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Tetrahedron
Tetrahedron 61 (2005) 9799–9807

Asymmetric styrene dimerisation using mixed palladium–indium catalysts

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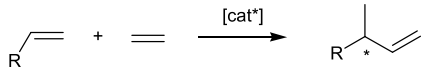
Received 12 May 2005; revised 10 June 2005; accepted 24 June 2005

Available online 18 July 2005

Abstract—Catalysts formed in situ from mixtures of palladium acetate, indium(III) triflate and a chiral non-chelating bis(phosphite) ligand give good to excellent conversions and reasonable enantioselectivity in the asymmetric dimerisation of styrenes.

1. Introduction

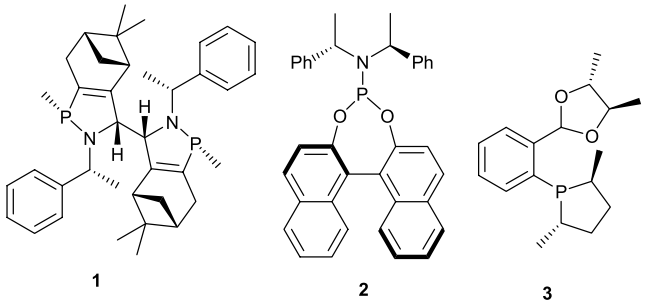
The asymmetric hetero-dimerisation of α-olefins with ethene (Eq. 1)—the asymmetric hydrovinylation reaction—is a well studied and topical area of research.[1,2] It provides access to chiral building-blocks from simple, cheap precursors with 100% atom economy; that is to say that all the atoms of all the starting material are incorporated into the product.



(1)

Typically, the most active and selective catalysts for this class of reaction are nickel based with appropriate chiral ligands.[1] Ligands **1**–**3** are amongst the best ligands yet reported, giving high activities and good to excellent enantioselectivities. The original benchmark was set by Wilke and co-workers who introduced the bis(azaphospholene) ligand **1**, which shows excellent activity and stereoselectivity.[3] Not only does this ligand perform well in classical media, but Leitner and co-workers demonstrated that catalysts containing **1** can be used in super-critical CO_2.[4] Leitner's group has also shown that phosphoramidite ligands such as ligand **2**, introduced by Ferringa and co-workers,[5] are remarkably active and selective.[6] Rajan-Babu and co-workers have extensively investigated the use of a range of chiral monodentate phosphines with secondary hemi-labile functions.[2e] One such ligand—ligand **3**—proves to be particularly effective in the asymmetric hydrovinylation of challenging substrates such as 4-isobutylstyrene.[2b,c]

Chiral palladium catalysts can also be exploited, however, their use is sometimes hampered by the deleterious isomerisation of the desired chiral products to non-chiral internal alkenes.[2a,7]



In contrast with hydrovinylation, the related asymmetric homo-dimerisation of alkenes has been somewhat under-investigated. One example of this class of reaction, which has been explored to a limited extent is the intramolecular cycloisomerisation of 1,6-dienes.[8] Recently, Leitner and co-workers demonstrated that nickel catalysts with appropriate chiral phosphoramidite or azaphospholene ligands could give the *exo*-methylene carbocycle **4** in high regioselectivity and good enantioselectivity from diethyl diallylmalonate (Eq. 2).[9]

Keywords: Palladium; Indium; Catalysis; Styrene; Dimerisation; Hydrovinylation.
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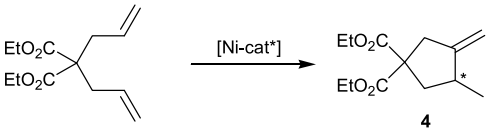
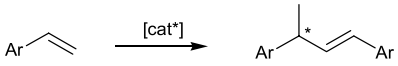
doi:10.1016/j.tet.2005.06.083



4 (2)

Intermolecular asymmetric alkene dimerisation reactions remain rare. One example of a non-selective reaction that is potentially amenable to the development of an enantioselective version is the dimerisation of styrenes (Eq. 3). RajanBabu and co-workers found that when a typical nickel catalyst system is used—[{NiBr(η^3-allyl)}$_2$]/PPh_3/AgOTf—poor conversion to the dimer is obtained, along with substantial formation of polystyrene.[2e] In contrast, palladium catalysts appear far more attractive; Shirakawa and co-workers demonstrated that a catalyst formed in situ from palladium acetate, triphenylphosphine and indium triflate is particularly effective.[10] We were interested to see whether an asymmetric version of this reaction could be realised, and we now report that mixed palladium–indium systems containing non-chelating chiral bis(phosphites) show considerable promise.

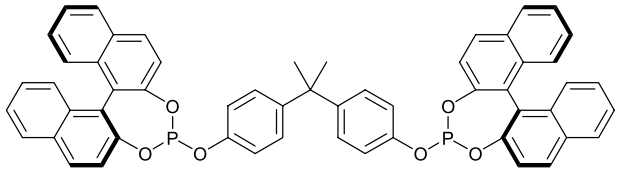


(3)

2. Results and discussion

2.1. Synthesis of ligands

The chiral non-chelating bis(phosphite) ligand **5** was shown by Faraone and co-workers to furnish the dimetallamacrocycles **6** and **7**.[11] We reasoned that any bimetallic asymmetric activation of styrene may be best served by such structural types and therefore, synthesized the analogous ligands **8** and **9**.



