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Tetrahedron 59 (2003) 7177–7187

TETRAHEDRON

Synthesis of allyl phosphine oxides/boranes via Horner reaction of bis(diphenylphosphine)ethane monoxide reagent with an aldehyde

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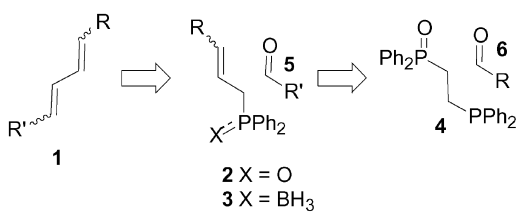
Received 27 May 2003; revised 3 July 2003; accepted 3 July 2003

Abstract—The Horner–Wittig addition–elimination reaction using bis(diphenylphosphine)ethane monoxide [DIPHOS(O)] with an aldehyde affords *Z*-allyl phosphine oxides/boranes. Alternatively, the stereoselective Lewis acid mediated intermolecular reduction of its γ-ketobisphosphoranes and stereoselective intramolecular reduction of γ-ketophosphine·borane derivatives followed by elimination of diphenylphosphinate affords *E*-allyl phosphine oxides/boranes with good to high selectivity. Allyl phosphine oxides are common intermediates in the synthesis of polyenes.

1. Introduction

Numerous natural products containing conjugated polyenes have been synthesized using the current state-of-the-art Pd-mediated coupling[1] of a vinyl halide and vinyl metal that have, in turn, been prepared from aldehydes/enones. Traditional methods using stabilized Wittig or Horner–Wadsworth–Emmons also necessitate functional group transformations to install a phosphorous moiety or to unmask a latent aldehyde.

In conjunction with our program to synthesize a collection of polypropionate segments with carbonyl differentiated termini,[2] we have also been investigating new methods for the formation of polyenes, specifically the ubiquitous 1,3-diene moiety[3] and methyl substituted versions thereof. We specifically sought development of a method that joined two aldehydes, with concomitant addition of the two central carbons.



Scheme 1. Synthesis of polyenes via allyl phosphine oxides.

Allyl phosphine oxides **2**, are common precursors for the synthesis of conjugated polyenes **1** (Scheme 1), upon reaction with aldehydes. Bisphosphorus reagents initially appear to be interesting candidates. Previously, bis-Wittig, bis-Horner–Wittig, and bis-HWE have been employed to prepare olefin and aryl polymers. More specifically, bisphosphorus reagents bis(diphenylphosphine oxide) ethane[4] and an in situ generated $Ph_3P{=}CHCH_2PO(OR)_2$[5] have been reported. These reagents have not been extensively developed and/or have shown limitations such as restricted aldehyde types, lack of regio- and stereocontrol, and low yields. The attraction of **4** was the possibility of a one pot bis-olefination reaction. Other encouraging attributes included its availability,[6] the potential for a stereocontrolled Horner-addition, regiocontrol due to oxidatively-differentiated bis-phosphines, and the well-known ease of work-up (the phosphinic acid anion is washed away with water). Additionally, the Horner reaction of simple alkyl[7] and allyl[8] phosphine oxides **2** have been extensively studied, providing a solid base of experimental and spectral data.

2. Results and discussion

2.1. Horner–Wittig addition–elimination using DIPHOS(O) 4

We wish to report our study on the use of **4** as a Horner reagent for the synthesis of **2**, a key diene precursor (Scheme 1).[8] Initial investigation of a one pot method, via addition of dimethylformamide as a cosolvent and K^+/Na^+ cation exchange prior to warming to room temperature, afforded unacceptably low yields of **2** due to incomplete

Keywords: polyenes; Horner–Wittig reaction; addition–elimination reaction.
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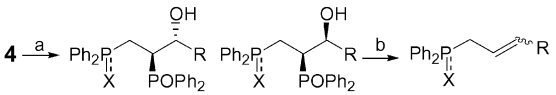
0040–4020/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0040-4020(03)01057-3

Table 1. Horner–Wittig addition using DIPHOS(O) **4**

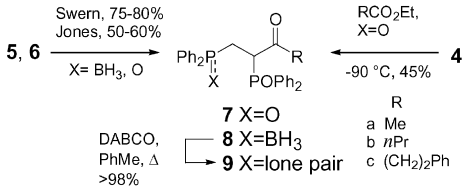


a) *n*BuLi, RHCO, H_2O_2/BH_3•DMS 46-91%, b) NaH, DMF, 51-96%.

	R	X	Additive[a]	Alcohol	*Anti*/*syn*[b] (yield)
1	Me	O	–	**5a**	75:25 (55%)
2	Me	BH_3	–	**6a**	75:25 (57%)
3	Me	BH_3	HMPA	**6a**	83:17 (74%)
4	Me	BH_3	TMEDA	**6a**	75:25 (64%)
5	*n*Pr	O	–	**5b**	75:25 (85%)
6	*n*Pr	O	HMPA	**5b**	86:14 (46%)
7	*n*Pr	BH_3	–	**6b**	75:25 (85%)
8	$Ph(CH_2)_2$	O	–	**5c**	89:11 (91%)[c]
9	$Ph(CH_2)_2$	O	HMPA	**5c**	87:13 (50%)
10	$Ph(CH_2)_2$	BH_3	–	**6c**	89:11 (73%)
11	*i*Pr	O	–	**5d**	50:50 (79%)

[a] 1 equiv. additive, added 15 min before addition of aldehyde.
[b] *Anti*/*syn* ratios determined by ^{31}P NMR.
[c] 2 equiv. hydrocinnamaldehyde.

elimination, retro-aldol, and β-elimination side reactions. A standard Warren protocol was adopted where the alcohol intermediates were isolated as the bisphosphine oxide **5** or the phosphine·borane[9] **6** respectively, in 50–91% yield (Table 1). The Horner addition reactions of **4** only gave moderate diastereoselectivity, favoring the *anti* alcohol adducts.[7a,10] The aldehyde with the larger alkyl group, hydrocinnamaldehyde gave the highest *anti* alcohol ratio ≥87:13. Aldehydes with smaller or branched substituents provided alcohols with lower selectivity. Additives such as HMPA[11] were only beneficial when the aldehyde was small, R=Me, *n*Pr. TMEDA[11] did not provide any improvement. Typical conditions involved deprotonation of **4** at −78°C in THF with 1.2 equiv. of *n*BuLi to afford a deep orange–red solution.[12] After 20–25 min, 1 equiv. of aldehyde is added as a THF solution. This was followed by functionalization of the remaining phosphine via addition of 30% hydrogen peroxide or BH_3·DMS to afford alcohols **5** and **6**, respectively. The primary Horner olefination reaction of alcohols **5b–c** and **6a–c** was generally initiated by treatment with NaH in DMF at 25–30°C. This served to eliminate diphenylphosphinate anion providing allylic phosphorus species **2b–c** and **3a–c** in 51–96% yield.[13] Although small amounts of vinyl phosphine oxides and vinyl phosphine·boranes stemming from isomerization of **2/3** were observed, the elimination reaction was uniformly stereospecific.



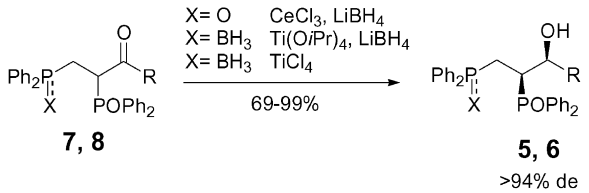
Scheme 2. Synthesis of γ-ketobisphosphorane derivatives **7–9**.

2.2. Stereoselective reduction of γ-ketobisphosphine oxide and γ-ketophosphine·borane derivatives

Stereoselective reduction of the γ-ketobisphosphine oxides and γ-ketophosphine·boranes was also investigated. Ketones **7/8** were primarily obtained by Swern[14] oxidation of alcohols **5** and **6**. γ-Ketobisphosphine oxide **7b** was also acquired in 45% yields, using Warren's modified conditions of lithiated **4** with ethyl buytrate at −90°C, followed by oxidation.[7a] Deprotection of phosphine·borane **8c** with DABCO[9b] in toluene afforded ketone **9c** with no evidence of borane-mediated ketone reduction.[14] (Scheme 2)

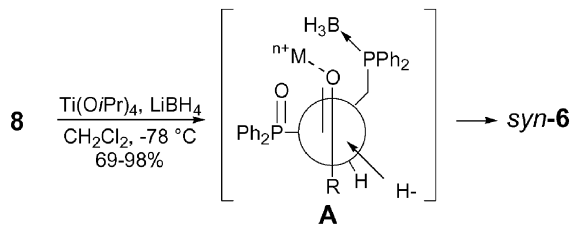
2.2.1. Intermolecular reduction. Preliminary studies using

Table 2. Lewis acid assisted reduction of ketones **7–9**



Entry	Ketone	R	X	Solvent	Lewis acid	H^-	Alcohol	X	*Anti*/*syn* (yield%)[a]
1	**7b**	*n*Pr	O	CH_2Cl_2	–	$LiBH_4$	**5b**	O	33:67 (97%)
2	**8c**	$(CH_2)_2Ph$	BH_3	CH_2Cl_2	–	$LiBH_4$	**6c**	BH_3	13:87 (98%)
3	**7c**	$(CH_2)_2Ph$	O	EtOH	$CeCl_3$	$NaBH_4$	**5c**	O	17:83 (93%)
4	**7c**	$(CH_2)_2Ph$	O	THF	$CeCl_3$	$LiBH_4$	**5c**	O	2:98 (≥98%)
5	**7c**	$(CH_2)_2Ph$	O	CH_2Cl_2	$CeCl_3$	$LiBH_4$	**5c**	O	1:99 (≥98%)
6	**7a**	Me	O	CH_2Cl_2	$CeCl_3$	$LiBH_4$	**5a**	O	2:98 (≥99%)
7	**7d**	*i*Pr	O	CH_2Cl_2	$CeCl_3$	$LiBH_4$	**5d**	O	1:99 (98%)
8	**8b**	*n*Pr	BH_3	CH_2Cl_2	$CeCl_3$	$LiBH_4$	**6b**	BH_3	33:67 (≥98%)
9	**9c**	$(CH_2)_2Ph$		CH_2Cl_2	$CeCl_3$	$LiBH_4$	**6c**	BH_3	30:70 (91%)
10	**8a**	Me	BH_3	CH_2Cl_2	$Ti(OiPr)_4$	$LiBH_4$	**6a**	BH_3	17:83 (69%)
11	**8b**	*n*Pr	BH_3	CH_2Cl_2	$Ti(OiPr)_4$	$LiBH_4$	**6b**	BH_3	6:94 (79%)
12	**8c**	$(CH_2)_2Ph$	BH_3	CH_2Cl_2	$Ti(OiPr)_4$	$LiBH_4$	**6c**	BH_3	6:94 (≥98%)
13	**7c**	$(CH_2)_2Ph$	O	CH_2Cl_2	$TiCl_4$	$LiBH_4$	**5c**	O	20:80 (98%)
14	**9c**	$(CH_2)_2Ph$		CH_2Cl_2	$TiCl_4$	$LiBH_4$	**6c**	BH_3	63:37 (93%)

