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Carbanion-Accelerated Claisen Rearrangements: Asymmetric Induction with Chiral Phosphorus-Stabilized Anions‡

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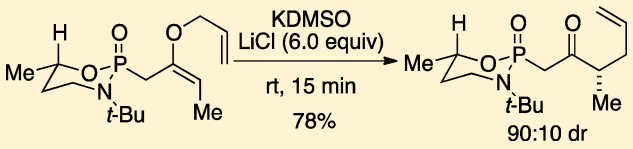
Supporting Information

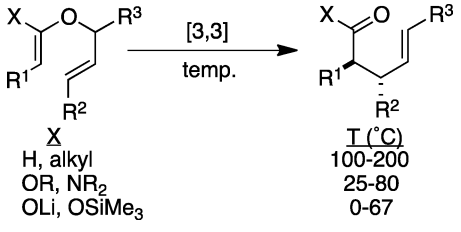
ABSTRACT: The carbanion-accelerated Claisen rearrangement has been extended to include phosphorus carbanion-stabilizing groups. The appropriately substituted allyl vinyl ethers are synthesized by the nucleophilic addition of allyl oxides to phosphorus-substituted allenes, which are obtained in one step from simple starting materials. The phosphorus-stabilized, carbanion-accelerated Claisen rearrangements proceed rapidly at room temperature in high yield, and the rearrangements are highly site- and stereoselective. The first examples of asymmetric induction in the Claisen rearrangement with chiral, phosphorus, anion-stabilizing groups are described. The observed asymmetric induction is highly dependent on the structure of the auxiliary and the metal counterion involved. Both internal and relative diastereoselectivity are high. A model for the observed sense of internal diastereoselectivity is proposed that is founded in the current understanding of the structure of phosphorus-stabilized anions.



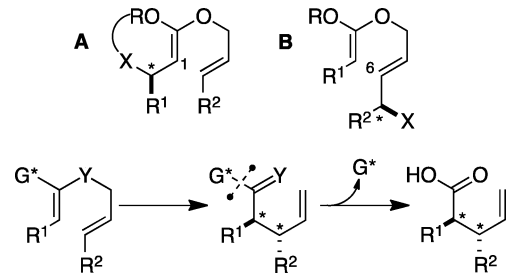
INTRODUCTION

The aliphatic Claisen rearrangement of allyl vinyl ethers enjoys recognition as one of the preeminent members of the important class of [3,3]-sigmatropic rearrangements. The vast literature on all aspects of the reaction continues to grow documenting new variations, synthetic applications, and mechanistic and theoretical details.[1] Synthetically, the most commonly employed variants are the thermally induced processes illustrated in Scheme 1, which produce a number of γ,δ-unsaturated carbonyl derivatives with varying degrees of facility. The highly selective and predictable creation of the new double bond and stereogenic centers is a hallmark of the rearrangement. These familiar issues of relative and internal stereogenesis attend all reactions within or between molecules containing enantio- or diastereotopic faces.[2] A less common manifestation of relative stereogenesis in the Claisen rearrangement involves the influence of remote stereocenters not contained within the pericyclic array. This is encountered in substrates bearing stereogenic carbons attached to positions 1 and 6 (A and B, Scheme 2). An intriguing subset of this phenomenon is the special case of auxiliary-based, relative stereocontrol wherein the preexisting stereogenic unit is ultimately recoverable unchanged (Scheme 2). A few, but notable, examples of this concept have been described for variants of the Claisen rearrangement,[3,4] as has the use of stoichiometric amounts of chiral modifiers.[5]

Scheme 1



Scheme 2



To further extend the synthetic utility and improve stereoselectivity, catalysis of the Claisen rearrangement constitutes an important objective.[6] Significant rate and selectivity enhancements are now on record employing catalysis with Lewis acids (both main group[7] and transition metal[8]), Brønsted acids,[9] antibodies,[10] and N-heterocyclic carbenes.[11] These advances have significantly improved the rate and enantioselectivity of the Claisen rearrangement. The continuing efforts in this area are testimony to the fact that a truly general solution to asymmetric Claisen rearrangements is still elusive. In addition, to enable catalysis by Lewis and Brønsted acids, Lewis basic binding sites (generally a carboalkoxy group at

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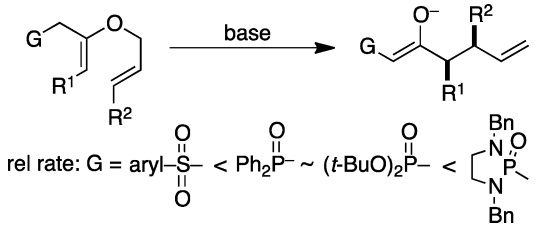
C(2)) are required to enable activation and provide rigidity for stereocontrol. This fact is not so much a criticism as a statement of opportunity to develop new concepts for addressing these key issues.

