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P-Stereogenic Monophosphines with the 2-*p*-Terphenylyl and 1-Pyrenyl Substituents. Application to Pd and Ru Asymmetric Catalysis

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Highlights

- *P*-stereogenic monophosphines with a polycyclic aromatic substituent
- Neutral and cationic allylic Pd complexes: [PdCl(η^3-allyl)P], [Pd(η^3-allyl)P_2]PF_6
- Neutral Ru complexes: [$RuCl_2$(η^6-*p*-cymene)P]
- Pd-catalysed hydrovinylation of styrene and allylic substitution reactions
- Ru-catalysed hydrogen transfer of acetophenone

Abstract

The synthesis of five optically pure *P*-stereogenic monophosphines of the type PPhArR (Ar = 2-*p*-terphenylyl (**a**), 1-pyrenyl (**b**); R = OMe, Me, *i*-Pr) is described. The ligands were fully characterised and the absolute configurations of PPh(1-pyrenyl)R (**3b** and **5b**; R = OMe and Me respectively) were confirmed by X-ray diffraction. The complexation of the monophosphines to Pd and Ru organometallic units yielded the neutral complexes [PdCl(η^3-2-Me-allyl)**P**] (**10**-**12**) and [$RuCl_2$(η^6-*p*-cymene)**P**] (**16**-**18**). Complete characterisation, including the crystal structure determination of [$RuCl_2$(η^6-*p*-cymene)(PMePh(2-*p*-terphenyl))] (**17a**) is provided. Neutral palladium complexes appeared as mixtures of two diastereomers in solution according to NMR. The synthesis and characterisation of four cationic [Pd(η^3-2-Me-allyl)(**P**)$_2$]PF_6 (**13** and **14**) is

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also described. The application of neutral Pd complexes to catalytic styrene hydrovinylation afforded moderate conversions, high chemoselectivities (> 92%) to 3-phenyl-1-butene and up to 43% ee with precursor **12a**. Cationic Pd complexes were tested as catalytic precursors in allylic substitution of *rac*-3-acetoxy-1,3-diphenyl-1-propene (***rac*-I**), with the anion of dimethylmalonate and benzylamine as nucleophiles, obtaining full conversions and up to 80% ee in alkylation and 60% ee in amination with precursor **13a**. Finally, ruthenium complexes were used as catalytic precursors in transfer hydrogenation of acetophenone, with complete conversions after several hours but low enantioselectivities.

Keywords

P-stereogenic ligands; Pd allylic complexes; Ru arene complexes; hydrovinylation; allylic substitution; transfer hydrogenation

1. Introduction

The development of new ligands for enantioselective catalysis with late transition metals has been the main driving force for the synthesis of new chiral P(III) compounds for the last decades, since phosphines and derivatives are known to be ideal ligands to some of the most catalytically active metals [1]. It is well known that no ligand is ever efficient enough for all the substrates in a particular reaction catalysed by a certain metal. Therefore, optimisation by fine-tuning the steric and electronic properties of the ligands is usually carried out. At present, all sources of chirality are intensively explored and hence a plethora of phosphorus ligands containing stereogenic carbon atoms, axes and planes have been described [1, 2].

Given the configurational stability of the phosphorus atoms it has been known for over a century [3] that the P atom itself can be a stereogenic element, giving rise to the family of *P*-stereogenic ligands [4]. This type of ligands has a very long history in enantioselective homogeneous catalysis, which started in the pioneering works of Horner [5] and Knowles [6, 7] in Rh-catalysed enantioselective hydrogenation. More recently, the interest in *P*-stereogenic ligands has been rising steadily thanks to new synthetic methodologies and applications in catalysis [4, 8, 9].

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We also devoted some effort to this field with the preparation of series of mono- and diphosphine ligands, which were used in Pd-catalysed reactions (hydrovinylation [10-13] and allylic alkylation [14]) and in Ru-catalysed (cyclopropanation [15] and hydrogen transfer [15, 16]) enantioselective reactions. Although the optically pure monophosphine ligands were initially obtained by resolution of the racemic mixtures by means of Pd complexes [10, 11], they have more recently obtained by methods based on asymmetric synthesis due to its superior versatility. Therefore, P-ligands obtained by the so-called Evans [17] and the Jugé-Stephan [18] methods have been reported. In particular, series of ligands prepared by the Jugé-Stephan method with the general structure depicted in Figure 1 were described [12, 14].

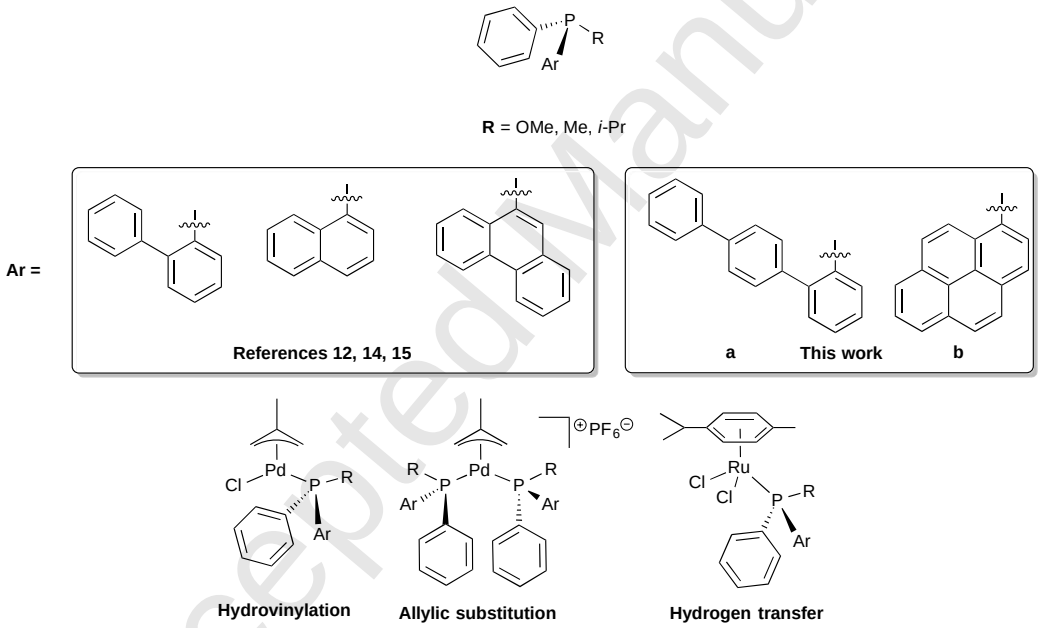

Figure 1. *P*-stereogenic monophosphines and their derived Pd and Ru complexes.

