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o-DPPB-Directed Copper-Mediated and -Catalyzed Allylic Substitution with Grignard Reagents**

Peter Demel, Manfred Keller, and Bernhard Breit*[a]

Abstract: The *ortho*-diphenylphosphanylbenzoyl (*o*-DPPB) group was explored as a directing leaving group in copper-mediated and copper-catalyzed allylic substitution with Grignard reagents. Complete control of chemo-, regio- and stereoselectivity with complete *syn*-1,3-chirality transfer was observed as a result of the directed nature of the reaction. No excess of organometallic reagent is required and the directing group can be recovered quantitatively. Coordination studies in the solid state and in solution have shown that two substrates are bound via the phosphine function of the directing group at copper. Dynamic NMR experiments in solution are in agreement with a ligand-exchange process at copper, a prerequisite for the development of a substoichiometric process.

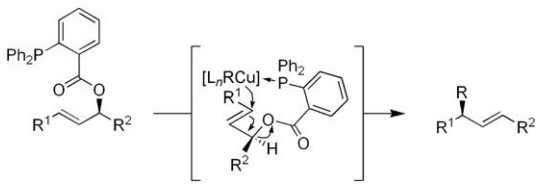
Keywords: allylic substitution · asymmetric synthesis · grignard reagents · organocopper reagents · synthetic methods

Introduction

Synthetic transformations which allow the regio- and stereoselective construction of a desired carbon skeleton in a predictable and reliable fashion are of fundamental importance for organic synthesis. In this respect the allylic substitution with organocopper reagents is an attractive operation since in contrast to many other transition-metal catalyzed allylic substitutions it allows the introduction of hard nucleophiles such as alkyl, alkenyl and aryl substituents.[1] However, the simultaneous control of regio- and stereochemistry is a difficult problem to solve, and only a few successful examples are known.[2] One solution to this problem makes use of reagent-directing leaving groups which control the trajectory of the incoming copper nucleophile to occur as an exclusive γ-attack.[1] Additionally, a directing leaving group reverses the stereochemical course of the allylic substitution to occur as a *syn* process in opposition to the natural *anti* attack relative to the leaving group.[3] Among the leaving groups evaluated for this purpose, carbamates[4] and benzothiazoles[5] have proven to be useful. However, both systems suffer from drawbacks. For instance, control over alkene geometry upon reaction of acyclic derivatives is often unsatisfactory, so that chirality transfer is incomplete.[1] Furthermore, in many cases an excess of the organometallic reagent is required, which is particularly undesirable if valuable organic residues are to be transferred.[4,5] Notably, the directing leaving group is generally irreversibly lost in the overall process.

In previous work we have identified the *ortho*-diphenylphosphanylbenzoyl (*o*-DPPB)-group as a multifunctional reagent-directing group (Scheme 1).[6] Several late transition-metal catalyzed or mediated processes such as hydroformylation,[7] rhodium catalyzed domino processes,[8] palladium catalyzed atropselective biaryl coupling,[9] palladium catalyzed allylic substitution[10] as well as conjugate addition of organocopper reagents[11] have been described.

We herein report in full detail on the exploration of the *o*-DPPB group as a reagent-directing leaving group for regio- and stereoselective allylic substitution with organo-



Scheme 1. *o*-DPPB-directed allylic substitution with organocopper reagents.

[a] Dr. P. Demel, Dr. M. Keller,[+] Prof. Dr. B. Breit
Institut für Organische Chemie und Biochemie
Albert-Ludwigs-Universität Freiburg
Albertstrasse 21, 79104 Freiburg (Germany)
Fax: (+49)761 203 8715
E-mail: bernhard.breit@organik.chemie.uni-freiburg.de

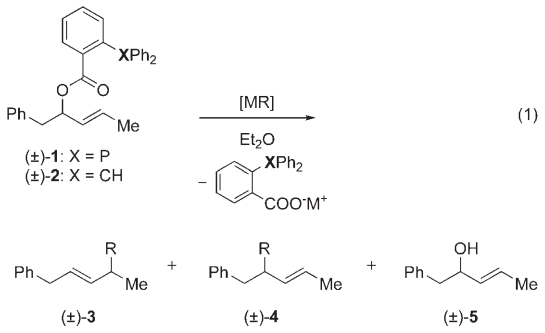
[+] X-ray crystal structure analysis of **34**.

[**] *o*-DPPB-Directed Copper-Mediated Allylic Substitution: Part 1.

copper reagents.[12] Specifically, experiments towards optimized reaction conditions as well as those clarifying the role of the *o*-DPPB group are described. Limit and scope of the regioselectivity of the *o*-DPPB-directed allylic substitution has been evaluated, and experiments clarifying the stereochemical course of the directed allylic substitution are presented. Furthermore, the coordination behavior of the allylic *o*-DPPB esters towards copper(I) was studied in solution as well as the solid state. Finally, first results employing substoichiometric amounts of copper(I) salts are reported.

Results and Discussion

Development of the *o*-DPPB-directed allylic substitution: **Orientating experiments**: Our investigations began with the allylic-*o*-DPPB ester (±)-**1**. This substrate was chosen since it is structurally not biased towards preference of either α- or γ-attack to give alkenes **3** and **4**, respectively (Table 1).



(1)

First experiments were conducted with Gilman cuprates. When allylic *o*-DPPB ester **1** was treated with two equivalents of dimethylcuprate at −20 °C a quantitative conversion was observed with formation of a 3:1 mixture of S_N2' substitution product **3** and S_N2 product **4** (Table 1, entry 1). Lowering the reaction temperature did not prove beneficial with respect to regioselectivity (Table 1, entry 2). In order to see whether this result was due to a directing effect of the *o*-DPPB group the CH-derivative **2** was employed (Table 1, entry 3). Here, the benzoate function should have similar electronic and steric properties except for the lack of capability for metal coordination, and hence for the ability to direct the organocopper reagent. As a result, substrate **2** gave almost the same regioselectivity of 78:22 (Table 1, entry 3) as found for the *o*-DPPB ester **1**. This suggests that for the dimethylcuprate reagent, the allylic substitution of *o*-DPPB ester **1** does not proceed via a directed reaction pathway.

We next turned our attention to organocopper reagents which should have both lower reactivity in combination with a pronounced affinity for phosphine coordination.[1,13] First, the "lower-order cyanocuprate" was looked at, since it is known to provide an intrinsically higher S_N2' selectivity.[1,13] Accordingly, the γ-substitution product **3** was obtained in a 97:3 ratio (Table 1, entry 4). However, the reaction rate was rather low.

In order to ensure a complete intramolecular transfer of the organocopper reagent we wondered whether a precomplexation of a copper(I) salt by the *o*-DPPB ester prior to the generation of the organocopper reagent could be the solution. In fact, best results were obtained when the *o*-DPPB ester **1** was pretreated with one equivalent of copper bromide dimethyl sulfide. Subsequent addition of 1.1 equivalents of methyl magnesium iodide at room temperature in diethyl ether led within less then two minutes to the quantitative formation of the S_N2' substitution product **3** exclusively with complete control of alkene geometry (Table 1, entry 5). When CH-benzoate **2** was subjected to identical conditions, six hours were required to achieve a conversion of 80 %. Furthermore, the reaction displayed a dramatically reduced chemo-, regio- and stereoselectivity. Hence, both observations, the striking differences in chemo-, regio- and diastereoselectivity as well as the significant rate acceleration underline the role of the *o*-DPPB group to function as a reagent-directing leaving group. Most interestingly, only one equivalent of Grignard reagent was necessary in order to achieve a quantitative reaction, which renders this method most attractive for transfer of valuable organic residues.[14,15]

Regioselectivity of the *o*-DPPB directed allylic substitution: Next, generality of the *o*-DPPB-directed regio- and stereoselective allylic substitution was probed with respect to the nature of the organic residue to be transferred. Thus, both *n*-butyl magnesium chloride as well as isopropyl magnesium bromide furnished the S_N2' substitution product **3** with excellent regio- and stereoselectivity (Table 2, entries 1 and 2). However, the S_N2' selectivity dropped when phenylmagnesium bromide was used. Interestingly, slowing down the addition rate of the Grignard reagent to the copper(I)-precomplexed substrate **2** led to excellent regioselectivity (Table 2,

Table 1. Results of the reaction of allylic benzoates **1** and **2** with different methylcopper reagents [see Eq. (1)].

Entry	Equiv. [MR]	X	*T* [°C]	*t* [h]	Yield[a] [%]	Ratio of **3**[b]:**4**:**5**
1	2 Me_2CuLi·LiI	P	−20	3	>95	75:25:–
2	2 Me_2CuLi·LiI	P	−80	6	>95	74:26:–
3	2 Me_2CuLi·LiI	CH	−20	3	>95	78:22:–
4	2 MeCu(CN)Li	P	−20	65	>95	95:5:–
5	1 CuBr·SMe_2/1.1 MeMgI	P	RT	2 min	>95	>99:1:–
6	1 CuBr·SMe_2/1.1 MeMgI	CH	RT	6	80[c]	42[d]:15:21
7	2.5 MeMgI	P	RT	48	98[e]	–:–:>99

[a] GC yield. [b] *E*/*Z* >99:1. [c] Conversion. [d] The S_N2' product **3** was obtained as a *E*/*Z* mixture (64:36). [e] Isolated yield after aqueous work-up and flash chromatography.

Table 2. Results of the *o*-DPPB-directed copper-mediated allylic substitution of *o*-DPPB ester **1** with Grignard reagents [Eq. (1)].

Entry	Equiv. [MR][a]	*t* [h]	Yield[b] [%]	Ratio[c] **3**[d]:**4**:**5**
1	1 CuBr·SMe_2/1.1 *n*BuMgCl	2	98	>99:1:–
2	1 CuBr·SMe_2/1.1 *i*PrMgBr	2	84	97:3:–
3	1 CuBr·SMe_2/1.1 PhMgBr	2	94	88:12:–
4	0.5 CuBr·SMe_2/1.1 PhMgBr	2	90	93:7:–
5	0.5 CuBr·SMe_2/1.1 PhMgBr[e]	5	84	97:3:–
6	0.5 CuBr·SMe_2/1.2 PhMgBr[f]	0.5	94	97:3:–
7	0.5 CuBr·SMe_2/1.1 (2-propenyl)MgBr[g]	2	81	85:15:–
8	0.5 CuBr·SMe_2/1.1 (2-propenyl)MgBr[h]	4	73	94:6:–[i]
9	0.5 CuBr·SMe_2/2.1 allylMgBr	2	87	–:–:>99

[a] All reactions were performed with (±)-**1** (X=P) at room temperature (25 °C) in Et_2O (0.05 M), if not otherwise quoted. [b] Isolated yield after aqueous work-up and flash chromatography. [c] GC Analysis of the crude product mixture. [d] *E*/*Z* >99:1. [e] $c(Et_2O)=0.005$ M, addition time (PhMgBr)=300 min. [f] As for [e] but substrate **1** was used in dichloromethane solution, c (CH_2Cl_2)=0.05 M. [g] $c(Et_2O)=0.01$ M, addition time [(2-propenyl)MgBr, $c=0.11$ mol L^{-1}]=5 min. [h] $c(Et_2O)=0.05$ M, addition time [(2-propenyl)MgBr, $c=0.122$ mol L^{-1}]=180 min. [i] GC Analysis showed a mixture (60:40) of the substitution products **3**/**4** and the elimination products (*E*,*E*)-1-phenyl-1,3-pentadiene, (*E*,*Z*)-1-phenyl-1,3-pentadiene and (*E*)-5-phenyl-1,3-pentadiene.[17] The relative ratio of the dienes was 40:17:43.

entries 5 and 6). The best yield for this reaction was achieved when a solvent mixture of dichloromethane and diethyl ether was used (Table 2, entry 6). Employing similar reaction conditions, transfer of an alkenyl residue (2-propenyl) was achieved with high S_N2' selectivity (Table 2, entry 8).

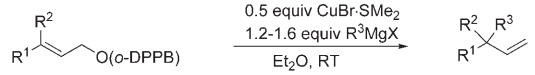
A unified explanation of these observations may suggest that only organocopper reagents (RCu) are capable to react via the highly selective *o*-DPPB-directed pathway.[16] On the other hand, experiments from above (Table 1, entries 1–3) suggest that cuprate species (R_2Cu^-) react via a non-directed unselective intermolecular pathway. Hence, in case of the more nucleophilic alkyl copper reagents (Table 2, entries 1, 2), the rate of the directed allylic substitution is greater than the rate of a competing cuprate formation followed by a non-directed unselective pathway, even under fast addition rates of the alkyl-Grignard reagent. However, in case of the less nucleophilic aryl- and alkenyl–organometallic reagents the rate of the directed process may be slower which may result in the accumulation of the corresponding cuprate reagent, which would react via a non-directed pathway resulting in a diminished regioselectivity. Hence, slowing down the Grignard addition rate could avoid formation and accumulation of the cuprate reagent, and would ensure directed and hence selective allylic substitution via the organocopper reagent.

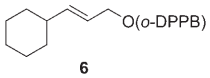
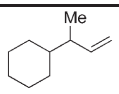
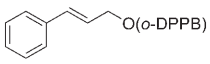
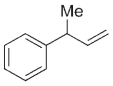
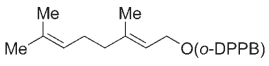
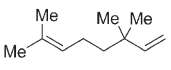
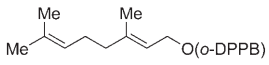
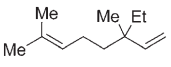
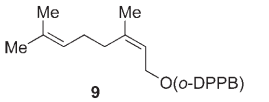
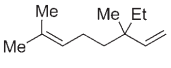
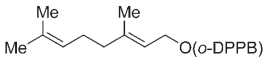
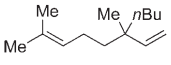
An obvious limitation at the present stage of this method is the reaction with allyl-Grignard reagent. In this case neither S_N2' (**3**) nor S_N2 product **4** were observed. Instead, quantitative formation of allylic alcohol **5** was noted (Table 2, entry 9).

Next, regioselectivity as a function of substrate structure was studied. A series of primary allylic alcohols was transformed into the corresponding *o*-DPPB esters **6**–**9**. Employing the protocol of the directed allylic substitution in general excellent S_N2' regioselectivities and yields were observed (Table 3). Irrespective of double-bond geometry [compare geraniol and nerol *o*-DPPB ester **8** and **9** (Table 3, entries 3–6)] excellent regioselectivity with concomitant construction of quaternary carbon centers was observed.

A series of secondary allylic *o*-DPPB esters starting from acyclic secondary allylic alcohols was prepared and subjected to the conditions of the directed allylic substitution (Table 4). Again, excellent levels of regioselectivity were found and isolated yields of the corresponding S_N2' products

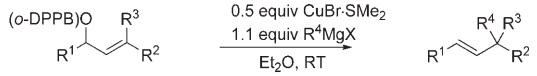
Table 3. *o*-DPPB-directed copper-mediated allylic substitution of primary *o*-DPPB esters with Grignard reagents.

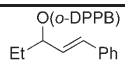
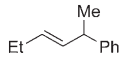
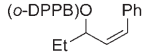
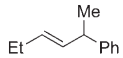
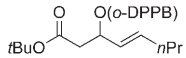
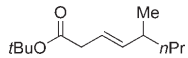
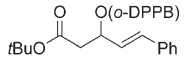
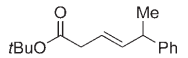
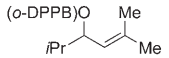
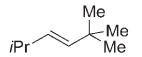
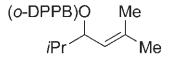
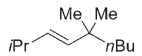


Entry[a]	*o*-DPPB-ester[b]	RMgX (equiv)	Product	S_N2'/S_N2[c]	Yield[d]
1[e]	 **6**	MeMgI (1.6)	 **10**	>99:1	99
2[f]	 **7**	MeMgI (1.1)	 **11**	92:8	99
3[g]	 **8**	MeMgI (1.2)	 **12**	95:5	91
4[h]	 **8**	EtMgBr (1.2)	 **13**	>98:2	80
5[h]	 **9**	EtMgBr (1.2)	 **13**	>98:2	95
6[i]	 **8**	*n*BuMgBr (1.2)	 **14**	>99:1	87

[a] The Grignard reagents in Et_2O were added to the reaction mixture using a syringe pump. [b] For preparation of *o*-DPPB esters see Experimental Section. [c] Determined by GC (CPSil5CB, 30 m, 0.32 mm ID, Chrompack). [d] Isolated yield after aqueous work-up and chromatographic purification. [e] c(substrate)=0.01 M, c(Grignard)=0.1 M, Grignard addition time 190 min. [f] c(substrate)=0.01 M, c(Grignard)=0.1 M, Grignard addition time 240 min. [g] c(Grignard)=0.83 M. [h] c(Grignard)=1.02 M. [i] c(Grignard)=1.23 M.

Table 4. *o*-DPPB-directed copper-mediated allylic substitution of secondary *o*-DPPB esters with Grignard reagents.



