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Diastereomeric P^*-chiral diamidophosphites with terpene fragments in asymmetric catalysis

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Abstract—Diamidophosphite P^*-monodentate, ligands based on terpene alcohols and (*S*)- or (*R*)-(2-anilinomethyl)pyrrolidine, induce high enantioselectivities (ee's up to 99%) in Pd-catalyzed allylic substitution reactions. In the Pd-catalyzed deracemization of ethyl (*E*)-1,3-diphenylallyl carbonate up to 92% enantioselectivity has been achieved. The Rh-catalyzed asymmetric hydrogenation of α-dehydrocarboxylic acid esters leads to a maximum of 56% ee with quantitative conversion. Diastereomeric diamidophosphites prepared from [(1*S*)-*endo*]-(−)-borneol were found to be the most efficient stereoselectors.

1. Introduction

The development of novel optically active ligands remains one of the most attractive areas in the field of transition metal-catalyzed asymmetric reactions.[1]Chiral phosphites represent an important type of chirality transfer agent for asymmetric catalysis. The most important advantages of phosphite-type ligands include their pronounced π-acidity, oxidation stability, as well as their synthetic availability and low cost.[2] Indeed, the induction ability of a common diphenylphosphine fragment within phosphine-type systems can be modulated only through the introduction of an electron-donating or electron-withdrawing substituent into available positions of the phenyl ring. As for the phosphites, they provide the possibility of using a much more efficient method, that is, the replacement of carbon atoms in the first coordination sphere of the phosphorus by heteroatoms (oxygen and/or nitrogen), which allows one to modify accurately the chemical stability of the ligand, its donor–acceptor capability and steric requirements. Most of the phosphites can be synthesized rather simply and in high yield from a variety of optically active precursors. Usually it is possible to perform a direct one-pot phosphorylation of suitable chiral compounds, whereas the synthesis of the corresponding phosphine derivatives involves several steps. In addition, phosphites exhibit higher oxidative stability because of the absence of P–C bonds. In many cases, protocols for a catalytic process can be developed that do not involve the use of a glovebox, including the ligand synthesis.

The idea of designing *P*-monodentate phosphites that possess a P^*-stereocenter is rather attractive, since ligands with asymmetric donor centers are particularly efficient stereoinductors.[1a] Nevertheless, there is a rather limited number of promising P^*-chiral monodentate phosphite-type ligands. Excellent results were achieved in the Rh-catalyzed hydrogenation of functionalized olefins with phosphoramidites derived from *ortho*-substituted BINOL[3] and (*S*)-diphenylprolinol.[4] (*S*)-Prolinol-, (*S*)-*N*-tosylvalinol- and (1*R*,2*S*)-ephedrine-based phosphoramidites and diamidophosphites were used in asymmetric C^*–C bond formating reactions, but enantiomeric excesses were moderate to low.[5]

In 2004, we and Schrader et al., and later Uozumi et al., have designed and prepared novel P^*-chiral monodentate diamidophosphites having the 3-phenyl-1,3-diaza-2-phosphabicyclo[3.3.0]octane backbone and *P*-alkoxy or *P*-phenoxy substituents.[6] These ligands have shown excellent

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to good enantioselectivity in Pd- and Ir-catalyzed allylic substitution,[6a,c] respectively, but low stereodiscrimination in Cu-catalyzed conjugate addition.[6b] Further expansion of the range and effectiveness of this class of ligands could be achieved due to: (a) substances with chiral exocyclic substituents at the phosphorus atom (b) diastereomeric compounds with different absolute configuration at the $C^*(5)$ stereocenter in a phosphabicyclic framework. By now in the literature there are only few examples of the first group of ligands[6a,7] and no examples of the second group. Herein we report the synthesis and application in catalytic asymmetric transformations of such new P^*-chiral diamidophosphites based on terpene alcohols as one of the more inexpensive natural optically active auxiliaries.