The monophosphine ligands, which contained a phenyl, a polycyclic aromatic group and a methoxy or an alkyl group were complexed to Pd and Ru organometallic moieties. The obtained complexes shown in the Figure were employed to the catalytic reactions mentioned before. Some of the phosphines, in particular those bearing the 2-biphenylyl group, were found to be competent ligands [12, 14, 16].

In this paper, the extension of these studies with new phosphines bearing the 2-*p*-terphenylyl (**a**) and 1-pyrenyl (**b**) groups, rarely found in the literature, chosen with the aim of improving the

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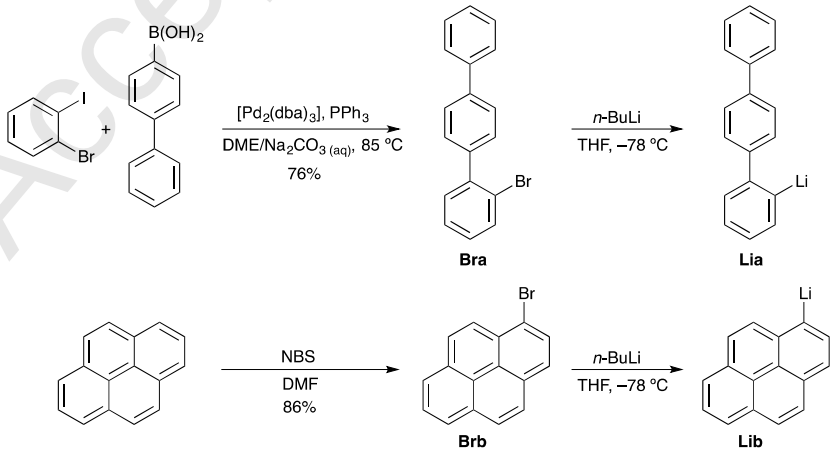
performance of the previous generation of ligands is reported. To the best of our knowledge, the only monophosphine reported to date that contains the unsubstituted 2-*p*-terphenylyl group is the racemic phenyl(2-*p*-terphenylyl)phosphine oxide [19]. Several achiral hydroxyterphenylylphosphines have been described and successfully used as ligands in Pd-catalysed cross-coupling reactions [20-22] and also extremely bulky phosphines containing a 2,3,4,5-tetraphenyl moiety have been reported and used in several Pd-catalysed reactions [23, 24]. Finally, a few achiral diphosphines, built around the terphenylyl skeleton, are also known [25-28]. Regarding the 1-pyrenyl substituent, 1-diphenylphosphinopyrene has been described [29].

2. Results and discussion

2.1. Ligand synthesis

From our previous studies [12, 13, 30] and from others [31, 32], it is known that standard Jugé-Stephan [18] procedure is very well suited to prepare *P*-stereogenic phosphines bearing *o*-monosubstituted aryl fragments. The introduction of the *o*-monosubstituted aryl fragment it is carried out via organolithiums and therefore it is mandatory to have the suitable precursors to prepare such species. In the present case, the most obvious precursors are the corresponding aryl bromides 2-bromo-*p*-terphenyl (**Bra)** and 1-bromopyrene (**Brb**), which can be easily lithiated with *n*-butyllithium at low temperatures (Scheme 1).



Scheme 1. Synthesis of **Bra**, **Brb**, **Lia** and **Lib**.

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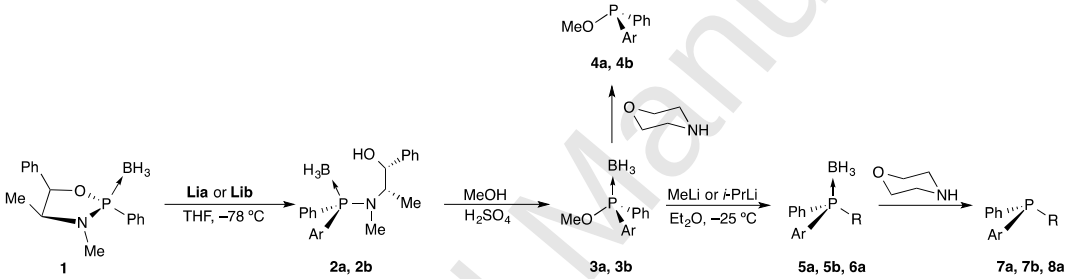
Following a literature precedent [33], the preparation of **Bra** was carried out by Suzuki-Miyaura coupling between *p*-biphenylylboronic acid and *o*-bromoiodobenzene, using $[Pd_2(dba)_3]/PPh_3$ as catalytic precursor and aqueous Na_2CO_3 solution as a base. After some optimisation, **Bra** could be obtained as a crystalline solid in good yield. Compound **Brb** was also prepared with a modified literature method [34], based on the direct bromination of pyrene with NBS in DMF. This method is very selective towards the monobromination in position 1 and **Brb** could be obtained in high yield with enough purity to be employed in the synthesis of the phosphines. With the bromoarene precursors in hand, the Jugé-Stephan methodology was followed to have access to the desired ligands (Scheme 2).



Scheme 2. Synthesis of the *P*-stereogenic ligands.