Our study of the Claisen rearrangement stems from a long-standing interest in the electronic modulation of the rearrangement.[12,13] Early reports from our laboratories documented the accelerating effect of a carbanion (π-donor) at the 2-position of an allyl vinyl ether, Scheme 3. The arylsulfonyl stabilizing group (G = $ArSO_2$) has been extensively investigated, and the resulting carbanion-accelerated Claisen rearrangements (CACR)[14] display the following characteristics: (1) >300-fold acceleration, (2) exclusive γ-site selectivity, (3) substitution compatible at all positions, (4) exclusive formation of *trans* olefins, and (5) high diastereoselectivity (95:5 dr) for syn or anti isomers. Although extension of the CACR with other sulfur-based anion stabilizing groups was unsuccessful, a number of phosphorus-based groups have shown considerable potential. As shown in Scheme 3, phosphine oxides, phosphonates, and phosphonamides are superior to sulfones in rate and selectivity in the CACR.[15]

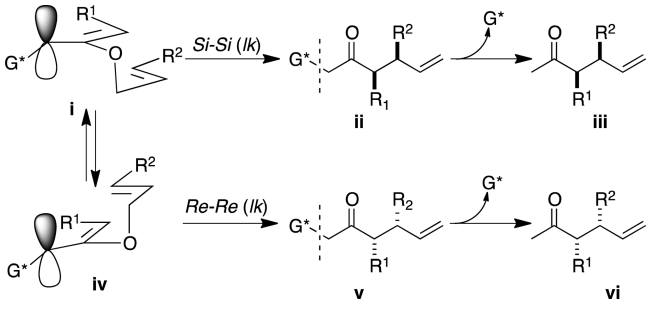
Scheme 3



In all of these cases, the anion-stabilizing groups are achiral. Thus, the two limiting chairlike transition states **i** and **iv** are enantiomeric, giving rise, necessarily, to racemic products **ii** (**iii**) and **v** (**vi**), Scheme 4. If, however, G* were chiral, **i** and **iv** would be diastereomeric leading to diastereomers **ii** and **v** which, after removal of G*, constitute enantiomers **iii** and **vi**. Insofar as the anionic charge is responsible for the rate enhancement, effective desymmetrization of that charge by chiral groups G* should lead to significant *differences* in rates of rearrangement for **i** and **iv**. These differences are manifested in the enantiomeric excess of the products.

The specific objective of the investigation described here is the development of an auxiliary-based, asymmetric CACR using chiral, anion-stabilizing groups. The success of this enterprise rests on the design of the chiral moiety G*, which should satisfy the following criteria: (1) ready construction from available, nonracemic materials, (2) effective acceleration of the CACR, (3) strong diastereofacial bias in the CACR, and (4) facile cleavage and recovery of the auxiliary unit. In addition to the stereoselective construction of new carbon–carbon bonds, the results of this study should provide valuable insights into the nature of heteroatom-stabilized allyl anions.[16]

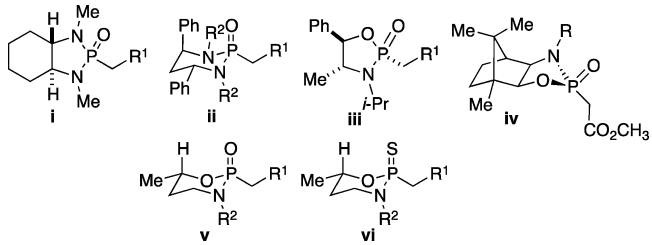
Scheme 4



BACKGROUND

The application of chiral phosphorus reagents in organic synthesis is not very common, apart from the ubiquitous use of chiral phosphines as ligands for transition-metal catalysts. Chiral organophosphorus reagents have been employed in asymmetric olefination,[17] asymmetric Michael addition,[18] asymmetric alkylation and amination,[19] and asymmetric Staudinger reactions.[20] A small number of common motifs have found good use in several of these transformations such as diazaphospholidines (**i**), diazaphosphorinanes (**ii**), oxazaphospholidines (**iii**, **iv**), and oxazaphosphorinanes (**v**, **vi**) (Chart 1).

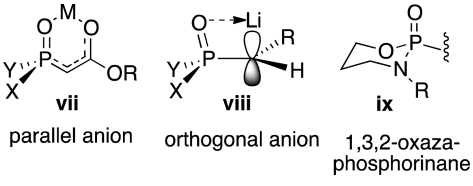
Chart 1



The de novo design of an auxiliary for a phosphorus-stabilized carbanion was nearly impossible since little was known at the time about the structure of the anion. Early design criteria were guided by our own studies in addition to the NMR and IR spectroscopic studies from Seyden-Penne[21] on *P*-stabilized carbanions bearing additional stabilizing groups (−COR, $-CO_2R$, −CN, Ph, etc.). Two limiting structures were proposed: a parallel, chelated anion **vii** and an orthogonal, (C−Li contact) anion **viii**, Chart 2. It was a priori difficult to predict which of these two structures the allyl vinyl ether anion would prefer. Indeed, it embodies features of both being an unstabilized allyl anion, but also containing a potentially coordinating β-oxygen. In either case, we reasoned that a key element in stereocontrol was to desymmetrize the region around the carbanion by maximally differentiating the groups X and Y, Chart 2. This condition was satisfied by the *N*-substituted 1,3,2-oxazaphosphorinane moiety **ix** depicted in Chart 2. The phosphorinane (six-ring) was selected in favor of the phospholidine (five-ring) for two reasons: (1) to move the N-ligand closer to the vicinity of the anion and (2) to reduce reactivity at phosphorus.[22]