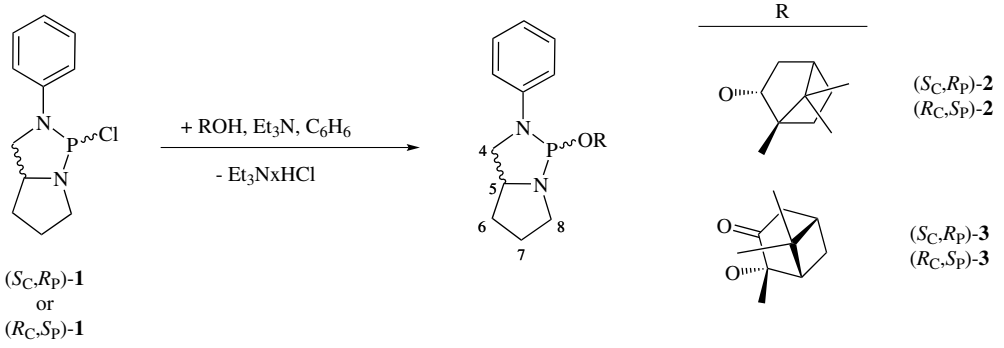
2. Results and discussion

2.1. Synthesis of P^*-monodentate diamidophosphites and their palladium complexes

As shown in Scheme 1, the synthesis of ligands (S_C,R_P)-**2**, (R_C,S_P)-**2**, (S_C,R_P)-**3**, and (R_C,S_P)-**3** is quite straightforward and involves the diastereoselective phosphorylation of [(1*S*)-*endo*]-(−)-borneol and (1*S*,2*S*,5*S*)-2α-hydroxypinan-3-one by reagents (S_C,R_P)-**1** or (R_C,S_P)-**1**[6a] derived from (*S*)- or (*R*)-(2-anilinomethyl)pyrrolidine. The last compounds can be easily obtained via the reaction of abundantly available (*S*)- or (*R*)-glutamic acids and aniline with subsequent reduction of the corresponding anilides according to a literature procedure.[8] During the phosphorylation of borneol, the exclusive formation of stereoindividual (S_C,R_P)-**2** or (R_C,S_P)-**2** takes place, whereas ligands **3** contain 33% and 4% of the second P^*-epimers, respectively (Table 1). According to the literature data, the ligand (S_C,R_P)-**2** based on the natural (*S*)-glutamic acid has the pseudoequatorial orientation of the exocyclic substituent at the phosphorus atom [i.e., *R* configuration at the P^*-stereocenter].[6a,c,8b,9] Correspondingly, the unnatural ligand (R_C,S_P)-**2** with the (*R*)-$C^*(5)$ stereocenter in the phosphabicyclic skeleton has an asymmetric phosphorus atom with an (*S*)-configuration. The same is valid for the major epimers of compounds **3**, too. Ligands **2** and major epimers of ligands **3** [(S_C,R_P)-**3**, δ_P 127.5 and (R_C,S_P)-**3**, δ_P 127.7, Table 1] have large ^2J(C(8),P) values (33.9–37.9 Hz) in their ^{13}C NMR spectra (see Section 4) owing to *cis*-orientations between the lone pair of the phosphorus atom and C(8).[5a,6a,9] The minor epimers of compounds **3** [(S_C,S_P)-**3**, δ_P 114.1 and (R_C,R_P)-**3**, δ_P 114.7, Table 1] are characterized by *trans*-orientations of the phosphorus lone pair to C(8) and, as a consequence, minimal values of ^2J(C(8),P).

Novel ligands are stable enough to allow manipulation in open air and can be stored under a dry atmosphere for several months without any degradation. It is noteworthy that owing to the ease of each step, as well as the easy-to-handle nature of all the related intermediates, diamidophosphites **2** and **3** can be prepared on multigram scales.

Compounds (S_C,R_P)-**2** and (R_C,S_P)-**2** react readily with [Pd(allyl)Cl]$_2$ ($CHCl_3$/THF, $AgBF_4$ as chloride scavenger, room temperature, 3 h) to give cationic complexes of the type [Pd(allyl)(L)$_2$]BF_4 bearing two molecules of the monodentate phosphorous ligand (Scheme 2). The ^{31}P spectra of isolated complexes exhibited broadened singlets at δ_P 111.5 for **4a** and 110.9 for **4b** due either to fast interconversion of the *exo* and *endo* isomers or to the absence of one of them (see Ref. 6a and references cited therein).



Scheme 1.

Table 1. ^{31}P NMR chemical shifts ($CDCl_3$) of ligands (S_C,R_P)-**2**, (R_C,S_P)-**2**, (S_C,R_P)-**3**, (R_C,S_P)-**3**

Ligand	δ_P
(S_C,R_P)-**2**	123.5
(R_C,S_P)-**2**	119.9
(S_C,R_P)-**3** (67%)[a]	127.5
(S_C,S_P)-**3** (33%)	114.1
(R_C,S_P)-**3** (96%)	127.7
(R_C,R_P)-**3** (4%)	114.7

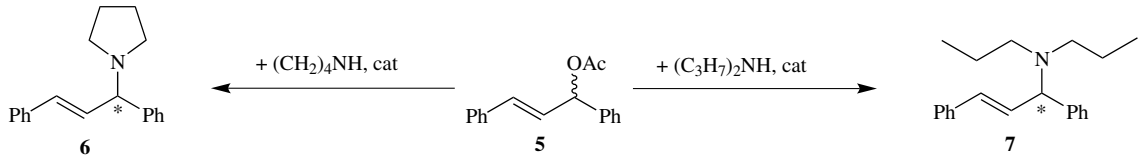
[a] Percentage of P^*-epimers.

Scheme 2.

