Calix[4]arene-diphosphite rhodium complexes in *solvent-free* hydroaminovinylation of olefins†

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Received 11th May 2010, Accepted 14th July 2010
DOI: 10.1039/c0gc00098a

Under *solvent-free* conditions rhodium complexes containing hemispherical diphosphites based on a calix[4]arene skeleton catalyse efficiently the hydroaminovinylation of α-olefins, thereby leading to high proportions of linear enamines/amines (when starting from secondary amines) or imines (when starting from primary amines). When applying a Rh/olefin ratio of 1 : 5000, the reaction turned out to be *ca.* 15 times faster than when operating in toluene at the same Rh/olefin ratio and at an olefin concentration of 6.6 mol L^{-1}. For example, in the hydroaminovinylation of 1-octene with piperidine using 5,11,17,23-tetra-*tert*-butyl-25,27-dipropyloxy-26,28-bis(1,1′binaphthyl-2,2′dioxyphosphanyloxy)calix[4]arene, TOFs up to 4640 mol(converted olefin).mol(Rh)$^{-1}$.h^{-1} were observed (l/b ratio of 24.1).

Introduction

Olefin hydroaminovinylation is a valuable atom-economical domino reaction combining terminal alkene hydroformylation with *in situ* formation of enamine/imine, the firstly generated aldehyde reacting in a second step with an amine.[1,2] When carrying out the reaction with secondary amines, hydroaminovinylation is often followed by another reaction, namely the formation of amines through catalytic hydrogenation.[3–7] A current industrial challenge is to stop the reaction at the formation of the enamine.[8–12] It is worth mentioning here that the linear selectivity in enamine mainly depends upon the regioselectivty of the hydroformylation step.

Recently, we developed highly regioselective olefin hydroformylation catalysts based on hemispherical diphosphites constructed on a calix[4]arene skeleton (two examples of such ligands are shown in Fig. 1).[12,13] The high selectivities observed with these catalysts mainly rely on a combination of a wide ligand bite angle and the confinement of the catalytic centre in a tight molecular pocket. Both features favour formation of Rh-alkyl intermediates with a linear structure, so as to minimise the steric interactions between the alkyl ligand formed and the surrounding pocket. In other terms the ligand shapes the outcoming product. It should be remembered that the ability to envelope the catalytic centre is much more pronounced in the above hemispherical diphosphites than in other diphosphanes possessing a large bite angle, such as *e.g.* Transphos,[14] Bisbi,[15] Xantphos,[16,17] Triptiphos[18,19] as well as biphenol-based diphosphites.[20,21] Pursuing our efforts to develop environmentally friendly systems for olefin functionalisation,[22] we now describe the use of two neutral [Rh(acac)(1,3-calix-diphosphite)] complexes (Fig. 1) in *solvent-free* hydroaminovinylation of 1-octene and styrene. Remarkably, both complexes were found to be highly *soluble* in these olefins. This work complements a recent study in which we have shown that under such conditions these complexes act as efficient hydroformylation catalysts.[23] To our knowledge, only one example of *solvent-free* hydroaminovinylation has been reported in the literature.[24] The term "1,3-calix[4]arene-diphosphites" used in this study designates calix[4]arenes in which two distal phenolic oxygen atoms are substituted by a $P(OR)_2$ moiety.

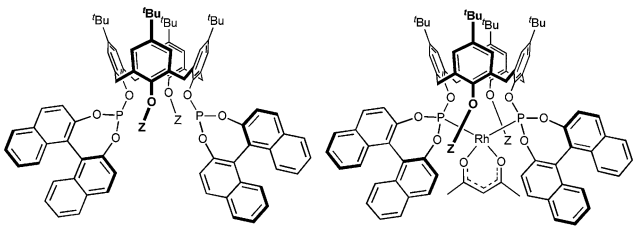

Fig. 1 Hemispherical ligands and rhodium complexes used in this study.

Results and discussion

Hydroaminovinylation with secondary amines

For the study concerning secondary amines, piperidine and dibutylamine were used. Each experiment was carried out in the presence of **3** or **4** and 9 equiv. of the corresponding diphosphite. All runs were performed under *solvent-free* conditions at 130 °C in a stainless steel autoclave, using an olefin/Rh ratio of 5000 : 1. The products which may form in these reactions are shown in Scheme 1.