Entry[a]	*o*-DPPB-ester[b]	RMgX	Product	S_N2'/S_N2[c] ($S_N2':E/Z$)	Yield[d]
1	 (±)-(*E*)-**15**	MeMgI	 (±)-**19**	97:3 (96:4)	84
2	 (±)-(*Z*)-**15**	MeMgI	 (±)-**19**	>99:1 (98:2)	88
3	 (±)-**16**	MeMgI	 (±)-**20**	95:5 (>95:5)	82
4	 (±)-**17**	MeMgI	 (±)-**21**	97:3 (97:3)	86
5	 (±)-**18**	MeMgI	 (±)-**22**	>99:1 (>99:1)	68[e]
6	 (±)-**18**	*n*BuMgBr	 (±)-**23**	99:1 (>99:1)	99

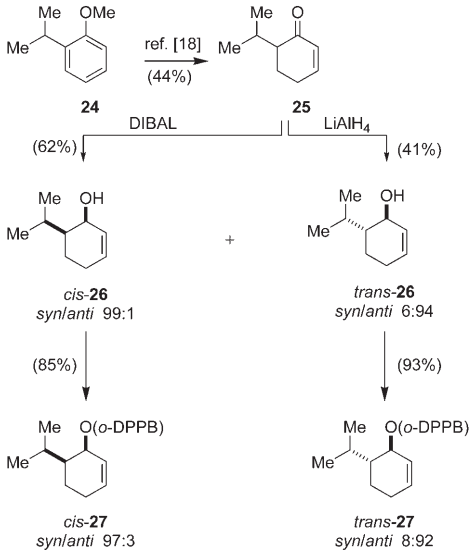
[a] The Grignard reagents (0.5–1.11 M in Et_2O) were added to the reaction mixture during 15-20 min using a syringe pump; *c*(substrate) = 0.05 M. [b] For preparation of *o*-DPPB esters see Experimental Section. [c] Determined by GC (CPSil5CB, 30 m, 0.32 mm ID, Chrompack). [d] Isolated yield after aqueous work-up and chromatographic purification. [e] Low yield due to high volatility of product.

were generally high, with the exception of highly volatile products [(Table 4, entry 5, (±)-**22**].

Stereochemistry of the o-DPPB-directed allylic substitution: In order to probe the stereochemistry of the *o*-DPPB-directed allylic substitution we chose the *cis*- and *trans*-cyclohexenol-*o*-DPPB esters **27** as model substrates. Thus, Birch reduction of *ortho*-isopropylanisol **24** followed by acid-catalyzed double-bond isomerization furnished the known enone **25** in 44% overall yield according to a known procedure.[18] Stereoselective reduction to give *cis*-**26** was achieved employing DIBAL as the reducing agent. Conversely, lithium aluminum hydride furnished *trans*-**26**. Esterification of alcohols **26** with *ortho*-diphenylphosphanyl benzoic acid following the Keck protocol[19] gave the desired *o*-DPPB esters *cis*- and *trans*-**27** in good yields (Scheme 2).

When *cis*-**27** and *trans*-**27** were independently subjected to the conditions of the directed allylic substitution with methyl magnesium bromide, in both cases a completely *syn*-selective nucleophile transfer was observed to give *cis*- and *trans*-menthene (**28**), respectively (Schemes 3 and 4).

Interestingly, even for *trans*-**27** a complete 1,3-chirality transfer was observed, even though in this case the substrate has to pass a reactive conformation which places the isopropyl substituent in a pseudo-axial position (Scheme 4) in order to fulfil stereoelectronic requirements [optimal π(C=C)/σ*(C–O) overlap].[3,20]



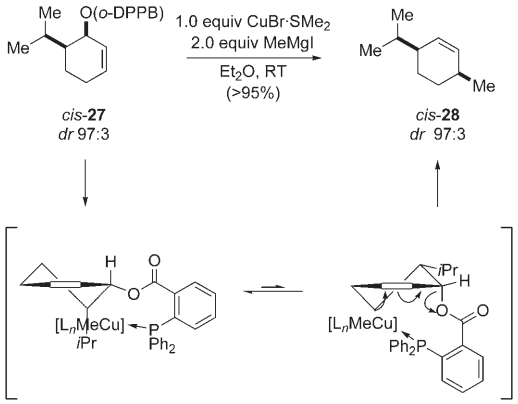
Scheme 2. Preparation of cyclic *o*-DPPB esters *cis*- and *trans*-**27**.

To explore chirality transfer in acyclic systems, enantiomerically pure allylic *o*-DPPB esters (−)-(*E*)-**15** and (+)-(*Z*)-**15** were chosen.

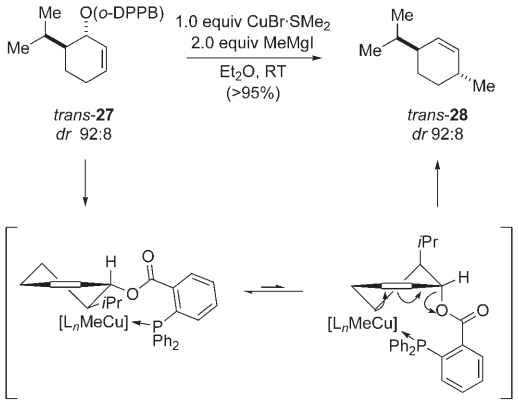
The enantiomerically pure *E* alcohol (−)-(*E*)-**29** was accessed through an efficient enzymatic kinetic resolution of the racemic alcohol (±)-(*E*)-**29** employing Novozym 435.[21] Esterification with *o*-DPPBA under Steglich conditions[22] furnished the enantiomerically pure allylic *o*-DPPB ester (−)-(*E*)-**15** (Scheme 5.)

The corresponding *cis*-configured ester (+)-(*Z*)-**15** could be prepared starting from propargylic alcohol (±)-**30**. Thus, *cis*-hydrogenation employing Lindlar's catalyst followed by enzymatic kinetic resolution employing Novozym 435, and esterification furnished the allylic *o*-DPPB ester (+)-(*Z*)-**15** in 97% *ee*. The absolute configuration of (+)-(*Z*)-**29** was determined through reductive transformation to the known alcohol (+)-**31** (Scheme 6).[23]

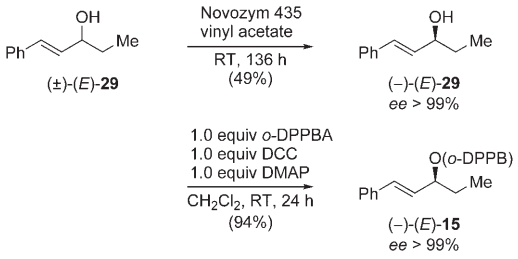
Subjection of (−)-(*E*)-**15** (99% *ee*) to the conditions of the directed allylic substitution with methyl magnesium iodide furnished in almost quantitative yield the S_N2' product (+)-**19** in perfect region-, stereoselectivity and in enantiomerically pure form (99% *ee*).



Scheme 3. *syn*-Selective *o*-DPPB-directed allylic substitution of *cis*-**27**.



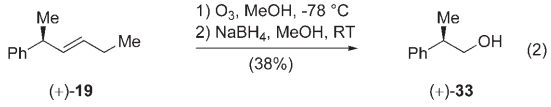
Scheme 4. *syn*-Selective *o*-DPPB-directed allylic substitution of *trans*-**27**.

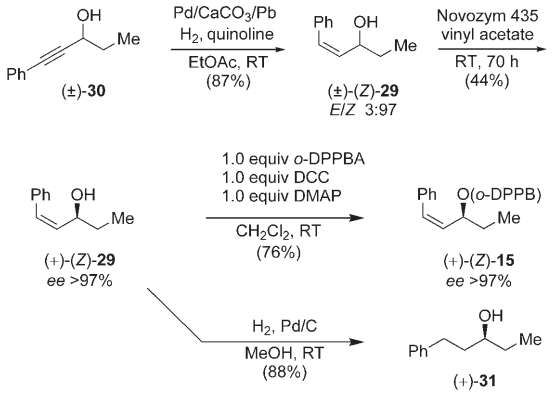


Scheme 5. Preparation of (−)-(*E*)-**15**.

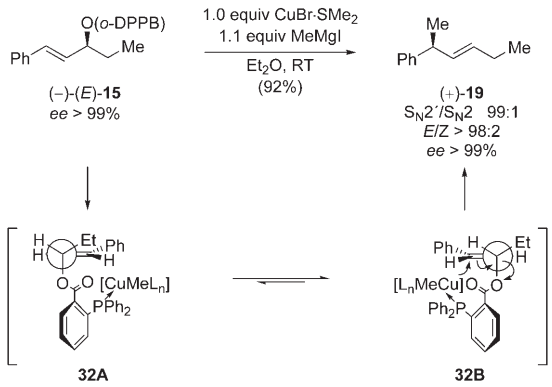
Interestingly, the *o*-DPPBA could be recovered almost quantitatively during the work-up process (see Experimental Section for details).

The absolute configuration of (+)-**19** could be determined upon oxidative cleavage of the alkene through ozonolysis followed by reductive ($NaBH_4$) workup to give the known alcohol (+)-**33**.[24] Hence, a perfect 1,3-chirality transfer followed a *syn*-S_N2' pathway had occurred, which can be rationalized through a reactive conformation which minimizes $A^{1,3}$ strain[25] (**32B** vs **32A**) and orients the *o*-DPPB leaving in a stereoelectronically favorable position (see **32B**, Scheme 7).



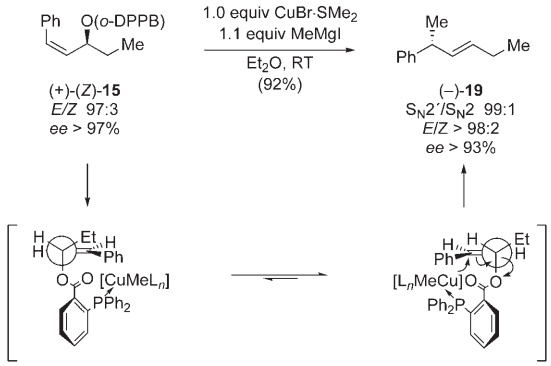


Scheme 6. Preparation of (+)-(*Z*)-**15** and determination of absolute configuration.



Scheme 7. *syn*-Selective *o*-DPPB-directed allylic substitution of acyclic (−)-(*E*)-**15** and proposed reactive conformation **32B**.

Accordingly, a switch of the alkene geometry in the starting allylic ester **15** from *E* to *Z* configuration should give access to the optical antipode, (−)-**19**, starting from substrates (−)-(*E*)-**15** and (+)-(*Z*)-**15** with the same absolute configuration. Indeed, subjection of (+)-(*Z*)-**15** to the conditions of the directed allylic substitution furnished (−)-**19**, with perfect 1,3-chirality transfer according to the directed *syn*-substitution pathway. Hence, the directed allylic substitution protocol employing *o*-DPPB-esters of secondary allylic alcohols occurs with perfect 1,3-chirality transfer for both, structurally defined cyclic systems as well as for conformationally more flexible acyclic derivatives. In the latter case the reaction enables the stereospecific construction of a tertiary stereogenic carbon center as a function of alkene geometry (Scheme 8).



Scheme 8. *syn*-Selective *o*-DPPB-directed allylic substitution of acyclic (+)-(*Z*)-**15** and proposed reactive conformation.

Coordination behavior of allylic *o*-DPPB esters towards copper(I) salts: In order to learn about the nature of the attractive interaction between the directing *o*-DPPB group and a copper(I) center, we studied the coordination behavior of (−)-(*E*)-**15** in the presence of a copper(I) salt. Thus, reaction of two equivalents of (−)-(*E*)-**15** with copper bromide dimethylsulfide in dichloromethane at room temperature gave in quantitative yields [(−)-(*E*)-**15**]$_2$CuBr (**34**). From a suitable single crystal an X-ray crystal structure analysis could be obtained (Figure 1, Table 5). Thus, the copper center shows trigonal-planar coordination geometry with two substrates (−)-(*E*)-**15** η^1-coordinated via the phosphine donor and one bromide ligand. The structure and geometry of complex **34** differs significantly from the known [Cu(PPh$_3$)$_3$Br] complex which displays tetrahedral geometry.[26] The lower coordination number for **34** may be rationalized on the basis of increased steric demand of phosphine (−)-(*E*)-**15**. Interestingly, in complex **34** both phosphine substrates show an almost coplanar orientation of the σ(C−O) bond of the *o*-DPPB ester with respect to the alkene π system as a result of minimizing A^{1,3} strain (torsion angle O22-C83-C84-C85 108.7°).[25] Hence, in the copper complex **34** the allylic *o*-DPPB substrates occupy a conformation which fulfils the stereoelectronic requirements for the directed allylic substitution in almost ideal manner, and is thus in agreement with the postulated reactive conformation **32B** (see Figure 2 and Scheme 7).

Table 5. Selected bond lengths [Å], bond and torsion angles [°] for [(−)-(*E*)-**15**]$_2$CuBr (**34**) and [(Ph$_3$P)$_3$CuBr].

	34		[(Ph$_3$P)$_3$CuBr][26]
Cu−P1	2.2390	P−Cu	2.353
Cu−P2	2.2278		
Cu−Br1	2.3464	Cu−Br	2.481
P1-Cu-P2	126.8	P-Cu-P	110.2
P1-Cu-Br	114.7	P-Cu-Br	108.6
P2-Cu-Br	118.5		
O12-C33-C34-C35	117.8		
O22-C83-C84-C85	108.7		

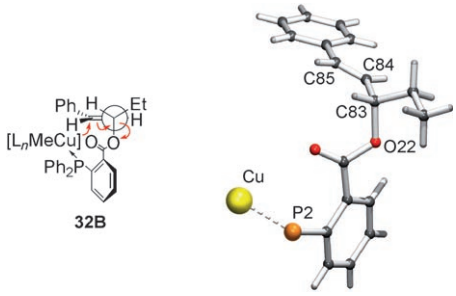


Figure 2. Postulated reactive conformation for the directed allylic substitution **32B** and conformation of (−)-(*E*)-**15** in the solid-state structure of copper complex **34**.

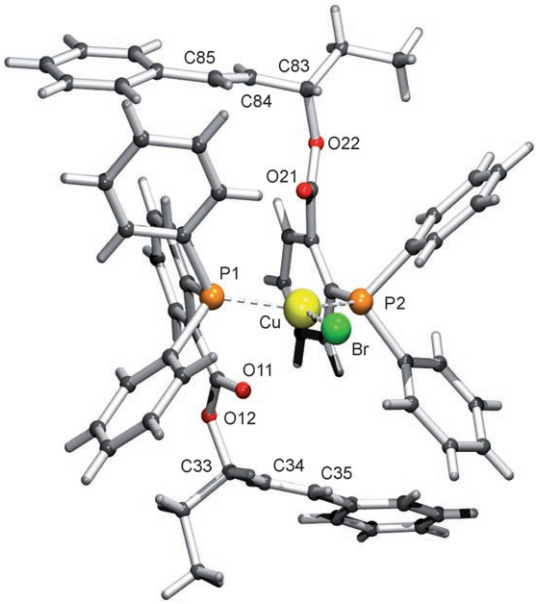


Figure 1. POV-ray plot of [(−)-(*E*)-**15**]$_2$CuBr (**34**) in the solid state.

In fact, in most reactions shown above 0.5 equivalents of copper(I) salt lead to optimal selectivities. This suggests that both substrates coordinated to copper(I) undergo the directed reaction pathway.

Ligand exchange of allylic *o*-DPPB esters on a copper(I) center: An interesting aspect would be to develop the stoichiometric-directed process into a copper-catalyzed variant. However, a prerequisite would be that the phosphine function of the *o*-DPPB group would allow for reversible binding of a copper(I) center. In order to learn about this possibility, we studied the coordination behavior of (−)-(*E*)-**15** in the presence of 0.25 equivalents of copper bromide dimethylsulfide employing temperature dependent ^{31}P NMR spectroscopy (Figure 3).

At 213 K two signals can be observed: A broad singlet at $\delta = -3.3$ for the copper complex **34** and a sharp singlet for the free phosphine, the *o*-DPPB ester (−)-(*E*)-**15**. Upon warming the two signals show coalescence at $T = 316$ (±2) K and merge at 353 K into a broad singlet. This behav-

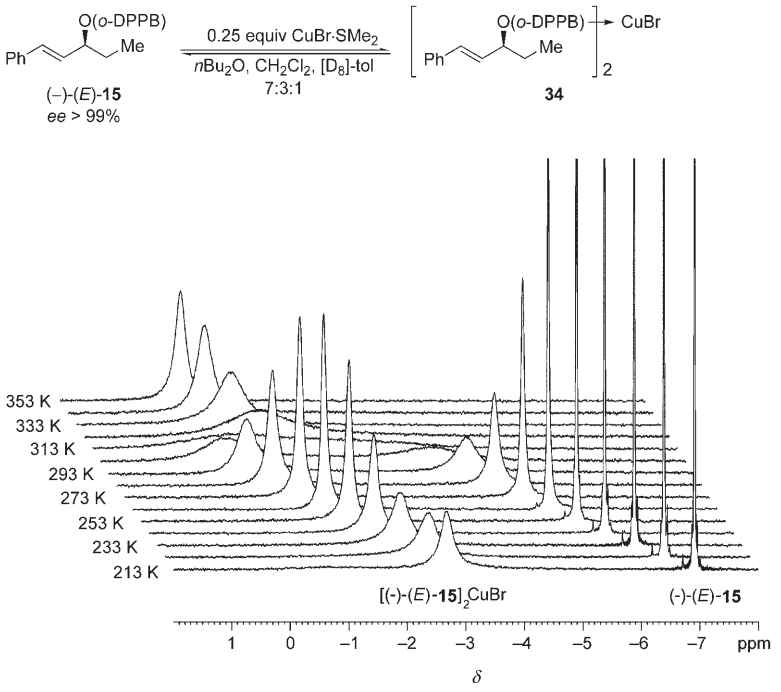
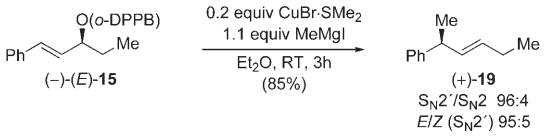


Figure 3. Dynamic behavior of (−)-(*E*)-**15** and [(−)-(*E*)-**15**]$_2$CuBr (**34**), temperature dependent ^{31}P NMR spectra.

ior can be rationalized as a result of rapid ligand exchange on copper(I). Employing a line shape analysis[27] the free activation energy could be estimated to 16.7 kcal mol^{-1}. Hence, the ligand exchange proceeds at room temperature with a rate of $k_{298\,K} = 13.1\ s^{-1}$ which suggests that experiments employing substoichiometric quantities of copper(I) salt should be possible.