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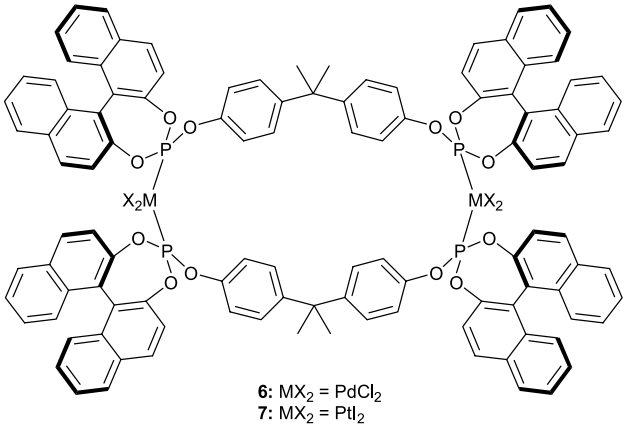


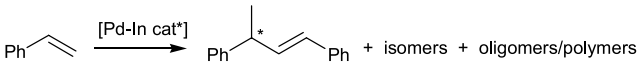
6: $MX_2 = PdCl_2$
7: $MX_2 = PtI_2$

These ligands were prepared by the reaction of the phosphine chloride **10**, derived from (*S*)-BINOL, with the bis-phenols **11a** and **b**, respectively, in the presence of triethylamine (Scheme 1). Ligand **9** could also be prepared by the reaction of the bis(chlorophosphite) **12a** with (*S*)-BINOL in the presence of triethylamine. The analogous reaction with the bulkier analogue **12b** proved unsuccessful. The compounds **12** were synthesised from the appropriate diols **11b** and **c** and PCl_3 in the presence of triethylamine.

The ^{31}P NMR spectrum for the ligand **8** shows a singlet at δ 145.6 ppm, very close to that reported for ligand **5** (δ 144.8 ppm, C_6D_6).[11] The ^{1}H NMR spectrum shows distinctive signals for the cyclohexyl ring in addition to resonances for the aromatic protons. The ^{31}P NMR spectrum of ligand **9** shows a singlet at δ 149.3 ppm, a little down-field of those for **8** and **5**, presumably due to the presence of the *ortho*-methyl groups. As well as aromatic signals, the ^{1}H NMR spectrum of ligand **8** shows two methyl signals at 1.44 and 2.28 corresponding to the xylyl and bridgehead methyl groups, respectively.

2.2. Catalysis

The reaction chosen for the optimisation studies was the dimerisation of unsubstituted styrene (Eq. 4).



13a (4)

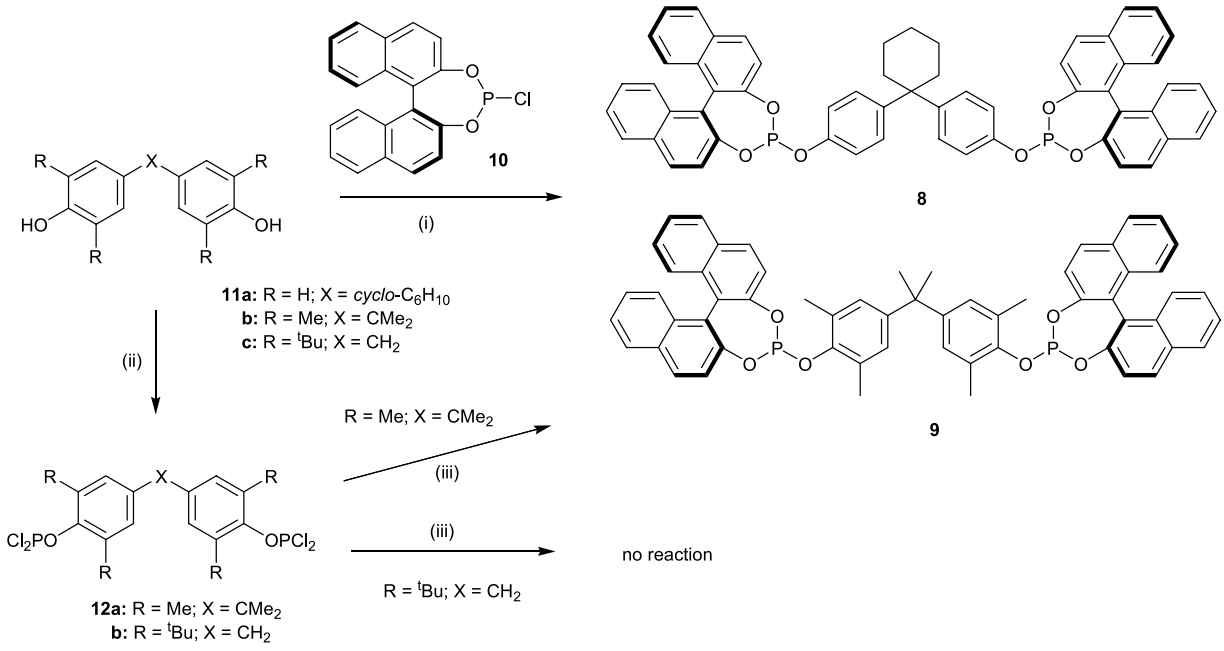
We initially performed a brief solvent optimisation study using ligand **9**, the results of which are summarised in Table 1. The use of 1,4-dioxane gives excellent yield and selectivity for the desired product dimer *E*-**13a** as well as moderate enantioselectivity. Dichloromethane, DME and THF give lower conversions and poorer selectivity for the desired product versus isomerisation and/or oligomerisation products. No reaction was observed in the absence of solvent. Having established that the best results are obtained in the dimerisation with dioxane as solvent, this was then used for the rest of the studies.