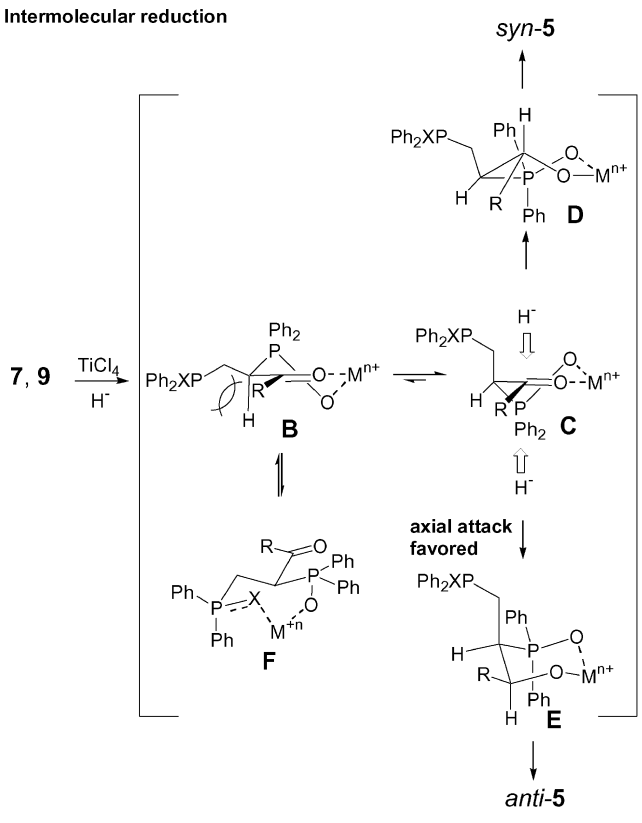
1.3 equiv. Lewis acid. 5 equiv. reducing agent was added at −78°C.
[a] *Anti*/*syn* ratio determined by ^{31}P NMR.



Scheme 3. Proposed Felkin–Anh transition state model of $Ti(OiPr)_4/LiBH_4$ reduction of γ-ketophosphine·borane.

Warren's[7a] modified reduction procedures ($NaBH_4$/EtOH, $CeCl_3/NaBH_4$/EtOH) afforded good selectivity but were quite substrate related. Other protocols such as $CeCl_3/LiBH_4/CH_2Cl_2$ and $TiCl_4/LiBH_4/CH_2Cl_2$ appeared less substrate dependent[15,16] and were, therefore, further investigated. The use of cerium trichloride provided excellent yields of alcohols **5** with high *syn* specificity. The selectivity was found to be most dependent on the functionalization of the distal phosphine. In the case of γ-ketobisphosphine oxides **7**, high diastereoselectivity was obtained (≤2:98 ratio) and was independent of the size of R. In contrast, γ-ketophosphine·borane **8b** and ketophosphine **9c** (X=lone pair) afforded lower ratios. Additionally, high *syn* selectivity is achieved when using $Ti(OiPr)_4$ with phosphine·borane **8a–c**. (Table 2)

The intermolecular reduction selectivity, when using $CeCl_3$, does not follow previously reported trends leading us to believe the reduction of substrates **7–9** may be governed by different Lewis acid–substrate complexes. Upon prolonged mixing of $CeCl_3$ and the ketone substrate, the $CeCl_3$ did not completely dissolve in either tetrahydrofuran or methylene chloride solvent, thus likely changing Lewis acid–substrate ratios. This is further supported by the high coordination ability of cerium. The *syn* favored reduction of **8** with $Ti(OiPr)_4/LiBH_4/CH_2Cl_2$ is attributed to formation of a reduction intermediate according to Felkin Anh guidelines. $Ti(OiPr)_4$ apparently is bulky enough to favor complexation with one lewis base. The largest substituent, the 2-diphenylphosphine oxide, is expected to be perpendicular to the carbonyl whereupon hydride delivery occurs opposite the phosphine oxide (transition state A, Scheme 3).

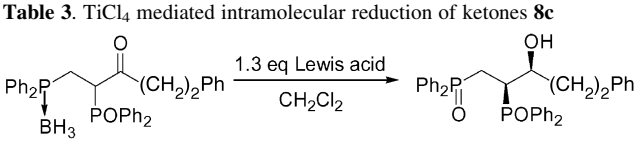


Scheme 4. Proposed closed chain transition states for the reduction of ketones **7**,**9** with $TiCl_4/LiBH_4$.

The $TiCl_4/LiBH_4/CH_2Cl_2$ method[15] was anticipated to favor formation of the *anti* alcohol due to chelation transition state **C** where the phosphinomethyl substituent is pseudoaxial, avoiding steric interaction with the R substituent (Scheme 4). As in the case of 5-alkyl-1,3-dioxanes,[17] the presence of only lone pairs in the two 1,3-diaxial positions nicely accommodates the axial phosphinomethyl group with minimal steric destabilization. Axial attack with a hydride is favored since a lower energy chair intermediate **E** will form as opposed to a twist boat conformation **D** via equatorial hydride attack. The unexpected *syn* isomer is obtained in a 20:80 ratio with **7b** (Entry 13, Table 2). Compound **9c** (X=lone pair) is the only substrate that favors the formation of an *anti* alcohol which is isolated as the borane-protected alcohol **6c**, albeit only a 63:37 *anti*/*syn* ratio is achieved. Ketone **9c** (X=lone pair), is protected in situ with borane that is generated during the reduction.[18] γ-Ketobisphosphine oxide **7c** and ketophosphine **9c** both bear an additional Lewis base which competes for chelation. The competitive chelation (**B**/**C** vs. **F**) is likely the cause for the lowered selectivity. Using the DIPHOS(O) methodology, *anti* alcohols are obtained with higher diastereoselectivity during initial Horner addition.

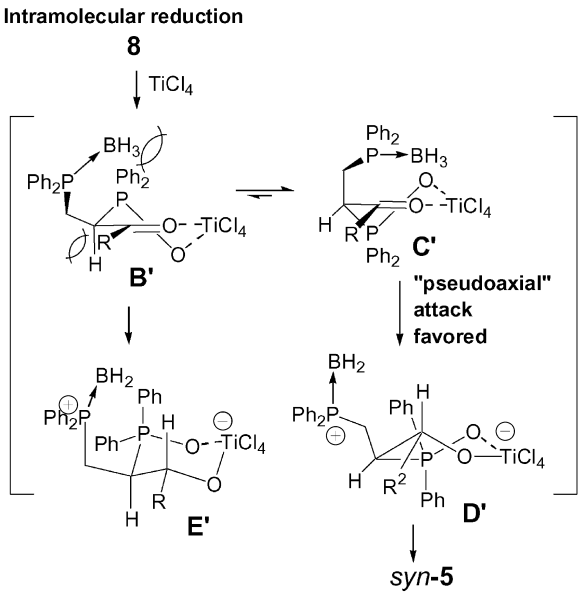
2.2.2. Intramolecular reduction. Addition of $TiCl_4$ to γ-ketophosphine·borane **8c** served to initiate intramolecular reduction (Table 3).[19] Similar to the intermolecular reductions, $TiCl_4$ was expected to form a six membered ring with the β-ketophosphine oxide favoring conformation **C** and **C′** [rotational isomer] (Scheme 5). In conformation **C′**, a hydride would add *syn* to the phosphinomethyl. Additionally, $TiCl_4$ was necessary to activate the carbonyl for reduction.[19] Heating γ-ketophosphine·borane **8c** in toluene at reflux afforded no reduction product. Conformation **C′**, as opposed to **B′**, is the expected transition state

Table 3. $TiCl_4$ mediated intramolecular reduction of ketones **8c**



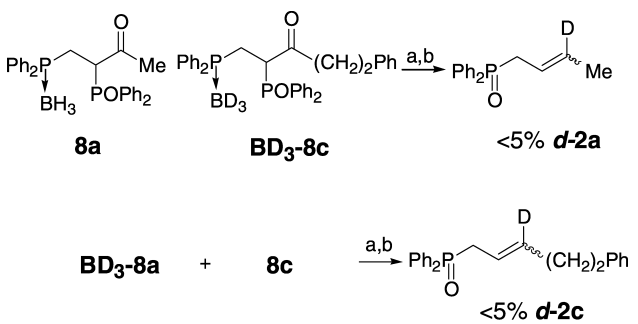
Entry	$[CH_2Cl_2]$	Lewis acid	*T* (°C)	*Anti*/*syn* (yield%)[a]
1	0.1	$TiCl_4$	25	20:80 (98%)
2	0.003	$TiCl_4$	25	5:95 (93%)[b]
3	0.003	$TiCl_4$	−78	13:87 (78%)
4	0.003	$BF_3{\cdot}OEt_2$	25	20:80 (90%)[c]

[a] *Anti*/*syn* ratio determined by ^{31}P NMR.
[b] 30 min, 20 equiv. K_2CO_3 or polyvinylpyridine.
[c] 12 h.