2.2. Palladium-catalyzed asymmetric allylic amination

Our initial studies on the application of new P^*-chiral diamidophosphites and their cationic palladium complexes in catalysis focused on the asymmetric allylic amination of the racemic (*E*)-1,3-diphenylallyl acetate **5** (Scheme 3). On the one hand, this is a common benchmark test for novel groups of stereoselectors. On other hand, this is a highly efficient procedure for preparing optically active aromatic amines with a stereocenter α to the nitrogen atom. Such amines are important structural motifs in a number of biologically active compounds.[10] We first tested the new ligands in the Pd-catalyzed asymmetric allylic amination of **5** with pyrrolidine as an N-nucleophile, using standard conditions (Table 2). Both enantiomers of the product can be obtained with good enantioselectivity (ee's up to 86% for (*R*)-**6** and 85% for (*S*)-**6**, Table 2, entries 4 and 16). Both ligands (S_C,R_P)-**2** and (R_C,S_P)-**2** display a rather close efficiency (e.g., compare entries 4 and 9). On the contrary, (S_C,R_P)-**3** is less effective as diastereomer (R_C,S_P)-**3** (Table 2, entries 11–16). As a rule, THF is the optimal solvent. The absolute configuration of the allyl amine **6** depends not only on the nature of ligands, but also on the nature of the solvent too. Thus, with the participation of (R_C,S_P)-**2**, (*S*)-**6** was obtained in CH_2Cl_2, whereas in THF—(*R*)-**6** (Table 2, entries 6–9).

We also performed the allylic amination of **5** with di-*n*-propylamine as an N-nucleophile. In this reaction diamidophosphites (S_C,R_P)-**2**, (R_C,S_P)-**2**, and (R_C,S_P)-**3** are good stereoinductors, too, providing up to 90%, 80%, and 88% ee, respectively (Table 2, entries 21, 26 and 32).



Scheme 3.

Table 2. Pd-catalyzed allylic amination of **5** with pyrrolidine and di-*n*-propylamine (20 °C, 48 h)

Entry	Catalyst	L/Pd	Solvent	Conv. (%)	ee (%)
With pyrrolidine					
1	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	1/1	CH_2Cl_2	100	76 (*R*)
2	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	2/1	CH_2Cl_2	100	80 (*R*)
3	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	1/1	THF	88	84 (*R*)
4	**[Pd(allyl)Cl]$_2$/(S_C,R_P)-2**	**2/1**	**THF**	**74**	**86 (*R*)**
5	**4a**	2/1	THF	100	83 (*R*)
6	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	1/1	CH_2Cl_2	87	67 (*S*)
7	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	2/1	CH_2Cl_2	100	73 (*S*)
8	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	1/1	THF	78	20 (*R*)
9	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	2/1	THF	56	85 (*R*)
10	**4b**	2/1	THF	100	43 (*R*)
11	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**3**	1/1	CH_2Cl_2	100	57 (*S*)
12	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**3**	2/1	CH_2Cl_2	100	62 (*S*)
13	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**3**	1/1	THF	14	27 (*R*)
14	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**3**	1/1	CH_2Cl_2	100	80 (*S*)
15	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**3**	2/1	CH_2Cl_2	100	79 (*S*)
16	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**3**	1/1	THF	72	85 (*S*)
With dipropylamine					
17	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	1/1	CH_2Cl_2	100	71 (+)
18	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	2/1	CH_2Cl_2	100	81 (+)
19	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	1/1	THF	37	80 (+)
20	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	2/1	THF	82	88 (+)
21	**4a**	**2/1**	**THF**	**100**	**90 (+)**
22	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	1/1	CH_2Cl_2	100	67 (−)
23	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	2/1	CH_2Cl_2	36	80 (−)
24	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	1/1	THF	17	76 (−)
25	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	2/1	THF	35	80 (−)
26	**4b**	2/1	THF	56	80 (−)
27	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**3**	1/1	CH_2Cl_2	53	50 (+)
28	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**3**	2/1	CH_2Cl_2	88	43 (+)
29	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**3**	2/1	THF	14	16 (+)
30	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**3**	1/1	CH_2Cl_2	86	80 (−)
32	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**3**	2/1	CH_2Cl_2	100	88 (−)
32	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**3**	2/1	THF	81	65 (−)

(S_C,R_P)-**3** again allows us to achieve only moderate enantiomeric excesses (Table 2, entries 27–29). For compounds **2** THF is the solvent of choice, for compounds **3**—CH_2Cl_2. It is remarkable, that in this reaction the absolute configuration of product **7** is determined exclusively by the stereochemistry of ligands **2** and **3**: combination ($5S_C$,$2R_P$) led to the formation of (+)-**7**, ($5R_C$,$2S_P$)—to (−)-**7**. As well as in the process with the participation of pyrrolidine, an increase in the molar ratio L/Pd from 1 to 2 almost always results in the growth of the enantioselectivity.

2.3. Palladium-catalyzed asymmetric allylic sulfonylation and allylic alkylation

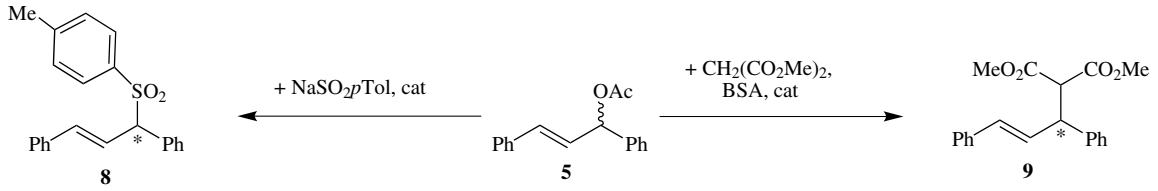
As a whole, ligands **2** are the most successful in allylic amination. The effectiveness of these stereoselectors was also assessed by employing them in enantioselective Pd-catalyzed allylic sulfonylation and allylic alkylation reactions (Scheme 4).