The effect of varying the ratios of palladium, indium and ligand **9** was examined next and the results are summarised in Table 2. At 1 mol% loading of palladium and ligand **9**, in the absence of indium triflate, no activity is observed (Table 2, entry 1), implying either that the active catalyst is a heterobimetallic species or that the indium triflate is

Table 1. Solvent optimisation

Entry	Solvent	Conversion, %[a]	Yield of **13a**, %[b]	ee %[c]
1	1,4-Dioxane	>99	99	30
2	Dichloromethane[d]	90	68	23
3	DME	82	57	22
4	THF	70	45.5	18
5	No solvent[e]	0	0	–

Conditions: $Pd(OAc)_2$ (1.0 mol%), $In(OTf)_3$ (5 mol%), ligand **9** (1.0 mol%), styrene (4.36 mmol), solvent (5 ml), rt, 18 h.
[a] Conversion of styrene determined by GC (hexadecane internal standard).
[b] Determined by GC (hexadecane internal standard).
[c] Determined by HPLC.
[d] Ligand **9** (0.5 mol%), 2.5 mol% $In(OTf)_3$.
[e] Ligand **9** (0.5 mol%).



Scheme 1. Conditions: (i) Et_3N, toluene, −40–90 °C, 18 h; (ii) PCl_3, Et_3N, toluene, −40 °C–rt, 18 h; (iii) (*S*)-BINOL, Et_3N, toluene, −40 °C–rt, 18 h.

required as a catalyst activator. By 0.5 mol% indium loading, good activity is seen (entry 3). Holding the loadings of palladium and ligand **9** at 1 mol% and increasing the amount of indium triflate leads to an increase in stereoselectivity to a maximum of 37% at 2.5 mol% loading (entry 5). Further, increasing the amount of indium leads to an increase in activity (entries 6–8) but this is sometimes offset by concomitant erosion in enantioselectivity. It may be imagined that this is due to a competing dimerisation mediated by the indium triflate. Indeed, when the reaction is repeated in the absence of palladium acetate (entry 9), small amounts of dimer **13a** are produced as a racemic mixture. By contrast, in the absence of the ligand **9**, indium triflate does not give any dimer **13a** (entry 10). Some conversion to the dimer **13a** is seen using a palladium–indium mixture in the absence of the phosphite ligand (entry 11).

The data obtained are consistent with a heterobimetallic active catalyst, but do such species form in the presence of ligand **9**? A ^{31}P NMR spectrum of a 2.3:1 mixture of ligand **9** and indium triflate in 1,4-dioxane/$CDCl_3$ (3:1) shows a very broad peak centred around δ 2 ppm demonstrating that the phosphite donor is perfectly capable of coordinating to the indium centre. The broadening of the peak is due to the quadrupolar nature of indium (96% $I=9/2$). This is very similar to the ^{31}P spectroscopic data reported for $[In(OTf)_3\{P(O^iPr\}_3]$, which shows a broad peak at 6.6 ppm.[12] In addition a sharp peak is seen at δ −1.5 ppm (as well as minor peaks at 21.88, 41.66 and 56.30 ppm) possibly corresponding to a hydrolysed species.

The spectrum of a 1:1 mixture of palladium acetate and ligand **9** in dioxane/$CDCl_3$ (3:1) shows two major peaks at δ 98.71 and 99.05 as well as smaller peaks at 164.43, 102.03 and −2.23 ppm. The peaks between 98 and 103 ppm are consistent with the formation of simple phosphite adducts of Pd(II). The smaller, downfield shift we very tentatively assign as a palladacycle resulting from C–H activation of one of the *ortho*-methyl groups of the ligand by the palladium acetate,[13] whilst the high field resonance is presumably due to hydrolysis of the ligand. Mixing palladium acetate, indium triflate and ligand **9** in a 1:2.3:1

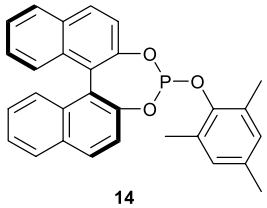
Table 2. Effect of varying relative ratios of Pd/In/ligand