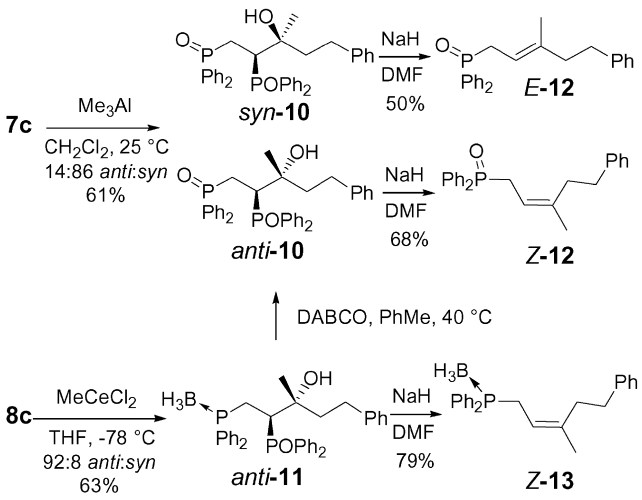
Scheme 5. Closed chain transition states for intramolecular reduction.

that leads to reduction where the phosphinomethyl takes a pseudoaxial position instead of a pseudoequatorial position. Reduction via **C**′ leads to an unfavored twist boat reduction transition state **D**′, instead of the lower energy chair transition state **E**′, but is favored since it avoids the 1,3-diaxial type interactions encountered in conformation **B**′. Preliminary experiments showed $TiCl_4$ in methylene chloride to be the best reaction system. Reduction occurred faster and afforded higher selectivity when compared to $BF_3{\cdot}Et_2O$. The addition of highly Lewis acidic $TiCl_4$ catalyzed intramolecular reduction in less than one minute at room temperature. When followed by peroxide oxidation this reaction afforded *syn*-**5c** with good selectivity 20:80 *anti*/*syn* in >90% yields. The selectivity was further improved to 5:95 *anti*/*syn* by diluting the solution and adding crushed potassium carbonate or polyvinyl pyridine. Lowering the reaction temperature still afforded good selectivity, justifying **C**′ leading to reduction, since the lower energy conformer increases at lower temperatures. The lowered activation energy of the intramolecular reaction overcomes the formation of a higher energy disfavored twist boat conformation **D**′ upon "pseudoaxial" attack. Cross reactions using deuterated borane[20] compounds **BD$_3$-8c** (R=$(CH_2)_2$Ph) with **8a** (R=Me) followed by standard Horner reaction resulted in <5±5% deuterium incorporation in the elimination products **2a** hence demonstrating intramolecular reduction. The rate of reduction was not a factor as the cross reduction of **BD$_3$-8a** (R=Me) with **8c** (R=$(CH_2)_2$Ph) provided similar deuterium incorporation in **2c** (Schemes 6 and 7).



a) i, 2.3 eq $TiCl_4$, 0.003 M CH_2Cl_2, rt, ii, H_2O_2, b) NaH, DMF.

Scheme 6. Determination of intramolecular reduction via deuterated cross reactions.



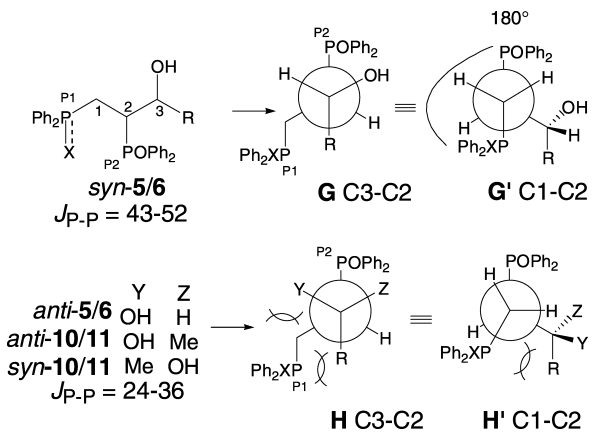
Scheme 7. Synthesis of trisubstituted allyl phosphine oxides/boranes **12**/**13**.

2.3. Trisubstituted allyl phosphoranes

Trisubstituted alkenes, such as 1-methyl-1,3-dienes, are very desirable targets which can be obtained from trisubstituted allyl phosphine oxides. Reactions with methyl ketones and **4** gave poor selectivity. Therefore methylations of the γ-ketobisphosphine oxides **7** and γ-ketobisphosphine·boranes **8** were attempted. Ketones **7c** and **8c** were employed as initial substrates in nucleophilic methylation reactions to provide alcohols **10** and **11**. Horner–Wittig elimination of these alcohols gave the trisubstituted allyl phosphines **12** and **13** in 50–79% yield (over two steps). Study of these reactions revealed that the methylation of **7c** and **8c** worked best with trimethylaluminum in methylene chloride and methyl organocerium in tetrahydrofuran,[21] respectively. Grignard reagent MeMgBr was too basic and other non-basic reagents such as methyltitaniumtrichloride[22] or methylmanganesechloride[23] afforded no product when applied to ketone **7b** or catalyzed unwanted intramolecular reduction with ketone **8b**. Trimethylaluminum was used on substrate **7c** which delivered the *syn*-**10** alcohol with 14:86 ratio in 61% conversion. Elimination of **10** then provided the *E*-**12** alkene in 50% yield. The *syn* alcohol is again attributed to Felkin–Anh transition state **A**, followed by intermolecular methyl addition. Comparisons with **8c** using Me_3Al could not be achieved because of competing intramolecular reduction. The use of $MeCeCl_2$ on ketone **8c** afforded the expected *anti*-**11** alcohol whereupon elimination afforded the alkene *Z*-**12** in 92:8 *Z*/*E* ratio in 50% yield over two steps. The *Z* assignment was further confirmed by deprotection of *anti*-**11** with DABCO[9b] and elimination to afford *Z*-**12** in 68% yield. The selectivity's attributed to intramolecular transfer from a $MeCeCl_2$ ketone complex similar to that of transition state **A** (Scheme 3).[15]

2.4. 31-Phosphorus NMR

The ^{31}P NMR of alcohols *syn*-**5/6** and *anti*-**5/6** revealed coupling constants and chemical shifts that were useful in assigning stereochemistry. The *syn*-**5/6** alcohols evidenced larger coupling constants (J_{P-P}=43–52 Hz) compared to the *anti*-**5/6** alcohols which displayed smaller coupling constants (J_{P-P}=24–36 Hz).[24] The difference in coupling constants between the *syn*- and *anti*-**5/6** alcohols is attributed to a change in dihedral angle Φ between the two phosphorus nuclei (P1 and P2), similar to a Karplus type correlation.[25] In turn, the P1–P2 Φ is affected by the conformation of the hydroxyl bearing carbon C3. The expected C3 conformation, has the larger R group *anti* to the large P2 substituent. The hydrogen bonding does not have an affect on this conformation.[26] The *syn*-**5/6** alcohols J_{P-P} correlates to a theoretical maximum value (50 Hz) associated with bisphosphines.[27] The *anti*-**5/6** alcohols have a decreased coupling constant due to interactions between the distal phosphine P1 and the substituents on C3. The additional *gauche* interaction between the methylene phosphine P1 with the hydroxyl and alkyl substituent of the *anti* alcohol (**H**) compared to a single gauche interaction with the alkyl substituent in the *syn* alcohol (**G**) instigates rotation of the C1–C2 bond and a decrease in the dihedral angle between P1 and P2 (**H′**). With respect to methyl carbinols **10** and **11**, J_{P-P} for both isomers are also closer in size (J_{P-P}=32–38 Hz) indicating the P1–P2 Φ in *syn*-**10/11** alcohols has shifted. The reason is easily seen in projection **H/H′**, where Y=Me for alcohols *syn*-**10/11** instead of Y=H for alcohols *syn*-**5/6**, introducing an additional 1,3-diaxial type interaction causing P1 to rotate away from the C3 substituents. (Scheme 8)



Scheme 8. Newman projections of alcohols **5**, **6** and **10**, **11**.

3. Conclusion

DIPHOS(O) **4** is a valuable reagent for the formation of polyene systems with carbonyl starting materials via allyl phosphorane intermediates. Initial stereoselective olefin synthesis is supplied via Horner–Wittig addition, stereoselective ketone reduction, intramolecular phosphine·borane ketone reduction, or stereoselective nucleophilic methylation.

4. Experimental

4.1. Synthesis of *anti*-5/6 alcohols

General procedure for the reaction of **4**. To a solution of **4** (4.82 mmol) in 161 mL THF at −78°C *n*BuLi (2.8 mL, 2.1 M hexanes) was added dropwise to afford an orange solution. After stirring for 25 min at −78°C the solution color darkened to a deep orange–red color. A tetrahydrofuran solution (1.2 M) of freshly distilled butanal (4.82 mmol) was transferred dropwise to lithiated **4**. The reaction color slowly changed to a light yellow color. The reaction continued to stir for 30 min. A saturated ammonium chloride solution was then added at −78°C, to minimize formation of elimination products, and the reaction was allowed to warm to room temperature. A slight excess of 30% H_2O_2 was added. The mixture was washed with water then saturated sodium bisulfite. The organic layer was then washed with brine, dried ($MgSO_4$), and filtered. The solvent was evaporated to afford a white solid and purified using column chromatography (EtOAc/hex).

General procedure for the synthesis of **6**. To a solution of **4** (7.25 mmol) in 242 mL THF at −78°C *n*BuLi (4.1 mL, 2.1 M hexanes) was added dropwise. After stirring for 25 min at −78°C, a THF solution (1.2 M) of freshly distilled acetaldehyde (7.25 mmol) was transferred dropwise. The reaction continued to stir for 30 min. BH_3·DMS (22 mmol, 2 M DMS) was then added and the reaction was allowed to warm to −10°C over 4 h. The excess borane was then quenched with excess water until hydrogen evolution ceased. The organic layer was separated from the aqueous layer. The aqueous layer was extracted with EtOAc. The organic layers were combined and washed with brine solution dried ($MgSO_4$), and filtered.