As well as allylic amination, these processes are powerful tools in the total synthesis of natural products.[11] In the allylic sulfonylation of **5** with $NaSO_2p$Tol as the S-nucleophile diamidophosphites **2** have shown good activity and enantioselectivity (Table 3, entries 1–6), and that (R_C,S_P)-**2** provides much greater asymmetric induction (up to 89% ee, entry 6) than (S_C,R_P)-**2**. The enantiomeric excesses practically do not depend on the molar ratio L/Pd, but cationic complexes **4a** and **4b** bearing two molecules of diamidophosphite and BF_4^- as the counter ion were found to be the most efficient (Table 3, entries 3 and 6). Compound (S_C,R_P)-**2** led to the formation of the (*S*)-enantiomer of product **8**, (R_C,S_P)-**2**—(*R*)-enantiomer. It is necessary to note that ligands **3** are appreciably less efficient (Table 3, entries 7 and 8).

The results achieved in the allylic alkylation of **5** with dimethyl malonate as the C-nucleophile are also shown in Table 3 (entries 9–20). Both ligands (S_C,R_P)-**2** and (R_C,S_P)-**2** have shown excellent enantioselectivity—up to 99% for (*S*)-**9** and 96% for (*R*)-**9**, correspondingly (Table 3, entries 11 and 17). Compounds **2** provided high enantiomeric excesses (more than 90%) of both enantiomers of product **9**, irrespective of the applied solvent, ligand/metal ratio, and counter ion.

2.4. Palladium-catalyzed deracemization

Deracemization presents a complete conversion of a racemate into one enantiomer, without intermediate separation

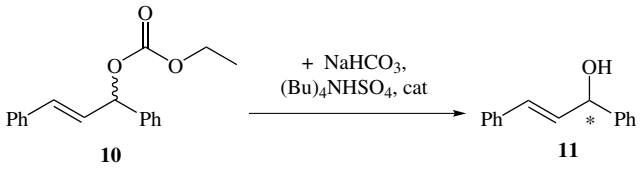


Scheme 4.

Table 3. Pd-catalyzed allylic sulfonylation of **5** with $NaSO_2p$Tol (20 °C, 48 h) and allylic alkylation of **5** with dimethyl malonate (BSA, KOAc, 20 °C, 48 h)

Entry	Catalyst	L/Pd	Solvent	Conv.[a] (%)	ee (%)
Allylic sulfonylation					
1	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	1/1	THF	34	68 (*S*)
2	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	2/1	THF	31	67 (*S*)
3	**4a**	2/1	THF	92	70 (*S*)
4	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	1/1	THF	51	77 (*R*)
5	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	2/1	THF	87	80 (*R*)
6	**4b**	**2/1**	**THF**	**92**	**89 (*R*)**
7	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**3**	2/1	THF	30	50 (*S*)
8	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**3**	2/1	THF	70	73 (*R*)
Allylic alkylation					
9	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	1/1	CH_2Cl_2	38	93 (*S*)
10	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	2/1	CH_2Cl_2	56	95 (*S*)
11	**4a**	**2/1**	**CH_2Cl_2**	**79**	**99 (*S*)**
12	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	1/1	THF	29	31 (*S*)
13	[Pd(allyl)Cl]$_2$/(S_C,R_P)-**2**	2/1	THF	40	93 (*S*)
14	**4a**	2/1	THF	54	92 (*S*)
15	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	1/1	CH_2Cl_2	84	91 (*R*)
16	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	2/1	CH_2Cl_2	100	92 (*R*)
17	**4b**	2/1	CH_2Cl_2	46	96 (*R*)
18	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	1/1	THF	66	89 (*R*)
19	[Pd(allyl)Cl]$_2$/(R_C,S_P)-**2**	2/1	THF	100	94 (*R*)
20	**4b**	2/1	THF	50	95 (*R*)

[a] Isolated yield of **8** in allylic sulfonylation.



Scheme 5.

Table 4. Pd-catalyzed deracemization of **10** (CH_2Cl_2, $NaHCO_3$, $(Bu)_4NHSO_4$, L/Pd = 2:1, 20 °C, 48 h)