Copper-catalyzed *o*-DPPB directed allylic substitution with Grignard reagents: In fact, lowering the amount of copper bromide to 0.2 equiv gave the allylic substitution product (+)-**19** in 85% yield in a regioselectivity of 96:4 and *E*/*Z* selectivity of 95:5 in 99% *ee*, which is only slightly worse compared with the results obtained from the stoichiometric variant (compare Schemes 9 and 7). However, any further reduction of the amount of copper salt lead so far to lower selectivities and to the formation of increasing amounts of allylic alcohol **29** resulting from an undesired attack of the Grignard reagent at the ester carbonyl function. Thus, in case when highest levels of selectivity are in demand, the stoichiometric process employing 0.5 equiv of copper(I) salt should be preferred.



Scheme 9. Copper-catalyzed *o*-DPPB-directed allylic substitution.

Conclusions

The present study introduces the *ortho*-diphenylphosphanyl benzoate function (*o*-DPPB) as an efficient directing leaving group for copper-mediated allylic substitution with Grignard reagents. Optimal levels of regioselectivity and *syn*-1,3-chirality transfer can be obtained with 0.5 equivalents of copper salt and stoichiometric amounts of Grignard reagent, and the directing *o*-DPPB group can be recovered during the work-up process as the corresponding carboxylic acid (*o*-DPPBA) almost quantitatively. Coordination studies in the solid state and solution have shown that two substrates are bound via the phosphine function of the directing group at copper. Dynamic NMR experiments in solution are in agreement with a ligand exchange process at copper, a prerequisite for the development of a catalytic process.

Hence, the copper-mediated *o*-DPPB-directed allylic substitution is an interesting synthetic methodology for the stereospecific construction of tertiary stereogenic carbon centers and thus may become an attractive alternative to established enolate alkylation chemistry.

Experimental Section

General methods: Reactions were performed in flame-dried glassware under argon (purity >99.998%). The solvents were dried by standard procedures, distilled and stored under argon. Copper bromide dimethyl sulfide was purchased from Aldrich (99%) and stored at 4 °C under argon. All temperatures quoted are uncorrected. ^{1}H, ^{13}C NMR spectra: Bruker ARX 200, Bruker DRX 300, Varian Mercury 300, Bruker AM 400, Bruker DRX 500 with tetramethylsilane (TMS) or chloroform ($CHCl_3$) as internal standards. ^{31}P NMR spectra: Bruker ARX 200, Bruker DRX 500, Varian Mercury 300 with 85% H_3PO_4 as external standard. Melting points: Dr. Tottoli (Büchi) melting point apparatus. Elemental Analyses: Elementaranalysen GmbH elementar vario EL. Optical rotation: Perkin–Elmer PE 241 or PE 342. Achiral Analytical GC: Hewlett Packard HP5880A or Varian CP3800. Chiral Analytical GC: Hewlett Packard HP5880A, Hewlett Packard HP5990A, CE Instruments GC8000^{TOP}. Flash chromatography: silica gel Si 60, E. Merck AG, Darmstadt, 40–63 μm.

The following compounds were prepared following literature procedures: *ortho*-Diphenylphosphanylbenzoic acid (*o*-DPPBA),[28] benzhydrylbenzoic acid,[29] (±)-(*E*)-1-phenyl-3-penten-2-ol,[30] cyclohexyl-2-propene-1-ol,[31] (*E*)-3-hydroxy-oct-4-enoic acid *tert*-butyl ester,[32] (*E*)-3-hydroxy-5-phenyl-pent-4-enoic acid *tert*-butyl ester,[33] 2,5-dimethyl-2-hexen-4-ol,[34] 2-isopropyl-anisole (**24**),[35] 6-isopropylcyclohex-2-en-1-one [(±)-**25**],[18]

(±)-(*E*)-1-phenyl-1-penten-3-ol [(±)-(*E*)-**29**],[36] (±)-1-phenyl-1-pentin-3-ol [(±)-**30**].[37]

Preparation of allylic alcohols

***trans*-(1*R**,6*R**)-6-Isopropyl-2-cyclohexen-1-ol (*trans*-26)**:[38] Enone (±)-**25** (1.321 g, 9.56 mmol) in Et_2O (1 mL) was added slowly at −78 °C to a magnetically stirred suspension of $LiAlH_4$ (381 mg, 10.04 mmol) in Et_2O (20 mL) and the reaction mixture was stirred for further 3.5 h at this temperature. Subsequently, the reaction mixture was warmed to room temperature and the reaction was quenched by careful addition of water (0.36 mL), stirred for further 30 min followed by successive addition of 2 N NaOH (0.36 mL) and water (0.36 mL). The resulting mixture was extracted with Et_2O (4×50 mL) and the combined organic phases were washed with brine (20 mL) and dried ($MgSO_4$). All volatile components were removed in vacuo and the residue was purified through flash chromatography (petroleum ether/Et_2O 95:5 → 85:15) to give *trans*-**26** as a colorless oil (837 mg, 62 %, *dr* 96:4). ^{1}H NMR (200.132 MHz, $CDCl_3$): δ = 0.85 (d, J = 7.0 Hz, 3H, CH_3), 0.97 (d, J = 7.0 Hz, 3H, CH_3), 1.31 (m, 2H, CH_2), 1.54 (brs, 1H, OH), 1.68 (m, 1H, CH), 2.03 (m, 3H, CH_2, CH), 4.05 (m, 1H, CH), 5.66 (ddd, J = 9.9, 4.1, 2.2 Hz, 1H, CH), 5.78 ppm (m, 1H, CH); ^{13}C NMR (75.469 MHz, $CDCl_3$): δ = 17.2, 20.7, 21.0, 25.3, 26.6, 48.0, 68.9, 129.5, 131.0 ppm. The analytical data correspond to those reported previously.[39] Analytical GC (OV1, 50 °C (1 min), 10 °C min^{-1}, 200 °C (14 min)): *cis*-**26** (t_R = 9.05 min); *trans*-**26** (t_R = 9.29 min), 6-isopropyl-2-cyclohexenone (**25**)(t_R=10.36 min).

***cis*-(1*R**,6*S**)-6-Isopropyl-2-cyclohexen-1-ol (*cis*-26)**: A solution of enone **25** (1.38 g, 10 mmol) in benzene (2 mL) was added slowly at 0 °C to a hexane solution of DIBAL (1.0 M, 20 mL) in benzene (10 mL). After further stirring for 4 h at this temperature the reaction was quenched upon addition of a sat. aq. solution of Rochelle salt (40 mL). The organic phase was separated and the aqueous phase extracted with Et_2O (3× 60 mL). The combined organic phases were washed successively with water (40 mL), brine (40 mL) and were dried ($MgSO_4$). All volatile components were removed in vacuo and the residue was purified through flash chromatography (petroleum ether/ethyl acetate) to give *cis*-**26** as a colorless oil (580 mg, 41 %, *dr* 95:5) which crystallized upon standing at room temperature. M.p. 42 °C (lit.[40] 43–45 °C); ^{1}H NMR (200.132 MHz, $CDCl_3$): δ = 0.97 (d, J = 6.6 Hz, 3H, CH_3), 1.02 (d, J = 6.6 Hz, 3H, CH_3), 1.13 (m, 1H), 1.29 (m, 1H), 1.69 (m, 2H), 1.98 (m, 1H, CH_2), 2.15 (m, 1H, CH_2), 4.16 (brs, 1H, C*H*(OH)), 5.90 ppm (m, 2H, C*H*=C*H*). The proton resonance of the hydroxyl group could not be detected. ^{13}C NMR (75.469 MHz, $CDCl_3$): δ = 20.2 (CH_3), 20.8(CH_3), 20.9, 26.6, 28.5, 46.5, 54.6, 128.9, 131.7 ppm. The analytical data correspond to those reported previously.[40]

(±)-(*Z*)-1-Phenyl-1-penten-3-ol [(±)-(*Z*)-29]: A solution of (±)-**30** (2.37 g, 14.8 mmol) in ethyl acetate (50 mL) was treated subsequently with quinoline (2.5 mL) and Pd/$CaCO_3$/Pb (240 mg; 5 % Pd, 0.11 mmol) and placed under an atmosphere of hydrogen (balloon) and the mixture was stirred vigorously for 18.5 h at room temperature. Subsequently, the reaction mixture was filtered through a plug of Celite and washed with ethyl acetate (20 mL). The organic phase was washed successively with aqueous HCl (10 %, 3×50 mL), water (30 mL) and was dried ($MgSO_4$). After removal of all volatile components in vacuo the remaining crude product was purified by Kugelrohr distillation (80 °C, 0.01 mbar) to give (±)-(*Z*)-**29** (2.09 g, 87 %, *E*/*Z* 3:97) as a colorless oil. ^{1}H NMR (300.135 MHz, $CDCl_3$): δ = 0.96 (t, J = 7.7 Hz, 3H, CH_3), 1.54 (d, J = 3.7 Hz, 1H, OH), 1.63 (m, 2H, CH_2), 4.51 (m, 1H, CH), 5.67 (dd, J = 11.8, 9.6 Hz, 1H, CH), 6.58 (d, J = 11.8 Hz, 1H, CH), 7.20–7.40 ppm (m, 5H, Ar-H); ^{13}C NMR (75.476 MHz, $CDCl_3$): δ = 9.7, 30.5, 69.2, 127.2, 128.3 (2C), 128.8 (2C), 131.3, 134.4, 136.7 ppm. Analytical data correspond to those reported previously.[37]

(−)-(*S*,*E*)-1-Phenyl-1-penten-3-ol [(−)-(*E*)-29]:[21] Novozym 435 (200 mg) was added to a solution of (±)-(*E*)-**29** (1.62 g, 10.0 mmol) in vinyl acetate (15 mL) and the resulting suspension was gently shaken for 136 h at ambient temperature. The enzyme was filtered and washed with Et_2O. The combined organic phases were evaporated and the residue purified by flash chromatography to give (*E*)-**29**-OAc (899 mg, 44 %, *ee* not determined) and the enantiomerically pure allylic alcohol (−)-(*E*)-**29** (794 mg, 49 %, *ee* > 99 %), both as colorless oils.

(−)-(*E*)-29: ^{1}H NMR (400.136 MHz, $CDCl_3$): δ = 0.94 (t, J = 7.4 Hz, 3H, CH_3), 1.55–1.78 (m, 3H, CH_2, OH), 4.23 (pq, J = 6.4 Hz, 1H, CH), 6.21 (dd, J = 15.9, 6.6 Hz, 1H), 6.58 (d, J = 15.9 Hz, 1H, CH), 7.19–7.41 ppm (m, 5H, Ar-H); ^{13}C NMR (100.629 MHz, $CDCl_3$): δ = 9.7, 30.2, 74.4, 126.5 (2C), 127.6, 128.6 (2C), 130.4, 132.3, 136.8 ppm; $[\alpha]_D^{20} = -7.0$ (c = 2.43, $CHCl_3$); GC analysis [Betadex 110, Supelco, 40 °C (15 min), 4 °C min^{-1}, 150 °C (60 min)]: t_R[(+)-(*E*)-**29**] = 60.96 min, not detected; t_R[(−)-(*E*)-**29**] = 61.26 min, 100 %. The analytical data corresponded to those reported previously.[21]

(*E*)-29-OAc: ^{1}H NMR (400.136 MHz, $CDCl_3$): δ = 0.87 (pt, 3H, J = 7.7 Hz, CH_3), 1.64 (pq, 1H, J = 7.3 Hz, CH_2), 1.68 (pq, 1H, J = 7.3 Hz, CH_2), 2.00 (s, 3H, CH_3), 5.27 (pq, 1H, J = 6.9 Hz, CH), 6.04 (dd, 1H, J = 15.9, 7.3 Hz, CH), 6.52 (d, 1H, J = 15.9 Hz, CH), 7.13–7.33 ppm (m, 5H, Ar-H); ^{13}C NMR (100.624 MHz, $CDCl_3$): δ = 9.5, 21.3, 27.6, 76.0, 126.5 (2C), 127.6, 127.8, 128.5 (2C), 132.5, 136.4, 170.3 ppm. The analytical data correspond to those reported previously.[21]

(+)-(*S*,*Z*)-1-Phenyl-1-penten-3-ol [(+)-(*Z*)-29]: According to the procedure described above for (−)-(*E*)-**29**, from (±)-(*Z*)-**29** (1.20 g, 7.4 mmol, *E*/*Z* 3:97), vinyl acetate (8 mL) and Novozym 435 (100 mg) was obtained after 70 h at ambient temperature (+)-(*Z*)-**29** (516 mg, 44 %, *E*/*Z* 3:97, *ee* > 97 %). The corresponding acetate *Z*-**29-OAc** was not isolated. $[\alpha]_D^{21}$ = +52.9 (c = 1.71, $CHCl_3$). HPLC (Chiralcel OD-H, *n*-hexane/isopropanol 9:1, 0.5 mL min^{-1}, 25 °C, 254 nm): t_R[(+)-(*Z*)-**29**] = 10.83 min, 98.6 %; t_R [(−)-(*Z*)-**29**] = 18.59 min, not detected; t_R[undefined by-product] = 17.72 min, 1.4 %.

(+)-(*S*)-1-Phenylpentan-3-ol [(+)-31]: Pd/C (10 % Pd, 5.2 mg, 4.9 μmol) was suspended in methanol (3 mL) and stirred 15 min under an atmosphere of hydrogen (balloon). Subsequently, a solution of (+)-(*Z*)-**29** (64 mg, 0.4 mmol) in methanol (2 mL) was added via syringe and the suspension was allowed to stir for further 24 h at ambient temperature. The reaction mixture was filtered over a plug of methanol-wetted Celite and washed with additional methanol (5 mL). Azeotropic removal of methanol with Et_2O furnished pure saturated alcohol (+)-**31** as white needles. M.p. 33 °C (lit.[23b] 36–38 °C); ^{1}H NMR (300.135 MHz, $CDCl_3$): δ = 0.95 (t, J = 7.4 Hz, 3H, CH_3), 1.38 (m, 1H, OH), 1.53 (m, 2H, CH_2), 1.7 (m, 2H, CH_2), 2.69 (dd, J = 13.6, 6.6 Hz, 1H, CH_2), 2.82 (dd, J = 13.6, 5.9 Hz, 1H, CH_2), 3.58 (m, 1H, CH), 7.21 (m, 3H, Ar-H), 7.31 (m, 2H, Ar-H); ^{13}C NMR (75.476 MHz, $CDCl_3$): δ = 9.8, 30.3, 32.1, 38.6, 72.7, 125.8, 128.39 (2C), 128.41 (2C), 142.2; $[\alpha]_D^{21}$ = +23.4 (c = 1.37, $CHCl_3$) [lit.[23b] $[\alpha]_D^{25}$ = +23.8 (c = 3.01, $CHCl_3$)]. The analytical data correspond to those reported previously.[23]

General procedure for the synthesis of *o*-DPPB-esters following the Steglich protocol:[22] *o*-DPPBA (1 equiv), DMAP (1 equiv) and DCC (1 equiv) were successively added to a solution of the allylic alcohol (1 equiv) in CH_2Cl_2 (0.5 M). The resulting mixture was stirred at ambient temperature until TLC showed complete consumption of the starting material. The reaction mixture was filtered through a plug of CH_2Cl_2-wetted Celite and washed with additional CH_2Cl_2. An appropriate amount of silica gel was added to the filtrate, which was then concentrated to dryness. Flash chromatography with petroleum ether/ethyl acetate provided the *o*-DPPB-esters as slightly yellow to colorless, highly viscous oils or solids.

General procedure for the synthesis of *o*-DPPB-esters following the Keck protocol:[19] *o*-DPPBA (1 equiv), DMAP (0.5 equiv), DMAP·HCl (0.5 equiv) and DCC (1.3 equiv) were successively added to a solution of the allylic alcohol (1 equiv) in CH_2Cl_2 (0.1 M) and the resulting mixture was stirred at ambient temperature until TLC showed complete consumption of the starting material. The reaction mixture was filtered through a plug of CH_2Cl_2-wetted Celite and washed with additional CH_2Cl_2. An appropriate amount of silica gel was added to the filtrate, which was then concentrated to dryness. Flash chromatography with petroleum ether/ethyl acetate provided the *o*-DPPB-esters as slightly yellow to colorless, highly viscous oils or solids.