This structural motif formed the basis for the three types of substrates examined, Chart 3. Preliminary studies, optimization and N-group dependence were carried out with model I in

Chart 2



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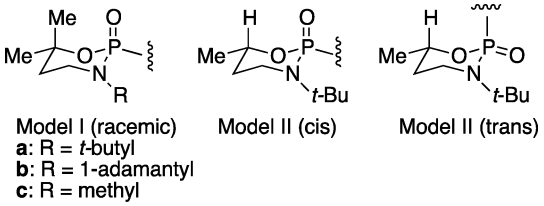
racemic form (derived from an achiral amino alcohol). Models II (*cis*) and II (*trans*) (derived from the same enantiomerically pure amino alcohol) were used to establish the absolute stereochemical course of the reaction and to produce enantiomerically enriched products. The synthesis and rearrangements of various allyl vinyl ethers in these families and stereochemical analysis of the keto phosphonamidate products is described in detail below. Some of these studies have been described previously in preliminary form.[23]

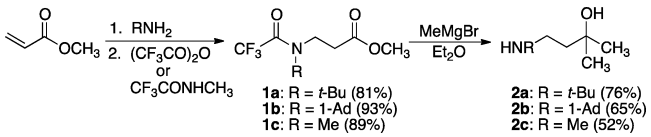
Chart 3



RESULTS AND DISCUSSION

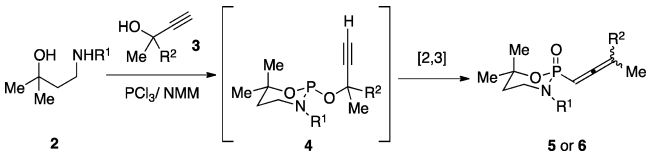
1. Racemic Oxazaphosphorinanes. *1.1. Synthesis of Amino Alcohol Auxiliaries.* The achiral amino alcohols **2a**, **2b**, and **2c** required for synthesis of model I were prepared by methylation of the 3-trifluoroacetamidopropanoates (**1a**–**c**) with excess methylmagnesium bromide, Scheme 5. The use of methyllithium or a simple acetamide protecting group led to considerably lower yields. Compounds **1a**–**c** were prepared by simple Michael addition to methyl acrylate followed by acetylation with trifluoroacetic anhydride.

Scheme 5



1.2. Synthesis of Allenes. The amino alcohols were directly converted to the required allenes in a one-pot operation via a facile Horner–Mark [2,3]-rearrangement (**4** to **5** or **6**, Table 1). Thus, addition of 3-butyn-2-ol (**3a**) to a cold solution of PCl_3 and 1.0 equiv of *N*-methylmorpholine (NMM), followed by sequential addition of an additional 2.0 equiv of NMM and the amino alcohol **2a**, **2b**, or **2c** produced allenes **5a**–**c**, respectively. Allene **6** was prepared under identical conditions by combining 2-methyl-3-butyn-2-ol (**3b**) with PCl_3 and amino alcohol **2a**.

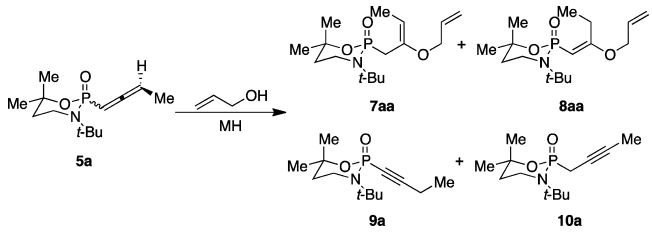
Table 1. Synthesis of Allenes 5 and 6



entry	R^1	R^2	product	yield (%)
1	*t*-Bu	H	**5a**	58
2	1-Ad	H	**5b**	70
3	Me	H	**5c**	79
4	*t*-Bu	Me	**6**	53

1.3. Synthesis of Allyl Vinyl Ethers. Previous studies demonstrated that very subtle changes in reaction conditions produce drastic differences in product distribution during allyl oxide additions to achiral phosphorus-substituted allenes, and similar behavior with these oxazaphosphorinanes was anticipated. Indeed, four products could be isolated following exposure of potassium or sodium allyloxide to allene **5a** (Table 2): the β,γ- and α,β-unsaturated oxazaphosphorinanes **7aa** and **8aa** resulting from allyloxide addition and acetylenic oxazaphosphorinanes **9a** and **10a** resulting from simple tautomerization. Formation of the β,γ-unsaturated oxazaphosphorinane **7aa** required the use of sodium allyl oxide at room temperature in the presence of *tert*-butyl alcohol (Table 2, entry 1). *tert*-Butyl alcohol serves as a proton source to trap the intermediate allyl anion prior to isomerization. The use of sodium hydride without *tert*-butyl alcohol at lower temperatures (Table 2, entry 3) afforded a mixture of **7aa** and both acetylenic products. Under no circumstances did the addition of potassium allyloxide lead to the exclusive formation of **7aa** (Table 2, entries 2, 4–6). However, the α,β-unsaturated derivative **8aa** was cleanly prepared at room temperature in the absence of *tert*-butyl alcohol in high yield by the addition of potassium allyl oxide (Table 2, entry 2).