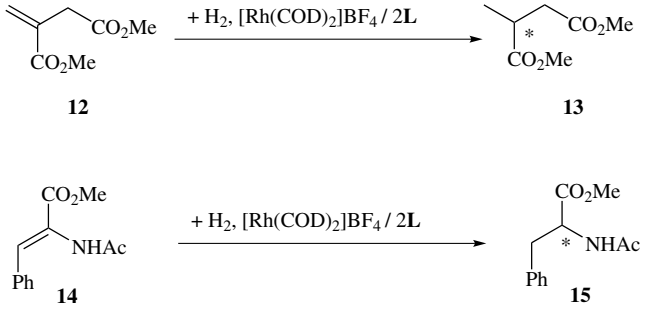
Entry	Catalyst	Conv. (%)	ee (%)
1	$[Pd(allyl)Cl]_2$/(S_C,R_P)-**2**	68	86 (*R*)
2	**4a**	80	87 (*R*)
3	**$[Pd(allyl)Cl]_2$/(R_C,S_P)-2**	**100**	**92 (*R*)**
4	**4b**	95	86 (*S*)

of isomers, and is one of the most important processes in asymmetric synthesis. Among the targets of practical significance are allyl alcohols because of their importance as building blocks in numerous organic reactions.[12,13] Their deracemization can be achieved by Pd-catalyzed substitution of allylic esters with carboxylate ions in the presence of chiral palladium complexes. Allylic ester deracemization is usually carried out in a mixture CH_2Cl_2/H_2O,[13] but we proposed water-free conditions with the formation of the $(Bu)_4NHCO_3$ salt in situ directly in organic media (Scheme 5).[7] Such a technique excludes the ester hydrolysis step from the catalytic cycle[13] and makes it possible to apply the hydrogen carbonate ion as an external nucleophile and water-sensitive organophosphorus compounds as suitable ligands.

As Table 4 shows, the deracemization of ethyl (*E*)-1,3-diphenylallyl carbonate **10** with ligands **2** and their complexes **4a** and **4b** proceeded with very good enantioselectivity (up to 92% ee, entry 3) and complete conversion. Both ligand (S_C,R_P)-**2** and its complex **4a** provided practically equal levels of asymmetric induction and the (*R*)-configuration of **11** (Table 4, entries 1 and 2). It is clear that (R_C,S_P)-**2** possesses catalytic activity and enantioselectivity higher than that of (S_C,R_P)-**2** (Table 4, entries 1 and 3). Remarkably, replacement of the counter ion in the palladium catalyst afforded product **11** with an opposite absolute configuration and slightly lower enantioselectivity (Table 4, entries 3 and 4). On a whole, ligands **2** gave an enantioselectivity of up to 92% for the asymmetric synthesis of chalcol **11**, which is very close to the maximum enantioselectivities altogether (see Ref. 7 and references cited therein).

2.5. Rhodium-catalyzed asymmetric hydrogenation

The catalytic performance of ligands **2** and **3** was also briefly explored in the enantioselective Rh-catalyzed hydrogenation of dimethyl itaconate **12** and (*Z*)-2-acetamido-3-phenylacrylate **14** as benchmark substrates, using standard conditions (Scheme 6, Table 5). Rhodium catalysts $[Rh(COD)(L)_2]BF_4$ were prepared by the reaction of



Scheme 6.

Table 5. Rh-catalyzed hydrogenation of α-dehydrocarboxylic acid esters (CH_2Cl_2, L/Rh = 2:1, 5 bar H_2, 20 °C, 40 h)

Entry	Ligand	Substrate	Conv. (%)	ee (%)
1	(S_C,R_P)-**2**	**12**	100	26 (*R*)
2	(R_C,S_P)-**2**	**12**	100	21 (*R*)
3	(S_C,R_P)-**3**	**12**	74	31 (*S*)
4	(R_C,S_P)-**3**	**12**	91	35 (*R*)
5	(S_C,R_P)-**2**	**14**	100	38 (*R*)
6	**(R_C,S_P)-2**	**14**	**100**	**56 (*S*)**
7	(S_C,R_P)-**3**	**14**	100	23 (*R*)
8	(R_C,S_P)-**3**	**14**	100	50 (*R*)

$[Rh(COD)_2]BF_4$ with 2 equiv of the ligand in CH_2Cl_2. Only doublets characterizing the desired complexes were found in the ^{31}P NMR spectra of the reaction solutions (S_C,R_P)-**2**: δ_P 90.0, ^1J(P,Rh) 213.4 Hz; (R_C,S_P)-**2**: δ_P 92.5, ^1J(P,Rh) 212.6 Hz; (S_C,R_P)-**3**: δ_P 101.1, ^1J(P,Rh) 212.7 Hz; (R_C,S_P)-**3**: δ_P 82.0, ^1J(P,Rh) 220.8 Hz. MALDI TOF/TOF MS spectroscopic data for the reaction solutions were also in good agreement with the proposed structure of the catalysts, as fragmentary ions $[Rh(L)_2]^+$ were registered with intensity of 100% [e.g., (S_C,R_P)-**2**: *m*/*z*: 820; (S_C,R_P)-**3**: *m*/*z*: 848].