4.1.1. *anti*-3,4-Bis-(diphenylphosphinoyl)-butan-2-ol (*anti*-5a). White solid: R_f=0.48 (90% EtOAc/MeOH). ^1H NMR (300 MHz, $CDCl_3$) δ 0.90 (3H, d, *J*=6 Hz), 2.48–2.65 (1H, m), 2.81–3.11 (2H, m), 4.24 (1H, m), 4.5 (1H, br s), 7.28–7.96 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 22.85 (d, *J*=11 Hz), 22.88 (d, *J*=68 Hz), 37.9, 64.3, 127.9–133.1. ^{31}P NMR (121 MHz, $CDCl_3$) δ 31.9, 40.0 (J_{P-P}=35 Hz). HRMS (CI) mixed sample calculated for $C_{28}H_{28}O_3P_2$ 475.1592, observed 475.1598.

4.1.2. *anti*-1,2-Bis-(diphenylphosphinoyl)-hexan-3-ol (*anti*-5b). A white solid was isolated with >95% purity. Mp 125–127°C; R_f=0.20 (EtOAc). ^1H NMR (300 MHz, $CDCl_3$) δ 0.52 (3H, t, *J*=7 Hz), 0.88 (1H, m), 1.01–1.28 (3H, m), 2.49–2.65 (1H, m), 2.93–3.20 (2H, m), 3.98–4.04 (1H, m), 4.50 (1H, br s), 7.30–7.93 (20H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.4, 18.7 (d, *J*=68 Hz), 36.7 (d, *J*=71 Hz), 38.8 (d, *J*=11 Hz), 68.1, 128.5–133.6. ^{31}P NMR (121 MHz, $CDCl_3$) δ 31.6, 41.0 (J_{P-P}=34 Hz). HRMS (CI) mixed sample calculated for $C_{30}H_{32}O_3P_2$ 503.1905, observed 503.1905.

4.1.3. *anti*-1,2-Bis-(diphenylphosphinoyl)-5-phenyl-pentan-3-ol (*anti*-5c). White solid (>95% purity): mp 98–99°C, R_f=0.40 (EtOAc). ^1H NMR (300 MHz, $CDCl_3$) δ 1.18–1.29 (1H, m), 1.50–1.62 (1H, m), 2.32–2.40 (1H, m),

2.42–2.67 (2H, m), 2.95–3.12 (2H, m), 4.00–4.07 (1H, m), 4.39 (1H, br s), 6.82–7.85 (25H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 23.1 (d, J=69 Hz), 31.8, 37.2 (dd, J=67, 4 Hz), 38.9 (d, J=10 Hz), 67.5, 125.3–141.3. ^{31}P NMR (121 MHz, $CDCl_3$) δ 32.5, 40.4 (J_{P-P}=36 Hz).

4.1.4. *anti*-2-Diphenylphosphinoyl (diphenylphosphine·borane-butan-3-ol) (*anti*-6a). White solid. Mp 142–150°C (slight dec.), R_f=0.54 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.4–1.7 (3H, br m), 0.78 (3H, d, J=6 Hz), 2.23–2.40 (1H, m), 3.01–3.15 (1H, m), 3.22–3.30 (1H, dt, J=20, 6 Hz), 3.98 (1H, br s), 4.19–4.27 (1H, m, J=11, 6 Hz), 6.96–7.93 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 18.1 (d, J=34 Hz), 21.4 (d, J=14 Hz), 39.1 (dd, J=64, 3 Hz), 64.9, 128.4–132.8. ^{31}P NMR (121 MHz, $CDCl_3$) δ 21.0 (br m), 42.2 (J_{P-P}=33 Hz). ^{11}B NMR (96 MHz, $CDCl_3$) δ 40 (br s). HRMS (ESI) mixed sample calculated for $C_{28}H_{32}O_2P_2B$ 473.3927, observed 473.3926. Anal. Calcd C, 71.20; H, 6.62; P, 13.12; B, 2.29. Found: C, 70.82; H, 6.65; P, 12.76; B, 2.46

4.1.5. *anti*-2-Diphenylphosphinoyl(diphenylphosphine·borane-hexan-3-ol) (*anti*-6b). The 75:25 *anti*/*syn* mixture afforded a white solid: mp 38–45°C (slight dec.); R_f=0.57 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.47 (3H, t, J=7 Hz), 0.6–1.8 (3H, br m), 0.77–1.20 (4H, m), 2.22–2.39 (1H, m), 3.09–3.36 (2H, m), 3.98 (1H, m), 4.18 (1H, s), 6.96–7.97 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.4, 18.5 (d, J=35 Hz), 18.9, 37.5, 38.0 (d, J=53 Hz), 68.9, 128.2–133.2. ^{31}P NMR (121 MHz, $CDCl_3$) δ 21.4 (br m), 42.5 (d, J_{P-P} =33 Hz). Anal. Calcd for $C_{30}H_{35}BO_2P_2$ (500.36): C, 72.01; H, 7.05. Found: C, 71.88; H, 7.25.

4.1.6. *anti*-2-Diphenylphosphinoyl-5-phenyl(diphenylphosphine·borane-pentan-3-ol) (*anti*-6c). White foam: mp 128–132°C; R_f=0.45 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.4–1.7 (3H, m), 1.05–1.30 (2H, m), 2.23–2.54 (3H, m), 3.12–3.39 (2H, m), 3.82 (1H, br s), 4.04 (1H, m), 6.75–7.93 (25H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 18.6 (d, J=34 Hz), 31.9, 37.1 (d, J=13 Hz), 38.3 (dd, J=68, 3 Hz), 68.4, 125.4–141.2. ^{31}P NMR (121 MHz, $CDCl_3$) δ 21.0 (br s), 42.3 (J_{P-P}=34 Hz). Anal. Calcd for $C_{35}H_{37}BO_2P_2$ (562.43): C, 74.74; H, 6.63. Found: C, 74.86; H, 6.63.

4.2. Synthesis of *syn*-5/6 alcohols

General procedure for the intermolecular reduction of ketones **7** *using $CeCl_3$/$LiBH_4$.* A flask containing $CeCl_3$ (0.081 mmol) was placed in a 0°C ice bath whereupon freshly distilled CH_2Cl_2 (1 mL) was added dropwise to form a suspension. The $CeCl_3$ was removed from the ice bath and allowed to stir at room temperature for 2 h. Ketone **7c** (0.063 mmol) was dissolved in CH_2Cl_2 (5 mL), cannulated into the $CeCl_3$ solution and stirred for 1 h. The mixture was cooled to −78°C and $LiBH_4$ (0.10 mL, 2 M THF) was added. The reaction was kept at −78°C for 2 h before slowly warming to room temperature over 12 h. The reaction was slowly quenched with 5% HCl solution followed by aqueous workup.

General procedure for the intermolecular reduction of ketones **8** *using Ti(OiPr)$_4$/$LiBH_4$.* To a solution of ketone **8a** (0.35 mmol) in CH_2Cl_2 (12 mL) at −78°C $Ti(OiPr)_4$ (0.45 mmol) was added. After stirring for 1 h $LiBH_4$ (0.88 mL, 2 M THF) was added. The reaction was kept at −78°C for 2 h before slowly warming up to room temperature over 12 h. The reaction was slowly quenched with water. The aqueous layer was extracted with CH_2Cl_2. The combined organic layers were then washed with brine, dried (Na_2SO_4), and filtered.

General procedure for the intramolecular reduction of ketone **8c** *to affordsyn-*-**5c** *alcohol*. To a solution of ketone **8c** (0.070 mmol) in 23 mL of CH_2Cl_2 at 25°C polyvinyl pyridine (60 mg) was added. After stirring for 5 min, neat $TiCl_4$ (0.091 mmol) was quickly added and the reaction was allowed to stir for another 30 min. The solvent was evaporated and the crude solid was redissolved in THF. The reaction solution was treated with 2 mL 30% H_2O_2. This solution was allowed to stir for 24 h before washing with water followed by sodium bisulfite wash. The organic layer was washed with brine, dried over Na_2SO_4, and filtered.

4.2.1. *syn*-3,4-Bis-(diphenylphosphinoyl)-butan-2-ol (*syn*-5a). White solid: R_f=0.64 (9:1 EtOAc/MeOH). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.43 (3H, d, J=7 Hz), 2.25–2.40 (1H, m), 2.80–3.00 (2H, m), 4.03–4.10 (1H, m), 6.05 (1H, br s), 7.34–7.87 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 20.7, 23.5 (d, J=66 Hz), 40.8 (d, J=64 Hz), 65.4, 129.1–132.6. ^{31}P NMR (121 MHz, $CDCl_3$) δ 34.2, 35.8 (J_{P-P}=51 Hz).

4.2.2. *syn*-1,2-Bis-(diphenylphosphinoyl)-hexan-3-ol (*syn*-5b). White solid (>95% purity): mp 140–142°C; R_f=0.30 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.78 (3H, t, J=8 Hz), 1.16–1.32 (1H, m), 1.50–1.80 (3H, m), 2.29–2.44 (1H, m), 2.81–3.01 (2H, m), 3.79 (1H, app t, J=9 Hz), 4.40 (1H, br s), 7.36–7.76 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.6, 19.5, 23.8 (d, J=66 Hz), 36.5, 40.3, (d, J=63 Hz), 69.0 (d, J=4 Hz), 128.7–132.3. ^{31}P NMR (121 MHz, $CDCl_3$) δ 34.5, 36.0 (J_{P-P}=51 Hz).