Table 2. Optimization of Allyloxide Addition to Allene 5a



entry	MH[a]	*t*-BuOH (equiv)	temp (°C)	time, (h)	result
1	NaH	2.4	20	0.5	**7aa** (64%)
2	KH	0	20	0.5	**8aa** (71%)
3	NaH	0	−20	3.5	**7aa**:**9a**:**10a** (4:3:3)
4	KH	2.4	0	0.5	**7aa**:**9a**:**10a** (1:1:1)
5	KH	1.8	20	0.25	**8aa** only
6	KH	solvent	20	1.0	**9a** and **10a** only

[a]All reactions performed with a full equivalent of MH.

The results for all of the optimized allyl and crotyl oxide additions in this series are collected in Table 3. All additions to the monomethylated allenes proceed rapidly at room temperature. Crotyl oxide addition to the dimethylated allene **6** proceeded more slowly and was free of contamination from the corresponding acetylenes or the α,β-unsaturated addition product. However, a small amount (<5%) of inseparable thermal Claisen rearrangement product was invariably formed.

1.4. Claisen Rearrangements. All anion-accelerated rearrangements in this series were conducted using 2.0–2.5 equiv of lithium dimsylate generated from either equimolar amounts of *n*-BuLi and DMSO in THF or KH in 3:1 DMSO/THF in the presence of 6 equiv of LiCl. Anion-accelerated rearrangements of all β,γ-unsaturated isomers are complete within 10–15 min at room temperature, while the corresponding thermal rearrangements require 2–4 h in refluxing toluene or at 100 °C in THF (sealed tube). As expected, anion-accelerated rearrangements of the α,β-unsaturated isomers required reaction times on the order of 1.5–3 h.

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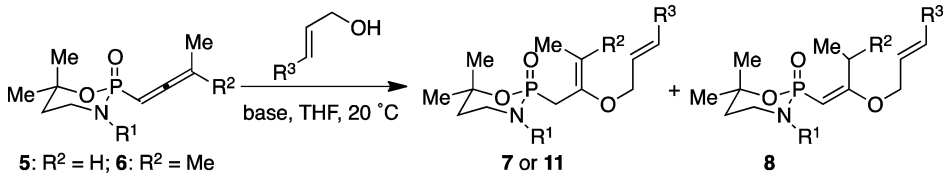
Table 3. Allyl and Crotyl Oxide Additions to Allenes 5 and 6[a]



5: R^2 = H; **6**: R^2 = Me — **7 or 11** — **8**

entry	allene	base	*t*-BuOH (equiv)	time (min)	product	R^1	R^2	R^3	yield (%)
1	**5a**	NaH	2.4	20	**7aa**	*t*-Bu	H	H	64
2	**5a**	KH	0	30	**8aa**	*t*-Bu	H	H	71
3	**5a**	NaH	2.4	20	**7ab**	*t*-Bu	H	CH_3	46
4	**5a**	KH	0	20	**8ab**	*t*-Bu	H	CH_3	80
5	**5b**	NaH	2.4	5	**7ba**	1-Ad	H	H	34
6	**5c**	NaH	2.4	2	**7ca**	Me	H	H	40
7	**6**	KH	0	180	**11**	*t*-Bu	CH_3	CH_3	51

[a]All reactions were performed using 1.2 equiv of base and allylic alcohol.

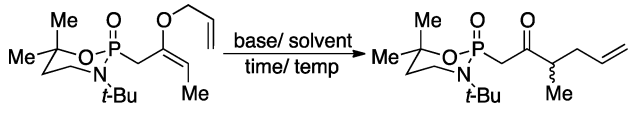
Two types of diastereoselectivity are manifest with chiral phosphorus-stabilized, carbanion-accelerated Claisen rearrangements. The relative asymmetric induction is defined as the ability of the chiral phosphorus subunit to influence the creation of the new stereogenic centers in the rearrangement. The internal asymmetric induction reflects the extent of chair/boat conformational selectivity. The absolute asymmetric induction describes the configuration of newly created stereogenic centers with respect to the configuration of the existing phosphorus atom. In the racemic series (model I), the particular substitution pattern of each allyl vinyl ether determined whether relative asymmetric induction could be studied separately or coupled with internal asymmetric induction. Therefore, the rearrangements of each allyl vinyl ether will be discussed individually. Absolute asymmetric induction will only be discussed with model II compounds (vide infra).

Anion-accelerated Claisen rearrangement of allyl vinyl ether **7aa** with LiDMSO afforded a mixture of two diastereomers (*l*- and *u*-**12aa**)[24] with as high as 90% diastereoselectivity (Table 4). The diastereomeric ratios were determined by integration of either the distinct singlets in the proton-decoupled ^{31}P NMR spectra or the C(3) methyl doublets in the ^1H NMR spectra. The thermal rearrangement is nonselective (Table 4, entry 1) as is the anion-accelerated rearrangement when KDMSO serves as base (Table 4, entry 2). All rearrangements of anions with lithium as the counterion gave excellent diastereoselectivities (Table 4, entries 3–8). The rate of reaction decreased with decreasing solvent polarity. Interestingly, use of the more bulky and more strongly basic lithium diisopropyl sulfoxide (Table 4, entry 7) increased the rate of rearrangement but did not affect stereoselectivity. Thus, it appears that the reaction rate is solvent dependent, but stereoselectivity is counterion dependent.