The regioselective ring opening of oxazaphospholidine-borane **1** was initially attempted preparing the organolithiums **Lia** and **Lib** in Et_2O at –78 ºC as in previous reports [12, 35]. It was found, however, that the very low solubility of these species, probably due to the extensive conjugation of the aryl groups employed, led to low yields of **2** and the recovery of large quantities of unreacted **1**. Therefore, Et_2O was switched to THF, in which the organolithium did not precipitate. With this modification, **1** was completely consumed and good yields of **2** could be obtained. The ring opening was very clean with organolithium **Lib** but, in contrast, **Lia** led to several byproducts as judged by ^{31}P spectroscopy. Phosphamide-borane **2a** featured a broad singlet at 70.2 ppm and another two peaks were also present at 133 and 107 ppm. The signal at higher field could be assigned to the product **9**, originated by base-promoted elimination on **1** instead of the expected substitution at the P atom (Scheme 3).

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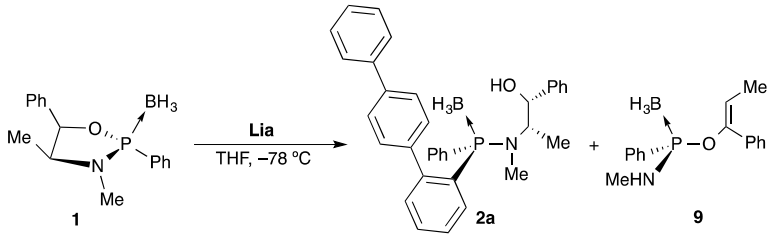

Scheme 3. Reaction of **1** with **Lia**.

This elimination reaction has been described previously in the literature [36] when bulky organolithium reagents are employed. In the case described, it also leads to 1,4-diphenylbenzene, which could indeed be recovered during the purification of **2a**. It was found that this compound and the other unidentified one reacted in the subsequent reactions and the formed byproducts could not be separated from the desired intermediates. Therefore, the optimisation of the ring-opening step was mandatory. After some experimentation, it was discovered that by simply carrying out the reaction in more diluted conditions was enough to maximise the formation of the desired phosphamide-borane **2a** and minimise the quantities of impurities to an acceptable level.

Following the standard procedure, acid-mediated methanolysis of **2** produced the corresponding phosphinite-boranes **3** in good yields. Whereas **3a** was a dense colourless oil, **3b** was a yellow solid that precipitated as a pure product during the methanolysis step.

Solutions of phosphinite boranes **3** in Et_2O were treated at low temperature with RLi (R = Me, *i*-Pr and *t*-Bu) to obtain monophosphine-boranes **5** and **6**. As expected [12] the bulky *t*-Bu group could no be introduced according to ^{31}P NMR spectroscopy. Depending on the exact reaction conditions, the peak of the starting phosphinite-boranes **3** (at δ around +110 ppm) and/or multiple peaks indicating decomposition could be detected. The less bulky *i*-Pr group could be successfully introduced by reaction of *i*-PrLi with **3a** but once again starting phosphinite-borane and/or multiple peaks were observed when **3b** was employed. These results are in line with previously published data [12] indicating that the introduction of a conjugated aromatic substituent in the ring-opening step of the Jugé-Stephan method precludes the introduction of the *t*-Bu group and sometimes even the *i*-Pr group. The protected phosphinite and phosphine

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ligands were air-stable oils (for Ar = 2-*p*-terphenylyl) or solids (for Ar = 1-pyrenyl), which were characterised by the usual techniques. HPLC analysis on a chiral column of the crude products showed that they were present as optically pure (ee > 95%) products. Single crystals, suitable to perform X-ray diffraction studies, were obtained for **3b** and **5b**. The molecular structures for the two compounds are displayed in Figure 2.

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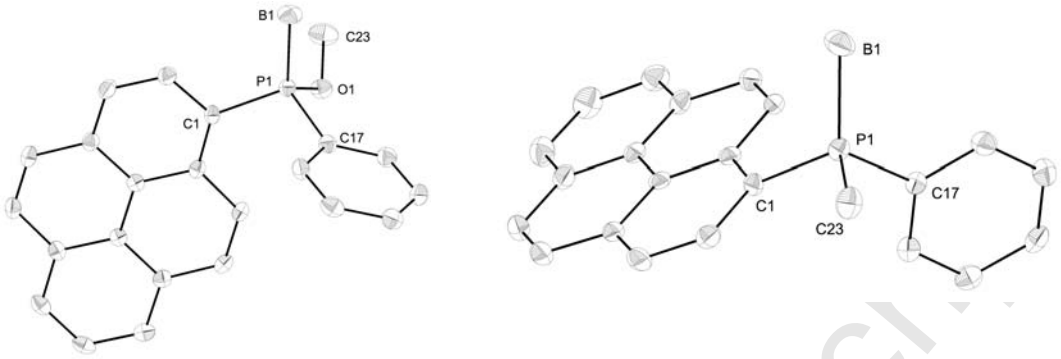

Figure 2. ORTEP representation of the molecular structures of **3b** (left) and **5b** (right). Hydrogen atoms have been omitted for clarity. Selected distances (Å) and angles (º) for **3b**: P1–O1, 1.6005(14); P1–C17, 1.7934(19); P1–C1, 1.8081(19); P1–B1, 1.899(2); C23–O1, 1.443(2); B1–P1–O1, 115.54(10); B1–P1–C17, 110.06(10); B1–P1–C1, 113.04(10). For **5b**: P1–C23, 1.804(3); P1–C17, 1.819(2); P1–C1, 1.816(2); P1–B1, 1.930(3); B1–P1–C23, 109.62(13); B1–P1–C17, 115.55(12); B1–P1–C1, 115.22(13).

The crystal structures confirmed that the absolute configurations of the P atom were *R* for **3b** and *S* for **5b**, as expected given the enantiomer of ephedrine employed to prepare **3 [**(1*R*, 2*S*)-(–)-ephedrine] and the stereochemical course of each of the Jugé-Stephan method steps [18]. Distances and angles of both borane adducts were similar to other previously reported phosphine-boranes [12, 16, 37]. A parameter that allows the evaluation of the steric hindrance of the ligand is the mean value of the three BPC angles. The smaller the value, the higher the steric hindrance of the ligand. In the present case, the values are 112.88 for **3b** and 113.46 for **5b**, meaning that the former is slightly more bulky than the latter. Both values are in the range observed for other *P*-stereogenic phosphine-boranes [12, 37]. Borane adducts **3**, **5** and **6** were conveniently deprotected by neat morpholine at room temperature [12, 37], affording the free phosphinites (**4a** and **4b**) and phosphines (**7a**, **7b**, and **8a**) ready for complexation.