4.2.3. *syn*-1,2-Bis-(diphenylphosphinoyl)-5-phenyl-pentan-3-ol (*syn*-5c). White solid (>95% purity). Mp 128–132°C; R_f=0.45 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.01–2.13 (1H, m), 2.18–2.31 (1H, m), 2.34–2.46 (1H, m), 2.58–2.68 (1H, m), 2.81–3.20 (3H, m), 3.82 (1H, t, J=10 Hz), 4.47 (1H, br s), 7.10–7.68 (25H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 23.9 (d, J=66 Hz), 32.2, 35.9, 40.4 (d, J=61 Hz), 67.9 (d, J=4 Hz), 125–142. ^{31}P NMR (121 MHz, $CDCl_3$) δ 34.4, 36.2 (J_{P-P}=52 Hz). HRMS (CI) mixed sample calculated for $C_{35}H_{34}O_3P_2$ 564.1878, observed 564.1878.

4.2.4. *syn*-2-Diphenylphosphinoyl (diphenylphosphine·borane-butan-3-ol) (*syn*-6a). Using the $Ti(OiPr)_4$/$LiBH_4$ reduction method the alcohol (115 mg, 69%) was obtained with a 20:80 *anti*/*syn* ratio. A white solid was obtained with mp 142–150°C (slight dec.) and R_f=0.52 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.4–1.7 (3H, br m), 0.92 (3H, d, J=7 Hz), 2.03 (1H, ap q, J=14 Hz), 2.72 (1H, br s), 3.10–3.26 (2H, m), 3.61 (1H, ap q, J=25, 6 Hz), 6.71–7.88 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 22.3 (d, J=34 Hz), 23.5, 38.5 (d, J=66 Hz), 69.0 (d, J=5 Hz), 114–134.5. ^{31}P NMR (121 MHz, $CDCl_3$) δ 19.4 (br m), 39.8 (J_{P-P}=43 Hz).

4.2.5. *syn*-2-Diphenylphosphinoyl(diphenylphosphine·borane-hexan-3-ol) (*syn*-6b). Using the $Ti(OiPr)_4/LiBH_4$ reduction method, ketone **8b** (0.067 mmol) was reduced to afford alcohol *syn*-**6b** (26.0 mg, 79%) with 6:94 *anti*/*syn* ratio. White solid: mp 135–137°C (slight dec.); R_f=0.57 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.40 (3H, t, J=7 Hz), 0.5–1.8 (3H, br m), 0.85–0.95 (2H, m), 0.98–1.13 (2H, m), 1.23–1.42 (2H, m), 2.11 (1H, m), 3.29 (1H, m), 4.06 (1H, br s), 7.30–7.94 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.1, 19.3, 22.5 (d, J=34 Hz), 37.1 (d, J=65 Hz), 39.2 (d, J=2 Hz), 73.0 (d, J=5 Hz), 127.8–133.6. ^{31}P NMR (121 MHz, $CDCl_3$) δ 19.1, 40.4 (J_{P-P}=44 Hz).

4.2.6. *syn*-2-Diphenylphosphinoyl-5-phenyl(diphenylphosphine·borane-pentan-3-ol) (*syn*-6c). Using the $Ti(OiPr)_4/LiBH_4$ reduction method, ketone **8c** (0.029 mmol) was reduced to afford the alcohol (16.2 mg, >98%), as an oil with 6:94 *anti*/*syn* ratio. R_f=0.67 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.40–1.60 (3H, m), 1.43–1.55 (1H, m), 1.62–1.75 (1H, m), 2.07–2.23 (2H, m), 2.41–2.50 (1H, m), 3.19–3.48 (3H, m), 4.45 (1H, br s), 6.68–7.94 (25H, m). ^{13}C NMR (125 MHz, $CDCl_3$) δ 22.6 (d, J=33 Hz), 32.3, 37.5 (d, J=65 Hz), 38.4, 73.0 (d, J=4 Hz), 125.1–1419. ^{31}P NMR (121 MHz, $CDCl_3$) δ 18.1 (br m), 40.4 (J_{P-P}=43 Hz). ^{11}B NMR (96 MHz, $CDCl_3$) δ −40 (br s).

4.3. General procedure for the synthesis of γ-keto-phosphines 7–9

General procedure for the Swern oxidation of alcohols.[14] To a solution of dimethyl sulfoxide (9.30 mmol) in CH_2Cl_2 (60 mL) at −78°C oxalyl chloride (9.30 mmol) was added dropwise. After letting stir for 10 min, alcohol **6a** (1.80 mmol) in CH_2Cl_2 (4 mL) was cannulated over. The reaction warmed to −50°C bath and allowed to stir for 2 h. The temperature was then lowered to −78°C prior to addition of triethylamine (18.6 mmol). The reaction was then allowed to warm to room temperature over 4 h. The reaction was washed with brine, dried (Na_2SO_4), and filtered. The solvent was removed via roto-evaporator to afford a white solid.

General procedure for the synthesis of ketones **7** *using Warren's modifications*. To a solution of 1.25 (0.118 mmol) in THF (4 mL) at −95°C *n*BuLi (0.056 mL, 2.1 M hexanes) was added and allowed to stir for 20 min. Ethyl butyrate (0.236 mmol) was added dropwise. The orange-colored solution changed to a yellow solution after warming to −78°C over 30 min. The reaction was quenched at −78°C with ammonium chloride and allowed to warm to room temperature. The mixture was extracted with EtOAc, washed with brine, dried ($MgSO_4$), and filtered. The solvent was removed via roto-evaporator to afford a white solid. General procedures for the synthesis of **10**, **11** alcohols.

4.3.1. 3,4-Bis-(diphenylphosphinoyl)-butan-2-one (7a). Using the Swern oxidation, after purification by chromatography (100% EtOAc to 10% EtOAc/MeOH) the ketone (603 mg, 71%) was obtained as a white solid: mp 185–187°C, R_f=0.45 (1:9 EtOAc/MeOH). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.77 (3H, s), 2.48 (1H, dq), 3.19–3.30 (1H, m), 4.19 (1H, ap q), 7.36–7.76 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 27.3 (ABX), 31.9, 48.7 (ABX), 128.5–132.7, 202.3 (d, J=3 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 30.9 (ap s). HRMS (CI) calc for $C_{28}H_{26}O_3P_2$ 473.1435, observed 473.1432.

4.3.2. 1,2-Bis-(diphenylphosphinoyl)-hexan-3-one (7b). Using Warren's modification after purification (100% EtOAc to 10% EtOAc/MeOH) the ketone (22.9 mg, 45% isolated) was obtained as a white solid: mp=212–215°C, R_f=0.23 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.53 (3H, t, J=7 Hz), 1.05–1.18 (2H, m), 1.81–2.11 (2H, m), 2.47–2.53 (1H, m), 3.23–3.34 (1H, m), 4.21 (1H, ap d, J=11 Hz), 7.33–7.79 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.1, 16.1, 27.0 (ABX), 47.7 (ABX), 128.4–132.8, 204.2. ^{31}P NMR (121 MHz, $CDCl_3$) δ 31.1 (ap s). HRMS (CI) calcd. for $C_{30}H_{30}O_3P_2$ 501.1748, found 501.1733.

4.3.3. 1,2-Bis-(diphenylphosphinoyl)-5-phenyl-pentan-3-one (7c). White solid: mp 218–221°C, R_f=0.21 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.21–2.50 (4H, m), 2.50–2.64 (1H, m), 3.31–3.35 (1H, m), 4.18–4.29 (1H, ap q, J=11 Hz), 6.88 (2H, m), 7.15–7.25 (3H, m), 7.4–7.9 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 27.2, (d, J=66 Hz), 29.0, 47.1, 47.8 (d, J=33 Hz), 123.5–132.5, 140.6, 203.5 (d, J=8 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 30.7, 31.2 (J_{P-P}=43 Hz). HRMS (EI) calcd for $C_{35}H_{32}O_3P_2$ 562.1827, found 562.1813.

4.3.4. 2-Diphenylphosphinoyl(diphenylphosphine·borane butan-3-one) (8a). Using the general Swern procedure, the oxidation of alcohol **6a** (1.33 mmol) afforded the ketone (270 mg, 43%) as a fluffy white solid: mp 136–140°C (slight dec.), R_f=0.47 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.4–1.9 (3H, br s), 1.67 (3H, s), 2.4 (1H, dt, J=15, 10 Hz), 3.3 (1H, ap q, J=14, 11, 2 Hz), 4.2 (1H, dt, J=14, 11 Hz), 7.34–7.81 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 23.0 (dd, J=36, 2 Hz), 32.1, 50.4 (dd, J=51, 2 Hz), 127.2–133.1, 201.8 (d, J=4 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 18.5 (br s), 31.2 (J_{P-P}=40 Hz). ^{11}B NMR (96 MHz, $CDCl_3$) δ −40 (br s). LRMS (EI) 469 (M−H). LRMS (CI) 469 (M−H). HRMS (CI) calculated for $C_{30}H_{30}O_3P_2$ (M−H) 469.1658, observed 469.1666. Anal. Calcd (470.29): C, 71.51; H, 6.22; P, 13.17. Found: C, 71.39; H, 6.13; P, 13.03.

4.3.5. 2-Diphenylphosphinoyl(diphenylphosphine·deuteroborane butan-3-one) (BD_3-8a). Using the general Horner–Wittig procedure followed by Swern oxidation, the product was isolated as a white solid with mp 129–132°C (slight dec.); R_f=0.53 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.68 (3H, s), 2.41 (1H, dt, J=15, 10 Hz), 3.30 (1H, q, J=13 Hz), 4.21 (1H, q, J=13 Hz), 7.39–7.80 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 22.9 (d, J=33 Hz), 32.1, 50.3 (d, J=53 Hz), 127.1–133.0, 201.8 (d, J=4 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 18.4 (br s), 31.1 (J_{P-P}=40 Hz). ^{11}B NMR (MHz, $CDCl_3$) δ −41 (br s). HRMS (CI, M−D) calculated for $C_{28}H_{26}D_3BO_2P_2$ 471.1781, found 471.1792. Anal. Calcd for (473.31): C, 71.05; H, 6.81. Found: C, 70.07; H, 6.95.