The diastereomeric ratios observed in the rearrangement of **7aa** are a direct reflection of the control that the chiral environment about the phosphorus atom exerts on the transition state during the rearrangement. Any change in the chair/boat transition-state selectivity will not affect the observed product ratio.

The importance of the local environment about the phosphorus atom was further demonstrated by studying the rearrangements of the *N*-adamantyl and *N*-methyl derivatives **7ba** and **7ca** (Table 5). Whereas both thermal Claisen rearrangements are unselective (Table 5, entries 1 and 4),

Table 4. Claisen Rearrangement of Oxazaphosphorinanes 7aa[a]



7aa — *l*- and *u*-**12aa**

entry	base[b]	solvent	time (h)	yield (%)	dr[c]
1[d]	none	THF	4.0	90	58:42
2	KDMSO	DMSO/THF (3:1)	0.25	77	52:48
3	KDMSO (LiCl)[e]	DMSO/THF (3:1)	0.25	81	91:9
4	LiDMSO[f]	DMSO/THF (3:1)	0.25	73	95:5
5	LiDMSO	THF	0.50	64	94:6
6	LiDMSO	Et_2O	1.0	31	90:10
7	LiDIPSO	THF	0.25	68	94:6
8	*n*-BuLi	THF	1.75	51	95:5

[a]All anionic rearrangements carried out at room temperature. [b]Usually 2.0–2.5 equiv of base used. [c]Diastereoselectivity determined by ^{31}P NMR or ^1H NMR (500 MHz). [d]Reaction performed at 100 °C in a sealed tube.. [e]6.0 equiv of LiCl used. [f]Prepared with *n*-BuLi. The reagent was insoluble in THF but dissolved upon addition of **7aa**.

anion-accelerated rearrangements of **7ba** (Table 5, entries 2–3) proceed with the same high stereoselectivity as seen with **7aa**. However, the high degree of stereoselectivity disappears under anion-forming conditions when the ligand bound to the oxazaphosphorinane nitrogen is small (R = methyl, Table 5, entry 5). Thus, a sterically bulky N-substituent is crucial for proper stereocontrol.

The α,β-unsaturated oxazaphosphorinane **8aa** underwent Claisen rearrangement under anion-forming conditions to afford a mixture of (*l*) and (*u*) keto oxazaphosphorinanes **12aa** (Scheme 6). However, this rearrangement is selective in the opposite sense when compared to that of compound **7aa**. The origin of the reversal of selectivity may be explained by a permutation of the allyl anion geometry. Chart 4 shows the geometries of the favored anions. α-Deprotonation of **7aa** gives *E* allyl anion **7aa**$^-$ since the configuration about C(1)–C(2) is fixed during allyl oxide addition and a high barrier to rotation relative to rearrangement exists. γ-Deprotonation of **8aa** then

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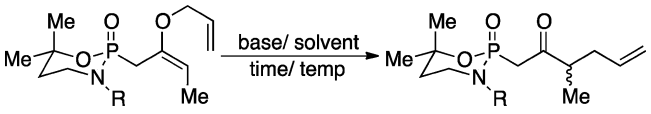
Table 5. Claisen Rearrangement of 7ba and 7ca[a]



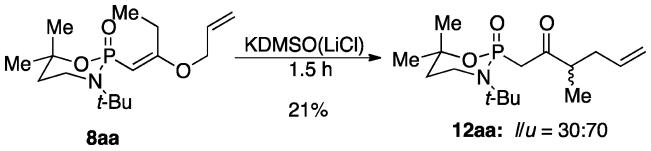
7ba or **7ca** — *l*- and *u*-**12ba** or **12ca**

entry	educt	R	base[b]	solvent	time (h)	yield (%)	dr[c]
1	**7ba**	1-Ad	none	toluene[d]	2.0	93	60:40
2	**7ba**	1-Ad	LiDMSO	THF	0.25	58	94:6
3	**7ba**	1-Ad	LiDMSO	DMSO/ THF	0.25	74	94:6
4	**7ca**	Me	none	toluene[d]	2.5	86	53:47
5	**7ca**	Me	LiDMSO	THF	0.25	62	52:48

[a]Anionic rearrangements carried out at room temperature. [b]2.5 equiv of base were used. [c]Diastereoselectivities determined by ^{1}H NMR (500 MHz) [d]Reactions run at 110 °C.

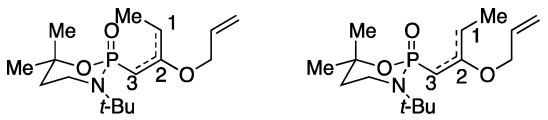
must be selective to form a preponderance of *Z* allyl anion **8aa**$^-$ having the opposite configuration at C(1).