(±)-(*E*)-2-[2-(Diphenylposphanyl)benzoyloxy]-1-phenyl-3-pentene [(±)-1 (X = P)]: Starting from (±)-(*E*)-1-phenyl-3-penten-2-ol (1.098 g, 6.77 mmol) was obtained (±)-**1** (2.81 g, 92 %) as a pale yellow, highly viscous oil following the Steglich protocol. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ = 1.49 (pd, J = 6.5 Hz, 3H, CH_3), 2.71 (dd, J = 13.7, 6.6 Hz, 1H, CH_2),

2.84 (dd, J=13.7, 6.6 Hz, 1H, CH_2), 5.24 (m, 1H, CH), 5.47 (m, 2H, 2× CH), 6.81 (m, 1H, Ar-H), 7.17 (m, 17H, Ar-H), 7.90 (m, 1H, Ar-H); ^{13}C NMR (75.469 MHz, $CDCl_3$): δ=17.6, 40.9, 76.3, 126.3, 128.06, 128.11, 128.4 (d, $J_{C,P}$=7.4 Hz, 4C), 128.48 (d, $J_{C,P}$=1.7 Hz, 2C), 128.50, 129.6 (4C), 130.5 (d, $J_{C,P}$=2.8 Hz), 131.5, 134.0 (d, $J_{C,P}$=20.4 Hz, 2C), 134.1 (d, $J_{C,P}$=20.9 Hz, 2C), 134.9 (d, $J_{C,P}$=19.2 Hz), 134.2, 137.1, 138.16 (d, $J_{C,P}$=11.9 Hz), 138.18 (d, $J_{C,P}$=11.9 Hz), 140.2 (d, $J_{C,P}$=27.1 Hz), 165.9 (d, $J_{C,P}$=2.3 Hz); ^{31}P NMR (121.495 MHz, $CDCl_3$): δ=−4.5; elemental analysis calcd (%) for $C_{30}H_{27}O_2P$ (450.51): C 79.98, H 6.04; found: C 79.95, H 6.12.

(±)-(*E*)-2-(2-Benzhydrylbenzoyloxy)-1-phenyl-3-pentene [(±)-2 (X= CH)]: Starting from (±)-(*E*)-1-phenyl-3-penten-2-ol (402 mg, 2.48 mmol) and benzhydrylbenzoic acid (715 mg, 2.48 mmol) was obtained (±)-**2** (968 mg, 2.24 mmol, 90%) as a colorless, highly viscous oil following the Steglich protocol. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ=1.53 (m, 3H, CH_3), 2.82 (d, J=6.6 Hz, 2H, CH_2), 5.31 (m, 1H, CH), 5.52 (m, 2H, 2× CH), 6.52 (s, 1H, CH), 7.02 (m, 4H, Ar-H), 7.22 (m, 14H, Ar-H), 7.66 (m, 1H, Ar-H); ^{13}C NMR (75.469 MHz, $CDCl_3$): δ=17.7, 41.0, 52.0, 75.7, 126.10, 126.12, 126.14, 126.4, 128.15 (4C), 128.21 (4C), 128.6, 129.3 (3C), 129.5, 129.7, 130.1, 130.8, 131.1, 131.5, 137.2, 143.8, 143.9, 144.2, 167.1; elemental analysis calcd (%) for $C_{31}H_{28}O_2$ (432.55): C 86.08, H 6.52; found: C 86.35, H 6.51; HRMS (FAB$^+$): m/z: calcd for $C_{31}H_{28}O_2$: 433.2168; found 433.2177 $[M+H]^+$.

(*E*)-3-Cyclohexyl-1-[(2-diphenylphosphanyl)benzoyloxy)-2-propene (6): Starting from (*E*)-3-cyclohexyl-2-propen-1-ol (351 mg, 2.50 mmol) was obtained *o*-DPPB ester **6** (1.020 g, 95%) as a colorless powder following the Steglich protocol. M.p. 87°C; ^{1}H NMR (400.136 MHz, $CDCl_3$): δ= 1.16 (m, 5H), 1.68 (m, 5H), 1.92 (m, 1H), 4.58 (d, J=6.4 Hz, 2H), 5.41 (dtd, J=15.5, 6.5, 1.3 Hz, 1H), 5.67 (dd, J=15.5, 6.9 Hz, 1H), 6.92 (m, 1H), 7.22–7.42 (m, 12H), 7.37 ppm (m, 1H); ^{13}C NMR (100.624 MHz, $CDCl_3$): δ=25.9 (2C), 26.1, 32.5 (2C), 40.3, 66.2, 121.2, 128.1, 128.4 (d, $J_{C,P}$=7.3 Hz, 4C), 128.5 (2C), 130.6 (d, $J_{C,P}$=2.9 Hz), 131.8, 133.9 (d, $J_{C,P}$=20.3 Hz, 4C), 134.3 (2C), 134.7 (d, $J_{C,P}$=19.2 Hz), 138.1 (d, $J_{C,P}$=11.6 Hz), 140.3 (d, $J_{C,P}$=26.6 Hz), 142.0, 166.7 ppm; ^{31}P NMR (121.464 MHz, $CDCl_3$): δ=−4.6 ppm; elemental analysis calcd (%) for $C_{28}H_{29}O_2P$ (428.50): C 78.48, H 6.82; found: C 78.22, H 6.65.

(*E*)-1-[(2-Diphenylphosphanyl)benzoyloxy)-3-phenyl-2-propene (7): Starting from cinnamyl alcohol (671 mg, 5.0 mmol) was obtained **7** (1.770 g, 84%) as a slightly yellow powder following the Steglich protocol. M.p. 95–98°C; ^{1}H NMR (400.136 MHz, $CDCl_3$): δ=4.80 (dd, J=6.5, 1.3 Hz, 2H), 6.16 (dt, J=15.9, 6.5 Hz, 1H), 6.60 (d, J=15.9 Hz, 1H), 6.93 (m, 1H), 7.22 (m, 17H), 8.09 ppm (m, 1H); ^{13}C NMR (100.624 MHz, $CDCl_3$): δ=65.8, 123.1, 126.7 (2C), 128.0 (2C), 128.2 (2C), 128.5 (d, $J_{C,P}$=7.3 Hz, 4C), 128.6 (2C), 130.8, 131.9, 133.9 (d, $J_{C,P}$=20.4 Hz, 4C), 139.3 (2C), 134.5 (d, $J_{C,P}$=18.9 Hz), 136.3, 138.0 (d, $J_{C,P}$=11.6 Hz, 2C), 140.4 (d, $J_{C,P}$=27.6 Hz), 166.7 ppm; ^{31}P NMR (121.464 MHz, $CDCl_3$): δ= −4.10 ppm; elemental analysis calcd (%) for $C_{28}H_{23}O_2P$ (422.45): C 79.61, H 5.49; found: C 79.46, H 5.50.

(*E*)-1-[(2-Diphenylphosphanyl)benzoyloxy]-3,7-dimethyl-2,6-octadiene (8): Starting from geraniol (439 mg, 2.85 mmol) was obtained *o*-DPPB ester **8** (1.039 g, 82%) as a slightly yellow highly viscous oil following the Steglich protocol. ^{1}H NMR (400.136 MHz, $CDCl_3$): δ = 1.60 (s, 3H), 1.64 (s, 3H), 1.68 (s, 3H), 1.99 (m, 2H), 2.07 (m, 2H), 4.67 (d, J=7.3 Hz, 2H), 5.08 (m, 1H), 5.26 (m, 1H), 6.92 (m, 1H), 7.25–7.33 (m, 10H), 7.37 (m, 2H), 8.05 ppm (m, 1H); ^{13}C NMR (100.624 MHz, $CDCl_3$): δ = 16.4, 17.7, 26.3, 39.5, 62.1, 118.2, 123.8, 128.1, 128.4 (d, $J_{C,P}$=7.3 Hz, 4C), 128.5 (2C), 130.6 (d, $J_{C,P}$=2.9 Hz), 131.67, 131.71, 133.9 (d, $J_{C,P}$=21.8 Hz, 4C), 134.2, 134.8 (d, $J_{C,P}$=18.9 Hz), 138.1 (d, $J_{C,P}$=11.6 Hz, 2C), 140.2 (d, $J_{C,P}$=26.2 Hz), 142.0, 166.9 ppm; ^{31}P NMR (121.449 MHz, $CDCl_3$): δ = −4.4 ppm; elemental analysis calcd (%) for $C_{29}H_{31}O_2P$ (442.53): C 78.71, H 7.06; found: C 78.43, H 7.13.

(*Z*)-1-[(2-Diphenylphosphanyl)benzoyloxy]-3,7-dimethyl-2,6-octadiene [9]: Starting from nerol (771 mg, 5.00 mmol) was obtained *o*-DPPB ester **9** (1.708 g, 77%) as a slightly yellow highly viscous oil following the Steglich protocol. ^{1}H NMR (400.136 MHz, $CDCl_3$): δ = 1.57 (s, 3H), 1.65 (s, 3H), 1.71 (m, 3H), 2.05 (m, 4H), 4.65 (d, J=7.3 Hz, 2H), 5.06 (m, 1H), 5.26 (td, J=7.3, 1.3 Hz, 1H), 6.92 (m, 1H), 7.22–7.40 (m, 12H), 8.04 ppm (m, 1H); ^{13}C NMR (100.624 MHz, $CDCl_3$): δ = 17.6, 23.9, 25.6, 26.6, 32.1, 61.8, 119.1, 123.6, 128.1, 128.4 (d, $J_{C,P}$=7.3 Hz, 4C), 128.5 (2C), 130.6 (d, $J_{C,P}$=2.9 Hz), 131.7, 132.0, 133.9 (d, $J_{C,P}$=20.4 Hz, 4C), 134.2, 134.8 (d, $J_{C,P}$=20.4 Hz), 138.1 (d, $J_{C,P}$=10.2 Hz, 2C), 140.2 ppm (d, $J_{C,P}$= 27.6 Hz), 142.2, 166.8; ^{31}P NMR (121.449 MHz, $CDCl_3$): δ = −4.4 ppm; elemental analysis calcd (%) for $C_{29}H_{31}O_2P$ (442.53): C 78.71, H 7.06; found: C 78.40, H 7.20.

(−)-(*S*,*E*)-3-[(Diphenylphosphanyl)benzoyloxy]-1-phenyl-1-pentene [(−)-(*E*)-15]: Starting from (−)-(*S*,*E*)-1-phenyl-1-penten-3-ol [(−)-(*E*)-**29**] (370 mg, 2.28 mmol, *ee* >99%) was obtained *o*-DPPB ester (−)-(*E*)-**15** (960 mg, 94%, *ee* >99%) as a colorless, highly viscous oil following the Steglich protocol. ^{1}H NMR (500.135 MHz, $CDCl_3$): δ=0.88 (pt, J= 7.4 Hz, CH_3, 3H), 1.65 (psept, J=7.4 Hz, 1H), 1.74 (psept, J=7.4 Hz, 1H), 5.46 (m, 1H, CH), 5.99 (dd, J=16.1, 8.0 Hz, 1H, CH), 6.55 (d, J= 16.1 Hz, 1H, CH), 6.90 (m, 1H, Ar-H), 7.21–7.46 (m, 17H, Ar-H), 8.10 ppm (m, 1H, Ar-H); ^{13}C NMR (125.771 MHz, $CDCl_3$): δ=9.6, 27.6, 77.3, 126.6 (2C), 127.3, 127.8, 128.2, 128.39 (d, $J_{C,P}$=7.3 Hz, 2C), 128.41 (d, $J_{C,P}$=7.4 Hz, 2C), 128.42 (2C), 128.5 (2C), 130.7 (d, $J_{C,P}$=2.8 Hz), 131.8, 132.7, 133.90 (d, $J_{C,P}$=19.8 Hz, 2C), 133.93 (d, $J_{C,P}$=20.7 Hz, 2C), 134.3, 134.9 (d, $J_{C,P}$=19.8 Hz), 136.4, 138.0 (d, $J_{C,P}$=11.3 Hz), 138.2 (d, $J_{C,P}$=11.3 Hz), 140.1 (d, $J_{C,P}$=27.3 Hz), 166.2 ppm (d, $J_{C,P}$=1.0 Hz); ^{31}P NMR (202.456 MHz, $CDCl_3$): δ=−4.7 ppm; $[\alpha]_D^{20}$ = −53.7 (c=1.9, $CHCl_3$); elemental analysis calcd (%) for $C_{30}H_{27}O_2P$ (450.51): C 79.98, H 6.04; found: C 79.72, H 6.08.

(±)-(*E*)-3-[(Diphenylphosphanyl)benzoyloxy]-1-phenyl-1-pentene [(±)-(*E*)-15]: Starting from (±)-(*E*)-1-phenyl-1-penten-3-ol [(±)-(*E*)-**29**] (623 mg, 3.84 mmol, *ee* >99%) was obtained *o*-DPPB ester (±)-(*E*)-**15** (1.365 g, 79%) as a yellowish highly viscous oil following the Steglich protocol.

(+)-(3*S*,*Z*)-3-[(Diphenylphosphanyl)benzoyloxy]-1-phenyl-1-pentene [(+)-(*Z*)-15]: Starting from (+)-(3*S*,*Z*)-1-Phenyl-1-penten-3-ol [(+)-(*Z*)-**29**] (392 mg, 2.42 mmol, *E*/*Z* 3:97 (NMR), *ee* >97%) was obtained *o*-DPPB ester (+)-(*Z*)-**15** (832 mg, 76%, *E*/*Z* 3:97 (NMR), *ee* >97%) as a colorless, highly viscous oil following the Steglich protocol. ^{1}H NMR (250.135 MHz, $CDCl_3$): δ=0.78 (t, J=7.5 Hz, 3H, CH_3), 1.61 (m, 2H, CH_2), 5.50 (dd, J=11.8, 9.3 Hz, 1H, CH), 5.79 (dpt, J=9.3, 6.3 Hz, 1H, CH), 6.50 (d, J=11.8 Hz, 1H, CH), 6.90 (m, 1H, Ar-H), 7.29 (m, 17H, Ar-H), 8.04 ppm (m, 1H, Ar-H); ^{13}C NMR (75.476 MHz, $CDCl_3$): δ=9.4, 27.8, 73.6, 127.2, 128.1, 128.3 (2C), 128.39 (d, $J_{C,P}$=6.8 Hz, 2C), 128.41 (d, $J_{C,P}$=6.7 Hz, 2C), 128.5 (2C), 128.6 (2C), 129.8, 130.6 (d, $J_{C,P}$= 2.8 Hz), 131.7, 131.9, 133.92 (d, $J_{C,P}$=20.9 Hz, 2C), 133.98 (d, $J_{C,P}$= 20.9 Hz, 2C), 134.2, 135.0 (d, $J_{C,P}$=19.2 Hz), 136.3, 138.1 (d, $J_{C,P}$= 11.3 Hz), 138.2 (d, $J_{C,P}$=11.9 Hz), 140.0 (d, $J_{C,P}$=27.1 Hz), 166.2 ppm (d, $J_{C,P}$=2.3 Hz); ^{31}P NMR (101.261 MHz, $CDCl_3$): δ=−6.5 ppm; $[\alpha]_D^{16}$ = +133.4° (c=5.04, $CHCl_3$); elemental analysis calcd (%) for $C_{30}H_{27}O_2P$ (450.51): C 79.98, H 6.04; found: C 79.72, H 5.92.

(±)-(3*S*,*Z*)-3-[(Diphenylphosphanyl)benzoyloxy]-1-phenyl-1-pentene [(±)-(*Z*)-15]: Starting from (±)-(*Z*)-1-Phenyl-1-penten-3-ol [(±)-(*Z*)-**29**] (585 mg, 3.61 mmol) was obtained *o*-DPPB ester (±)-(*Z*)-**15** (1.455 g, 90%) as a yellowish, highly viscous oil following the Steglich protocol.

(±)-(*E*)-3-[2-(Diphenylphosphanyl)benzoyloxy]-oct-4-enoic acid *tert*-butyl ester [(±)-16]: Starting from (*E*)-3-hydroxy-oct-4-enoic acid *tert*-butyl ester[32] (544 mg, 2.54 mmol) was obtained (±)-**16** (936 mg, 73%) as a slightly green-yellow highly viscous oil following the Steglich protocol. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ=0.85 (t, J=7.4 Hz, 3H), 1.30 (m, 2H), 1.37 (s, 9H), 1.92 (pq, J=6.6 Hz, 2H), 2.43 (dd, J=15.1, 6.6 Hz, 1H), 2.59 (dd, J=15.1, 7.7 Hz, 1H), 5.32 (ddt, J=15.4, 7.0, 1.5 Hz, 1H), 5.69 (m, 2H), 6.89 (m, 1H), 7.18–7.42 (m, 12H), 8.06 ppm (m, 1H); ^{13}C NMR (75.476 MHz, $CDCl_3$): δ=13.6, 21.9, 28.0 (3C), 34.2, 41.1, 72.3, 80.8, 126.8, 128.1, 128.2 (d, $J_{C,P}$=6.8 Hz, 4C), 128.5 (2C), 130.7 (d, $J_{C,P}$= 2.8 Hz), 131.8, 133.88 (d, $J_{C,P}$=20.4 Hz, 2C), 133.91 (d, $J_{C,P}$=20.4 Hz, 2C), 134.3, 134.7 (d, $J_{C,P}$=19.2 Hz), 135.0, 138.1 (d, $J_{C,P}$=11.9 Hz), 138.2 (d, $J_{C,P}$=11.9 Hz), 140.2 (d, $J_{C,P}$=27.7 Hz), 165.5 (d, $J_{C,P}$=2.3 Hz), 169.0 ppm; ^{31}P NMR (121.496 MHz, $CDCl_3$): δ=−4.9 ppm; elemental analysis calcd (%) for $C_{31}H_{35}O_4P$ (502.58): C 74.08, H 7.02; found: C 73.89, H 6.98.