4.3.6. 2-Diphenylphosphinoyl(diphenylphosphine·borane hexan-3-one) (8b). Swern oxidation of alcohol **6b**

(4.12 mmol) afforded ketone **8b** (1.16 g, 57%) as a white solid with mp=141–142°C (slight dec.); R_f=0.58 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.4–1.6 (3H, br m), 0.48 (3H, t, J=8 Hz), 0.99 (2H, m, J=7 Hz), 1.91 (2H, t, J=7 Hz), 2.37 (1H, dt, J=16, 10 Hz), 3.35 (1H, ap q, J=16 Hz), 4.20 (1H, ap q, J=14 Hz), 7.33–7.80 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 12.9, 15.9, 22.7 (d, J=35 Hz), 47.3, 49.2 (d, J=52 Hz), 126.7–133.0, 203.5 (d, J=4 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 18.2 (br m), 31.6 (J_{P-P}=41 Hz). ^{11}B NMR (96 MHz, $CDCl_3$) δ −41 (br s). LRMS (EI) 497 (M−H). HRMS (EI) Calculated for $C_{30}H_{33}BO_2P_2$ (M−H) 497.1971, observed 497.1986. Anal. Calcd (498.34): C, 72.30; H, 6.67. Found: C, 71.94; H, 6.46.

4.3.7. 2-Diphenylphosphinoyl-5-phenyl(diphenylphosphine·borane pentan-3-one) (8c). After Swern oxidation purification (70% EtOAc/hexanes) afforded the ketone (639 mg, 82%) as a white foam: mp=164–166°C (slight dec.); R_f=0.67 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.40–1.60 (3H, d), 2.09–2.23 (4H, m), 2.36 (1H, dt), 3.32 (1H, ap q), 4.14 (1H, ap q, J=13 Hz), 6.83–7.21 (5H, m), 7.23–7.84 (20H, m) ^{13}C NMR (75 MHz, $CDCl_3$) δ 22.9 (d, J=35 Hz), 28.9, 47.4, 49.3 (d, J=52 Hz), 125.8, 126.9–133.3, 140.4, 202.9 (d, J=4 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 18.6 (br m), 31.3 (J_{P-P}=41 Hz). ^{11}B NMR (96 MHz, $CDCl_3$) δ −40 (br s). Anal. Calcd for $C_{35}H_{35}BO_2P_2$ (560.41): C, 75.01; H, 6.30. Found: C, 74.72; H, 6.26.

4.3.8. 2-Diphenylphosphinoyl-5-phenyl(diphenylphosphine·deuteroborane pentan-3-one) (BD_3-8c).[20] Following the procedure for Horner–Wittig addition alcohol BD_3-**6c** (440 mg, 85%) was oxidized using Swern conditions to the ketone (370 g, 78%) as a white solid with mp 156–160°C (slight dec.). ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.18–2.28 (4H, m), 2.42 (1H, dt, J=15, 10 Hz), 3.37 (1H, ap q, J=13 Hz), 4.19 (1H, ap q, J=13 Hz), 6.80–7.26 (5H, m), 7.39–7.99 (20H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 22.8 (d, J=34 Hz), 28.9, 47.3, 49.2 (d, J=53 Hz), 125.8–140.4, 202.9 (d, J=4 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 18.1 (br m), 31.1 (J_{P-P}=40 Hz). Anal. Calcd for $C_{35}H_{32}D_3BO_2P_2$ (563.43): C, 74.61; H, 6.80. Found: C, 74.10; H, 6.73.

4.3.9. 2-(Diphenylphosphinoyl)-5-phenyl(diphenylphosphinoyl pentan-3-one) (9c). A solution of ketone **8c** (0.68 mmol) and DABCO[9a,14] (1.19 mmol) in toluene was heated at 40°C for 12 h. The reaction was allowed to cool for 24 h upon which time the ketone crystallized out of solution. The toluene was carefully pipetted out and after further removal of solvent, 368 mg (>99%) was isolated; mp 175–185°C. Plug silica gel filtration of an aliquot afforded a white solid: mp 190–193°C; R_f=0.78 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.31 (1H, t, J=13 Hz), 2.58–2.89 (5H, m), 3.54 (1H, q, J=12 Hz), 7.01–7.61 (25H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.2 (d, J=20 Hz), 29.2, 46.6 (d, J=12 Hz), 52.5 (dd, J=53, 17 Hz), 125.9–140.7, 204.6. ^{31}P NMR (121 MHz, $CDCl_3$) δ −15.5, 30.4 (J_{P-P}=37 Hz). HRMS (CI) calculated for $C_{35}H_{32}O_2P_2$ 547.1956, observed 547.1958.

4.4. General procedures for the synthesis of 10, 11 alcohols

4.4.1. *syn*-1,2-Bis-(diphenylphosphinoyl)-3-methyl-5-phenyl-pentan-3-ol (*syn*-10). General procedure for the 1,2-methylation with Me_3Al. To a solution of ketone **7c** (0.20 mmol) in 5 mL CH_2Cl_2 at 0°C was added Me_3Al (0.90 mL, 2 M toluene). The mixture was allowed to reach 25°C and stirred at this temperature for 48 h. The reaction was cooled to 0°C and quenched with 5% HCl. After aqueous work up removal of solvent, the crude product (ca. 61% conversion) was chromatographed (100% EtOAc) to afford the mixture of alcohols (42 mg, 36%). A purified fraction (5:95 *anti*/*syn*) afforded a white solid with mp=185–189°C, R_f=0.40. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.98 (3H, s), 2.02 (2H, m), 2.42–2.80 (3H, m), 2.88–3.01 (1H, m), 3.39–3.46 (1H), 5.28 (1H, br s), 6.89–7.98 (25H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.8 (d, J=68 Hz), 27.6 (d, J=6 Hz), 29.9, 42.1 (dd, J=64, 4 Hz), 42.4 (d, J=3 Hz), 74.5, 125.4–142.3. ^{31}P NMR (121 MHz, $CDCl_3$) δ 32.1, 37.9 (J_{P-P}=31 Hz). HRMS (CI) calculated for the mixed sample for $C_{36}H_{36}O_3P_2$ 579.2218, found 579.2213.

4.4.2. *anti*-2-Diphenylphosphinoyl-3-methyl-5-phenyl (diphenylphosphine·borane pentan-3-ol) (*anti*-11). To a freshly made solution of $MeCeCl_2$ (1.40 mmol) in 9 mL of THF at −78°C was cannulated a solution of ketone **8c** (0.182 mmol) in 1 mL of THF. The mixture was stirred at this temperature for 2 h. Afterward, the solution was allowed to reach room temperature over 12 h, quenched with ammonium chloride, extracted with EtOAc, and dried over $MgSO_4$. After removal of solvent, the crude reaction was chromatographed (70% EtOAc/hexanes) to afford the alcohol *anti*-**11** (65.9 mg, 63%), with a 92:8 *anti*/*syn* ratio, as a white foam: mp 75–80°C (slight dec.), R_f=0.63 (EtOAc) mp ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.6–1.7 (3H, m), 1.04–1.47 (2H, m), 1.31 (3H, s), 2.50 (2H, t, J=9 Hz), 2.50–2.64 (1H, m), 3.08–3.22 (1H, m), 3.61 (1H, m, J=22 Hz), 4.29 (1H, br s), 6.70–8.06 (25H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.7 (d, J=35 Hz), 26.8 (d, J=4 Hz), 29.1, 43.1 (d, J=9 Hz), 43.1 (d, J=65 Hz), 74.9, 125.2–141.6. ^{31}P NMR (121 MHz, $CDCl_3$) δ 20.8 (br s), 41.1 (J_{P-P}=28 Hz). Minor isomer ^{31}P NMR (121 MHz, $CDCl_3$) δ 21 (br s), 42.6 (J_{P-P}=30 Hz). HRMS (CI) calculated. for $C_{36}H_{39}BO_2P_2$ 577.2596, found 577.2597. Anal. Calcd: C, 75.01; H, 6.82; P, 10.75. Found: C, 74.63; H, 6.72; P, 10.51.

4.4.3. *anti*-1,2-Bis-(diphenylphosphinoyl)-3-methyl-5-phenyl-pentan-3-ol (*anti*-10). A solution of alcohol *anti*-**11** (0.081 mmol) and DABCO[9b] (0.162 mmol) in toluene, open to atmosphere, was heated at 40°C for 12 h to afford (29.8 mg, 64%). Additionally, the alcohol is a minor component from the alkylation of ketone **7c** with Me_3Al and was isolated via column chromatography (SiO_2, 70% EtOAc/hexanes to 100%) to afford a sample of >90:10 *anti*/*syn* ratio. White solid: mp 185–188°C; R_f=0.30 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.32 (3H, s), 1.39 (2H, m), 2.40–2.68 (3H, m), 2.89–3.05 (1H, m), 3.23–3.41 (1H, m), 5.13 (1H, s), 6.71–7.84 (25H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.2, 25.4 (d, J=68 Hz), 29.4, 41.5 (d, J=63 Hz), 44.7, 73.6, 125.3–142.1. ^{31}P NMR (121 MHz, $CDCl_3$) δ 32.9, 35.7 (J_{P-P}=32 Hz).

4.5. General procedure for the synthesis of allyl phosphine oxides/boranes

To a solution of alcohol *syn*-**5b** (0.167 mmol, 5:95 *anti*/*syn*)

in DMF (2 mL) at 0°C NaH (60% oil dispersion, 0.20 mmol) was added. The reaction was then removed from the ice bath and allowed to stir for 1 h. The reaction was quenched with ammonium chloride. The aqueous solution was extracted with ethyl acetate. The combined ethyl acetate fractions were washed with 50% lithium chloride solution. The ethyl acetate was dried ($MgSO_4$), then filtered. After evaporation, (47 mg, >99%) the product contained 1% vinyl phosphine oxide analog and 5% *Z*-**2b**.