Scheme 6



8aa — **12aa:** *l*/*u* = 30:70

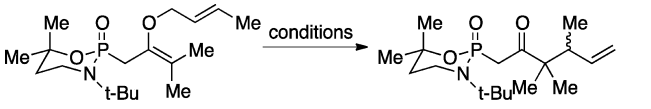
Chart 4



7aa$^-$ **8aa**$^-$

Rearrangement of the trimethyl-substituted allyl vinyl ether **11** also leads to a mixture of two diastereomeric products (**13**, Scheme 7). Although the chair/boat conformational selectivity does affect the product ratios in this rearrangement, it is not possible to quantify this internal selectivity. This result implies that, assuming complete chair selectivity, the minimum relative asymmetric induction is 92:8. Anything less than complete chair selectivity would make the relative asymmetric induction even better.

Scheme 7



11 — *l*- or *u*-**13**

thermal: 66% yield; (*l*/*u* = 68:32)
anionic: 94% yield; (*l*/*u* = 92:8)

The rearrangements of allyl vinyl ethers **7ab** and **8ab** (Table 6) result in the formation of two new stereogenic centers and, thus, mixtures of four diastereomers. In these cases, it was possible to quantify the degrees of internal and relative asymmetric induction. The four diastereomers are distinguishable in the ^{31}P NMR spectra (note the ^{31}P chemical shifts in Scheme 8). Assignment of the diastereomers was made according to the following arguments. The major product from the CACR of compound **7ab** (δ ^{31}P 15.74 ppm) was assumed to be a *syn*-dimethyl diastereomer by analogy to all other CACRs (i.e., sulfones, phosphonates, etc.) in that similarly substituted allyl vinyl ethers produce *syn*-dimethyl diastereomers.

Thermal rearrangements are also *syn* selective, and thermal rearrangement of **7ab** gave two major diastereomers (δ ^{31}P: 15.74, 16.25 ppm). The *anti* dimethyl diastereomers were identified from the anion-accelerated rearrangement of the α,β-unsaturated oxazaphosphorinane **8ab**. These assignments were also based on analogy to other CACRs of similarly substituted allyl vinyl ethers which have been shown to be *anti* selective. To assign numbers to the internal and relative asymmetric induction selectivities, we still needed to determine which transition state was responsible for each product. Making the reasonable assumption that the major diastereomer in each rearrangement resulted from a chairlike transition state, all products can be assigned as having resulted from either a chair- or boatlike transition state from either face of the allyl anion. The internal diastereoselectivity is then the sum of the integrals of the products arising from a chair- versus a boatlike transitions state. Thus, the internal diastereoselectivities are 98:2 for **7ab** and 94:6 for **8ab**. The relative diastereoselectivities are the sum of the integrals of the products arising from rearrangement on the same face of the allyl anion. Thus, the relative diastereoselectivities are 92:8 for **7ab** and 13:87 for **8ab**.

2. Enantiomerically Pure Oxazaphosphorinanes. Model II. Because CACR products **12xx** and **13** are racemic and noncrystalline, it was not possible to determine the configuration of the newly formed stereogenic centers by degradative or X-ray crystallographic methods. Thus, it was necessary to employ a chiral oxazaphosphorinane which was generated from enantiomerically pure amino alcohol **15**.

2.1. Synthesis of Amino Alcohol ***15***. Amino alcohol **15** was chosen for its structural similarity to amino alcohol **2a**. Thus, the oxazaphosphorinane ring, and hence the environment about the phosphorus atom, would experience minimal perturbation. The preparation of **15** is shown in Scheme 9. Yeast reduction of ethyl acetoacetate afforded (*S*)-ethyl 3-hydroxybutanoate in 55% yield (er 98:2).[25] The enantiomeric purity was determined by optical rotation and GC analysis of the Mosher esters.[26] The observed enantiomeric excess is significantly higher than previously reported and can only be explained by the brand of yeast used.[27] Amidation without hydroxyl protection by the method of Weinreb[28] gave (*S*)-*N*-*tert*-butyl-3-hydroxybutyramide (**14**) in 72% yield (er >99:1). This reaction required a careful quenching protocol followed by acidification to pH ~6. At lower pH, β-elimination to the butenamide occurred. The enantiomeric excess was determined by derivatization to a 3,5-dinitrophenyl carbamate (**14′**) and HPLC analysis on a Pirkle L-naphthylalanine column.[29] Diborane reduction then produced amino alcohol **15** in 67% yield.

2.2. Synthesis and Assignment of Allenes cis- and trans- ***16***. Allene formation from **15**, PCl_3, and propargylic alcohol **3a** using standard reaction conditions produced a mixture of four diastereomers (Scheme 10). From this mixture, diastereomeric allene pairs *cis*-**16** (54%) and *trans*-**16** (20%) could be easily separated by chromatography. Assignment of these phosphorus epimers was tentatively based on the downfield chemical shifts of phosphorus in the ^{31}P NMR spectrum and the C(6) proton in the ^{1}H NMR spectrum of *cis*-**16**.[30] These assignments were later confirmed by X-ray crystallography (vide infra).