2.2. Neutral Pd complexes

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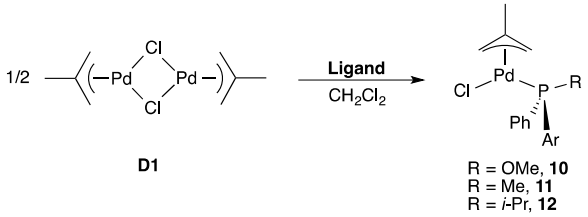
Neutral Pd allylic complexes of the type [PdCl(η^3-(2-Methylallyl)(**P**)] (**10-12)**, were easily prepared by the standard method, consisting of splitting Pd dimer **D1** with two equivalents of the ligands in dichloromethane at room temperature (Scheme 4) [12].



Scheme 4. Synthesis of complexes **10-12**.

The complexes were obtained as air-stable pale yellow solids. The analysis of the NMR spectra in $CDCl_3$ indicated that, as expected, they were present as mixtures of two diastereomeric species, because of the presence of one chiral phosphine and the allyl moiety. Accordingly, two sharp singlets were present in the ^{31}P NMR spectra and duplication of the allylic peaks was clearly observable in the ^{1}H NMR spectra. It has to be pointed out that the presence of the chiral phosphine ruled out the presence of any symmetry element and hence in principle H and C atoms of the each different isomer were all different. The proportion of each isomer is indicative of the discrimination ability of the chiral ligand in the neutral complexes. The isomeric ratio was 1:1 for complexes bearing the phosphines with the 1-pyrenyl group (**10b** and **11b**) and for complex **10a**. In contrast, it was around 1:2 for complexes **11a** and **12a**, similarly to complexes with phosphines containing the 2-biphenylyl group [12].

2.3. Cationic Pd complexes

Cationic Pd allylic complexes of the type [Pd(η^3-(2-Methylallyl)(**P**)$_2$]PF_6 (**13-15**), were easily prepared following a previously reported method [14]. Thus, dimer **D1** dissolved in dichloromethane was treated with four equivalents of monophosphine in the presence of excess of ammonium hexafluorophosphate (Scheme 5).

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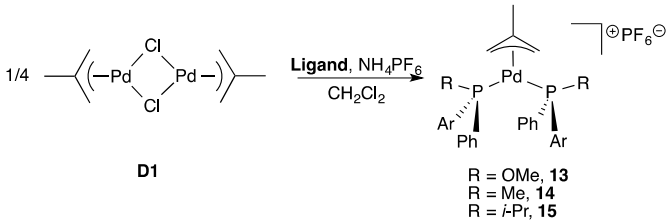

Scheme 5. Synthesis of complexes **13**-**15**.

An aqueous final work-up allowed the isolation of the desired cationic complexes as air-stable solids. In solution they slowly decomposed to Pd black and other unknown species as ^{31}P NMR spectroscopy evidenced. This process was faster for complexes with phosphines containing the 2-*p*-terphenylyl group (**13a** and **14a**). The complexes are present as single species in solution but the chirality of the phosphine makes each phosphine and each half of the allyl group to appear different in the NMR spectra. For that reason, two sharp doublets (J_{PP} = 29-55 Hz) with strong roof effect were observed in the ^{31}P NMR spectra and four resonances assignable to the allylic protons could be seen. Two of them, corresponding to the *anti* protons, appeared as sharp doublets (J_{PP} = 9-13 Hz) whereas the remaining two appeared as broad singlets and corresponded to the two *syn* protons. In contrast to **13** and **14**, solutions of complex **15a** displayed only two peaks in the ^{31}P NMR spectrum and several peaks belonging to the *i*-Pr and the allylic moieties in the ^{1}H NMR spectrum, which could not be assigned. It is possible the bulkiness of the phosphine **8a** precludes the appropriate coordination of two ligands to stabilise **15a**. This complex was not further used in catalysis.

2.4. Ru complexes

Similarly to the Pd complexes discussed above, neutral Ru complexes of the type [$RuCl_2$(η^6-(*p*-cymene)(**P**)] (**16**-**18**), were prepared by splitting the well-known Ru dimer **D2** with two equivalents of the appropriate phosphorus ligand (Scheme 6) [15, 38].

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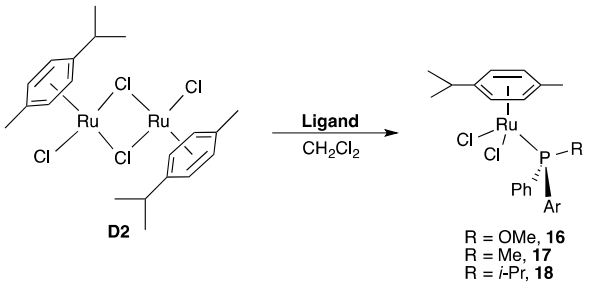

Scheme 6. Synthesis of complexes **16-18**.

The desired complexes were obtained as air-stable red solids after recrystallisation. In solution they were conveniently characterised by NMR. They featured a singlet in the ^{31}P NMR spectra. In ^{1}H and ^{13}C NMR spectra, the chirality of the phosphine made all the H and C atoms of the coordinated aryl moiety of the *p*-cymene to appear differentiated as well as the two methyl groups of the isopropyl substituent.

Suitable monocrystals to perform X-ray diffraction studies could be obtained for **17a**. Its ORTEP representation is displayed in Figure 3.