4.5.1. *E*-Diphenylphosphinoyl-2-hexene (*E*-2b). White solid: mp 34–36°C, R_f=0.40 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.75 (3H, t, *J*=7 Hz), 1.24 (2H, m, *J*=7 Hz), 1.91 (2H, m), 3.08 (2H, dd, *J*=14, 7 Hz), 5.45 (2H, m), 7.46–7.76 (10H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.4, 22.2 (d, *J*=3 Hz), 34.7 (d, *J*=2 Hz), 34.9 (d, *J*=70 Hz), 118.1 (d, *J*=9 Hz), 137.2 (d, *J*=12 Hz), 128.4–133.3.

4.5.2. *Z*-Diphenylphosphinoyl-2-hexene (*Z*-2b). Elimination of alcohol *anti*-**5b** (0.086 mmol) afforded 21 mg (88%) of *Z*-**2b**. Isolated as a white solid: mp 81–83°C; R_f=0.40 (EtOAc). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.81 (3H, t, *J*=7 Hz), 1.22 (2H, m, *J*=7 Hz), 1.87 (2H, m), 3.14 (2H, dd, *J*=15, 7 Hz), 5.42–5.59 (2H, m), 7.44–7.78 (10H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.7, 22.3 (d, *J*=2 Hz), 29.5 (d, *J*=2 Hz), 30.2 (d, *J*=70 Hz), 117.4 (d, *J*=8 Hz), 128.4–133.5, 135.2 (d, *J*=59, 11 Hz). HRMS (EI) sample calcd for $C_{18}H_{21}OP$ 284.1330, observed 284.1335.

4.5.3. *E*-5-phenyl-diphenylphosphinoyl-2-pentene (*E*-2c). Elimination of alcohol *syn*-**5c** (0.173 mmol) afforded 30.5 mg (51%) of *E*-**2c**. Isolated as a white solid: mp 120–125°C. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.20 (2H, m), 2.45 (2H, t, *J*=7 Hz), 2.99 (2H, dd, *J*=15, 6 Hz), 5.42 (2H, m), 6.96–7.17 (5H, m), 7.35–7.66 (10H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 34.3 (d, *J*=2 Hz), 34.8 (d, *J*=68 Hz), 35.5 (d, *J*=3 Hz), 118.7 (d, *J*=10 Hz), 136.2 (d, *J*=12 Hz), 128.2–141.5. HRMS (CI) sample calculated for $C_{23}H_{23}OP$ 347.1565, observed 347.1561.

4.5.4. *Z*-5-phenyl-diphenylphosphinoyl-2-pentene (*Z*-2c). Elimination of alcohol *anti*-**5c** (1.10 mmol) afforded 242 mg (63%) of *Z*-**2c**. White solid: mp 90–95°C. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.14 (2H, m), 2.42 (2H, t, *J*=8 Hz), 2.98 (2H, dd, *J*=13, 8 Hz), 5.44–5.54 (1H, m), 5.58 –5.66 (1H, m), 7.00–7.18 (5H, m, Ph), 7.37–7.68 (10H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 28.9, 29.9 (d, *J*=70 Hz), 34.9, 117.9 (d, *J*=9 Hz), 133.8 (d, *J*=12 Hz), 128.0 – 141.2. HRMS (EI) sample calcd for $C_{23}H_{23}OP$ 346.1486, observed 346.1486.

4.5.5. *Z*-diphenylphosphine·borane-2-butene (*Z*-3a). Elimination of alcohol *anti*-**6a** (2.67 mmol) afforded 503 mg (75%) of *Z*-**3a**. Isolated as a clear oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.40–1.70 (3H, br m), 1.43 (3H, m), 3.03 (2H, dd, *J*=13 Hz), 5.35–5.46 (1H, m), 5.56–5.68 (1H, m), 7.40–7.71 (10H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 12.9 (d, *J*=2 Hz), 25.2 (d, *J*=37 Hz), 119.6 (d, *J*=6 Hz), 129.1 (d, *J*=11 Hz), 128.6–132.4. ^{31}P NMR (121 MHz, $CDCl_3$) δ 17.3 (ap d, J_{P-P}=71 Hz) ^{11}B NMR (96 MHz, $CDCl_3$) δ −39 (d, *J*=54 Hz). LRMS (EI): 253 (M−H), 240 (M−BH_3). LRMS (CI) 253 (M−H). HRMS (CI) calcd for $C_{16}H_{20}BP$ (M−H) 253.1317, found 253.1308.

4.5.6. *E*-diphenylphosphine·borane-2-butene (*E*-3a). Clear oil with 6:94 *Z*/*E* ratio (^{1}H NMR). ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.51–1.42 (3H, q, *J*=96 Hz), 1.59 (3H, t, *J*=5 Hz), 2.98 (2H, dd, *J*=12, 7 Hz), 5.32–5.50 (2H, m), 7.41–7.71 (10H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 18.0 (d, *J*=2 Hz), 30.6 (d, *J*=36 Hz), 120.3 (d, *J*=6 Hz), 131.4 (d, *J*=12 Hz), 128.6–132.5. ^{31}P NMR (121 MHz, $CDCl_3$) δ 17.0 (br m).

4.5.7. *Z*-diphenylphosphine·borane-2-hexene (*Z*-3b). Elimination of alcohol *anti*-**6b** (0.56 mmol, 86:14 *anti*/*syn*) afforded *Z*-**3b** (130 mg, 82%) as an oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.54–1.40 (3H, m), 0.81 (3H, t, *J*=7 Hz), 1.21 (2H, m, *J*=7 Hz), 1.83 (2H, m), 3.05 (2H, dd, *J*=13, 8 Hz), 5.34–5.50 (1H, m), 5.51–5.57 (1H, m), 7.41–7.78 (10H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.7, 22.3 (d, *J*=2 Hz), 26.6 (d, *J*=36 Hz), 29.4 (d, *J*=2 Hz), 118.6 (d, *J*=5 Hz), 135.0 (d, *J*=11 Hz), 128.6–132.5. ^{31}P NMR (121 MHz, $CDCl_3$) δ 16.6 (br m). LRMS (EI) 281 (M−H), 268 (M−BH_3). LRMS (CI) 281 (M−H). HRMS (EI) calcd for $C_{18}H_{24}BP$ (M−H) 281.1630, found 281.1600.

4.5.8. *Z*-5-phenyl-diphenylphosphine·borane-2-pentene (*Z*-3c). Clear oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.3–1.7 (3H, m), 2.12 (2H, m), 2.41 (2H, m), 2.88, (2H, dd, *J*=13, 7 Hz), 5.27–5.37 (1H, m), 5.42–5.54 (1H, m), 6.97–7.58 (15H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.5 (d, *J*=36 Hz), 29.3 (d, *J*=2 Hz), 35.2 (d, *J*=2 Hz), 119.3 (d, *J*=5 Hz), 133.9 (d, *J*=11 Hz), 125.9–141.5. ^{31}P NMR (121 MHz, $CDCl_3$) δ 15.9 (br m, *J*=71 Hz). HRMS (EI) calcd for $C_{23}H_{26}BP$ (M−H) 343.1787, found 343.1798.

4.5.9. *E*-5-phenyl-diphenylphosphine·borane-2-pentene (*E*-3c). Clear oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.2–1.8 (3H, m), 2.11–2.18 (2H, m), 2.44 (2H, q, *J*=8 Hz), 2.86–2.94 (2H, m), 5.34–5.38 (2H, m), 6.98–7.61 (15H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 30.6 (d, *J*=36 Hz), 34.2 (d, *J*=2 Hz), 35.5 (d, *J*=4 Hz), 120.0 (d, *J*=6 Hz), 135.6 (d, *J*=11 Hz), 125.8–141.5.

4.5.10. *E*-3-methyl-5-phenyl-(diphenylphosphinoyl pent-2-ene) (*E*-12). White solid: mp 172–175°C dec. R_f=0.38. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.49 (3H, s), 2.26 (2H, t, *J*=8 Hz), 2.59 (2H, t, *J*=8 Hz), 3.08 (2H, dd, *J*=15, 8 Hz), 5.27 (1H, q, *J*=8 Hz), 7.09–7.74 (15H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.5, 30.9 (d, *J*=70 Hz), 34.3, 41.5, 112.9 (d, *J*=8 Hz), 140.7, 125.7–141.9.

4.5.11. *Z*-3-methyl-5-phenyl-(diphenylphosphinoyl pent-2-ene) (*Z*-12). After standard borane deprotection of *anti*-**11** and standard elimination a white solid was isolated in (25 mg) 68% yield with a mp 79–81°C. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.71 (3H, s), 2.19 (2H, t, *J*=8 Hz), 2.53 (2H, t, *J*=8 Hz), 2.90 (dd, 2H, *J*=15, 8 Hz), 5.25 (1H, q, *J*=8 Hz), 7.00–7.72 (15H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 24.6, 30.2 (d, *J*=74 Hz), 33.7, 33.9, 113.4 (d, *J*=8 Hz), 140.4, 125.9–141.9. HRMS (EI) calcd on a mixed sample for $C_{24}H_{25}OP$ 360.1643, found 360.1643.

4.5.12. *Z*-3-methyl-5-phenyl-(diphenylphosphine·borane pent-2-ene) (*Z*-13). Elimination of alcohol *anti*-**11** (.092 mmol) using standard NaH/DMF conditions afforded the alkene (26 mg, 79%), with 92:8 *anti*/*syn* ratio, as an oil.

^{1}H NMR (300 MHz, $CDCl_3$) δ 0.35–0.62 (3H, br, m), 1.70 (3H, d, J=3 Hz), 2.16 (2H, t, J=8 Hz), 2.52 (2H, t, J=8 Hz), 2.80 (2H, dd, J=12, 8 Hz), 5.16 (1H, q, J=7 Hz), 7.10–7.64 (15H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 23.4 (d, J=2 Hz), 25.7 (d, J=37 Hz), 33.6 (d, J=2 Hz), 33.9 (d, J=2 Hz), 114.6 (d, J=5 Hz), 139.9 (d, J=11 Hz), 125.9–141.9. HRMS (CI, M−H) calculated on a mixed sample for $C_{24}H_{28}BP$ 357.1943.1643, found 360.1943.