(*E*)-3-[2-(Diphenylphosphanyl)benzoyloxy]-5-phenyl-pent-4-enoic acid *tert*-butyl ester [(±)-17]: Starting from (*E*)-3-hydroxy-5-phenyl-pent-4-enoic acid *tert*-butyl ester[33] (2.00 g, 8.05 mmol) was obtained (±)-**17**

(3.883 g, 7.24 mmol, 90%) as a slightly yellow highly viscous oil following the Steglich protocol. ^{1}H NMR (500.135 MHz, $CDCl_3$): $\delta = 1.37$ (s, 9H), 2.56 (dd, $J = 15.4$, 6.7 Hz, 1H), 2.70 (dd, $J = 15.4$, 7.4 Hz, 1H), 5.89 (m, 1H), 6.02 (dd, $J = 16.1$, 7.4 Hz, 1H), 6.60 (d, $J = 16.1$ Hz, 1H), 6.91 (m, 1H), 7.21–7.41 (m, 17H), 8.08 ppm (m, 1H); ^{13}C NMR (125.771 MHz, $CDCl_3$): $\delta = 28.0$ (3C), 41.0, 72.2, 81.0, 125.9, 126.7 (2C), 128.0, 128.2, 128.4 (m, 6C), 128.53, 128.55, 130.8, 131.9, 133.2, 133.9 (d, $J_{C,P} = 10.4$ Hz, 3C), 134.3, 134.5 (d, $J_{C,P} = 18.5$ Hz, 2C), 136.1, 137.9 (d, $J_{C,P} = 10.4$ Hz), 138.1 (d, $J_{C,P} = 11.3$ Hz), 140.3 (d, $J_{C,P} = 27.3$ Hz), 165.5 (d, $J_{C,P} = 1.9$ Hz), 168.7 ppm; ^{31}P NMR (121.495 MHz, $CDCl_3$): $\delta = -4.7$ ppm; elemental analysis calcd (%) for $C_{34}H_{33}O_4P$ (536.60): C 76.10, H 6.20; found: C 75.86, H 6.19.

(±)-2,5-Dimethyl-4-[2-(diphenylphosphanyl)benzoyloxy]-2-hexene [(±)-18]: Starting from 2,5-dimethyl-2-hexen-4-ol[34] (1.28 g, 10.0 mmol) was obtained (±)-**18** (2.42 g, 58%) as a yellowish glass following the Steglich protocol. ^{1}H NMR (300.066 MHz, $CDCl_3$): $\delta = 0.75$ (d, $J = 7.3$ Hz, 6H), 1.54 (d, $J = 1.2$ Hz, 3H), 1.58 (d, $J = 1.0$ Hz, 3H), 1.72 (m, 1H), 4.92 (m, 1H), 5.33 (dd, $J = 9.4$, 6.9 Hz, 1H), 6.81 (m, 1H), 7.12–7.34 (m, 12H), 7.98 ppm (m, 1H); ^{13}C NMR (100.624 MHz, $CDCl_3$): $\delta = 17.9$, 18.4, 18.6, 25.8, 32.5, 71.1, 121.7, 128.0, 128.3 (d, $J_{C,P} = 7.3$ Hz, 2C), 128.38 (d, $J_{C,P} = 5.8$ Hz, 2C), 128.43 (2C), 130.6, 131.6, 134.0 (d, $J_{C,P} = 20.4$ Hz, 5C), 134.2, 137.7, 138.3 (d, $J_{C,P} = 11.6$ Hz), 138.4 (d, $J_{C,P} = 11.6$ Hz), 140.2 (d, $J_{C,P} = 27.6$ Hz), 166.2 ppm; ^{31}P NMR (121.474 MHz, $CDCl_3$): $\delta = -3.4$ ppm; elemental analysis calcd (%) for $C_{27}H_{29}O_2P$ (416.49): C 77.86, H 7.13; found: C 77.55, H 7.02.

(±)-(1*R,6*R**)-1-[(Diphenylphosphanyl)benzoyloxy]-6-isopropyl-2-cyclohexene [(±)-*cis*-27]**: Starting from (±)-*cis*-**26** (573 mg, 4.09 mmol, *cis*/*trans* 99:1) was obtained (±)-*cis*-**27** (1.494 g, 85%, *cis*/*trans* 97:3, determined by NMR) as a colorless, highly viscous oil following the Keck protocol. ^{1}H NMR (300.135 MHz, $CDCl_3$): $\delta = 0.78$ (d, $J = 6.6$ Hz, 3H, CH_3), 0.91 (d, $J = 6.6$ Hz, 3H, CH_3), 1.20 (m, 1H), 1.49 (m, 2H), 1.73 (m, 1H), 2.01 (m, 1H), 2.15 (m, 1H), 5.35 (m, 1H, CH), 5.77 (m, 1H, CH), 5.89 (m, 1H, CH), 6.88 (m, 1H, Ar-H), 7.22–7.36 (m, 12H, Ar-H), 8.02 ppm (m, 1H, Ar-H); ^{13}C NMR (75.476 MHz, $CDCl_3$): $\delta = 20.7$, 20.8 (2C), 26.4, 28.6, 44.1, 68.5, 124.9, 128.0, 128.31 (2C), 128.36 (d, $J_{C,P} = 7.9$ Hz, 4C), 130.4 (d, $J_{C,P} = 2.8$ Hz), 131.7, 133.2, 133.6, 134.0 (d, $J_{C,P} = 16.4$ Hz), 134.1 (d, $J_{C,P} = 20.4$ Hz, 2C), 134.7 (d, $J_{C,P} = 18.1$ Hz, 2C), 138.23 (d, $J_{C,P} = 12.4$ Hz), 138.24 (d, $J_{C,P} = 11.3$ Hz), 140.7 (d, $J_{C,P} = 27.1$ Hz), 166.2 ppm (d, $J_{C,P} = 2.8$ Hz); ^{31}P NMR (202.468 MHz, $CDCl_3$): $\delta = -4.3$ ppm; elemental analysis calcd (%) for $C_{28}H_{29}O_2P$ (428.50): C 78.48, H 6.82; found: C 78.36, H 6.98.

(±)-(1*R,6*S**)-1-[(Diphenylphosphanyl)benzoyloxy]-6-isopropyl-2-cyclohexene [(±)-*trans*-27]**: Starting from (±)-*trans*-**26** (187 mg, 1.33 mmol, *anti*/*syn* 94:6) was obtained (±)-*trans*-**27** (528 mg, 1.23 mmol, 93%, *anti*/*syn* 92:8, determined by NMR) as a colorless, highly viscous oil following the Keck protocol. ^{1}H NMR (200.131 MHz, $CDCl_3$): $\delta = 0.79$ (d, $J = 6.8$ Hz, 3H, CH_3), 0.91 (d, $J = 6.8$ Hz, 3H, CH_3), 1.29–1.78 (m, 4H), 2.07 (m, 2H), 5.48 (m, 2H), 5.82 (m, 1H), 6.95 (m, 1H, Ar-H), 7.30–7.43 (m, 12H, Ar-H), 8.08 ppm (m, 1H, Ar-H); ^{13}C NMR (74.469 MHz, $CDCl_3$): $\delta = 17.6$, 20.7, 20.9, 24.7, 28.1, 43.8, 72.5, 126.6, 128.0, 128.38 (d, $J_{C,P} = 7.4$ Hz, 4C), 128.40 (2C), 130.5 (d, $J_{C,P} = 2.8$ Hz), 131.1, 131.7, 133.8 (d, $J_{C,P} = 12.9$ Hz), 134.08 (d, $J_{C,P} = 13.1$ Hz, 2C), 134.1, 134.8 (d, $J_{C,P} = 18.4$ Hz, 2C), 138.1 (d, $J_{C,P} = 11.4$ Hz, 2C), 140.1 (d, $J_{C,P} = 27.2$ Hz), 166.8 ppm (d, $J_{C,P} = 2.6$ Hz); ^{31}P NMR (81.018 MHz, $CDCl_3$): $\delta = -3.1$ ppm; elemental analysis calcd (%) for $C_{28}H_{29}O_2P$ (428.50): C 78.48, H 6.82; found: C 78.36, H 6.98.; HR-MS (FAB^+): *m*/*z*: calcd for $C_{28}H_{29}O_2P$: 429.1983; found: 429.1970 $[M+H]^+$.

Allylic substitution reactions

Reaction of (±)-1 (X = P) with Me_2CuLi·LiI at −20 °C (Table 1, entry 1, R = Me): A 1.45 M methyl lithium solution in Et_2O (1.76 mL, 2.66 mmol) was added dropwise at −5 °C to a suspension of copper(I) iodide (254 mg, 1.33 mmol) in Et_2O (17 mL) and stirred for further 30 min. After cooling to −20 °C a solution of (±)-**1** (300 mg, 0.67 mmol) in Et_2O (3.5 mL) was added dropwise during 10 min und the resulting yellow suspension was stirred for 2 h until TLC showed complete consumption of the starting material. The reaction was quenched by successive addition of a saturated aqueous NH_4Cl solution (13 mL) and an aqueous ammonia solution (12.5%, 10 mL) followed by the addition of Et_2O (35 mL). The mixture was stirred for 10 min, the organic phase was separated and the aqueous phase was extracted with Et_2O (2×20 mL). The combined organic phases were washed with brine, dried ($MgSO_4$), and the solvent was removed in vacuo to give (±)-(*E*)-4-methyl-1-phenyl-2-pentene [(±)-**2**] and (±)-(*E*)-2-methyl-1-phenyl-3-pentene [(±)-**3**] as an inseparable mixture in a ratio of 75:25. Analytical GC (Carbovax, Hewlett Packard; 50 °C, 1 min, 10 °C min^{-1}, 200 °C, 14 min): t_R[(±)-**3**] = 10.36 min, t_R[(±)-**4**] = 10.01 min, GC yield: >95%; (±)-**3** (R = Me): ^{1}H NMR (200.131 MHz, $CDCl_3$): $\delta = 1.05$ (d, $J = 6.8$ Hz, 6H), 2.33 (m, 1H), 3.37 (pd, $J = 4.8$ Hz, 2H), 5.54–5.59 (m, 2H), 7.21–7.38 ppm (m, 5H); ^{13}C NMR (50.328 MHz, $CDCl_3$) $\delta = 22.6$ (2C), 31.0, 39.0, 125.7, 125.8, 128.1 (2C), 128.5 (2C), 139.2, 141.2 ppm. The analytical data correspond to those reported previously.[41]

(±)-4 (R = Me): ^{1}H NMR (300.13 MHz, $CDCl_3$): $\delta = 0.94$ (d, $J = 6.6$ Hz, 3H), 1.62 (m, 3H), 2.43 (m, 2H), 2.65 (dd, $J = 12.87$, 6.25 Hz, 1H), 5.35–5.4 (m, 2H), 7.2 ppm (m, 5H); ^{13}C NMR (75.48 MHz, $CDCl_3$): $\delta = 17.9$, 19.9, 38.3, 43.8, 123.1, 125.6, 128.0 (2C), 129.2 (2C), 136.7, 141.0 ppm. The analytical data correspond to those reported previously.[42]

Reaction of (±)-1 (X = P) with Me_2CuLi·LiI at −80 °C (Table 1, entry 2, R = Me): Following the above described procedure from (±)-**1** (300 mg, 0.666 mmol) (±)-**3** and (±)-**4** were obtained after 6 h at −80 °C in a ratio of 74:26. Analytical GC (Carbovax, Hewlett Packard; 50 °C, 1 min, 10 °C min^{-1}, 200 °C, 14 min): t_R[(±)-**2**] = 10.28 min, t_R[(±)-**3**] = 9.96 min, GC yield: >95%.

Reaction of (±)-2 (X = CH) with Me_2CuLi·LiI (Table 1, entry 3, R = Me): Following the above described procedure from (±)-**2** (222 mg, 0.51 mmol) (±)-**3** and (±)-**4** were obtained after 3 h at −20 °C in a ratio of 78:22. Analytical GC (Carbovax, Hewlett Packard; 50 °C, 1 min, 10 °C min^{-1}, 200 °C, 14 min): t_R[(±)-**3**] = 10.94 min, t_R[(±)-**4**] = 10.61 min, GC yield: >95%.

Reaction of (±)-1 (X = P) with MeCu(CN)Li (Table 1, entry 4, R = Me): Following the above described procedure from (±)-**1** (200 mg, 0.444 mmol) (±)-**3** and (±)-**4** were obtained after 65 h at −20 °C with MeCu(CN)Li[43] in a ratio of 95:5. Analytical GC (Carbovax, Hewlett Packard; 50 °C, 1 min, 10 °C min^{-1}, 200 °C, 14 min): t_R[(±)-**3**] = 10.79 min, t_R[(±)-**4**] = 10.48 min, GC yield: >95%.

Reaction of (±)-1 (X = P) with copper(I) bromide dimethyl sulfide/methyl magnesium iodide (Table 1, entry 5, R = Me): To a solution of (±)-**1** (100 mg, 0.22 mmol) in Et_2O (4.4 mL, 0.05 M) at room temperature was added copper(I) bromide dimethyl sulfide (46 mg, 0.22 mmol, 1.0 equiv) in one portion. The resulting yellow solution was stirred for 5 min after which a 1.29 M solution of methyl magnesium iodide in Et_2O (0.21 mL, 0.27 mmol, 1.2 equiv) was added within 0.5 min. The resulting bright yellow suspension was stirred vigorously. After 2 min TLC showed quantitative consumption of starting material. The reaction was quenched by successive addition of a saturated aqueous NH_4Cl solution (4 mL) and an aqueous ammonia solution (12.5%, 2 mL) followed by the addition of Et_2O (10 mL). The mixture was stirred for 10 min, the organic phase was separated and the aqueous phase was extracted twice with Et_2O (20 mL each). The combined organic phases were washed with brine, dried ($MgSO_4$) and the solvent removed in vacuo to give (±)-**3** (R = Me) in a regioselectivity of >99:1. Analytical GC (Carbovax, Hewlett Packard; 50 °C, 1 min, 10 °C min^{-1}, 200 °C, 14 min): t_R[(±)-**3**] = 10.66 min, t_R[(±)-**4**] = 10.36 min, GC yield: >95%.

Reaction of (±)-2 (X = CH) with copper(I) bromide dimethyl sulfide/methyl magnesium iodide (Table 1, entry 6, R = Me): Copper(I) bromide dimethyl sulfide (72 mg, 0.35 mmol, 1.0 equiv) was added in one portion at ambient temperature to a solution of (±)-**2** (150 mg, 0.35 mmol) in Et_2O (7 mL, 0.05 M). After the resulting white suspension was stirred for 5 min a 0.5 M solution of methyl magnesium iodide in Et_2O (0.77 mL, 0.39 mmol, 1.1 equiv) was added within 0.5 min and the resulting slight yellow-orange suspension stirred vigorously for further 6 h at which time TLC showed no further reaction progress. The reaction was quenched by successive addition of sat. aq. NH_4Cl (8 mL), and aq. NH_3 (12.5%, 4 mL) followed by the addition of Et_2O (20 mL) and *tert*-butyl acetate (50 μL, 43.1 mg, 0.37 mmol) as an internal standard for NMR. The mixture was stirred for 10 min, the organic phase was separated and the aqueous phase was extracted twice with Et_2O (20 mL). The combined organic

phases were washed with brine, dried ($MgSO_4$) and the solvent removed in vacuo. NMR spectroscopy of the crude product showed 80% conversion (vs *tert*-butyl acetate, $\delta = 1.87$ ppm). Column chromatography (silica gel, pentane, then pentane/Et_2O 95:5, then PE/EtOAc 4:1) yielded an inseparable mixture of (±)-(*E*)-**3** (R = Me), (±)-**4** (R = Me) and (±)-(*Z*)-**3** (32 mg, 0.20 mmol, 57%) in a ratio of 47:27:26 (determined by ^{1}H NMR). Analytical GC (Chrompack, CP-SIL 5CB; 40 °C, 5 min, 10 °C min^{-1}, 200 °C, 9 min): t_R[(±)-(*E*)-**3** (R = Me)] = 14.29 min, t_R[(±)-**4** (R = Me)] 13.89 min, t_R[(±)-(*Z*)-**3**] = 13.74 min. Additionally, starting material (±)-**2** (X = CH) (28 mg, 0.07 mmol, 19%) and (±)-(*E*)-1-phenyl-3-penten-2-ol (12 mg, 0.07 mmol, 21%) were isolated.

(±)-(*Z*)-4-Methyl-1-phenyl-2-pentene [(±)-(*Z*)-**3**]: ^{1}H NMR (300.133 MHz, $CDCl_3$): $\delta = 1.00$ (d, $J = 6.6$ Hz, 6H), 2.74 (m, 1H), 3.4 (d, $J = 7.0$ Hz, 2H), 5.2–5.45 (m, 2H), 7.1–7.3 ppm (m, 5H); ^{13}C NMR (75.469 MHz, $CDCl_3$): $\delta = 23.2$ (2C), 26.5, 33.6, 125.6, 125.8, 128.4 (2C), 136.1, 138.4 ppm; two carbon resonances of the aromatic system could not be detected presumably due to overlap with the carbon resonances of (±)-(*E*)-**3** at 128.5 ppm. The analytical data correspond to those reported previously.[42]

Control experiment of (±)-1 (X = P) with methyl magnesium iodide (Table 1, entry 7, R = Me): A 0.83 M solution of methyl magnesium iodide in Et_2O (1.29 mL, 1.07 mmol, 2.5 equiv) within 0.5 min was added at ambient temperature to a solution of (±)-**1** (193 mg, 0.43 mmol) in Et_2O (9 mL, 0.05 M). The resulting reaction mixture was stirred vigorously for further 16 h until TLC showed complete consumption of starting material. The reaction was quenched by successive addition of a saturated aqueous NH_4Cl solution (6 mL) followed by the addition of Et_2O (20 mL). The mixture was stirred for 10 min, the organic phase was separated and the aqueous phase was extracted with Et_2O (3×20 mL). The combined organic phases were washed with brine, dried ($MgSO_4$) and the solvent was removed in vacuo. Flash chromatography (petroleum ether/ethyl acetate 9:1) yielded (±)-(*E*)-1-phenyl-3-penten-2-ol (68 mg, 0.42 mmol, 98%).[30]

General procedure for the copper-mediated allylic substitution with Grignard reagents: Copper bromide dimethyl sulfide (0.5–1.0 equiv) was added to a stirred solution of the allylic *o*-DPPB ester in the solvent indicated ($c = 0.01$–0.05 M, see Tables 1–4, Schemes 3 and 4, 7 and 8 for details). After 15 min, the Grignard reagent (1.0–1.4 equiv) was added during the specified time (syringe pump addition was used for addition times greater than 5 min). After complete consumption of the starting material (TLC control, the reaction was in most cases complete after the Grignard addition was finished) the reaction was quenched with saturated aqueous NH_4Cl solution (20 mL mmol^{-1} ester) and 12.5% aqueous NH_3 solution (10 mL per mmol). After stirring for 5 min, the phases were separated and the aqueous phase was extracted with Et_2O (2×40 mL per mmol). The combined organic phases were washed with brine (40 mL mmol^{-1}), dried ($MgSO_4$), and the solvent was removed carefully to give in many cases already pure products. In some cases further purification was achieved by flash chromatography (silica gel, pentane or pentane/Et_2O). The ratio of S_N2' and S_N2 products was detected by analytical GC of the crude reaction mixture.