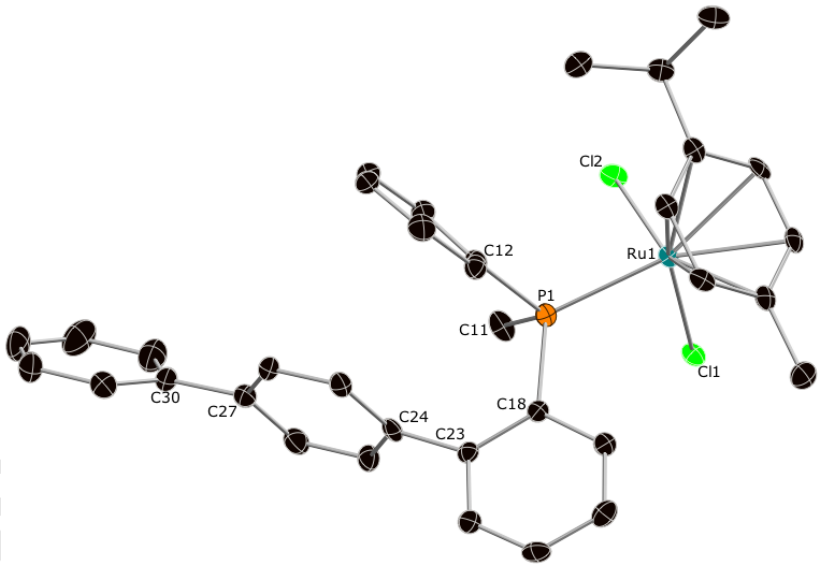

Figure 3. ORTEP representation of **17a**. Thermal ellipsoids drawn at 50% probability level. Hydrogen atoms have been omitted for clarity. Distances (Å) and angles (º): Ru(1)–Cl(1): 2.4115(8); Ru(1)–Cl(2): 2.4170(8); Ru(1)-P(1): 2.3615(6); P(1)–C(11): 1.818(3); P(1)–C(12): 1.818(3); P(1)–C(18): 1.841(3); C(23)–C(24): 1.491(4); C(27)–C(30): 1.487(4); P(1)–Ru(1)–Cl(1): 82.84(3); P(1)–Ru(1)–Cl(2): 85.04(3); Cl(1)–Ru(1)–Cl(2): 89.90(3).

The complex shows the typical "piano-stool" pseudotetrahedral geometry around the Ru atom with the *p*-cymene ring coordinated in η^6 fashion, making the Ru to adopt a distorted octahedral

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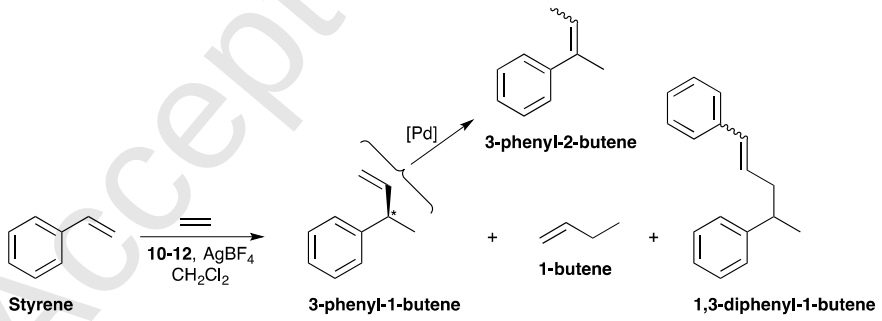
coordination environment. The structure allows an additional confirmation of the absolute configuration of the phosphorus atom of the phosphine (*S*, as a free ligand). The geometric parameters of the structure are similar to other previously reported [$RuCl_2(\eta^6$-*p*-cymene)(**P**)] complexes [15, 16, 39]. As expected, the two Ru-Cl distances are very similar and that the imaginary line defined by the two Cl atoms is approximately parallel to the line defined by the substituted carbons of the *p*-cymene ring. The average distance between Ru and each of the six aromatic carbon atoms of the *p*-cymene ring is 2.218 Å. These distances can be divided in two groups: the relatively short ones (those involving the three C atoms closer to the phosphine, average distance of 2.203 Å) and the relatively long ones (those involving the three C atoms further away from the phosphine, average distance of 2.232 Å).

2.4. Asymmetric hydrovinylation

Catalytic hydrovinylation can be viewed as the heterocodimerisation between an activated olefin and ethylene catalysed by a transition metal complex, usually based on Ni or Pd [40, 41]. The interest in this reaction is steadily increasing, especially regarding the asymmetric version [41-43]. The model vinyl arene substrate used was styrene with neutral Pd complexes **10**-**12** as catalytic precursors (Scheme 7).



Scheme 7. Styrene hydrovinylation.

The desired hydrovinylation product, 3-phenyl-1-butene, is a chiral compound amenable to enantioselection. The Pd catalytic species, however, are also active in isomerising it to achiral (*E*/*Z*)-3-phenyl-2-butenes. Other typically encountered byproducts in small amounts are those arising from the dimerization of either ethylene (1-butene) or styrene (1,3-diphenyl-1-butenes). The main challenge of the hydrovinylation reactions is the design of ligands capable of forming

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catalytic precursors leading to high chemo- and enantioselectivities of the hydrovinylation product [41]. With Ni and Pd systems, the ligand, usually with P as a donor atom, has to be monodentate due to the particularities of the catalytic cycle [41] a feature that makes more challenging the design of efficient ligands.

Previous research carried out with monophosphines PArPhR (Ar = 1-naphthyl, 9-phenanthryl, 2-biphenylyl; R = OMe, Me, *i*-Pr) led to some selective catalysts towards 3-phenyl-1-butene in the hydrovinylation of styrene [12, 13, 30]. In this paper, these results can be conveniently compared to those obtained with the catalytic precursors based on the 2-*p*-terphenylyl and 1-pyrenyl phosphines presented here. The results are given in Table 1.

Table 1. Styrene hydrovinylation catalysed with **10**-**12** complexes.