High conversions and moderate enantioselectivities in the range of 21–56% ee were observed (Table 5). There is no direct correlation between the stereochemistry of compounds **2** and **3** and the absolute configuration of products **13** and **15**. In general, enantioselectivities were inferior in comparison to those reported with MOP-type P^*-chiral diamidophosphites having a rigid axially chiral monomethylated BINOL exocyclic fragment.[7]

3. Conclusion

In conclusion, several P^*-chiral monodentate diamidophosphites based on (*S*)- or (*R*)-(2-anilinomethyl)pyrrolidine and terpene alcohols were obtained for the first time over the course of a simple synthesis. The results obtained with these compounds in the Pd-catalyzed asymmetric allylation and deracemization reactions, and in the Rh-catalyzed asymmetric hydrogenation reactions show the great potential of such type of ligands in enantioselective catalysis. In particular, the inversion of the absolute configuration at the $C^*(5)$ stereocenter, and as result,

at the $P^*(2)$ stereocenter in phosphabicyclic frameworks of the novel ligands allows us to control the size and sign of asymmetric induction. The advantageous features of this type of ligands, such as inexpensive starting materials, facile preparation, and structural diversity, as well as the possibility of varying the phosphabicyclic backbone stereochemistry, will stimulate future studies directed at testing the ligands in other transition metal-catalyzed asymmetric reactions.

4. Experimental

4.1. General

^{31}P, ^{13}C, and ^{1}H NMR spectra were recorded with a Bruker AMX 400 instrument (162.0 MHz for ^{31}P, 100.6 MHz for ^{13}C, and 400.13 MHz for ^{1}H). Complete assignment of all the resonances in ^{13}C NMR spectra was achieved by the use of DEPT techniques. Chemical shifts (ppm) are given relative to Me_4Si (^{1}H and ^{13}C) and 85% H_3PO_4 (^{31}P NMR). Mass spectra were recorded with a Varian MAT 311 spectrometer (EI) and a Bruker Daltonics Ultraflex spectrometer (MALDI TOF/TOF). Optical rotations were measured on a Perkin–Elmer 341 polarimeter. Elemental analyses were performed at the Laboratory of Microanalysis (Institute of Organoelement Compounds, Moscow).

The conversion of substrate **5**[14] and enantiomeric excess of products **6**,[15] **7**[16] and **9**[14] were determined using HPLC (Daicel Chiralcel OD-H column) as previously described. The enantiomeric excess of product **8** was determined using HPLC [(*R*,*R*)-WHELK-01 column] according to the literature.[17] The conversion of substrate **10** and the ee of product **11** were determined using HPLC (Daicel Chiralcel OD-H column) according to the literature.[18] The conversion of substrates **12** and **14** was determined by ^{1}H NMR. Enantiomeric excess of products **13** and **15** was determined using HPLC (Daicel Chiralcel OD-H column) according to the literature.[19]

All reactions were carried out under a dry argon atmosphere in freshly dried and distilled solvents; Et_3N, pyrrolidine and dipropylamine were twice distilled over KOH and then over a small amount of $LiAlH_4$ before use. (1*S*,2*S*,5*S*)-2α-Hydroxypinan-3-one was synthesized using the literature procedures.[20] Phosphorylating reagents—(2*R*,5*S*)- or (2*S*,5*R*)-2-chloro-3-phenyl-1,3-diaza-2-phosphabicyclo[3.3.0]octane were prepared as published.[6a] $[Pd(allyl)Cl]_2$[21] and $[Rh(COD)_2]BF_4$[22] were prepared as described earlier. Cationic palladium complexes **4a** and **4b** were synthesized analogously by the known procedures.[6a] Catalytic experiments: allylic amination of substrate **5** with pyrrolidine, allylic amination with dipropylamine, allylic sulfonylation with sodium *para*-toluene sulfinate, allylic alkylation with dimethyl malonate and deracemization of substrate **10** were performed according to the appropriate procedures.[23,24,6a,7]

Starting substrates **5**, **10**, and **14** were synthesized as published.[21,25,26] Dimethyl malonate, dimethyl itaconate, BSA (*N*,*O*-bis(trimethylsilyl) acetamide), and sodium *para*-toluene sulfinate were purchased from Aldrich and Acros Organics and used without further purification.

4.2. General procedure for the synthesis of ligands (S_C,R_P)-2, (R_C,S_P)-2, (S_C,R_P)-3, and (R_C,S_P)-3

A solution of Et_3N (1.9 mmol) and the appropriate terpene alcohol (1.8 mmol) in benzene (10 ml) was added to a vigorously stirred solution of phosphorylating reagent (1.8 mmol) in benzene (20 ml). The mixture was heated while stirring to the boiling point and then cooled down to 20 °C. Solid $Et_3N \times HCl$ was filtered off; benzene was removed under reduced pressure (40 Torr). The residue was dissolved in hexane (12 ml), filtered, evaporated, and dried in vacuum (1 Torr) for 2 h. Compounds (S_C,R_P)-**3** and (R_C,S_P)-**3** were additionally purified by flash chromatography on silica gel (ethylacetate/hexane 1:1).