(±)-(*E*)-4-Methyl-1-phenyl-2-octene [**(±)-3**, R = *n*Bu, Table 2, entry 1]: Starting from (±)-**1** (X = P) (257 mg, 0.57 mmol), copper(I) bromide dimethyl sulfide (117 mg, 0.57 mmol) and a 0.46 M solution of *n*-butyl magnesium chloride (1.36 mL, 0.63 mmol) in Et_2O (11.4 mL) was obtained after column chromatography (pentane) (±)-**3** (R = *n*Bu) (113 mg, 0.56 mmol, 98%) as a colorless oil in a regioselectivity of >99:1. Analytical GC (CP-SIL 5CB, Chrompack; 40 °C, 2 min, 10 °C min^{-1}, 200 °C, 12 min): t_R[(±)-**3** (R = *n*Bu)] = 15.38 min; ^{1}H NMR (500.13 MHz, $CDCl_3$): $\delta = 0.88$ (m, 3H), 0.97 (d, $J = 6.7$ Hz, 3H), 1.27 (m, 6H), 2.09 (m, 1H), 3.32 (d, $J = 6.7$ Hz, 2H), 5.38 (dd, $J = 15.1$, 8.0 Hz, 1H), 5.51 (m, 1H), 7.17 (m, 3H), 7.25 ppm (m, 2H); ^{13}C NMR (125.76 MHz, $CDCl_3$): $\delta =$ 14.1, 20.8, 22.8, 29.7, 36.7, 36.9, 39.1, 125.8, 126.8, 128.3 (2C), 128.5 (2C), 138.3, 141.3 ppm. The analytical data correspond to those reported previously.[44]

(±)-(*E*)-4,5-Dimethyl-1-phenyl-2-hexene [**(±)-3**, R = *i*Pr, Table 2, entry 2]: Starting from (±)-**1** (X = P)(156 mg, 0.35 mmol), copper(I) bromide dimethyl sulfide (71 mg, 0.35 mmol) and a 0.71 M solution of isopropyl magnesium bromide (0.54 mL, 0.38 mmol, 1.1 equiv) in Et_2O (7 mL) was obtained after column chromatography (pentane) (±)-**3** (R = *i*Pr) (55 mg, 0.29 mmol, 84%) in a regioselectivity of 97:3. Analytical GC (CP-SIL 5CB, Chrompack; 40 °C, 2 min, 10 °C min^{-1}, 200 °C, 12 min): t_R[(±)-**2** (R = *i*Pr)] = 14.01 min, t_R[(±)-**3** (R = *i*Pr)] = 14.09 min; ^{1}H NMR (300.13 MHz, $CDCl_3$): $\delta = 0.85$ (d, $J = 6.6$ Hz, 3H), 0.86 (d, $J = 6.6$ Hz, 3H), 0.96 (d, $J = 7.0$ Hz, 3H), 1.52 (m, 1H), 1.95 (m, 1H), 3.34 (d, $J =$ 6.3 Hz, 2H), 5.47 (m, 2H), 7.23 ppm (m, 5H); ^{13}C NMR (75.47 MHz, $CDCl_3$): $\delta = 17.5$, 19.7, 19.9, 33.1, 39.2, 42.9, 125.8, 127.7, 128.3 (2C), 128.5 (2C), 136.4, 141.3 ppm; HRMS (EI, 70 eV): *m*/*z*: calcd for $C_{14}H_{20}$ 188.1565; found 188.1564 $[M]^+$.

(±)-(*E*)-1,4-Diphenyl-2-pentene [**(±)-3**, R = Ph, Table 2, entry 6]: Starting from (±)-**1** (X = P) (222 mg, 0.49 mmol), copper(I) bromide dimethyl sulfide (50 mg, 0.24 mmol) and a 1.33 M solution of phenyl magnesium bromide (0.44 mL, 0.59 mmol, 1.2 equiv) in CH_2Cl_2 (0.05 M, 9.8 mL) was obtained after flash chromatography (pentane) (±)-**3** (R = Ph) and (±)-**4** (R = Ph) as an inseparable mixture (102 mg, 0.46 mmol, 94%) in a ratio of 97:3. Analytical GC (CP-SIL 5CB, Chrompack; 40 °C, 2 min, 10 °C min^{-1}, 200 °C, 12 min): t_R[(±)-**3** (R = Ph)] = 19.03 min, t_R[(±)-**4** (R = Ph)] = 18.03 min. (±)-**3** (R = Ph): ^{1}H NMR (300.13 MHz, $CDCl_3$): $\delta = 1.47$ (d, $J = 7.3$ Hz, 3H), 3.47 (d, $J = 6.2$ Hz, 2H), 3.55 (pquintet, $J = 6.8$ Hz, 1H), 5.74 (pdt, $J = 15.3$, 6.4 Hz, 1H), 5.83 (dd, $J = 15.3$, 6.2 Hz, 1H), 7.13–7.72 ppm (m, 10H); ^{13}C NMR (125.76 MHz, $CDCl_3$): $\delta = 21.4$, 39.0, 42.2, 125.8, 125.9, 127.2, 127.7 (2C), 128.3 (2C), 128.4 (2C), 128.5 (2C), 136.6, 140.8, 146.2 ppm.

(±)-**4** (R = Ph): ^{1}H NMR (300.13 MHz, $CDCl_3$): $\delta = 1.72$ (d, $J = 6.4$ Hz, 3H), 3.09 (d, $J = 7.5$ Hz, 2H), 5.45 ppm (m, 1H). One olefinic proton signal as well as the resonance of the aromatic protons of (±)-**4** could not be resolved due to overlap with the major regioisomer (±)-**3**. The analytical data correspond to those reported previously.[45]

(±)-(*E*)-2,3-Dimethyl-6-phenyl-1,4-hexadiene [**(±)-3**, R = 2-propenyl, Table 2, entry 7]: Starting from (±)-**1** (X = P) (60 mg, 0.133 mmol), copper(I) bromide dimethyl sulfide (13.7 mg, 0.067 mmol) and a 0.111 M solution of 2-propenyl magnesium bromide (1.45 mL, 0.16 mmol, 1.2 equiv) in Et_2O (0.05 M, 2.7 mL) was obtained after flash chromatography (pentane) (±)-**3** (R = 2-propenyl) and (±)-**4** (R = 2-propenyl) as an inseparable mixture (20 mg, 0.11 mmol, 81%) in a ratio of 85:15 in addition to traces of inseparable impurities. Analytical GC (CP-SIL 5CB, Chrompack; 40 °C, 2 min, 10 °C min^{-1}, 200 °C, 12 min): t_R[(±)-**3** (R = 2-propenyl)] = 15.25 min, t_R[(±)-**4** (R = 2-propenyl)] = 17.43 min; (±)-**3** (R = 2-propenyl); ^{1}H NMR (300.065 MHz, $CDCl_3$): $\delta = 1.12$ (d, $J = 6.9$ Hz, 3H, CH_3-C_8), 1.70 (s, 3H, CH_3-C_7), 2.78 (m, 1H, CH-C_3), 3.35 (d, $J = 6.4$ Hz, 2H, CH_2-C_6), 4.73 (m, 2H, CH_2-C_1), 5.47 (pdd, $J = 15.4$, 6.9 Hz, 1H, CH-C_4), 5.59 (pdt, $J = 15.4$, 6.5 Hz, 1H, CH-C_5), 7.26 ppm (m, 5H, Ar-H); MS (EI, 70 eV): *m*/*z* (%): 186 (15) $[M]^+$, 171 (61), 157 (21), 143 (24), 129 (21), 115 (31), 104 (18), 95 (100), 67 (90); HRMS (EI, 70 eV): *m*/*z*: calcd for $C_{14}H_{18}$: 186.1409; found: 186.1412 $[M]^+$.

Reaction of (±)-1 with allyl magnesium bromide (Table 2, entry 9, R = allyl): Starting from (±)-**1** (X = P) (88 mg, 0.195 mmol), copper(I) bromide dimethyl sulfide (20.0 mg, 0.098 mmol) and a 1.07 M solution of allyl magnesium bromide (0.39 mL, 0.37 mmol, 2 equiv) in Et_2O (3.9 mL) was obtained after flash chromatography (cyclohexane/ethyl acetate 95:5) (27.4 mg, 0.169 mmol, 87%) of the corresponding allylic alcohol (±)-(*E*)-1-phenyl-3-penten-2-ol.

3-Cyclohexenyl-1-butene (10): Starting from *o*-DPPB-ester **6** (93 mg, 0.22 mmol), copper bromide dimethyl sulfide (22.5 mg, 0.11 mmol) and a 0.1 M solution of methyl magnesium iodide (3.5 mL, 0.35 mmol, 1.6 equiv, addition within 3.2 h) in Et_2O (22 mL, 0.01 M) was obtained after stirring for 12 h the substitution product **10** (30 mg, 99%) in a regioselectivity of $S_N2'/S_N2 > 99:1$ after aqueous work-up and chromatographic purification (silica gel, pentane). Analytical GC (CPSil5CB, 40 °C (5 min), 5 °C min^{-1}, 200 °C (5 min)): t_R[**10**] = 12.19 min, t_R[S_N2] = 13.14 min; ^{1}H NMR (400.136 MHz, $CDCl_3$): $\delta = 0.96$ (d, $J = 6.9$ Hz, 3H), 1.04–1.35 (m, 6H), 1.59–1.76 (m, 5H), 1.95 (m, 1H), 4.90 (m, 1H), 4.99 (m, 1H), 5.71 ppm (m, 1H); ^{13}C NMR (100.614 MHz, $CDCl_3$): $\delta = 17.1$, 26.65 (2C), 26.69, 30.2, 30.4, 42.9, 43.5, 112.9, 143.6 ppm. The analytical data correspond to those reported previously.[46]

3-Phenyl-1-butene (11): Starting from *o*-DPPB ester **7** (135 mg, 0.32 mmol), copper bromide dimethyl sulfide (32.9 mg, 0.16 mmol), and MeMgI (0.1 M in Et_2O, 4.8 mL, 0.48 mmol, addition within 4 h) in Et_2O (32 mL, 0.01 M) was obtained crude **11** (conv. > 95 %) in a regioselectivity of S_N2'/S_N2 92:8. Column chromatography (silica gel, pentane) gave pure **11** (31 mg, 73 %). Analytical GC (CPSil5CB, 40 °C (1 min), 10 °C min^{-1}, 200 °C (2 min): t_R[**11**] = 8.16 min, t_R[S_N2] = 10.06 min; ^{1}H NMR (400.136 MHz, $CDCl_3$): δ = 1.36 (d, J = 7.3 Hz, 3H), 3.46 (m, 1H), 5.02 (dpt, J = 10.3, 1.3 Hz, 1H), 5.04 (dpt, J = 17.1, 1.3 Hz, 1H), 6.01 (ddd, J = 17.1, 10.3, 6.5 Hz, 1H), 7.15–7.35 ppm (m, 5H); ^{13}C NMR (100.624 MHz, $CDCl_3$): δ = 20.8, 43.3, 113.2, 126.2, 126.8 (2C), 128.6 (2C), 143.4, 145.7 ppm. The analytical data correspond to those reported previously.[47]

3,3,7-Trimethyl-1,6-octadiene (12): Starting from *o*-DPPB ester **8** (50 mg, 0.113 mmol), copper bromide dimethyl sulfide (12.3 mg, 0.06 mmol), and MeMgI (0.83 M in Et_2O, 0.08 mL, 0.136 mmol, addition time 15 min) was obtained **12** (16 mg, 91 %, S_N2'/S_N2 95:5 (GC), $E/Z(S_N2')$ 92:8 (GC). Analytical GC (CPSil5CB; 40 °C, 5 min, 5 °C min^{-1}, 200 °C, 12 min): t_R[**12**] = 12.52 min, t_R[(*Z*)-S_N2] = 14.20 min, t_r[(*E*)-S_N2] = 14.58 min; ^{1}H NMR (300.066 MHz, $CDCl_3$): δ = 0.99 (s, 6H), 1.29 (m, 2H), 1.58 (s, 3H), 1.67 (s, 3H), 1.88 (m, 2H), 4.90 (m, 2H), 5.09 (m, 1H), 5.77 ppm (m, 1H); ^{13}C NMR (100.624 MHz, $CDCl_3$): δ = 17.5, 23.3, 25.6, 26.7 (2C), 36.6, 42.8, 110.3, 125.1, 131.0, 148.5 ppm. The analytical data correspond to those reported previously.[48]

3,7-Dimethyl-3-ethyl-1,6-octadiene (13): Starting from *o*-DPPB ester **8** (57 mg, 0.129 mmol), copper bromide dimethyl sulfide (14.4 mg, 0.07 mmol), and EtMgBr (1.02 M in Et_2O, 0.15 mL, 0.155 mmol, addition time 15 min) was obtained **13** (17 mg, 80 %, S_N2'/S_N2 > 98:2, $E/Z(S_N2')$ 92:8).

Starting from *o*-DPPB ester **9** (68 mg, 0.154 mmol), copper bromide dimethyl sulfide (16.4 mg, 0.08 mmol), and EtMgBr (1.02 M in Et_2O, 0.18 mL, 0.185 mmol, addition time 15 min) were obtained **13** (24 mg, 0.146 mmol, 95 %; S_N2'/S_N2 98:2 (GC), $E/Z(S_N2')$ 97:3 (GC)). Analytical GC (CPSil5CB; 40 °C, 5 min, 5 °C min^{-1}, 200 °C): t_R[**13**] = 16.2 min, t_R[(*Z*)-S_N2] = 17.00 min, t_R[(*E*)-S_N2] = 17.4 min; ^{1}H NMR (300.066 MHz, $CDCl_3$): δ = 0.78 (t, J = 7.5 Hz, 3H), 0.94 (s, 3H), 1.30 (m, 4H), 1.58 (s, 3H), 1.67 (m, 3H), 1.86 (m, 2H), 4.89 (dd, J = 17.6, 1.5 Hz, 1H), 4.99 (dd, J = 10.9, 1.5 Hz, 1H), 5.09 (m, 1H), 5.67 ppm (dd, J = 17.6, 10.9 Hz, 1H); ^{13}C NMR (100.624 MHz, $CDCl_3$): δ = 8.3, 22.0 (2C), 22.8, 25.7, 33.0, 39.6, 40.4, 111.6, 125.2, 130.9, 147.2 ppm. The analytical data correspond to those reported previously.[49]

2,6-Dimethyl-6-ethenyl-2-decene (14): Starting from *o*-DPPB ester **8** (51 mg, 0.115 mmol) and *n*BuMgBr (1.23 M in Et_2O, 0.11 mL, 0.138 mmol, addition time 15 min) was obtained **14** (20 mg, 87 %, S_N2'/S_N2 > 99:1). Analytical GC (CPSil5CB; 40 °C, 5 min, 5 °C min^{-1}, 200 °C): t_R[**8**] = 21.0 min, t_R[(*Z*)-S_N2] = 22.0 min, t_R[(*E*)-S_N2] = 22.4 min; ^{1}H NMR (400.136 MHz, $CDCl_3$): δ = 0.88 (t, J = 7.3 Hz, 3H), 0.95 (s, 3H), 1.21 (m, 8H), 1.58 (s, 3H), 1.67 (s, 3H), 1.87 (m, 2H), 4.88 (dd, J = 17.6, 1.7 Hz, 1H), 4.97 (dd, J = 10.8, 1.7 Hz, 1H), 5.09 (m, 1H), 5.70 ppm (dd, J = 17.6, 10.7 Hz, 1H); ^{13}C NMR (100.620 MHz, $CDCl_3$): δ = 14.1, 17.5, 22.6, 22.8, 23.5, 26.3, 39.4, 40.6, 40.8, 111.2, 125.2, 130.9, 147.5 ppm. The analytical data correspond to those reported previously.[50]

(±)-(*E*)-2-Phenyl-3-hexene [(±)-19]: Starting from *o*-DPPB ester (±)-(*E*)-**15** (256 mg, 0.57 mmol), copper bromide dimethyl sulfide (58.6 mg, 0.29 mmol) and MeMgI (0.96 M in Et_2O, 0.65 mL, 0.63 mmol, addition time 15 min) was obtained after column chromatography (silica gel, pentane) (±)-**19** (84 mg, 92 %, S_N2'/S_N2 97:3).

