; Anal. Calcd. for $C_{46}H_{55}O_5P$: C, 76.85; H, 7.71. Found: C, 76.91; H, 8.21%.

***p-tert*-Butyl-calix[4]arene-25-benzoyloxy-26,27,28-phosphite (up-up-out-down) (9).** Method A. Yield 0.85 g (1.1 mmol, 87%); mp = 170 °C; $^1$H NMR: $\delta$ = 1.26 (s, 9H; *t*-Bu), 1.28 (s, 18H; *t*-Bu), 1.35 (s, 9H; *t*-Bu), 3.64 (d, $^2J_{HH}$ = 16.0 Hz, 2H; CH$_2$ eq), 3.66 (d, $^2J_{HH}$ = 15.4 Hz, 2H; CH$_2$ eq), 4.09 (d, $^2J_{HH}$ = 15.4 Hz, 2H; CH$_2$ ax), 4.38 (d, $^2J_{HH}$ = 16.0 Hz, 2H; CH$_2$ ax), 7.09 (broad s, 2H; ArH), 7.16 (broad s, 2H; ArH), 7.19 (s, 2H; ArH), 7.24 (s, 2H; ArH), 7.41 (t, $^2J_{HH}$ = 7.4 Hz, 1H; ArH), 7.78 (d, $^2J_{HH}$ = 7.2 Hz, 2H; ArH) ; $^{13}$C NMR: $\delta$ = 31.2, 31.2, 31.5 (s; *C*H$_3$), 33.9, 34.2, 34.3 (s; *C*(CH$_3$)$_3$), 35.0, 36.6 (s; *C*H$_2$), 124.9, 125.6, 126.3, 127.9, 132.8 (s; Ar*C*H), 130.1 (d, $J$ = 3.8 Hz; Ar*C*H), 129.0, 131.8, 144.5, 146.3, 146.4, 147.0, 149.1 (s; Ar*C*), 133.2 (d, $J_{PC}$ = 3.0 Hz; Ar*C*), 133.3 (d, $J_{PC}$ = 3.8 Hz; Ar*C*), 164.6 (s; O*C*(O)C$_6$H$_5$); $^{31}$P NMR: $\delta$ = 114 (s, 1P; P(OR)$_3$); IR(KBr): $\nu$(cm$^{-1}$) 3054 (C–H arom.); 2930, 2903, 2869 (C–H aliph.); 1735 (C=O); 1478 (C=C); 1267, 1174 (C–O); 1106 (C–O–P); FD: *m*/*z* (%) 780(100) [M$^+$]; Anal. Calcd. for $C_{51}H_{57}O_5P$: C, 78.43; H, 7.36. Found: C, 78.60; H, 7.95%.

***p-tert*-Butyl-calix[4]arene-25-hydroxy-26-benzyloxy-27,28-*N*,*N*-dimethyl phosphorus amidite (12).** Side product formed using method B. $^1$H NMR: $\delta$ = 0.95 (s, 9H; *t*-Bu), 1.24 (s, 9H; *t*-Bu), 1.31 (s, 9H; *t*-Bu), 1.41 (s, 9H; *t*-Bu), 1.88 (d, $^3J_{PH}$ = 9 Hz, 6H; N(C*H*$_3$)$_2$), 3.34 (d, $^2J_{HH}$ = 13.0 Hz, 1H; CH$_2$), 3.43 (d, $^2J_{HH}$ = 12.2 Hz, 1H; CH$_2$), 3.77 (d, $^2J_{HH}$ = 13.0 Hz, 1H; CH$_2$), 3.88 (d, $^2J_{HH}$ = 16.8 Hz, 1H; CH$_2$), 3.97 (d, $^2J_{HH}$ = 17.2 Hz, 1H; CH$_2$), 4.05 (d, $^2J_{HH}$ = 16.8 Hz, 1H; CH$_2$), 4.22 (d, $^2J_{HH}$ = 17.2 Hz, 1H; CH$_2$), 4.43 (d, $^2J_{HH}$ = 11.7 Hz, 1H; CH$_2$), 4.52 (dd, $^2J_{HH}$ = 12.1 Hz, $J$ = 2.43 Hz, 1H; CH$_2$), 4.84 (d, $^2J_{HH}$ = 11.7 Hz, 1H; CH$_2$), 6.16–6.20 (m, 3H; ArH), 6.90–7.35 (m, 10H; ArH); $^{13}$C NMR: $\delta$ = 30.8, 31.1, 31.4, 31.4 (s; C(*C*H$_3$)$_3$), 33.5, 33.6, 33.9 (s; *C*(CH$_3$)$_3$), 31.6, 34.7, 38.7, 38.9 (s; *C*H$_2$), 34.4, 34.7 (d, $^2J_{PC}$ = 23 Hz; N(*C*H$_3$)$_2$), 74.6 (s; O*C*H$_2$(C$_6$H$_5$)), 123.1, 124.0, 124.7, 125.6, 125.7, 126.0, 126.6, 127.2, 127.8, 128.0 (s; Ar*C*H), 129.5, 131.8, 132.2, 134.2, 134.6, 135.4, 137.1, 147.8, 148.3, 151.4 (d; Ar*C*), 135.7, 142.0, 145.4, 145.8, 147.2 (s; Ar*C*); $^{31}$P NMR: $\delta$ = 138 (septet, $^3J_{PH}$ = 9 Hz, 1P; P(OR)$_2$(N(CH$_3$)$_2$)); IR(KBr): $\nu$(cm$^{-1}$) 3380 (O-H); 3042 (C–H arom.); 2962, 2900, 2864 (C–H aliph.); 1474 (C=C); 1295, 1123 (C–O–P); 982 (C–O); FAB: *m*/*z* calcd. for $C_{53}H_{67}O_4NP$ [M + H]$^+$: 812.4808. Found: 812.4797.