Entry	Pd mol%	$In(OTf)_3$ mol%	Ligand **9** mol%	Conversion, %[a]	Yield of **13a**, %[b]	ee %[c]
1	1	0	1	<1	<1	nd
2	1	0.1	1	9	9	14 (*R*)
3	1	0.5	1	87	81	28 (*R*)
4	1	1	1	80	80	32 (*R*)
5	1	2.5	1	75	75	37 (*R*)
6	1	3	1	87	87	31 (*R*)
7	1	5	1	>99	>99	30 (*R*)
8	1	10	1	75	43	35 (*R*)
9	0	2.5	1	24	8	0
10	0	5	0	55	0	—
11	1	2.5	0	55	15	—

Conditions: styrene (4.36 mmol), dioxane (5 ml), rt, 18 h.
[a] Conversion of styrene determined by GC (hexadecane internal standard).
[b] Determined by GC (hexadecane internal standard).
[c] Determined by HPLC.

ratio in dioxane/$CDCl_3$ (3:1) led to immediate and substantial precipitation. A ^{31}P NMR spectrum of this mixture at a reaction time of 1.5 h shows a broad peak centred around δ 164 ppm, a smaller broad peak at 126 ppm and a third at around -3 ppm (major species). The high-field shift is again probably due to hydrolysis of the ligand but we are not able to completely rule out the possibility that it may be an indium–phosphite species, due to the broad nature of the peak. When the reaction is left longer (hours) the precipitate dissolves and the ^{31}P NMR shows only one sharp peak at -2.0 ppm. When the reaction is performed in $CDCl_3$, the precipitate is not observed and the ^{31}P NMR spectrum recorded within 45 min shows only the broad peak at 165 ppm and a sharp peak at -1.99 ppm (major species). Again, over the course of several hours, the ^{31}P spectrum reveals complete hydrolysis.

Taken together, the spectroscopic data show that palladium competes effectively with indium triflate for the ligand **9** with little or no evidence for the formation of indium–phosphite complexes in the presence of palladium. It is also apparent that the hydrolysis of the ligand **9** is relatively facile in the presence of either indium triflate or palladium acetate. The reaction of the model ligand **14** with palladium acetate (1:1, toluene, rt) again leads to the formation of a small amount of a compound tentatively assigned as a palladacycle formed by C–H activation of an *ortho*-methyl group as well as substantial amounts (major compound) of hydrolysis product.



14

If the indium triflate, either free or complexed with ligand **9**, plays a role in enantiodiscrimination then it may be imagined that the use of a chiral indium analogue would have an influence on the enantioselectivity of the reaction. This could be either positive or deleterious, depending on diastereomeric matching or mis-matching. BINOL-modified indium species, formed in situ from (*S*)-BINOL and $InCl_3$ give good to excellent enantioselectivity in allylation of aldehydes with allyl tin reagents.[14] Therefore, $In(OTf)_3$ was pre-treated with (*S*)-BINOL in 1,4-dioxane and the resultant mixture was used in the dimerisation of styrene with palladium acetate and ligand **9**. Surprisingly the results from this experiment (Table 3, entry 2) do not show particularly significant deviation from those obtained in a control experiment performed in the absence of the BINOL (entry 1). It is possible that the triflic acid produced in the reaction of BINOL with indium triflate provides an alternative activation pathway that coincidently gives similar performance/activity to the non-BINOL modified catalyst system. In order to test this, anhydrous triflic acid was used in place of indium triflate in the standard reaction (entry 3). Conversion remains high but selectivity for the desired dimer is substantially reduced, as is enantioselectivity. Interestingly, when triflic anhydride is used in place of triflic acid (entry 4) then the opposite enantiomer of **13a** predominates.

Table 3. Effect of varying Lewis acid co-catalyst

Entry	Lewis acid	Conversion, %[a]	Yield of **13a**, %[b]	ee %[c]
1	$In(OTf)_3$	94	94	31 (*R*)
2	$In(OTf)_3+2.7$ (*S*)-BINOL	96	96	33 (*R*)
3	HOTf	77	45	23 (*R*)
4	Tf_2O	47	43	22 (*S*)
5	$Yb(OTf)_3$	10	2	27.5 (*R*)
6	AgOTf	17	13	21.5 (*R*)
7	$Sc(OTf)_3$	100	67	21 (*R*)
8	$Sn(OTf)_2$	8	8	20 (*R*)
9	$La(OTf)_3$	17	<1	nd
10	$Zn(OTf)_2$	<1	<1	nd
11	$InCl_3$	4	<1	nd
12	$SmCl_3$	<1	<1	nd

Conditions: $Pd(OAc)_2$ (1.0 mol%), additive (2.5 mol%), ligand **9** (1.0 mol%), styrene (4.36 mmol), 1,4-dioxane (5 ml), rt, 18 h.
[a] Conversion of styrene determined by GC (hexadecane internal standard).
[b] Determined by GC (hexadecane internal standard).
[c] Determined by HPLC.

A range of alternative Lewis acid co-catalysts was examined and in all cases, where discernable, the same enantiomer (*R*) of product dimer **13a** predominates (Table 3, entries 5–12). Of the other triflate salts tested, only scandium triflate shows good conversion (entry 7), however, the selectivity to the desired product is substantially lower than with indium triflate. Both indium chloride and samarium chloride prove ineffective.