We began the catalytic study by assessing complex **4** in the hydroaminovinylation of styrene with piperidine. Using a 1 : 1 CO/H_2 mixture and applying a pressure of 20 bar for 4 h

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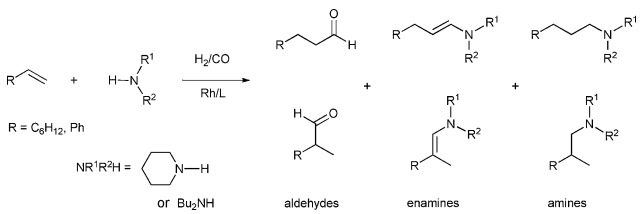
† Electronic supplementary information (ESI) available: Typical chromatograms obtained after hydroformylation and hydroaminovinylation experiments. See DOI: 10.1039/c0gc00098a

Table 1 Rhodium-catalysed hydroaminovinylation of styrene using complexes **3** and **4** in the presence of piperidine[a]

Entry	[Rh]	P(CO/H_2)/bar V(CO)/V(H_2)	Time/h	Conv. (%)	TOF[b]	Product distribution[c] Aldehydes (%) l:b	Enamines (%) l:b	Amines (%) l:b	PhEt (%)
Solvent-free reaction									
1	**4**	20 1/1	4	64.4	800	2.7 62.2 : 31.8	59.5 63.2 : 36.8	35.6 98.7 : 1.3	1.1
2	**4**	20 1/2	4	77.0	920	3.7 55.2 : 44.8	53.1 59.2 : 40.8	43.1 97.3 : 2.7	1.2
3	**4**	20 1/2	8	100	630	0.8 51.2 : 48.8	39.4 55.2 : 44.7	58.0 88.8 : 12.2	1.8
4	**3**	20 1/2	8	100	630	Traces	41.2 63.0 : 37.0	55.9 80.6 : 19.4	2.9
5	**3**	10 1/1	4	68.8	860	7.7 73.8 : 26.2	52.0 82.8 : 17.2	39.9 84.0 : 16.0	0.4
6	**4**	10 1/1	4	60.7	760	8.4 65.8 : 34.2	57.7 85.2 : 24.8	33.7 96.4 : 3.6	0.2
Reaction in toluene (20 mL), 130 °C									
7	**4**	20 1/2	4	48.5	610	5.1 81.9 : 18.1	14.9 85.1 : 14.9	13.3 87.4 : 12.6	15.2
Reaction in cyclohexane (20 mL), 100 °C									
8	**4**	20 1/2	4	62.2	780	4.8 76.4 : 23.6	30.3 93.3 : 6.7	2.4 100:traces	24.7
Reaction in THF (20 mL), 85 °C									
9	**4**	20 1/2	4	0.8	10	/	/	/	0.8

[a] Styrene (10 mmol), amine (12 mmol), [Rh] (2 μmol, styrene/Rh = 5000), ligand (18 μmol), 130 °C. [b] Mol(converted styrene).mol(Rh)$^{-1}$.h^{-1}. [c] Determined by GC using decane (0.5 mL) as standard and ^{1}H NMR spectroscopy.



Scheme 1 Rhodium-catalyzed hydroaminovinylation of α-olefins.