***p-tert*-Butyl-calix[4]arene-25,26-dihydroxy-27,28-(H-phosphonate) (13).** Yield 4.17 g (6 mmol, 60%); because the product probably contained small amounts of water and triflic acid salts no correct microanalytical data could be obtained; mp = 220 °C; $^1$H NMR: $\delta$ = 1.20 (s, 18H; *t*-Bu), 1.28 (s, 18H; *t*-Bu), 3.41 (d, $^2J_{HH}$ = 14.5 Hz, 2H; CH$_2$ eq), 3.52 (d, $^2J_{HH}$ = 15.2 Hz, 1H; CH$_2$ eq), 3.80 (d, $^2J_{HH}$ =14.5 Hz, 1H; CH$_2$ eq), 4.03 (d, $^2J_{HH}$ = 14.5 Hz, 1H; CH$_2$ ax), 4.37 (d, $^2J_{HH}$ =14.5 Hz, 2H; CH$_2$ ax),4.47 (d, $^2J_{HH}$ = 15.2 Hz, 1H; CH$_2$ ax), 6.93 (d, $^4J_{HH}$ = 2 Hz, 2H; ArH), 7.02 (d, $^4J_{HH}$ = 2 Hz, 2H; ArH), 7.10 (d, $^4J_{HH}$ = 2 Hz, 2H; ArH), 7.16 (d, $^4J_{HH}$ = 2 Hz, 2H; ArH); $^{13}$C NMR: $\delta$ = 31.2 (s; *C*H$_3$), 33.1, 35.2, 35.5 (s; *C*H$_2$), 33.7, 34.0 (s; *C*(CH$_3$)$_3$), 124.8, 125.5, 126.3, 126.9 (s; Ar*C*H), 126.0, 127.5, 129.5, 143.5, 147.7, 149.7 (s; Ar*C*), 131.5 (d, $J$ = 6 Hz; Ar*C*), 145.8 (d, $J$ = 11 Hz; Ar*C*); $^{31}$P NMR: $\delta$ = 1.3 (d, $^1J_{PH}$ = 794 Hz; 1P; HP(O)(OR)$_2$); IR(KBr): $\nu$(cm$^{-1}$) 3024 (C–H arom.); 2959, 2901, 2863 (C–H aliph.); 1476 (C=C); 1252 (P=O); 1195 (C–O–P); FAB$^+$: *m*/*z* (%) 695(100) [M$^+$].