4.2.1. (2*R*,5*S*,1′*S*,2′*R*)-2-(1′,7′,7′-Trimethylbicyclo[2.2.1]-heptyl-2′-oxy)-3-phenyl-1,3-diaza-2-phosphabicyclo[3.3.0]-octane (S_C,R_P)-2. Yield: 89% as a colorless oil; $[\alpha]_D^{20} = -251.4$ (*c* 1.0, CH_2Cl_2); ^{13}C NMR ($CDCl_3$): δ 13.5 [s, C(10′)], 18.9 [s, C(8′)], 20.0 [s, C(9′)], 26.4 [d, $^{3}J = 3.6$ Hz, C(7)], 26.8 [s, C(6′)], 28.2 [s, C(5′)], 31.9 [s, C(6)], 38.5 [s, C(3′)], 45.1 [s, C(4′)], 47.3 [s, C(7′)], 48.2 [d, $^{2}J = 36.5$ Hz, C(8)], 49.4 [s, C(1′)], 54.7 [d, $^{2}J = 7.3$ Hz, C(4)], 62.4 [d, $^{2}J = 8.8$ Hz, C(5)], 78.5 [s, C(2′)], 114.9 (d, $^{3}J = 12.4$ Hz), 118.5 (s), 128.9 (s), 146.1 (d, $^{2}J = 16.1$ Hz) (C_{Ar}); MS (EI), *m*/*z* (I, %): 358 (34) $[M]^+$, 222 (51) $[M-Bornyl+H]^+$, 205 (100) $[M-BornylO]^+$ (Bornyl = $C_{10}H_{17}$). Anal. Calcd for $C_{21}H_{31}N_2OP$: C, 70.36; H, 8.72; N, 7.81. Found: C, 70.58; H, 8.83; N, 7.72.

4.2.2. (2*S*,5*R*,1′*S*,2′*R*)-2-(1′,7′,7′-Trimethylbicyclo[2.2.1]-heptyl-2′-oxy)-3-phenyl-1,3-diaza-2-phosphabicyclo[3.3.0]-octane (R_C,S_P)-2. Yield: 86% as a white solid; mp: 80–81 °C; $[\alpha]_D^{20} = +237.7$ (*c* 1.0, CH_2Cl_2); ^{13}C NMR ($CDCl_3$): δ 13.2 [s, C(10′)], 18.9 [s, C(8′)], 20.1 [s, C(9′)], 26.3 [d, $^{3}J = 4.4$ Hz, C(7)], 26.8 [s, C(6′)], 28.2 [s, C(5′)], 32.4 [s, C(6)], 37.3 [s, C(3′)], 45.1 [s, C(4′)], 47.3 [s, C(7′)], 48.3 [d, $^{2}J = 37.9$ Hz, C(8)], 49.3 [s, C(1′)], 54.3 [d, $^{2}J = 8.0$ Hz, C(4)], 63.4 [d, $^{2}J = 8.8$ Hz, C(5)], 78.1 [d, $^{2}J = 5.8$ Hz, C(2′)], 114.9 (d, $^{3}J = 11.7$ Hz), 118.5 (s), 129.0 (s), 146.0 (d, $^{2}J = 16.1$ Hz) (C_{Ar}); MS (EI), *m*/*z* (I, %): 358 (42) $[M]^+$, 222 (55) $[M-Bornyl+H]^+$, 205 (100) $[M-BornylO]^+$ (Bornyl = $C_{10}H_{17}$). Anal. Calcd for $C_{21}H_{31}N_2OP$: C, 70.36; H, 8.72; N, 7.81. Found: C, 70.66; H, 8.87; N, 7.88.

4.2.3. (2*R*,5*S*,1′*S*,2′*S*,5′*S*)-2-(2′,6′,6′-Trimethylbicyclo[3.1.1]-heptan-3′-one-2′-oxy)-3-phenyl-1,3-diaza-2-phosphabicyclo-[3.3.0]octane (S_C,R_P)-3. Yield: 72% as a yellowish oil; $[\alpha]_D^{25} = -197.1$ (*c* 1.0, CH_2Cl_2); ^{13}C NMR ($CDCl_3$): δ 22.7 [s, C(8′)], 24.3 [d, $^{3}J = 10.9$ Hz, C(10′)], 26.3 [d, $^{3}J = 4.4$ Hz, C(7)], 27.4 [s, C(9′)], 28.7 [s, C(7′)], 31.9 [s, C(6)], 38.5 [s, C(5′)], 43.4 [s, C(6′)], 44.1 [s, C(4′)], 48.2 [d, $^{2}J = 34.3$ Hz, C(8)], 51.5 [s, C(1′)], 53.1 [d, $^{2}J = 7.3$ 0 Hz, C(4)], 62.8 [d, $^{2}J = 8.0$ Hz, C(5)], 81.3 [s, C(2′)], 115.4 (d, $^{3}J = 13.1$ Hz), 118.6 (s), 128.9 (s), 145.7 (d, $^{2}J = 14.6$ Hz) (C_{Ar}), 210.7 (s, C=O) (major epimer) and 22.9 [s, C(8′)], 25.3 [d, $^{3}J = 10.2$ Hz, C(10′)], 27.0 [s,

C(7)], 27.3 [s, C(9′)], 28.4 [s, C(7′)], 32.4 [s, C(6)], 38.3 [s, C(5′)], 42.6 [s, C(6′)], 43.0 [s, C(4′)], 44.9 [d, $^2J = 5.6$ Hz, C(8)], 49.8 [s, C(1′)], 51.6 [d, $^2J = 6.9$ 0 Hz, C(4)], 65.4 [d, $^2J = 10.2$ Hz, C(5)], 80.6 [s, C(2′)], 117.3 (d, $^3J = 12.4$ Hz), 119.7 (s), 129.2 (s), 145.9 (d, $^2J = 13.6$ Hz) (C_{Ar}), 210.2 (s, C=O) (minor epimer); MS (EI), *m*/*z* (I, %): 372 (8) $[M]^+$, 222 (63) $[M-(\text{Pinan-3-one-2-yl})+H]^+$, 205 (100) $[M-(\text{Pinan-3-one-2-ylO})]^+$ (Pinan-3-one-2-yl = $C_{10}H_{15}O$). Anal. Calcd for $C_{21}H_{29}N_2O_2P$: C, 67.72; H, 7.85; N, 7.52. Found: C, 67.85; H, 7.91; N, 7.60.