Acknowledgements

The authors would like to thank Dr Douglas Lantrip for assistance with manuscript preparation, Professor Alexander Wei for helpful discussions of ^{31}P NMR, the Boron Research Center for access to ^{11}B NMR, and Arlene Rothwell and Dr Karl Wood for mass spectrometry services.

References

1. (a) Suzuki, A. *Pure Appl. Chem.* **1994**, *66*, 213–222. (b) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457–2483. (c) Stille, J.; Groh, B. *J. Am. Chem. Soc.* **1987**, *109*, 813–817. (d) Milstein, D.; Stille, J. *J. Am. Chem. Soc.* **1978**, *100*, 3636–3638. (e) Milstein, D.; Stille, J. *J. Am. Chem. Soc.* **1979**, *101*, 4992. (f) Stille, J. *Angew. Chem. Int. Ed. Engl.* **1986**, *25*, 508–523. (g) Negishi, E.; Van Horn, D. *J. Am. Chem. Soc.* **1978**, *100*, 2252–2254. (h) Negishi, E.; Okukado, N.; King, O.; Van Horn, D.; Spiegel, B. *J. Am. Chem. Soc.* **1978**, *100*, 2254–2256. (i) Panek, J.; Hu, T. *J. Org. Chem.* **1997**, *62*, 4912–4913, see also 4914–4915. (j) Panek, J.; Hu, T. *J. Org. Chem.* **1999**, *64*, 3000–3001.
2. (a) Hentemann, M.; Fuchs, P. L. *Tetrahedron Lett.* **1997**, *38*, 5615–5618. (b) Jiang, W.; Lantrip, D.; Fuchs, P. L. *Org. Lett.* **2000**, 2181–2184. (c) Meyers, D.; Fuchs, P. *J. Org. Chem.* **2002**, *67*, 200–204. (d) Torres, E.; Chen, Y.; Kim, I.; Fuchs, P. L. *Angewandte. Chemie. Int. Ed. Engl.* **2003**, *115*, 3124–3131.
3. (a) Barrett, A. G. M.; Pena, M.; Willardsen, J. A. *J. Org. Chem.* **1996**, *61*, 1082–1100. (b) Jyojima, T.; Katohno, M.; Miyamoto, N.; Nakata, M.; Matsumura, S.; Toshima, K. *Tetrahedron Lett.* **1998**, *39*, 6003–6006. (c) Nicolaou, K. C.; Murphy, F.; Barluenga, S.; Ohshima, T.; Wei, H.; Xu, J.; Gray, D. L. F.; Baudoin, O. *J. Am. Chem. Soc.* **2000**, *122*, 3830–3838.
4. Hagenbruch, B.; Hunig, S. *Liebigs Ann. Chem.* **1984**, 340–353.
5. Shen, Y.; Yao, J. *J. Chem. Res. (S)* **1996**, 428.
6. Crystalline diphosmonoxide **4** is available on the >100 g scale by palladium catalyzed monooxidation of diphos Grushin, V. V. *J. Am. Chem. Soc.* **1999**, *121*, 5831–5832.
7. (a) Clayden, J.; Warren, S. *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 241–270, and references therein. (b) Maryanoff, B. E.; Reitz, A. B. *Chem. Rev.* **1989**, *89*, 863–927.
8. (a) Lythgoe, B.; Moran, T. A.; Nambudiry, M. E. N.; Ruston, S. *J. Chem. Soc., Perkin Trans. 1* **1976**, *76*, 2386. (b) Ikeda, Y.; Ukai, J.; Ikeda, N.; Yamamoto, H. *Tetrahedron* **1987**, *43*, 723–730. (c) Ukai, J.; Ikeda, Y.; Ikeda, N.; Yamamoto, H. *Tetrahedron Lett.* **1983**, *24*, 4029–4032. (d) Clough, J. M.; Pattenden, G. *Tetrahedron* **1981**, *37*, 3911–3920. (e) Lir, R.-q.; Schlosser, M. *Synlett* **1996**, 1195–1196, see also 1197–1198.
9. (a) Imamoto, Y.; Kusumoto, Y.; Suzuki, N.; Sato, K. *J. Am. Chem. Soc.* **1985**, *107*, 5301–5303. (b) Brisset, H.; Gourdel, Y.; Pellon, P.; Le Corre, M. *Tetrahedron Lett.* **1993**, *34*, 4523–4526. (c) Gourdel, Y.; Ghanimi, A.; Pellon, P.; Le Corre, M. *Tetrahedron Lett.* **1993**, *34*, 1011–1012. (d) Pellon, P. *Tetrahedron Lett.* **1992**, *33*, 4451–4452.
10. (a) Hutton, G.; Jolliff, T.; Mitchell, H.; Warren, S. *Tetrahedron Lett.* **1995**, *36*, 7905–7908. (b) Buss, A. D.; Warren, S. *Tetrahedron Lett.* **1983**, *24*, 3931–3934.
11. Buss, A.; Warren, S. *Tetrahedron Lett.* **1983**, *24*, 3931–3934.
12. Beta elimination of the distal phosphine occurs only when lithiated/metalated **4** is warmed to room temperature (a) Spangler, C. W.; McCoy, R. K.; Dembek, A. A.; Sapochak, L. S.; Gates, B. D. *J. Chem. Soc., Perkin Trans. 1* **1989**, 151–154. (b) Schow, S. R.; Bloom, J. D.; Thompson, A. S.; Winzenberg, K. N.; Smith, A. B., III, *J. Am. Chem. Soc.* **1986**, *108*, 2662–2674. (c) Smith, A. B., III.; Schow, S. R.; Bloom, J. D.; Thompson, A. S.; Winzenberg, K. N. *J. Am. Chem. Soc.* **1982**, *104*, 4015–4018.
13. Gourdel, Y.; Ghanimi, K. A.; Pellon, P.; Le Corre, M. *Tetrahedron Lett.* **1993**, 1011–1012.
14. Lutz, C.; Graf, C.-D.; Knochel, P. *Tetrahedron* **1998**, *54*, 10317–10328.
15. Bartoli, G.; Bosco, M.; Dalpozzo, R.; Marcantoni, E.; Sambri, L. *Chem. Eur. J.* **1997**, 1941–1950.
16. Bartoli (Ref. 14) initially found $CeCl_3$/$LiBH_4$ to be solvent dependent and tetrahydrofuran being the best solvent. However, in our case, solvent did not affect selectivity and CH_2Cl_2 was utilized.
17. Eliel, E. L. *Conformational Analysis*; Interscience: New York, 1965.
18. Imamoto, T.; Kusumoto, T.; Suzuki, N.; Sato, K. *J. Am. Chem. Soc.* **1985**, *107*, 5301–5303.
19. (a) Brunel, J.-M.; Pardigon, O.; Faure, B.; Buono, G. *J. Chem. Soc., Chem. Commun.* **1982**, 287. (b) Lopusinski, A.; Bernet, B.; Linden, A.; Vasella, A. *Helv. Chim. Acta* **1993**, *76*, 94–112. (c) Brunel, J.-M.; Buono, G. *Synlett* **1996**, 177. (d) Brunel, J. M.; Faure, B.; Maffei, M. *Coord. Chem. Rev.* **1998**, 665. (e) Carboni, B.; Monnier, L. *Tetrahedron* **1999**, *55*, 1197–1248. (f) Brisset, H.; Gourdel, Y.; Pellon, P.; Le Corre, M. *Tetrahedron Lett.* **1993**, *34*, 4523–4526. (g) Caumont, A.-C.; Bourumeau, K.; Denis, J.-M.; Guenot, P. *J. Organomet. Chem.* **1994**, *484*, 9–12. (h) Schmidbaur, H.; Sigl, M.; Schier, A. *J. Organomet. Chem.* **1997**, *529*, 323–327.
20. Kanth, J.; Brown, H. C. *Inorg. Chem.* **2000**, *39*, 1795–1802.
21. Bartoli, G.; Marcantoni, E.; Sambri, L.; Tamburini, M. *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 2045–2048.
22. (a) Lentsch, L. M.; Wiemer, D. F. *J. Org. Chem.* **1999**, *64*, 5205–5212. (b) Reetz, M. T.; Westermann, J.; Steinbach, R.; Wenderoth, B.; Peter, R.; Ostarek, R.; Maus, S. *Chem. Ber.* **1985**, *118*, 1421–1440. (c) Reetz, M. T.; Kyung, S. H.; Hüllmann, M. *Tetrahedron* **1986**, *42*, 2931–2935.
23. (a) Cahiez, G.; Rivas-Enterrios, J.; Granger-Veyron, H. *Tetrahedron Lett.* **1986**, *27*, 4441–4444. (b) Cahiez, G.; Normant, J. F. *Tetrahedron Lett.* **1977**, *77*, 3383–3384.
24. (a) Table 3 in Supplementary Information. (b) Cacatian, S. Ph.D. Thesis, Purdue University, May 2003.
25. (a) Jameson, C. Phosphorous-31 NMR spectroscopy. In *Stereochemical Analysis*; Verkade, J., Quin, L., Eds.; VCH: New York, 1987; p 227. (b) Haasnoot, C. A. G.; de Leeuw,

F. A. A. M.; Altona, C. *Tetrahedron* **1980**, *36*, 2783–2792. (c) van Beuzekom, A.; de Leeuw, F.; Altona, C. *Magn. Res. Chem.* **1990**, *28*, 68–74. (d) Grossmann, G.; Lang, R.; Ohms, G.; Scheller, D. *Magn. Res. Chem.* **1990**, *28*, 500–504.

26. Genov, D.; Kresinski, R.; Tebby, J. *J. Org. Chem.* **1998**, *63*, 2574–2585.
27. de Rene, C.; Kagan, H.; Mathey, F.; Sameul, O.; Santini, C. *C. R. Acad. Sci., Ser. C* **1980**, *291*, 29–32.