The effect on activity of changing the chiral ligand was examined next and the results are presented in Table 4. Small changes in the non-coordinating bis(phosphite) ligand's structure appear to have a substantial impact on both activity and enantioselectivity (entry 1). One significant structural difference between the ligands **9** and **8** is the absence in the latter of *ortho*-methyl functions on the bridging bis-phenol group, indicating that steric bulk in these positions is a prerequisite for decent performance. However, as outlined above, attempts to produce analogues of these ligands with *ortho-tert*-butyl groups have so far proved unsuccessful.

The ligand **14** can be envisaged as half of the non-chelating bis(phosphite), **9**. As can be seen whilst activity remains high using **14**, selectivity for the dimeric product **13a** is vastly reduced (entry 2). Interestingly, the enantioselectivity obtained, while reduced, is substantially higher than that obtained with ligand **8**, again supporting the idea that the *ortho*-methyl groups are an important structural motif. Replacing one of the two *ortho*-methyl groups with a proton and the other with a *tert*-butyl leads to an erosion in both activity and enatioselectivity (ligand **15**; entry 3). The incorporation of a 2-phenyl group leads to increased selectivity for **13a** but at the expense of enantioselectivity (ligands **16** and **17**; entries 4 and 5). Whilst two phenyl groups in the 2- and 6-positions give substantially improved selectivity for the dimer **13a** compared with methyl groups (compare entries 6 and 2) this is again is at the detriment of enantioselectivity. It is interesting to note that, in this case,

Table 4. Effect of varying chiral ligands

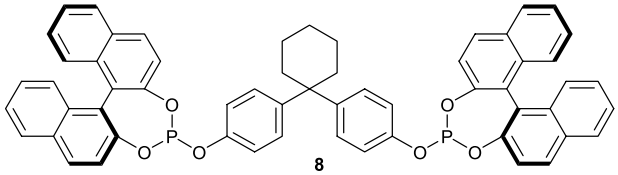
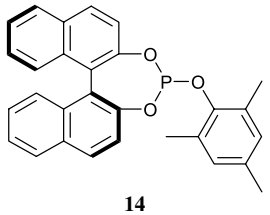
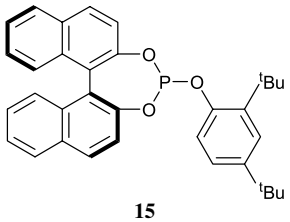
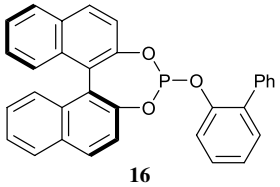
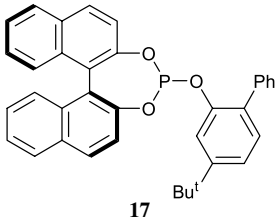
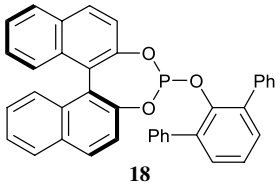
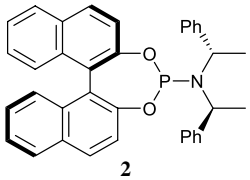
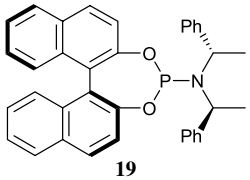
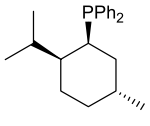
Entry	Ligand (or preformed palladium complex)	Ratio Pd:In:ligand (mol%)	Conversion, %[a]	Yield of **13a**, %[b]	ee %[c]
1	 **8**	1:2.5:1	52	33	5.5 (*R*)
2	 **14**	1:2.5:2	93	11	29 (*R*)
3	 **15**	1:2.5:2	60	10	12 (*R*)
4	 **16**	1:5:2	75	64	1.5 (*S*)
5	 **17**	1:5:2	84	63	1.5 (*R*)
6	 **18**	1:5:2	>99	69	9 (*S*)
7	 **2**	1:2.5:2	<1	<1	nd
8	 **19**	1:2.5:2	<1	<1	nd
9		1:2.5:2	62	9	7 (*S*)

Table 4 (*continued*)