4.2.4. (2*S*,5*R*,1′*S*,2′*S*,5′*S*)-2-(2′,6′,6′-Trimethylbicyclo[3.1.1]-heptan-3′-one-2′-oxy)-3-phenyl-1,3-diaza-2-phosphabicyclo-[3.3.0]octane (R_C,S_P)-3. Yield: 75% as an off-white solid; mp: 115–117 °C; $[\alpha]_D^{25} = +217.4$ (*c* 1.0, CH_2Cl_2); ^{13}C NMR ($CDCl_3$): δ 22.6 [s, C(8′)], 24.1 [d, $^3J = 10.9$ Hz, C(10′)], 26.0 [d, $^3J = 4.0$ Hz, C(7)], 27.3 [s, C(9′)], 28.8 [s, C(7′)], 31.8 [s, C(6)], 38.4 [s, C(5′)], 43.0 [s, C(6′)], 44.0 [s, C(4′)], 47.9 [d, $^2J = 33.9$ Hz, C(8)], 51.3 [s, C(1′)], 53.1 [d, $^2J = 6.6.0$ Hz, C(4)], 62.6 [d, $^2J = 8.4$ Hz, C(5)], 80.9 [d, $^2J = 3.8$ Hz, C(2′)], 115.3 (d, $^3J = 13.5$ Hz), 118.5 (s), 128.8 (s), 146.3 (d, $^2J = 15.7$ Hz) (C_{Ar}), 210.5 (d, $^3J = 2.6$ Hz, C=O); MS (EI), *m*/*z* (I, %): 372 (10) $[M]^+$, 222 (58) $[M-(\text{Pinan-3-one-2-yl})+H]^+$, 205 (100) $[M-(\text{Pinan-3-one-2-ylO})]^+$ (Pinan-3-one-2-yl = $C_{10}H_{15}O$). Anal. Calcd for $C_{21}H_{29}N_2O_2P$: C, 67.72; H, 7.85; N, 7.52. Found: C, 67.82; H, 7.80; N, 7.63.

4.3. Palladium complexes

4.3.1. [Pd(allyl)((S_C,R_P)-2)$_2$]BF_4 4a. Yield: 89% as a yellow solid; mp: 152 °C (dec); MS (MALDI TOF/TOF), *m*/*z* (I, %): 864 (100) $[M-BF_4]^+$, 823 (21) $[M-BF_4\text{-allyl}]^+$. Anal. Calcd for $C_{45}H_{67}BF_4N_4O_2P_2Pd$: C, 56.82; H, 7.10; N, 5.89; Found: C, 57.11; H, 7.24; N, 6.0.

4.3.2. [Pd(allyl)((R_C,S_P)-2)$_2$]BF_4 4b. Yield: 91% as a yellow solid; mp: 123 °C (dec); MS (MALDI TOF/TOF), *m*/*z* (I, %): 864 (100) $[M-BF_4]^+$, 823 (30) $[M-BF_4\text{-allyl}]^+$. Anal. Calcd for $C_{45}H_{67}BF_4N_4O_2P_2Pd$: C, 56.82; H, 7.10; N, 5.89; Found: C, 56.99; H, 7.17; N, 5.73.

4.4. General procedure for the hydrogenation

$[Rh(COD)_2]BF_4$ (4 mg, 0.01 mmol) and the appropriate ligand (0.02 mmol) were dissolved in CH_2Cl_2 (3 ml) under argon and the solution was stirred at room temperature for 30 min at 20 °C. A solution of substrate **12** or **14** (1 mmol) in CH_2Cl_2 (3 ml) was added to the above catalyst solution. The resulting mixture was then transferred to a stainless steel autoclave under an argon atmosphere. A vacuum was applied three times until the solvent began to evaporate gently, and hydrogen was introduced. Hydrogenation was carried out at 5 bar for 40 h. Following dilution, the reaction solution was passed through a silica gel prior to the ^1H NMR or HPLC analysis. Removal of the solvent under reduced pressure afforded the product residue which was submitted to ^1H NMR analysis to assess the conversion of the starting materials. The enantiomeric excesses of products **13** and **15** were determined by chiral HPLC (Daicel Chiralcel OD-H, C_6H_{14}/*i*-PrOH = 98:2, 0.8 ml/min, 215 nm and C_6H_{14}/*i*-PrOH = 9:1, 1.0 ml/min, 254 nm, respectively).

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