Entry[a]	*Precursor*	*Time/h*	*Conv.*[b]*/%*	*Codimers*[c]*/%*	*Select.*[d]*/%*	*TOF*[e]*/h*$^{-1}$	*ee/%*
1	**10a**	6	9.1	9.1	> 99.9	15	34 (*R*)
2	**10b**	6	43.2	41.9	92.6	68	5 (*S*)
3	**11a**	6	23.1	22.8	95.0	38	19 (*S*)
4	**11b**	6	> 99.9	97.5	3.7	–	–
5	**11b**	1	16.9	16.9	> 99.9	165	3 (*S*)
6[f]	**12a**	6	62.6	62.6	95.8	106	43 (*S*)

[a]Catalytic conditions: 25 ºC, ≈ 15 bar of initial pressure of ethylene in 15 mL of CH_2Cl_2. Ratio styrene/Pd = 1000/1; [b]Conversion of starting styrene; [c]Total amount of codimers; [d]Percentage of 3-phenyl-1-butene/codimers; [e]TOF values calculated from the total amount of codimers formed; [f]This result had already been reported in a review [41].

As expected, all neutral allylic complexes are active in catalytic hydrovinylation with very different activities depending on the substituents at the P atom, as clearly evidenced by the TOF values at 6 h. The order of increasing activity is **10a** < **11a** < **11b** < **12a** < **11b**. In fact, precursor **11b** leads to a very fast catalytic system so in order to avoid extensive isomerisation of 3-phenyl-1-butene the reaction time had to be shortened (cf. entries 4 and 5). The catalytic systems are very selective towards the primary α-hydrovinylation product, namely 3-phenyl-1-butene, which is higher than 92% at moderate conversions (entries 2 and 6). Regarding the enantioselectivity, only the systems containing the 2-*p*-terphenylyl substituent in the phosphine lead to some enantioenriched 3-phenyl-1-butene (entries 1, 3 and 6). As no secondary interaction can be envisaged with this kind of ligands, the moderate enantioselectivities obtained can be explained by pure steric differentiation [12]. In this regard, the linearity of the 2-*p*-

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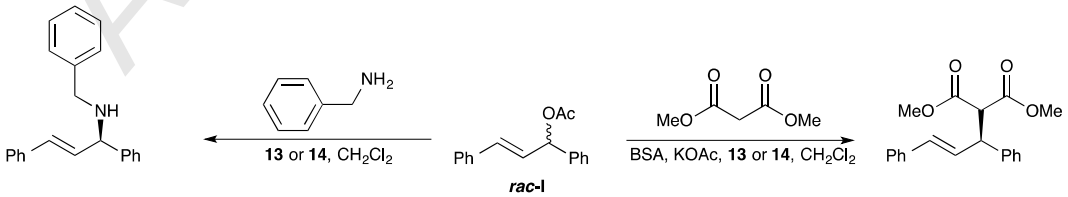
terphenylyl group in the monophosphorus ligands is clearly better to the planarity of the 1-pyrenyl substituent.

The comparison these results with previously published data with similar phosphines [12, 13, 30] show that overall the activities are somewhat lower for the phosphines discussed here. The selectivities are maintained whereas the enantioselectivities of the precursors with phosphines bearing the 2-*p*-terphenylyl group are very similar to those of the precursors with phosphines bearing the 2-biphenylyl group [12, 30]. These results show that the introduction of an extra phenyl ring at the end of the 2-biphenylyl moiety does not improve the performance of the ligands, pointing out that probably it situates in a position too far away from the catalytically active Pd centre to have any remarkable effect. The fact that the 1-pyrenyl-containing phosphine ligands generate precursors that give to racemic 3-phenyl-1-butene (compared to up to the 22% ee obtained with the 1-naphthyl-containing phosphines [12]), demonstrates that this substituent is not adequate for the asymmetric hydrovinylation of styrene.

2.5. Pd-catalysed allylic substitution

Allylic substitution reactions can be defined as the substitution of a leaving group, located in an allylic position, by an incoming nucleophile, catalysed by a catalytic precursor very often based on Pd. Its asymmetric version has been thoroughly studied and applied to numerous natural product syntheses [44] and it is commonly used to test the performance of new bidentate chiral ligands [45]. One of the model substrates in this reactions is racemic *trans*-1,3-diphenyl-2-propen-1-acetate (1,3-diphenylallyl acetate), ***rac*-I**, and two of the nucleophiles of reference are the anion derived from dimethyl malonate and benzylamine (Scheme 8).



Scheme 8. Allylic substitution reactions on ***rac*-I**.

Cationic Pd complexes (usually prepared in situ) of the type [Pd(η^3-allyl)(**PP**)]X (**PP** = chiral diphosphine, two monodentate phosphines or in general a bidentate ligand) are the usual

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precursors in this type of transformation. In order to compare [14] the effect of the modification of the phosphine substituents on the catalytic outcome, the performance of complexes **13** and **14** in asymmetric allylic substitutions was explored. The results are given in Table 2.

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Table 2. Results of asymmetric allylic substitutions of ***rac*-I** with complexes **13** and **14**.

Entry[a]	*Nucleophile*	*Precursor*	*Conversion/%*[b]	*ee/%*[c]
1	DMM	**13a**	> 99	80 (*S*)
2	DMM	**14a**	> 99	< 5
3	DMM	**13b**	> 99	< 5
4	DMM	**14b**	> 99	7 (*S*)
5	Benzylamine	**13a**	> 99	60 (*R*)
6	Benzylamine	**14a**	> 99	< 5
7	Benzylamine	**13b**	> 99	< 5
8	Benzylamine	**14b**	> 99	< 5

[a]Catalytic conditions for allylic alkylations with dimethyl malonate: Pd complex (0.01 mmol), ***rac*-I** (1 mmol), dimethyl malonate (3 mmol), BSA (3 mmol) and KOAc (1 mg) in 4 mL of CH_2Cl_2 at rt for 24 h; for allylic substitutions with benzylamine: Pd complex (0.01 mmol), ***rac*-I** (1 mmol) and benzylamine (3 mmol) in 4 mL of CH_2Cl_2 at rt for 24 h; [b]Conversion percentage expressed as ***rac*-I** consumption, determined by NMR and HPLC; [c]Enantiomeric excesses determined by HPLC.