produced the corresponding enamines and amines in 59.5% and 35.6%, respectively (Table 1, entry 1). As expected, the proportion of linear product increased in the order aldehyde < enamine < amine, this variation corresponding to the higher reactivity of the linear product both in the condensation with amine and in the hydrogenation step. Increasing the partial pressure of hydrogen by 33% and doubling the reaction time raised both the conversion and the proportion of amines (58.0%, Table 1, entry 3), the latter consisting then of 88.8% of linear product. As previously observed in styrene hydroformylation experiments carried out either in toluene or water,[12,22] replacement of the benzyl substituents of **4** by propyl groups (leading to **3**), resulted in lower proportions of linear products (Table 1, entry 4), as a consequence of a somewhat wider pocket surrounding the catalytic centre. Reducing the CO/H_2 pressure to 10 bar and applying a CO/H_2 mixture of 1 : 1 for 4 h led, for both complexes, to an increase of the enamine and a decrease of the amine proportion (Table 1, entries 5 and 6). For example, using **4** gave 57.7% of enamines, 33.7% of amines, the corresponding linear selectivities being 85.2% and 96.4%, respectively. It is worth mentioning here that carrying out the hydroaminovinylation reactions in toluene or cyclohexane gave lower conversions, the linear selectivities remaining high (Table 1, entries 7 and 8). We further observed that under these conditions, high proportions of ethylbenzene were produced. The catalyst showed no hydroformylation activity when THF was used (Table 1, entry 9).

Repeating the above reactions with the slightly more basic dibutylamine increased the enamine hydrogenation rate and therefore led to a lower proportion of enamines (Table 2). Complex **4**, for example, gave 29.9% of enamines with a regioselectivity towards the linear product of 89.8% (Table 2, entry 4).

In a second series of reactions, 1-octene was subjected to hydroaminovinylation with piperidine and dibutylamine. For both diphosphites, the proportion of enamines was higher with piperidine than with dibutylamine (Table 3, entries 3,7 and 4,8). This result can again be explained by the different reactivities towards hydrogenation of the enamines generated,

Table 2 Solvent-free rhodium-catalysed hydroaminovinylation of styrene using the rhodium complexes **3** and **4** in the presence of dibutylamine[a]

Entry	[Rh]	P(CO/H_2)/bar V(CO)/V(H_2)	Time/h	Conv. (%)	TOF[b]	Product distribution Aldehydes (%) l:b	Enamines (%) l:b	Amines (%) l:b	PhEt (%)
1	**3**	20 1/2	4	98.1	610	5.7 62.1 : 37.9	13.7 66.4 : 33.6	79.7 75.7 : 24.3	0.9
2	**4**	20 1/2	4	100	630	4.5 61.2 : 38.8	23.8 69.2 : 30.8	71.7 79.3 : 20.7	0.6
3	**3**	10 1/1	4	89.9	1120	2.2 82.3 : 17.7	22.4 81.7 : 18.3	75.1 86.4 : 13.6	0.3
4	**4**	10 1/1	4	87.7	1100	7.7 84.0 : 16.0	29.9 89.8 : 10.2	62.1 90.9 : 9.1	0.3

[a] Styrene (10 mmol), amine (12 mmol), [Rh] (2 μmol, styrene/Rh = 5000), ligand (18 μmol), 130 °C. [b] Mol(converted styrene).mol(Rh)$^{-1}$.h^{-1}. [c] Determined by GC using decane (0.5 mL) as standard and ^{1}H NMR spectroscopy.

Table 3 Solvent-free rhodium-catalysed hydroaminovinylation of 1-octene using complexes **3** and **4**[a]

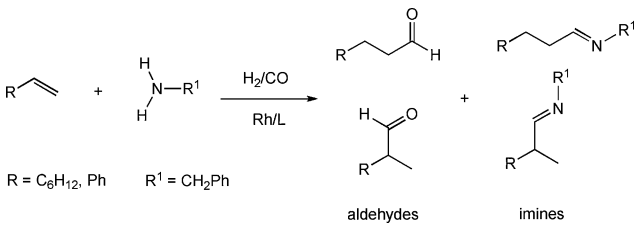
						Product distribution[c]			
Entry	[Rh]	V(CO)/V(H_2)	Time/h	Conv. (%)	TOF[b]	Aldehydes (%) (l/b)	Enamines (%) (l/b)	Amines (%) (l/b)	Isomer (%)
Piperidine									
1	**3**	1/1	1	92.9	4640	7.9 (15.2)	68.7 (24.2)	11.4 (43.8)	12.0
2	**4**	1/1	1	78.0	3900	0.2 (nd)	75.1 (25.0)	8.9 (56.3)	15.8
3	**3**	1/2	4	98.5	1230	3.3 (11.7)	48.3 (22.8)	36.1 (37.1)	12.3
4	**4**	1/2	4	89.4	1120	5.1 (17.5)	47.2 (23.5)	29.6 (40.4)	18.1
Dibutylamine									
5	**3**	1/1	1	86.7	4340	2.5 (2.8)	75.1 (28.9)	8.8 (39.8)	13.6
6	**4**	1/1	1	89.7	4490	0.7 (nd)	74.8 (30.9)	10.1 (41.4)	14.4
7	**3**	1/2	4	98.1	1230	2.5 (3.0)	28.9 (20.8)	54.5 (12.5)	14.1
8	**4**	1/2	4	98.7	1230	2.8 (4.4)	42.1 (24.8)	37.9 (15.5)	17.2
9	**4**	1/1	4	97.5	1220	3.0 (4.6)	57.9 (28.9)	17.8 (29.5)	21.3