### Crystal structure analysis of 4

$C_{51}H_{59}O_4P{\cdot}CH_2Cl_2$, $M_r$ = 767.0, triclinic, $P\bar{1}$, $a$ = 12.013(2), $b$ = 13.353(1), $c$ = 16.616(6) Å, $\alpha$ = 75.59(2), $\beta$ = 73.23(2), $\gamma$ = 67.61(1)°, $V$ = 2330(1) Å$^3$, $Z$ = 2, $D_x$ = 1.21 g cm$^{-3}$, $\lambda$(Cu-K$\alpha$) = 1.5418 Å, $\mu$(Cu-K$\alpha$) = 19.21 cm$^{-1}$, $F$(000) = 908, $T$ = 223 K. Final $R$ = 0.097 for 8336 observed reflections.

A crystal with approximate dimensions 0.40 × 0.40 × 0.50 mm was used for data collection on an Enraf-Nonius CAD-4 diffractometer with graphite-monochromated Cu-K$\alpha$ radiation and $\omega$–2$\theta$ scans. A total of 9560 unique reflections was measured within the range $0 \le h \le 15$, $-14 \le k \le 16$, $-19 \le l \le 20$. Of these, 8336 were above the significance level of 2.5 $\sigma(I)$. The range of (sin $\theta$)/$\lambda$ was 0.032–0.626 Å$^{-1}$ ($2.8 \le \theta \le 74.8°$). Two reference reflections (121, 204) were measured hourly and showed no decrease during the 130 h collecting time. Unit-cell parameters were refined by a least-squares fitting procedure using 23 reflections with $80 < 2\theta < 82°$. Corrections for Lorentz and polarisation effects were applied. Absorption correction was performed with the program ABSCAL[35] using $\psi$-scans of the 303 reflections, with coefficients in the range 1.00–1.14. The structure was solved by the PATTY option of the DIRDIF 94 program system.[36] After isotropic refinement of the initial model a $\Delta F$ synthesis revealed 3 peaks, which were interpreted as $CH_2Cl_2$, one of the solvents used during the crystallisation. The hydrogen atoms were fixed in calculated positions. Full-matrix least-squares refinement on $F$, anisotropic for the non-hydrogen atoms converged to $R$ = 0.097, $R_w$ = 0.094, $(\Delta/\sigma)_{max}$ = 0.67, $S$ = 0.844. A weighting scheme $w = [4.0 + 0.15(\sigma(F_o))^2 + 0.001/(\sigma(F_o))]^{-1}$ was used. The secondary isotropic extinction coefficient[37,38] refined to Ext = 0.16(1). A final difference Fourier map revealed a residual electron density between −1.4 and 1.0 e Å$^{-3}$ in the vicinity of the solvent molecule. The atoms of the *tert*-butyl moieties and the (chlorine)atoms of the solvent are rather anisotropic (C37, C42 and Cl2s are highly anisotropic). No attempts were made to split those atoms in order to get a better fit. Scattering factors were taken from Cromer and Mann.[39] The anomalous scattering of Cl and P was taken into account. All calculations were performed with XTAL, unless stated otherwise.[40]

### Crystal structure analysis of 5

$C_{51}H_{59}O_4P{\cdot}C_7H_8$, $M_r$ = 859.09, orthorhombic, *Pbca* (no. 61), $a$ = 17.900(3), $b$ = 21.4197(19), $c$ = 24.477(2) Å, $V$ = 9384.9(18) Å$^3$, $Z$ = 8, $\rho_c$ = 1.216 g cm$^{-3}$, $\mu$(Mo-K$\alpha$) = 0.11 mm$^{-1}$, $T$ = 150(2) K, (sin $\theta/\lambda)_{max}$ = 0.482 Å$^{-1}$, colourless block 0.25 × 0.25 × 0.38 mm, measured reflections: 8602, unique reflections: 4389 ($R_{int}$ = 0.11), $R$-values ($I > 2\sigma I$): $R1$ = 0.0755, $wR2$ = 0.1487, all data: $R1$ = 0.1543, $wR2$ = 0.1798. Diffractometer: Enraf-Nonius CAD4T with rotating anode. Mo-K$\alpha$ radiation ($\lambda$ = 0.71073 Å). Structure solution with direct methods (SIR-97[41]). Structure refinement with SHELXL-97[42] against $F^2$. 253 parameters, no restraints. Non-hydrogen atoms were refined freely with isotropic displacement parameters, hydrogen atoms were refined as rigid groups. No absorption correction was considered necessary. Structure graphics and

checking for higher symmetry were performed with the program PLATON.[43]

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See http://www.rsc.org/suppdata/dt/a9/a909103c/ for crystallographic files in .cif format.

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