Regardless of the substituents of the phosphine, all the cationic complexes were active both in alkylation and amination of ***rac-I***, leading to quantitative conversions to the substituted product after 24 h of reaction time. The enantioselectivities were found to be very dependent on the ligand. It can be seen that phosphines containing the 1-pyrenyl substituent (entries 3, 4, 7 and 8) are clearly not a good choice for allylic substitutions on ***rac-I***, since they give very low chiral induction in the products. More interesting results are obtained with precursors with phosphines PPh(2-*p*-terphenylyl)R (entries 1, 2, 5, 6). For both substitution reactions racemic products are obtained for R = Me (entries 2 and 6) whereas good enantioselectivities are achieved for R = OMe (entries 1 and 5). These results are slightly better but follow the same trend than those previously published with 2-biphenylyl containing monophosphines in allylic alkylation [14].

2.6. Ru-hydrogen transfer

In hydrogen transfer reactions, a carbonyl from a ketone is reduced to the parent alcohol by a hydrogen donor, usually an alcohol, under Ru or Ir catalysis [46, 47]. These reactions are interesting because they avoid using hydrogen gas or dangerous metallic hydrides to reduce the ketone. In the asymmetric version [46, 48-50], the model substrate is undoubtedly acetophenone, dissolved in isopropanol as hydrogen donor (Scheme 9).

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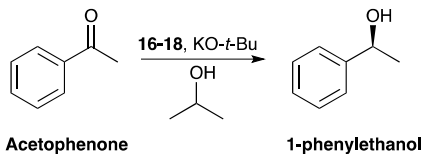

Scheme 9. TH of actophenone.

Although they are not the most typically used precursors, complexes of the type [$RuCl_2(\eta^6$-*p*-cymene)**P**] (**P** = monophosphorus ligand) in the presence of a base, are known to be active in hydrogen transfer reactions [15, 16, 38, 51]. Following previous studies with analogous complexes, the performance of complexes **16-18** was studied. The results are given in Table 3.

Table 3. Hydrogen transfer of acetophenone catalysed by complexes **16-18**.

Entry[a]	*Precursor*	*Time/h*	*Conversion/%*[b]	*ee/%*[c]
1	**16a**	1/3/5/24	9/29/48/99	< 5
2	**17a**	1/3/5/24	11/29/41/99	< 5
3	**18a**	1/3/5/24	12/29/42/99	12 (*R*)
4	**16b**	1/3/5/24	43/72/85/99	9 (*S*)
5	**17b**	1/3/5/24	8/24/39/83	6 (*R*)

[a]Catalytic conditions: Ru complex (0.02 mmol) and *t*-BuOK (0.1 mmol) dissolved in 25 mL of *i*-PrOH and activated at 82 ºC during 15 minutes before adding acetophenone (4.0 mmol); [b]Conversion of starting acetophenone; [c]Enantiomeric excess at 24 h.

All catalytic precursors are active in the reaction at reflux of isopropanol in the present of excess of *t*-BuOK, after activating the system for 15 minutes in the absence of acetophenone. Full conversions were obtained in all cases after 24 of reaction time except for **17b** (entry 5). Interestingly, the conversions at the same reaction times are all very similar except for **16b** (entry 4), which is considerably faster than the rest. This result is in contrast to previously published series of similar ligands, for which phosphines always led to faster precursors compared to the parent phosphinites [15]. On the enantioselectivities side, very low enantioselectivities were obtained for the five precursors. In this case, the elongation of the 2-biphenylyl substituent is very detrimental to enantioselectivity since precursor containing the phosphine P(*i*-Pr)Ph(2-biphenylyl) [15] leads to a 45% ee under the same conditions but precursor containing the phosphine P(*i*-Pr)Ph(2-*p*-terphenylyl) leads to only 12% ee (entry 3). A possible explanation is that the long 2-*p*-terphenylyl moiety forces the phosphine to direct the

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substituents far away from the Ru centre as it is observed in the crystal structure of **17a** described above.

3. Conclusions

In conclusion, the successful preparation of *P*-stereogenic phosphines containing a bulky 2-*p*-terphenylyl or 1-pyrenyl group by the Jugé-Stephan method has been described. The new ligands have been used to prepare and characterise three families of organometallic complexes: neutral Pd allylic complexes (**10**-**12**), cationic Pd allylic complexes (**13** and **14**) and neutral Ru *p*-cymene complexes (**16**-**18**). Neutral Pd complexes have been used in catalytic hydrovinylation of styrene with good chemo- and regioselectivity results for all the ligands and a moderate enantioselectivity (43% ee) with **12a**. Cationic Pd complexes have been used in catalytic allylic substitutions on ***rac-I***, reaching full conversions both for alkylations and aminations, with up to 80% ee in allylic alkylation and up to 60% in amination with complex **13a**. Finally, Ru complexes have been used in hydrogen transfer reactions with good activities but very low diastereoselectivities.

The best enantioselectivities have been invariably obtained with ligands containing the 2-*p*-terphenylyl group. In spite of this, the best enantioselectivities are only marginally better than those with phosphines containing the 2-biphenylyl group and the overall catalytic performance of the presented ligands is not significantly better than previous results with phosphines with smaller substituents [12, 14, 15].

4. General procedures for catalytic runs

4.1. Hydrovinylation reactions

Hydrovinylation reactions were carried out in a stainless-steel autoclave fitted with an external jacket connected to an ethanol bath and the temperature controlled using a thermostat to ± 0.5 ºC. The internal temperature was controlled with a thermocouple. The Pd precursor (0.01 mmol), styrene (1.04 g, 20 mmol) and $AgBF_4$ (2.1 mg, 0.011 mmol) were dissolved in 15 mL of dichloromethane and stirred for 10 min, protected from light. After filtering off the AgCl formed, the solution was quickly placed, by syringe, into the autoclave, which had been purged by successive vacuum/nitrogen cycles and thermostated to 25 ºC. Ethylene was admitted until a pressure of around 15 bar was reached. After the allotted time, the autoclave was slowly depressurized and 10 mL of a 10% aqueous NH_4Cl solution was added. The mixture was stirred

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for 10 min in order to quench the catalyst. The organic layer was separated, dried with Na_2SO_4, filtered through a plug of SiO_2 and subjected to GC analysis.