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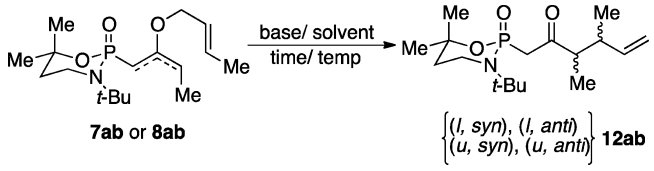
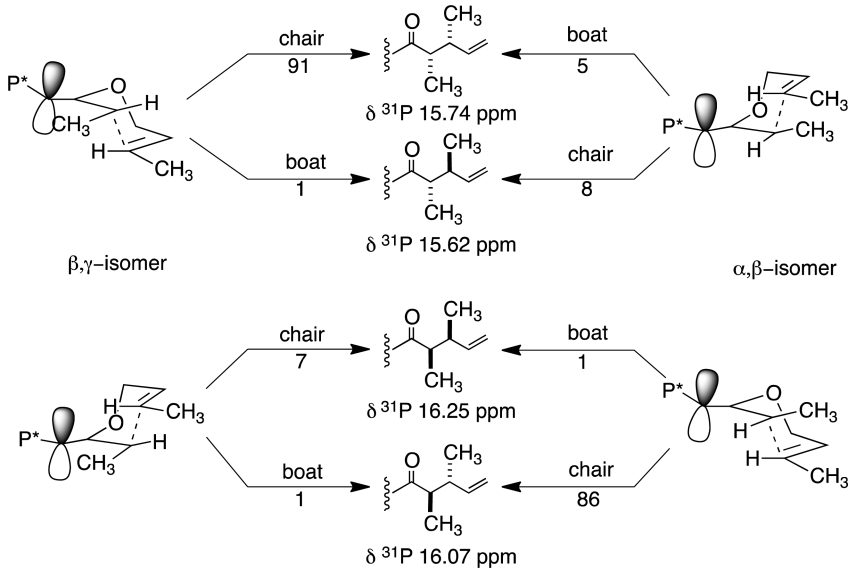
Table 6. Claisen Rearrangement of Oxazaphosphorinanes 7ab and 8ab



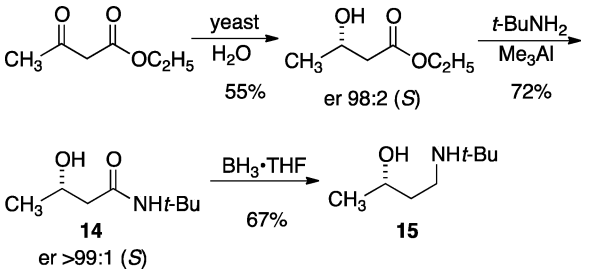
entry	educt	base[a]	solvent	time, h	temp, °C	yield, %	induction[b] relative	induction[b] internal
1	**7ab**	none	THF	4.0	100	84	58:42	77:23
2	**7ab**	KDMSO/LiCl[c]	DMSO/THF (3:1)	0.25	20	80	92:8	98:2
3	**8ab**	KDMSO/LiCl[c]	DMSO/THF (3:1)	3.0	20	60	13:87	94:6

[a]2.0–2.5 equiv of base were used. [b]See text for definition. [c]6.0 equivalents of LiCl were used.

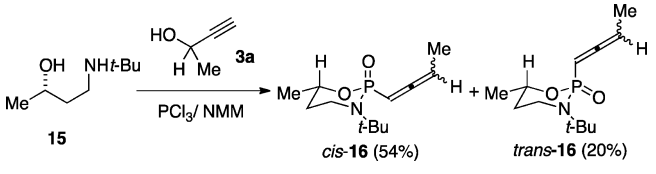
Scheme 8



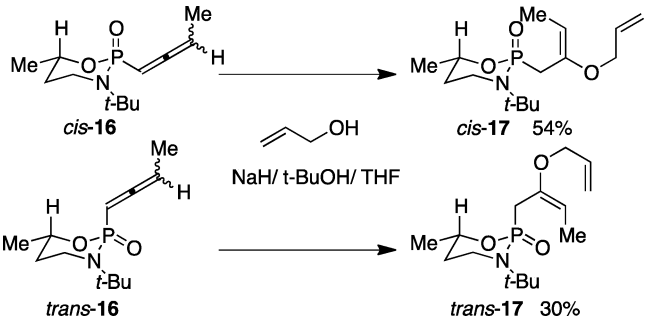
Scheme 9



Scheme 10



Scheme 11



2.3. Synthesis and Assignment of Allyl Vinyl Ethers. Allyl vinyl ethers *cis*-**17** and *trans*-**17** were prepared by sodium allyl oxide addition to allenes *cis*- and *trans*-**16**, respectively, in the presence of *tert*-butyl alcohol (Scheme 11). The formation of acetylenic tautomers was responsible for the low yield in the preparation of *trans*-**17**.