Starting from *o*-DPPB ester (±)-(*Z*)-**15** (230 mg, 0.51 mmol), copper bromide dimethyl sulfide (52 mg, 0.255 mmol) and MeMgI (0.96 M in Et_2O, 0.58 mL, 0.56 mmol, addition time 0.5 min, reaction time after Grignard addition 30 min) was obtained after column chromatography (silica gel, pentane) (±)-**19** (72 mg, 88 %, S_N2'/S_N2 99:1). Analytical GC (CPSil5CB; 40 °C, 2 min, 10 °C min^{-1}, 200 °C, 12 min): t_R[(*E*)-**19**] = 11.17 min, t_R[S_N2] = 11.82 min, t_R[(*Z*)-**19**] = 12.31 min; ^{1}H NMR (500.132 MHz, $CDCl_3$): δ = 0.98 (t, J = 7.4 Hz, 3H), 1.33 (d, J = 7.4 Hz, 3H), 2.03 (pquint, J = 7.4 Hz, 2H), 3.41 (pquint, J = 7.4 Hz, 1H), 5.49 (dpt, J = 15.4, 6.0 Hz, 1H), 5.59 (dd, J = 15.4, 6.69 Hz, 1H), 7.16–7.3 ppm (m, 5H); ^{13}C NMR (125.758 MHz, $CDCl_3$): δ = 13.8, 21.6, 25.5, 41.3, 125.9, 127.2 (2C), 128.3 (2C), 130.8, 133.9, 146.6 ppm.

(±)-(*E*)-5-Methyloct-3-enoic acid *tert*-butyl ester [(±)-20]: Starting from the *o*-DPPB ester (±)-**16** (251 mg, 0.50 mmol), copper bromide dimethyl sulfide (103 mg, 0.50 mmol) and a solution of MeMgI (1.17 M in Et_2O, 0.86 mL, 1.00 mmol, addition within 3 min) in Et_2O (15 mL) was obtained after 48 h at 0 °C after aqueous work-up and column chromatography (silica gel, pentane/Et_2O 95:5) (±)-**20** (89 mg, 82 %, S_N2'/S_N2 95:5) as a colorless oil. Analytical GC (OV-1, 40 °C (5 min), 10 °C min^{-1}, 200 °C (9 min): t_R[S_N2] = 16.29 min, t_R[(±)-**20**] = 16.42 min; ^{1}H NMR (300.135 MHz, $CDCl_3$): δ = 0.87 (t, J = 7.0 Hz, 3H), 0.96 (d, J = 6.6 Hz, 3H), 1.23 (m, 4H), 1.44 (s, 9H), 2.12 (psept, J = 6.6 Hz, 1H), 2.92 (d, J = 5.9 Hz, 2H), 5.38 (dd, J = 15.5, 6.6 Hz, 1H), 5.46 ppm (dt, J = 15.5, 6.3 Hz, 1H); ^{13}C NMR (75.476 MHz, $CDCl_3$): δ = 14.1, 20.3, 20.5, 28.1 (3C), 36.4, 39.1, 39.4, 80.2, 120.4, 140.2, 171.6 ppm; HRMS (EI, 70 eV): *m*/*z*: calcd for $C_{13}H_{24}O_2$: 212.1776; found 212.1777 $[M]^+$.

(±)-(*E*)-5-Phenyl-hex-3-enoic acid *tert*-butyl ester [(±)-21]: Starting from the *o*-DPPB-ester (±)-**17** (392 mg, 0.73 mmol), copper bromide dimethyl sulfide (150 mg, 0.73 mmol), and MeMgI (0.50 M in diethylether, 1.6 mL, 0.80 mmol, addition within 3 min) in Et_2O (14.6 mL) was obtained after aqueous work-up and column chromatography (silica gel, pentane) (±)-**21** (155 mg, 0.63 mmol, 86 %, S_N2'/S_N2 97:3; E/Z[(±)-**17**] 97:3) as a clear colorless oil. Analytical GC (CPSil5CB, 40 °C (2 min), 10 °C min^{-1}, 200 °C (2 min)): t_R[(±)-(*Z*)-**21**] = 17.34 min, t_R[(*E*)-S_N2] = 18.05 min, t_R[(±)-(*E*)-**21**] = 18.63 min; ^{1}H NMR ($CDCl_3$, 300.133 MHz): δ = 1.36 (d, J = 7.0 Hz, 3H), 1.44 (s, 9H), 2.96 (m, 2H), 3.47 (m, 1H), [5.42 (dd, J = 9.2, 7.0 Hz, 1H], 5.57 (dptd, J = 15.5, 6.4, 1.1 Hz, 1H), 5.71 (ddpt, J = 15.5, 6.6, 1.1 Hz, 1H), 7.29 ppm (m, 5H); ^{13}C NMR ($CDCl_3$, 75.469 MHz): δ = 21.1, 28.0 (3C), 39.2, 42.1, 80.4, 121.3, 126.0, 127.2 (2C), 128.3 (2C), 138.6, 145.7, 171.3 ppm; elemental analysis calcd (%) for $C_{16}H_{22}O_2$ (246.34): C 78.01, H 9.00; found: C 78.02, H 8.99.

(*E*)-2,2,5-Trimethyl-3-hexene [(±)-22]: Starting from *o*-DPPB-ester (±)-**18** (161 mg, 0.387 mmol), copper bromide dimethyl sulfide (39.7 mg, 0.193 mmol), and MeMgI (1.11 M in Et_2O, 0.38 mL, 0.425 mmol, addition time 15 min) (±)-**22** (33 mg, 68 %, S_N2'/S_N2 > 99:1, E/Z (S_N2') > 99:1). In deviation from the general procedure aqueous work-up was omitted. Instead, all volatile components of the crude reaction mixture were evaporated in oil pump vacuo and condensed in a cold trap at −196 °C. Ethereal solvent was removed upon distillation under ambient pressure to give pure (±)-**22**. Analytical GC (CPSil5CB; 40 °C, 5 min, 5 °C min^{-1}, 100 °C, 13 min, 40 °C min^{-1}, 200 °C): t_R = 3.42 min (0.6 %), t_R[(±)-**22**] = 4.32 min (99.4 %); ^{1}H NMR (400.136 MHz, $CDCl_3$): δ = 0.93 (d, J = 6.9 Hz, 6H), 0.95 (s, 9H), 2.18 (m, 1H), 5.23 (dd, J = 15.9, 6.5 Hz, 1H), 5.35 ppm (m, 1H); ^{13}C NMR (100.624 MHz, $CDCl_3$): δ = 22.8 (2C), 29.9 (3C), 31.0, 32.5, 131.9, 138.4 ppm; MS (EI, 70 eV): *m*/*z* (%): 126 (12) $[M]^+$, 111 (28), 83 (68), 70 (77), 69 (100), 55 (52).

(±)-(*E*)-2,5,5-Trimethyl-3-nonene [(±)-(*E*)-23]: Starting from *o*-DPPB-ester (±)-**18** (121 mg, 0.290 mmol), copper bromide dimethyl sulfide (30 mg, 0.145 mmol), and *n*BuMgBr (0.51 M in Et_2O, 0.63 mL, 0.32 mmol, addition time 15 min) was obtained (±)-(*E*)-**23** (50 mg, 99 %, S_N2'/S_N2 > 99:1, E/Z (S_N2') > 99:1). Analytical GC (CPSil5CB; 40 °C, 5 min, 5 °C min^{-1}, 100 °C, 13 min, 40 °C min^{-1}, 200 °C): t_R = 12.25 min (1 %), t_R[(±)-(*E*)-**23**] = 14.06 min (98 %), t_R = 15.24 min (1 %); ^{1}H NMR (400.136 MHz, $CDCl_3$): δ = 0.81 (t, J = 6.9 Hz, 3H), 0.86 (s, 6H), 0.89 (d, J = 6.4 Hz, 6H), 1.16 (m, 6H), 2.15 (m, 1H), 5.15 (dd, J = 15.9, 6.0 Hz, 1H), 5.22 ppm (d, J = 15.9 Hz, 1H); ^{13}C NMR (100.624 MHz, $CDCl_3$): δ = 14.1, 23.0 (2C), 23.5, 26.8, 27.5 (2C), 31.2, 35.2, 43.1, 133.1, 137.3 ppm; HRMS (EI, 70 eV): *m*/*z*: calcd for $C_{12}H_{24}$: 168.1878; found 168.1878 $[M]^+$.

Chirality transfer experiments

(±)-(3*R,6*R**)-3-Isopropyl-6-methyl-1-cyclohexene (*cis*-menthene, *cis*-28)**:[51] Starting from *o*-DPPB ester *cis*-**27** (223 mg, 0.52 mmol, *cis*/*trans* 97:3), copper(I) bromide dimethyl sulfide (107 mg, 0.52 mmol), and MeMgI (1.50 M in Et_2O, 0.38 mL, 0.57 mmol) in additional Et_2O (10.4 mL) was obtained *cis*-**28** and *trans*-**28** as an inseparable mixture (97:3). Analytical GC (CP-SIL 5CB, Chrompack; 40 °C, 5 min, 5 °C min^{-1}, 160 °C, 1 min) t_R[*cis*-**28**] = 11.85 min, t_R[*trans*-**28**] = 11.63 min, GC yield > 95 %; ^{1}H NMR ($CDCl_3$, 500.135 MHz): δ = 0.88 (d, J = 6.7 Hz, 3H),

0.91 (d, $J=6.7$ Hz, 3H), 0.96 (d, $J=7.4$ Hz, 3H), 1.28 (m, 1H), 1.38 (m, 1H), 1.51 (m, 2H), 1.68 (m, 1H), 1.85 (m, 1H), 2.16 (m, 1H), 5.58 ppm (m, 2H); ^{13}C NMR ($CDCl_3$, 125.771 MHz): $\delta=19.8$, 20.0, 21.2, 22.0, 28.9, 29.4, 32.2, 41.5, 129.9, 133.5 ppm. The ^{1}H and ^{13}C NMR data correspond to a sample of *cis*-menthene (*cis*-**28**) prepared from the corresponding carbamate and $Me_5Cu_3Li_2$ following a literature procedure.[51]

(±)-(3*R,6*S**)-3-Isopropyl-6-methyl-1-cyclohexene (*trans*-menthene, *trans*-28)**: Starting from *o*-DPPB ester *trans*-**27** (54 mg, 0.13 mmol, *trans*/*cis* 92:8), copper(I) bromide dimethyl sulfide (26 mg, 0.13 mmol), and MeMgI (1.27 M in Et_2O, 0.20 mL, 0.26 mmol) in additional Et_2O (4 mL) was obtained *trans*-**28** and *cis*-**28** as an inseparable mixture (92:8). Analytical GC (Carbovax, Hewlett Packard; 50 °C, 1 min, 10 °C min^{-1}, 200 °C, 14 min): t_R[*trans*-**28**] = 6.45 min, t_R[*cis*-**28**] = 6.66 min, GC yield >95%; ^{1}H NMR ($CDCl_3$, 500.135 MHz): $\delta=0.86$ (d, $J=6.7$ Hz, 3H), 0.89 (d, $J=6.7$ Hz, 3H), 0.95 (d, $J=6.7$ Hz, 3H), 1.10 (m, 1H), 1.24 (m, 1H), 1.56 (psept, $J=6.7$ Hz, 1H), 1.70 (m, 1H), 1.83 (m, 1H), 1.91 (m, 1H), 2.11 (m, 1H), 5.52 ppm (m, 2H); ^{13}C NMR ($CDCl_3$, 125.771 MHz): $\delta=19.3$, 19.6, 22.0, 25.6, 31.0, 32.0, 32.2, 41.9, 129.9, 134.0 ppm. The ^{1}H and ^{13}C NMR data correspond to a sample of commercially available (Aldrich) sample of *trans*-menthene (*trans*-**28**).

(+)-(2*S*,*E*)-2-Phenyl-3-hexene [(+)-19] with recovery of the *o*-DPPBA: Copper bromide dimethyl sulfide (257 mg, 1.25 mmol, 1.0 equiv) in one portion was added to a solution of *o*-DPPB ester (−)-(*E*)-**15** (565 mg, 1.25 mmol, *ee* >99%) in Et_2O (25 mL) and the resulting yellow suspension was stirred for 5 min at room temperature. A 1.06 M ethereal solution of methyl magnesium iodide (1.3 mL, 1.38 mmol) was added within 5 min and the bright yellow suspension was stirred for further 2 h at room temperature. The reaction was quenched by successive addition of a saturated aqueous NH_4Cl solution (8 mL) and an aqueous ammonia solution (12.5%, 10 mL) followed by the addition of pentane/Et_2O (5:1, 20 mL). The mixture was stirred for 10 min during which time a yellow precipitate formed. The mixture was filtered and the residue washed with additional pentane/Et_2O (5:1, 20 mL). The organic phase of the filtrate was separated and the aqueous phase was extracted with three further portions of Et_2O (10 mL each). The combined organic phases were washed with brine, dried ($MgSO_4$) and the solvent removed in vacuo. Column chromatography (silica gel, PE/EtOAc 9:1) furnished (+)-**19** (184 mg, 92%, S_N2'/S_N2 99:1, $E/Z(S_N2')$ 98:2, *ee* >99%). Analytical GC (CP-SIL 5CB, Chrompack; 40 °C, 2 min, 10 °C min^{-1}, 200 °C, 12 min), t_R[(+)-**19**] = 11.29 min (97%), (*Z*)-alkene isomer, t_R = 11.10 min (1%) and regioisomer (*E*)-1-phenyl-3-methyl-1-pentene, t_R = 12.27 min (2%); chiral GC (permethyl-β-cyclodextrin, Chrompack; 65 °C), t_R[(+)-**19**] = 69.07 min; $[\alpha]_D^{20}$ = +10 (*c*=1.5, pentane); ^{1}H NMR (500.132 MHz, $CDCl_3$): $\delta=0.98$ (t, $J=7.4$ Hz, 3H), 1.33 (d, $J=7.4$ Hz, 3H), 2.03 (pquint, $J=7.4$ Hz, 2H), 3.41 (pquint, $J=7.4$ Hz, 1H), 5.49 (dpt, $J=15.4$, 6.0 Hz, 1H), 5.59 (dd, $J=15.4$, 6.69 Hz, 1H), 7.16–7.3 ppm (m, 5H); ^{13}C NMR (125.758 MHz, $CDCl_3$): $\delta=13.8$, 21.6, 25.5, 41.3, 125.9, 127.2 (2C), 128.3 (2C), 130.8, 133.9, 146.6 ppm; HRMS (EI, 70 eV): *m*/*z*: calcd for $C_{12}H_{16}$: 160.1256; found 160.1238 $[M]^+$.

Recovery of 2-diphenylphosphanyl benzoic acid (*o*-DPPBA): The yellow residue obtained in the filtration process above was dissolved in dichloromethane (20 mL), washed with water (10 mL), followed by addition of pH 4.75 buffer in methanol/water (1:1, 20 mL) and KCN (600 mg, 9.2 mmol) upon which the color of the organic phase changed from yellow to colorless. The phases were separated and the aqueous phase washed with three more portions of dichloromethane (10 mL each). The combined organic phases were washed with water (20 mL), dried ($MgSO_4$) and the solvent removed in vacuo to give *o*-DPPBA as a pale yellow solid (303 mg, 79%). Analytical data were identical to those reported previously.[28]

(−)-(2*R*,*E*)-2-Phenyl-3-hexene [(−)-19]: Copper bromide dimethyl sulfide (43 mg, 0.21 mmol) was added in one portion to a solution of *o*-DPPB ester (+)-(*Z*)-**15** (190 mg, 0.42 mmol, *ee* >97%) in Et_2O (8.4 mL) and the resulting yellow solution was stirred for 5 min at room temperature. A 1.34 M ethereal solution of methyl magnesium iodide (0.35 mL, 0.46 mmol) was added within 5 min and the bright yellow suspension was stirred for further 2 h at room temperature. The reaction was quenched by successive addition of a saturated aqueous NH_4Cl solution (8 mL) and an aqueous ammonia solution (12.5%, 10 mL) followed by the addition of Et_2O (10 mL). The mixture was stirred for 10 min, the organic phase was separated and the aqueous phase was extracted twice with Et_2O (20 mL each). The combined organic phases were washed with brine, dried ($MgSO_4$) and the solvent removed in vacuo to give (−)-**19** (57 mg, 0.36 mmol, 86%, S_N2'/S_N2 >99:1, E/Z (S_N2') >98:2, *ee* 93%) as a colorless oil after column chromatography (pentane). Analytical GC (CP-SIL 5CB, Chrompack; 40 °C, 2 min, 10 °C min^{-1}, 200 °C, 12 min), t_R[(−)-**19**] = 11.82 min (97%), (*Z*)-alkene isomer, t_R = 11.17 min (1%) and regioisomer (*E*)-1-phenyl-3-methyl-1-pentene, t_R = 12.31 min (2%). Chiral GC (Permethyl-β-cyclodextrin, Chrompack; 65 °C), t_R[(−)-**19**] = 66.43 min (96.3%), t_R[(+)-**17**] = 70.63 min (3.7%); $[\alpha]_D^{20}$ = −13.7 (*c*=3.12 in $CHCl_3$).