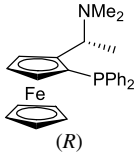
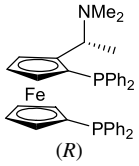
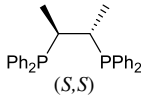
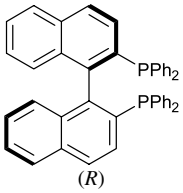
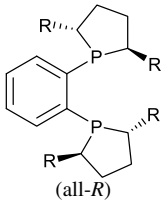
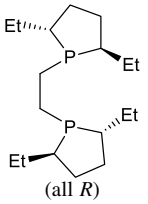
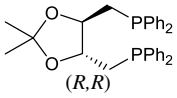
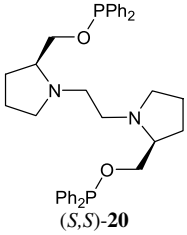
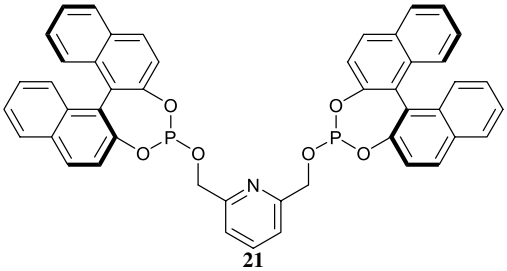
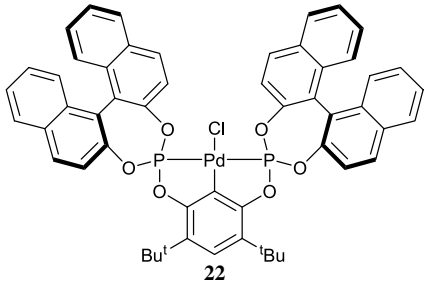
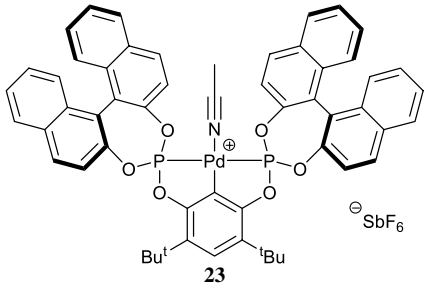
Entry	Ligand (or preformed palladium complex)	Ratio Pd:In:ligand (mol%)	Conversion, %[a]	Yield of **13a**, %[b]	ee %[c]
10	 (*R*)	1:2.5:2	<1	<1	20.5 (*R*)
11	 (*R*)	1:2.5:1	10	4	2.5 (*S*)
12	 (*S,S*)	1:2.5:1	27	<1	n.d
13	 (*R*)	1:2.5:1	5	3	3.5 (*R*)
14	 (all-*R*)	1:2.5:1	R=Et<1	0	nd
15			R=^{i}Pr<1	0	nd
16	 (all *R*)	1:2.5:2	4	2	9.5 (*S*)
17	 (*R,R*)	1:2.5:1	51	51	12.5 (*S*)
18	 (*S,S*)-**20**	1:2.5:1	89	49	0.5 (*S*)
19	 **21**	1:2.5:1	97	73	0.5 (*S*)

Table 4 (*continued*)

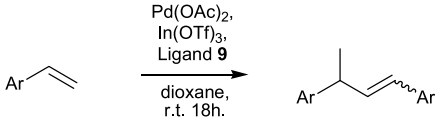
Entry	Ligand (or preformed palladium complex)	Ratio Pd:In:ligand (mol%)	Conversion, %[a]	Yield of **13a**, %[b]	ee %[c]
20	 **22**	Pd:In = 1:2.5	62	0	—
21	 **23**	Pd:In = 1:2.5	70	2	nd

Conditions: $Pd(OAc)_2$ (1.0 mol%), additive (2.5 mol%), ligand **9** (1.0 mol%), styrene (4.36 mmol), 1,4-dioxane (5 ml), rt, 18 h.
[a] Conversion of styrene determined by GC (hexadecane internal standard).
[b] Determined by GC (hexadecane internal standard).
[c] Determined by HPLC.

the opposite enantiomer of **13a** is obtained compared with using ligands **8**, **9**,**14** and **15**, despite the fact that they are all derived from (*S*)-BINOL. This may be due to the fact that the 2,6-diphenyl groups of ligand **18** show a pronounced tendency to undergo π-interactions with a metal centre.[15] This may well lead to the adoption of an alternative catalytic manifold.

Interestingly, in contrast with the monodentate ligands **14**–**18**, the diastereomeric phosphoramidite ligands **2** and **19** show essentially no activity (entries 7 and 8). This is despite the fact that these ligands are amongst the most effective tested in asymmetric hydrovinylation reactions with nickel catalysts.[9,6] The other monodentate ligands tested also proved to be poor (entries 9 and 10) as did the chelating bisphosphines BPPFA, chiraphos, BINAP, Et-Duphos, ^{i}Pr-Duphos and Et-BPE (entries 11–16, respectively). This is perhaps not surprising since RajanBabu and co-workers found that the chelating bisphosphines BINAP and Me-Duphos show no activity in asymmetric hydrovinylation reactions.[2e] By contrast (−)-diop (entry 17) shows moderate conversion with high regioselectivity and some enantioselectivity. This may be due to increased size and flexibility of the chelate ring. Indeed the more flexible bidentate ligands **20**[16] and **21** (entries 18 and 19) both show good activity and reasonable selectivity but give the desired product as essentially racemic mixtures. Both of the preformed 'PCP'-pincer complexes **22** and **23** do not yield the desired dimerisation product (entries 20 and 21).

Having established that the initial catalyst system tested—that formed in situ from palladium acetate, indium triflate and ligand **9**—shows the best performance and enantioselectivity. We briefly screened this against selected substrates. Both 4-fluorostyrene and 2-methylstyrene are converted to the desired dimers in reasonable yields at rt (Scheme 2). The enantioselectivity observed in the dimerisation of 4-fluorostyrene is somewhat lower than that with styrene and in contrast with the unsubstituted substrate, the product **13b** is formed exclusively as the *Z*-isomer. The dimerisation of 2-methylstyrene yields the *E*-isomer in an encouraging 56% ee.