[a] 1-Octene (10 mmol), amine (12 mmol), [Rh] (2 μmol, 1-octene/Rh = 5000), ligand (18 μmol), P(CO/H_2) = 20 bar, 130 °C. [b] Mol(converted 1-octene).mol(Rh)$^{-1}$.h^{-1}. [c] Determined by GC using decane (0.5 mL) as standard and ^{1}H NMR spectroscopy.

the enamine formed with piperidine being somewhat more difficult to hydrogenate than the one formed with dibutylamine. On the other hand, decreasing the partial pressure of hydrogen reduced, as expected, the rate of hydrogenation, hence leading to a higher proportion of enamines. For example, with dibutylamine and complex **4** (4 h run) the proportion of enamines increased from 42.1% to 57.9% when the CO/H_2 ratio passed from 1 : 2 to 1 : 1 (Table 3, entries 8 and 9). By reducing the reaction time from 4 h to 1 h, the proportion of enamines increased to 74.8% (Table 3, 6). The highest linear enamine selectivity ($CO : H_2 = 1 : 1$) was obtained with diphosphite **2**, the linear/branched ratios being then 25.0 and 30.9 with piperidine and dibutylamine, respectively. In these latter experiments, the corresponding proportions of enamine were 75.1% (piperidine) and 74.8% (dibutylamine) (Table 3, entries 2 and 6).

Hydroaminovinylation with secondary amines (formation of imines)

Primary amines are known to react with aldehydes thereby forming imines. Since the hydrogenation of imines with rhodium is unfavourable, we anticipated that carrying out the hydroaminovinylation with a primary amine would selectively produce imines (Scheme 2). The following investigations, in which benzylamine was employed, were again performed under *solvent-free* conditions.



Scheme 2 Formation of imines *via* tandem reactions.

Our expectations were first confirmed with styrene. Thus, in a typical run carried out with complex **4** at a pressure of 20 bar ($CO/H_2 = 1 : 2$), styrene was fully converted into *N*-benzylimines within 8 h, no trace of amine being detected. The linear imine selectivity was 82.1% (Table 4, entry 2). Reducing the pressure to 10 bar and using a 1 : 1 CO/H_2 mixture only slightly increased the proportion of linear imine (85.1% with complex **4**; Table 4, entry 4). Consistent with the observations previously made for these ligands in hydroformylation studies,[23] the highest TOF,

Table 4 Solvent-free rhodium-catalysed formation of imines using the rhodium complexes **3** and **4**[a]

						Product distribution[c]		
Entry	[Rh]	P(CO/H_2)/bar V(CO)/V(H_2)	Time/h	Conv. (%)	TOF[b]	Aldehydes (%)	Imines (%) l% : b% = *l*/b	Isomer (%)
Styrene								
1	**3**	20 (1/2)	8	99.6	620	Traces	100 76.9 : 33.1 = 2.3	/
2	**4**	20 (1/2)	8	99.6	620	Traces	100 82.1 : 21.9 = 3.7	/
3	**3**	10 (1/1)	4	98.6	1230	Traces	100 81.3 : 18.7 = 4.3	/
4	**4**	10 (1/1)	4	92.1	1180	Traces	100 85.1 : 14.9 = 5.7	/
1-Octene								
5	**3**	20 (1/1)	1	88.7	4440	1.7	83.7 95.5 : 4.5 = 21.4	14.6
6	**4**	20 (1/1)	1	89.1	4450	1.3	83.2 96.9 : 3.1 = 30.9	15.5
7	**3**	20 (1/2)	4	99.5	1240	2.2	81.8 91.3 : 8.7 = 10.8	16.0
8	**4**	20 (1/2)	4	96.7	1210	1.5	82.2 92.2 : 7.8 = 11.9	16.3