Ozonolysis of (+)-19 and reductive work-up: **(+)-(*R*)-2-phenylpropanol [(+)-33]**: A solution of (+)-**19** (67 mg, 0.42 mmol) in methanol (7 mL) was cooled to −78 °C under a stream of oxygen. Subsequently, ozone was bubbled through this solution for 7 min (the typical blue color appeared and persisted after 1 min) followed by oxygen for further 3 min. Sodium boron hydride (60 mg, 1.68 mmol) was added, the solution was allowed to warm during 10 h to room temperature, and was stirred for further 24 h. The reaction mixture was poured into an aqueous HCl solution (5%, 20 mL), followed by the addition of Et_2O (10 mL). The organic phase was separated and the aqueous phase was extracted with Et_2O (3× 20 mL). The combined organic phases were washed with water and brine, dried ($MgSO_4$) and the solvent was removed in vacuo. Column chromatography (silica gel, PE/EtOAc 4:1) furnished (+)-**33** (21 mg, 0.15 mmol, 37%). $[\alpha]_D^{20}$ = +11.3 (*c*=0.95, $CHCl_3$) {lit.[24] $[\alpha]_D^{20}$ = +14.3 (*c*=16.5, $CHCl_3$)}. Analytical and spectroscopic data correspond to those reported previously.[24]

[(−)-(*E*)-15]$_2$CuBr (34): Copper(I) bromide dimethyl sulfide (39.9 mg, 0.194 mmol) in one portion was added to a solution of (−)-(*E*)-**15** (175 mg, 0.388 mmol) in CH_2Cl_2 (1 mL). The reaction mixture was stirred for about 5 min to give an intensive yellow solution. Removal of all volatile components in oil pump vacuum gave **34** (203 mg, quant.) as a yellow solid. M.p. 98–105 °C; $[\alpha]_D^{20}$ = −162.0 (*c*=2.35, $CHCl_3$); ^{1}H NMR (300.063 MHz, $CDCl_3$): $\delta=0.73$ (t, $J=7.2$ Hz, 6H, 2×CH_3-C_5), 1.57 (m, 2H, 2×CH_2-C_4), 5.05 (brs, 2×CH-C_3), 5.95 (dd, $J=15.9$, 7.4 Hz, 2×-CH-C_2), 6.17 (d, $J=16.1$ Hz, 2×CH-C_1), 6.76 (d, $J=7.6$ Hz, 2H, Ar-H), 7.05–7.32 (m, 26H, Ar-H), 7.48 (d, $J=7.0$ Hz, 4H, Ar-H), 7.60 (d, $J=6.4$ Hz, 4H, Ar-H), 7.85 ppm (m, 2H, Ar-H); ^{31}P NMR (121.450 MHz, $CDCl_3$): $\delta=-0.3$ ppm (brs).

Temperature dependent NMR spectroscopy of [(−)-(*E*)-15]$_2$CuBr + 2 equiv (−)-(*E*)-15: A solution of (−)-(*E*)-**15** (95 mg, 0.211 mmol) in nBu_2O (1.4 mL) was treated with copper(I) bromide dimethyl sulfide (10.8 mg, 0.053 mmol) and stirred at room temperature for 5 min. The yellow precipitate, which was formed immediately, was dissolved with additional CH_2Cl_2 (0.6 mL). As a reference for the NMR spectroscopy additional [D_8]toluene (0.2 mL) was added to this mixture. An aliquot (0.8 mL) of this solution was transferred into a flame-dried NMR tube under an atmosphere of argon, and analyzed by ^{31}P NMR spectroscopy (121.450 MHz) at temperatures between 213 and 353 K. The coalescent temperature was determined to T_C = 316 K (±2 K), see Table 6.

Storage of the remaining solution for several days at room temperature furnished slightly yellow crystals of **34** suitable for X-ray diffraction.

X-ray crystal structure analysis of [(−)-(*E*)-14]$_2$CuBr (34): Crystal data: $C_{60}H_{54}BrCuO_4P_2 \cdot C_7H_8$, $M=1044.42$, $0.2\times0.2\times0.15$ mm^3, orthorhombic, space group $P2_12_12_1$, $a=10.32610(10)$, $b=18.6890(4)$, $c=29.2748(6)$ Å, $V=5649.58(18)$ Å^3, $Z=4$, $\rho_{calcd}=1.228$ g cm^{-3}, $\theta_{max}=27.48°$, $Mo_{K\alpha}=0.71073$ Å, $T=100(2)$ K, Data were collected on a Nonius KappaCCD

Table 6. Exchange rates determined with WinDynA.[27]

T [K]	213	223	233	243	253	263	273	283	293
k_T [s^{-1}]	1.30	0.84	2.25	2.39	3.07	6.13	5.40	7.23	13.58

diffractometer, 39857 reflections collected, 12825 were independent ($R_{int}=0.0670$), absorption correction was performed semi-empirical from equivalents ($\mu=1.193\ mm^{-1}$, min. transmission = 0.960, max. transmission = 1.037). The structure was solved by direct methods (SIR-97 (Giacovazzo, 1997)) and refined by full-matrix least squares on F^2 (SHELXL-97 (Sheldrick, 1997)). Application of Platon/SQUEEZE removed unassigned residual electron density due to disordered solvent.[52] The unit cell contains two voids of about 411 $Å^3$ each. The total electron density taken into account was 96 and 97 ē, respectively, per void, equivalent to two toluene molecules. The derived quantities (M, μ and ρ_{calcd}) do not contain the contribution from this disordered solvent. The H atoms were constructed in geometrically idealized positions and refined in a riding model. Parameters = 613, final $R1=0.0395$ [$I>2\sigma(I)$] and $wR2=0.0806$ (all data). Residual electron density = 0.395 e $Å^{-3}$.

CCDC-299832 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

(+)-(*S,E*)-2-Phenyl-3-hexene [(+)-19] employing catalytic conditions (20 mol% copper(I) bromide dimethyl sulfide): Following the representative procedure for (−)-**19** described above from (−)-(*E*)-**15** (276 mg, 0.61 mmol, *ee* >99%), copper(I) bromide dimethyl sulfide (25.1 mg, 0.12 mmol) and a 0.96 M ethereal solution of methyl magnesium iodide (0.70 mL, 0.67 mmol, 1.1 equiv, addition time 5 min, room temperature) in Et_2O (12.2 mL, 0.05 M) was obtained after flash chromatography (pentane) (+)-**19** as an inseparable mixture with the S_N2 regioisomer (76 mg, 0.47 mmol, 78%, *ee* >99%) in a ratio of 93:7 (*E*/*Z*[(+)-**19**] 93:7). Analytical GC (CP-SIL 5CB, Chrompack; 40 °C, 2 min, 10 °C min^{-1}, 200 °C, 12 min), t_R[(+)-(*Z*)-**19**] = 11.10 min, t_R[(+)-(*E*)-**19**] = 11.29 min, $t_R[S_N2]$ = 12.27 min. Chiral GC (permethyl-β-cyclodextrin, Chrompack; 65 °C), t_R[(+)-**19**] = 67.58 min.

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[1] a) Y. Yamamoto, *Methods of Organic Chemistry (Houben-Weyl)*, *Vol. E21*, **1995**, pp. 2011–2040; b) B. Breit, P. Demel in *Modern Organocopper Chemistry* (Ed.: N. Krause), Wiley-VCH, Weinheim, **2002**, pp. 188–223.

[2] a) T. Ibuka, M. Tanaka, S. Nishii, Y. Yamamoto, *J. Chem. Soc. Chem. Commun.* **1987**, 1596–1598; b) T. Ibuka, N. Akimoto, M. Tanaka, S. Nishii, Y. Yamamoto, *J. Org. Chem.* **1989**, *54*, 4055–4061; c) N. Harrington-Frost, H. Leuser, M. I. Calaza, F. F. Kneisel, P. Knochel, *Org. Lett.* **2003**, *5*, 2111–2114; d) H. Leuser, S. Perrone, F. Liron, F. F. Kneisel, *Angew. Chem.* **2005**, *117*, 4703–4707; *Angew. Chem. Int. Ed.* **2005**, *44*, 4627–4631; e) for a review on the progress in enantioselective catalysis with chiral copper catalysts see: H. Yorimitsu, K. Oshima, *Angew. Chem.* **2005**, *117*, 4509–4513; *Angew. Chem. Int. Ed.* **2005**, *44*, 4435–4439.

[3] E. J. Corey, N. W. Boaz, *Tetrahedron Lett.* **1984**, *25*, 3063–3066.

[4] a) C. Gallina, *Tetrahedron Lett.* **1982**, *23*, 3094–3096; b) H. L. Goering, S. S. Kantner; C. C. Tseng, *J. Org. Chem.* **1983**, *48*, 715–721; c) J. H. Smitrovich, K. A. Woerpel, *J. Am. Chem. Soc.* **1998**, *120*, 12998–12999; d) J. H. Smitrovich, K. A. Woerpel, *J. Org. Chem.* **2000**, *65*, 1601–1614.

[5] a) P. Barsanti, V. Calò, L. Lopez, G. Marchese, F. Naso, G. Pesce, *J. Chem. Soc. Chem. Commun.* **1978**, 1085–1086; b) V. Calò, L. Lopez, W. F. Carlucci, *J. Chem. Soc. Perkin Trans. 1* **1983**, 2953–2956; c) S. Valverde, M. Bernabé, S. Garcia-Ochoa, A. M. Gómez, *J. Org. Chem.* **1990**, *55*, 2294–2298.

[6] B. Breit, *Chem. Eur. J.* **2000**, *6*, 1519–1524.

[7] a) B. Breit, *Acc. Chem. Res.* **2003**, *36*, 264–275; b) B. Breit, P. Demel, A. Gebert, *Chem. Commun.* **2004**, 114–115; c) B. Breit, G. Heckmann, S. K. Zahn, *Chem. Eur. J.* **2003**, *9*, 425–434; d) B. Breit, M. Dauber, K. Harms, *Chem. Eur. J.* **1999**, *5*, 2819–2827; e) B. Breit, *Eur. J. Org. Chem.* **1998**, 1123–1134; f) B. Breit, *Chem. Commun.* **1997**, 591–592; g) B. Breit, *Liebigs Ann./Recl.* **1997**, 1841–1851; h) B. Breit, *Angew. Chem.* **1996**, *108*, 3021–3023; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 2835–2837.

[8] a) B. Breit, S. K. Zahn, *Tetrahedron* **2005**, *61*, 6171–6179; b) B. Breit, S. K. Zahn, *Angew. Chem.* **2001**, *113*, 1964–1967; *Angew. Chem. Int. Ed.* **2001**, *40*, 1913–1916; c) B. Breit, S. K. Zahn, *Angew. Chem.* **1999**, *111*, 1022–1024; *Angew. Chem. Int. Ed.* **1999**, *38*, 969–971; d) B. Breit, *Tetrahedron Lett.* **1998**, *39*, 5163–5166.

[9] B. H. Lipshutz, J. M. Keith, *Angew. Chem.* **1999**, *111*, 3743–3746; *Angew. Chem. Int. Ed.* **1999**, *38*, 969–971.

[10] U. Kazmeier, T. Lindner *Angew. Chem.* **2005**, *117*, 3368–3371; *Angew. Chem. Int. Ed.* **2005**, *44*, 3303–3306.

[11] a) B. Breit, P. Demel, *Tetrahedron* **2000**, *56*, 2833–2846; b) B. Breit, *Angew. Chem.* **1998**, *110*, 535–538; *Angew. Chem. Int. Ed.* **1998**, *37*, 525–527.

[12] For a preliminary report see: B. Breit, P. Demel, *Adv. Synth. Catal.* **2001**, *343*, 429–432.

[13] For reviews see: a) N. Krause, A. Gerold, *Angew. Chem.* **1997**, *109*, 194–213; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 186–204; b) B. H. Lipshutz, Z. Sengupta, *Org. React.* **1992**, *41*, 135–601.

[14] B. Breit, C. Herber, *Angew. Chem.* **2004**, *116*, 3878–3880; *Angew. Chem. Int. Ed.* **2004**, *43*, 3790–3792.

[15] C. Herber, B. Breit, *Angew. Chem.* **2005**, *117*, 5401–5403; *Angew. Chem. Int. Ed.* **2005**, *44*, 5267–5269.

[16] J.-E. Bäckvall, M. Sellén, B. Grant, *J. Am. Chem. Soc.* **1990**, *112*, 6615–6621.

[17] a) W. Kirmse, S. Kopannia, *J. Org. Chem.* **1998**, *63*, 1178–1184; b) B. M. Trost, G. B. Tometzki, *Synthesis* **1991**, 1235–1245.

[18] L. A. Paquette, R. F. Doehner, Jr., *J. Org. Chem.* **1980**, *45*, 5105–5113.

[19] E. G. Boden, G. E. Keck, *J. Org. Chem.* **1985**, *50*, 2394–2395.

[20] R. M. Magid, *Tetrahedron* **1980**, *36*, 1901–1930.

[21] U. Kazmaier, F. L. Zumpe, *Eur. J. Org. Chem.* **2001**, 4067–4076.

[22] G. Höfle, W. Steglich, H. Vorbrüggen, *Angew. Chem.* **1978**, *90*, 602–615; *Angew. Chem. Int. Ed. Engl.* **1978**, *17*, 569–583.

[23] a) C. Lutz, P. Knochel, *J. Org. Chem.* **1997**, *62*, 7895–7898; b) R. Bernardi, C. Fuganti, P. Grasselli, G. Marinoni, *Synthesis* **1980**, 50–52.

[24] a) E. L. Eliel, J. P. Freeman, *J. Am. Chem. Soc.* **1952**, *74*, 923–928; b) C. Spino, C. Beaulier, J. Lafrenière, *J. Org. Chem.* **2000**, *65*, 7091–7097.

[25] R. W. Hoffmann, *Chem. Rev.* **1989**, *89*, 1841–1860.

[26] P. F. Barron, J. C. Dyason, P. C. Healy, L. M. Engelhardt, C. Pakawatchai, V. A. Patrick, A. H. White, *J. Chem. Soc. Dalton Trans.* **1987**, 1099–1106.

[27] a) T. Lenzen, G. Hägele, Bruker Analytik GmbH, *WinDynA*, **1994–1998**; for a review see: b) J. Sandstrom, *Dynamic NMR-spectroscopy*, Academic Press, London, **1982**; c) J. Sandstrom, *Dynamic NMR-spectroscopy*, Academic Press, London, **1982**, pp. 93–123.

[28] J. E. Hoots, T. B. Rauchfuss, D.-A. Wrobleski, *Inorg. Synth.* **1982**, *21*, 175–179.

[29] W. Wykypiel, J.-J. Lohmann, D. Seebach, *Helv. Chim. Acta* **1981**, *64*, 1337–1346.

[30] a) R. Miravalles, A. Jacot-Guillarmod, *Helv. Chim. Acta* **1966**, *49*, 2313–2320; b) J. Fässler, A. Linden, S. Bienz, *Tetrahedron* **1999**, *55*, 1717–1730.

[31] E. S. M. Perrson, J.-E. Bäckvall, *Acta Chem. Scand.* **1995**, *49*, 899–906.

[32] A. R. Chamberlain, M. Dezube, S. H. Reich, D. J. Sall, *J. Am. Chem. Soc.* **1989**, *111*, 6247–6256.

[33] G. Uccello-Barretta, D. Pini, A. Mastantuono, P. Salvatori, *Tetrahedron: Asymmetry* **1995**, *6*, 1965–1972.

[34] W. Adam, V. R. Stegmann, *Synthesis* **2001**, 1203–1214.

[35] Y. Kitano, T. Matsumoto, F. Sato, *Tetrahedron* **1988**, *44*, 4073–4086.

[36] L. F. Tietze, M. Henrich, A. Niklaus, M. Bubach, *Chem. Eur. J.* **1999**, *5*, 297–304.

[37] K. A. Parker, M. W. Ledeboer, *J. Org. Chem.* **1996**, *61*, 3214–3217.
[38] J.-L. Luche, *J. Am. Chem. Soc.* **1978**, *100*, 2226–2227.
[39] K. Tamao, A. Kawachi, Y. Tanaka, H. Ohtani, Y. Ito, *Tetrahedron* **1996**, *52*, 5765–5772.
[40] G. Stork, A. F. Kreft III, *J. Am. Chem. Soc.* **1977**, *99*, 3850–3851.
[41] E. Zadok, S. Rubinraut, Y. Mazur, *J. Org. Chem.* **1987**, *52*, 385–390.
[42] M. Newcomb, W. T. Ford, *J. Org. Chem.* **1974**, *39*, 232–236.
[43] H. L. Goering, S. S. Kantner, *J. Org. Chem.* **1984**, *49*, 422–426.
[44] A. Yanagisawa, N. Nomura, Y. Noritake, H. Yamamoto, *Synthesis* **1991**, 1130–1136.
[45] D. Roulet, J. Caperos, A. Jacot-Guillarmod, *Helv. Chim. Acta* **1984**, *67*, 640–647.
[46] Y. Masuda, M. Hoshi, A. Arase, *Bull. Chem. Soc. Jpn.* **1992**, *65*, 3294–3299.
[47] V. Fassina, C. Ramminger, M. Seferin, A. L. Monteiro, *Tetrahedron* **2000**, *56*, 7403–7410.
[48] A. Yanagisawa, H. Hibino, N. Nomura, H. Yamamoto, *J. Am. Chem. Soc.* **1993**, *115*, 5879–5880.
[49] J.-P. Morizur, J. Tortajada, *Bull. Soc. Chim. Fr.* **1983**, 175–179.
[50] E. S. Persson, M. van Klaveren, D. M. Grove, J. E. Bäckvall, G. van Koten, *Chem. Eur. J.* **1995**, *1*, 351–359.
[51] a) Preparation of $Me_5Cu_3Li_2$: E. C. Ashley, J. J. Lin, J. J. Watkins, *J. Org. Chem.* **1977**, *42*, 1099–1101; b) preparation of *cis*-menthene: C. Gallina, *Tetrahedron Lett.* **1982**, *23*, 3093–3096.
[52] A. L. Spek, *J. Appl. Crystallogr.* **2003**, *36*, 7–13.

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