13b: Ar = 4-FC_6H_4: 77%; *Z*-isomer; 20% e.e. [a]
c: Ar = 2-MeC_6H_4: 79%; *E*-isomer; 56% e.e.[b]

Scheme 2. [a] Isolated yield, ee determined by HPLC. [b] Spectroscopic yield determined by ^{1}H NMR, isolated yield = 20%, ee determined by HPLC.

The electron rich substrate 4-methoxystyrene does not give any of the desired dimerisation product under the standard conditions, but rather yields polymeric material. It appears that the polymerisation is catalysed by an indium species; control reactions with indium triflate with or without ligand **9** also give essentially quantitative conversion to polymeric materials, whereas a reaction containing palladium acetate and ligand **9** in the absence of indium leads only to recovered starting material.

3. Conclusions

In summary, we have realised the asymmetric dimerisation of styrenes using mixed palladium–indium catalysts

supported by chiral non-chelating bis(phosphite) ligands. While the enantioselectivities obtained with the current catalyst systems are modest, the performances observed are considerably better than those using some of the best ligand systems reported for the related asymmetric hydrovinylation reaction. In addition, the more successful catalyst systems identified are amenable to simple modification, which holds promise for future optimisation of both activity and selectivity. These studies are ongoing in our group and the results will be reported at a later date.

4. Experimental

4.1. General

All reactions and manipulations of air-sensitive materials were performed under nitrogen, either in a glove-box or using standard Schlenk techniques. Solvents were distilled from appropriate drying reagents prior to use. Ligands **14–18** were prepared by modification of a procedure reported for a closely related phosphite.[17] Ligand **21** and complexes **22** and **23** were prepared according to literature methods.[18,19] All other materials, except where noted, were obtained commercially and used as received. GC analysis was performed on a Varian 3800 GC fitted with a 25 m CP Sil 5CB column and data were recorded on a Star workstation. Enantioselectivity was determined by HPLC on a Varian Prostar 210 fitted with a Chiralcel OD or OB column.

4.1.1. Synthesis of ligand 8. A mixture of bisphenol, **11a**, (1.53 g, 5.70 mmol) and the chlorophosphite **10** (2.00 g, 5.70 mmol) in toluene (60 ml) was cooled to −40 °C and then treated drop-wise with a solution of Et_3N (3.0 ml, 21.4 mmol) in toluene (20 ml). The reaction was stirred and allowed to warm to rt overnight. The mixture was filtered through a pad of Celite, which was then washed with toluene (2×20 ml) and the solvent removed from the combined solutions in vacuo and the resultant solid was recrystallised from dichloromethane/hexane to give compound **8** as a white solid. Yield 3.48 g, 70%, $C_{58}H_{42}O_6P_2$ requires C, 77.7; H, 4.7%; Found: C, 74.60; H, 5.47. ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.36–1.51 (8H, br s, CyH), 2.07–2.19 (2H, br s, CyH), 6.97–7.23 (16H, m, ArH), 7.25–7.51 (8H, m, ArH), 7.75–7.96 (8H, m, ArH); ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.43, 25.25, 36.24 (CH_2), 44.05 (*C*-(CH_2)$_2$), 114.00, 118.78, 118.88, 121.80 (ArH), 123.37 (ArC), 123.97, 124.19, 125.34, 125.68, 125.99, 126.52, 126.84, 126.89, 128.06, 128.83 (ArH), 130.19, 130.60, 131.49, 131.76, 143.45, 146.47, 146.52, 148.21, 148.32 (ArC); ^{31}P NMR (121 MHz, $CDCl_3$): δ 145.63.

4.1.2. Synthesis of ligand 9. *Method A*. This was prepared by an analogous method to that outlined above. Yield 87%. $C_{59}H_{46}O_6P_2$ requires C, 77.6; H, 5.1%; Found: C, 75.5; H, 5.4. ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.44 (6H, s, CH_3), 2.28 (12H, s, CH_3), 6.83 (4H, s, ArH), 7.14–7.24 (4H, m, ArH), 7.28–7.40 (8H, m, ArH), 7.41 (4H, d, $^1J_{HH}$=8 Hz, ArH), 7.81–7.94 (8H, m, ArH); ^{13}C NMR (75 MHz, $CDCl_3$): δ 18.81, 31.58 (CH_3), 42.44 (*C*(CH_3)$_2$), 122.31, 122.49 (ArH), 123.40 (ArC), 125.70, 125.85, 126.72, 126.89, 127.52, 127.59, 127.84, 128.78, 128.87 (ArH), 130.32 (ArC), 130.97, 131.69 (ArH), 132.15, 133.11, 133.36, 133.38, 147.30, 147.54, 147.65, 148.40 (ArC); ^{31}P NMR (121 MHz, $CDCl_3$) δ 149.33.

Method B. A mixture of the appropriate bisphenol **11a** (4.0 g, 16.1 mmol) and freshly distilled PCl_3 (10 ml, 115 mmol) in toluene (80 ml) was cooled to −40 °C and treated drop-wise with Et_3N (8 ml, 58 mmol) in toluene (20 ml). The reaction was allowed to warm to rt overnight. The mixture was filtered through a pad of Celite, which was then washed with toluene (2×20 ml) and the solvent removed from the combined solutions in vacuo to give the intermediate **12a** as a white solid. This was held under vacuum until all of the PCl_3 had been removed as determined by ^{31}P NMR. Yield 6.67 g; 86%. ^{31}P NMR ($CDCl_3$): δ 200.8 ppm. This was used in the subsequent step without further purification.