[a] Olefin (10 mmol), H_2NBn (12 mmol), [Rh] (2 μmol, styrene/Rh = 5000), ligand (18 μmol), 130 °C. [b] Mol(converted olefin).mol(Rh)$^{-1}$.h^{-1}. [c] Determined by GC using decane (0.5 mL) as standard and ^{1}H NMR spectroscopy.

1230 mol(converted styrene).mol(Rh)$^{-1}$.h^{-1}, was obtained with complex **3** (corresponding to a conversion of 98.6%; Table 4, entry 3).

Performing the hydroaminovinylation with 1-octene (20 bar; CO/H_2 = 1 : 1) led to conversions of 88.7% (complex **3**) and 89.1% (complex **4**), respectively, after 1 h reaction time. As in the case of styrene, no amine was produced. We noted that the activities (TOF = 4440 (**3**) and 4450 (**4**) mol(converted 1-octene).mol(Rh)$^{-1}$.h^{-1}) were *ca.* 4 times higher than those obtained with styrene. The linear imine selectivities (l/*b* = 21.4 (**3**); l/*b* = 30.9 (**4**); Table 4, entries 5 and 6) compare with those observed for the enamines obtained in the reactions with piperidine and dibutylamine (see above). Increasing the reaction time and the partial pressure of hydrogen led to lower l/*b* ratios. It is well known that higher hydrogen pressures favour formation of internal octenes, which then may lead to branched imines, so as to result in a regioselectivity decrease (Table 4, entries 7 and 8).

Conclusion

In conclusion, the results outlined in this study show that *solvent-free* conditions do not modify the linear product selectivities obtained with "Rh(1,3-calix-diphosphite)" catalysts with respect to those obtained when carrying out the reaction in toluene.[12] Remarkably, the *solvent-free* conditions led to a considerable activity increase of the calix-diphosphite complexes, both catalysts converting the substrates about 15 times faster than in the presence of solvent, as a result of a higher olefin concentration. Although these conditions led to a drop in enamine selectivity of *ca*. 20%, the proportion of isolable enamine remains satisfactory for an industrial process. Overall, the *solvent-free* conditions are particularly adapted to a selective production of linear imines from primary amines. Finally this study also constitutes a rare illustration of the potential of hydroformylation catalysts that are soluble in the usual olefins.

Experimental

General methods

All syntheses were performed in Schlenk-type flasks under dry nitrogen. Solvents were dried by conventional methods and were distilled immediately prior to use. Routine ^{1}H NMR spectra were recorded by using a Bruker AVANCE 300. ^{1}H NMR spectra were referenced to residual protonated solvents (7.26 ppm for $CDCl_3$). The catalytic solutions were analysed by using a Varian 3900 gas chromatograph equipped with a WCOT fused-silica column (25 m × 0.25 mm). The "1,3-calix-diphosphites" **1** and **2** and the [Rh(acac)(1,3-calix-diphosphite)] complexes **3** and **4** were prepared according to literature procedures.[12]

General procedure for the hydroaminovinylation experiments

The hydroaminovinylation experiments were carried out in a glass-lined, 100 mL stainless steel autoclave containing a magnetic stirring bar. In a typical run, the autoclave was charged under nitrogen with [Rh(acac)(1,3-calix-diphosphite)] (0.002 mmol), the corresponding "1,3-calix-diphosphite", olefin (10 mmol), amine (12 mmol) and the internal standard (decane, V = 0.5 mL). Once closed, the autoclave was flushed twice with syngas (CO/H_2 1 : 1 v/v), pressurised with the appropriate CO/H_2 mixture and heated. At the end of each run, the autoclave was cooled to room temperature before being depressurised. A sample was taken and analysed by GC and ^{1}H NMR.

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