4.2. Allylic substitutions with dimethyl malonate

Under a nitrogen atmosphere, the appropriate Pd precursor (0.01 mmol), *trans*-1,3-diphenyl-2-propen-1-acetate (***rac*-I**, 1 mmol), dimethyl malonate (3 mmol), BSA (3 mmol) and KOAc (1 mg) were dissolved, in this precise order, in 4 mL of dichloromethane. The flask was covered with an aluminium foil and left stirring for the allotted time. In order to quench the reaction, diethyl ether (20 mL) and aqueous 10% ammonium chlorides solution (20 mL) were added. After extraction, the organic phase was dried with anhydrous sodium sulfate, filtered and the solvents removed *in vacuo*. The crude was analysed by ^{1}H NMR in order to estimate the conversion. The crude was dissolved in dichloromethane and passed trough a column of silica to remove the metallic impurities. The eluent was removed *in vacuo* and the residue was analysed by NMR and HPLC.

4.3. Allylic substitutions with benzylamine

Under a nitrogen atmosphere, the Pd precursor (0.01 mmol), *trans*-1,3-diphenyl-2-propen-1-acetate (***rac*-I**, 1 mmol) and benzylamine (3 mmol) were dissolved, in this precise order, in 4 mL of dichloromethane. The flask was covered with an aluminium foil and left stirring for the allotted time. In order to quench the reaction, diethyl ether (20 mL) and aqueous 10% ammonium chloride solution (20 mL) were added. After extraction, the organic phase was dried with anhydrous sodium sulfate, filtered and the solvents removed *in vacuo*. The eluent was removed *in vacuo* and the residue was analysed by NMR and HPLC.

4.4. Transfer hydrogenation reactions

A 50 mL *schlenk* flask was charged with the ruthenium precursor (0.02 mmol) and potassium *tert*-butoxide (11.2 mg, 0.1 mmol) and was purged with three vacuum/argon cycles. Under a gentle flow of argon, 25 ml of 2-propanol were added and the flask heated to reflux (85 ºC) for 15 minutes. After that time acetophenone (0.468 □L, 4.0 mmol) was rapidly added to start the catalytic run. The reaction was monitored at the allotted times by taking aliquots of around 0.1 mL and analysing them by GC.

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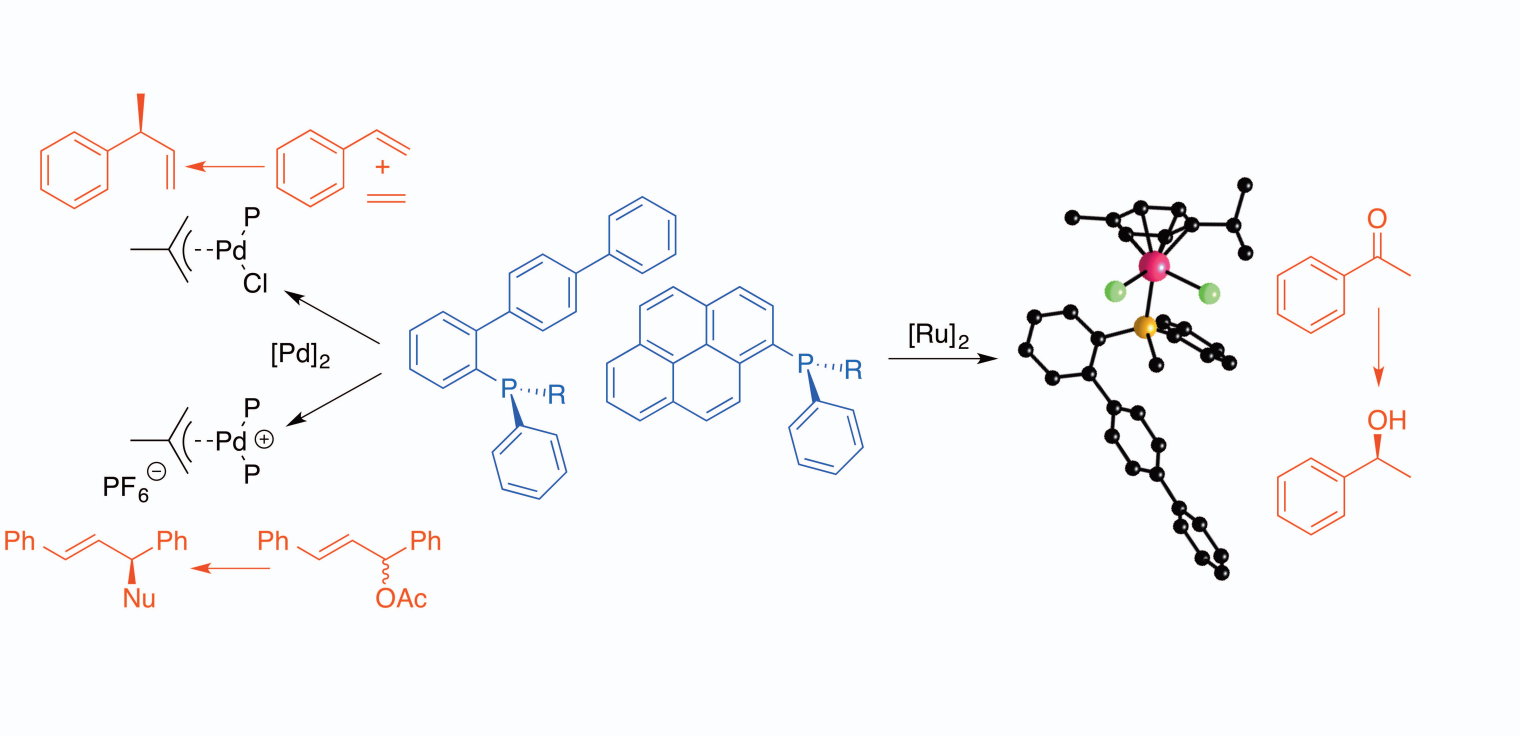
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