A mixture of Et_3N (8.0 ml, 57.1 mmol) and **12a** (3.29 g, 6.76 mmol) in toluene (60 ml) was cooled to −40 °C and treated drop-wise with a solution of (*S*)-binaphthol (3.90 g, 13.62 mmol) in toluene (20 ml). The reaction was allowed to warm to rt overnight. The mixture was filtered through a pad of Celite, which was then washed with toluene (2× 20 ml), the solvent removed from the combined solutions in vacuo and the resultant solid was recrystallised (dichloromethane/hexane) to give ligand **9** as a white solid (5.12 g, 83%). Spectroscopic data as above.

4.2. Typical method for catalysis

Ligand **9** (0.041 g, 0.044 mmol) was added to a solution of palladium acetate in 1,4-dioxane (0.022 M, 2.00 ml), the solution was diluted with dioxane (2 ml) and stirred at rt for 5 min. The appropriate stryrene (4.36 mmol) was added followed by indium triflate (0.061 g, 0.1085 mmol) in one portion. More dioxane (1 ml) was used to wash down any indium triflate stuck to the side of the reaction flask and the reaction mixture was then stirred at rt for 18 h. The reaction was quenched with water (25 ml), the resultant mixture extracted with dichloromethane (3×25 ml), the organic phase dried ($MgSO_4$) and the solvent removed under reduced pressure. The crude product was dissolved in toluene (10 ml) and hexadecane (internal standard, 0.068 M in toluene, 5.00 ml) was added. The conversion and yield were determined by GC analysis.

4.2.1. Compound 13a. Isolated by column chromatography (silica, chloroform) as a yellow oil, 0.431 g, 48%. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.30 (3H, d, $^3J_{HH}$=7 Hz, CH_3), 3.42–3.50 (1H, dq, $^3J_{HH}$=5, 7 Hz, R_3CH), 6.24 (1H, d, $^3J_{HH}$= 5 Hz, =CH), 6.25 (1H, s, =CH), 6.98–7.20 (10H, m, ArH). The ee was determined by HPLC, Chiralcel OD, heptane/isopropanol 99.8:0.2, flow rate 0.9 ml/min, λ 215 cm^{-1}, R_f *S*-isomer=11.24 min, *R*-isomer=11.87 min, absolute configuration determined by order of R_f in comparison with literature data.[20]

4.2.2. Compound 13b. Isolated by column chromatography (silica, hexane then 5% dichloromethane in hexane), as a yellow oil, 0.041 g, 77%. HRMS *m*/*z*=244.1074; $C_{16}H_{14}F_2$ requires 244.1064. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.35 (3H, d, $^3J_{HH}$=7 Hz, CH_3), 3.52 (1H, m, R_3CH), 6.10–6.20 (1H,

dd, $^3J_{HH}=7$, 16 Hz, =CH), 6.26 (1H, d, $^3J_{HH}=16$ Hz,=CH), 6.85–6.89 (2H, d, $^3J_{HH}=9$ Hz, ArH), 6.91–6.94 (2H, d, $^3J_{HH}=9$ Hz, ArH), 7.09–7.15 (2H, q, $^3J_{HF}=5$, 9 Hz, ArH). The ee was determined by HPLC, Chiralcel OD, heptane/isopropanol 99.8:0.2, flow rate 0.9 ml/min, λ 215 cm^{-1}, R_f major isomer=9.39 min, minor isomer=10.26 min, absolute configuration not determined.

4.2.3. Compound 13c. Isolated by column chromatography (silica, chloroform), as a yellow oil, 0.01 g, 19%. HRMS *m/z*=236.1558; $C_{18}H_{20}$ requires 236.1565. ^1H NMR (300 MHz, $CDCl_3$) δ 1.36–1.39 (3H, d, $^3J_{HH}=7$ Hz, CH_3), 2.23 (3H, s, $ArCH_3$), 2.33 (3H, s, $ArCH_3$), 3.75–3.84 (1H, dq, $^3J_{HH}=7$, 7 Hz, R_3CH), 6.10–6.17 (1H, dd, $^3J_{HH}=7$, 16 Hz, =CH), 6.46–6.52 (1H, d, $^3J_{HH}=16$ Hz, =CH), 7.03–7.11 (6H, m, ArH), 7.14–7.20 (1H, d, $^3J_{HH}=7$ Hz, ArH). The ee was determined by HPLC, Chiralcel OB, heptane/isopropanol 98.0:2.0, flow rate 0.5 ml/min, λ 254 cm^{-1}, R_f major isomer=11.24 min, minor isomer=14.36 min, absolute configuration not determined.

Acknowledgements

We thank the Universidad Rey Juan Carlos for the provision of a postdoctoral grant (A. G.) and funding through Project GVC-2004-12 (S. P., A. G.), the EPSRC (Advanced Research Fellowship for RBB, PDRAs for MB and MEB, DTA for SLM) and Johnson Matthey for the loan of palladium acetate.

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