The tentative assignments of configuration at the phosphorus center made earlier on the basis of ^{1}H and ^{31}P NMR spectroscopic data could be confirmed by single-crystal X-ray crystallographic determinations of both allyl vinyl ethers *cis*-**17** and *trans*-**17** (Figure 1).[31] These structures verified the *S*-configuration at phosphorus and a *cis* relationship between the C(6) methyl group for *cis*-**17** and the *R*-configuration at phosphorus and a *trans* relationship between the C(6) methyl group for *trans*-**17**. Furthermore, the geometry about the vinyl ether double bond was also unambiguously established in both cases. As expected, nucleophilic attack on a monomethylated

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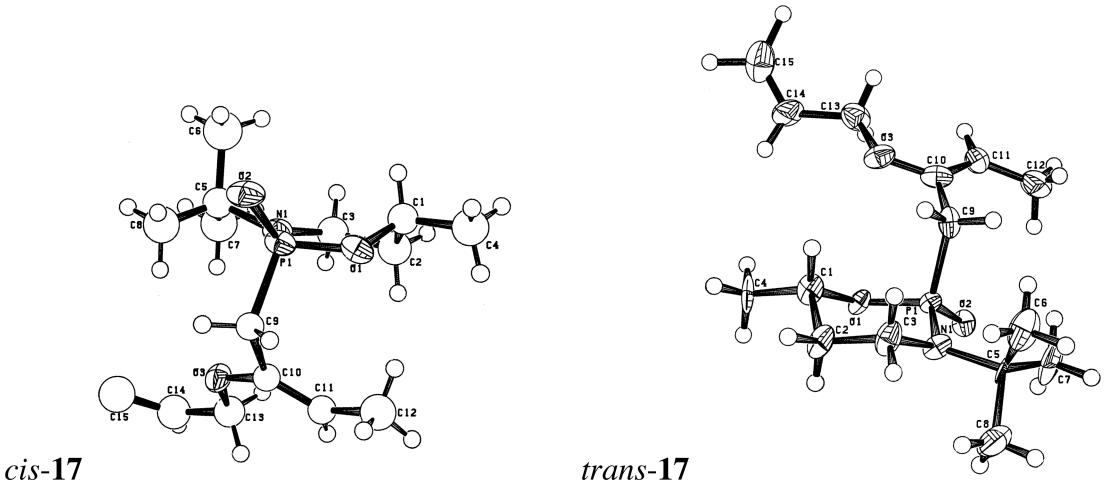
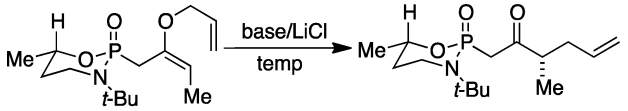


Figure 1. ORTEP images of *cis*-**17** and *trans*-**17**.

Table 7. Carbanionic Claisen Rearrangement of *cis*-17[a]



cis-**17** (*S*)-(*l,l*)-**18**

entry	educt	product	base[b]	LiCl, equiv[c]	temp (°C)	yield[d] (%)	relative induction[e]
1	*cis*-**17**	*cis*-**18**	KDMSO	0	20	62	50:50
2	*cis*-**17**	*cis*-**18**	KDMSO	1	20	77	65:35
3	*cis*-**17**	*cis*-**18**	KDMSO	2	20	69	80:20
4	*cis*-**17**	*cis*-**18**	KDMSO	6	20	78	90:10
5	*cis*-**17**	*cis*-**18**	KDMSO	12	20	65	89:11
6	*cis*-**17**	*cis*-**18**	LiDMSO[f]	0	20	65	90:10
7	*cis*-**17**	*cis*-**18**	none	0	100	93	66:34
8	*cis*-**17**	*cis*-**18**	none	6	100	90	64:36

[a]All anionic rearrangements (15 min) were done in 3:1 DMSO/THF except entry 6 which was done in 2:1 THF/DMSO, thermal rearrangements (240 min) were done in THF. [b]2−2.5 equiv of freshly prepared base was used. [c]LiCl was added to KDMSO before addition of **17**. [d]Yield after chromatography. [e]See text for explanation. [f]Prepared from *n*-BuLi.

allene is governed by steric approach of the allyloxide to the less hindered face of the allene.

Other interesting features of these structures include the observation that the oxazaphosphorinane ring in *cis*-**17** is nearly flat with bond angles between the substituents on nitrogen of approximately 120°. The planarity at nitrogen, in accord with other reported 1,3,2-oxazaphosphorinanes,[32] stems from the longer P−O and P−N bond lengths that widen the angles between the atoms in the ring. The wider angles also contribute to the flattening of the ring. However, the most important interaction governing the ring conformation is the geminal-P(1)−N(1) substitution pattern which places the phosphorus substituent in a pseudoaxial position. Bentrude has shown that N-unsubstituted 1,3,2-oxazaphosphorinanes exist predominantly in a chair conformation, whereas N-substituted 1,3,2-oxazaphosphorinanes exist exclusively in a twist-chair conformation.[33] Clearly, the geminal P(1)−N(1) interaction in *cis*-**17** strongly influences 1,3,2-oxazaphosphorinane ring conformation. In *trans*-**17**, the nitrogen is lightly pyramidalized and the ring takes up a chairlike conformation wherein the phosphorus substituent again takes up an axial position.

2.4. Claisen Rearrangements. Under anion-forming conditions, allyl vinyl ether *cis*-**17** (Table 7) rearranged rapidly at room temperature with high relative diastereoselectivity. As in the racemic series, the thermal rearrangement required 4 h at 100 °C and showed poor diastereoselectivity (compare Table 7, entries 4 and 7). At this point, the effect of added LiCl on the stereoselectivity of the CACR was studied. In the absence of LiCl, there is no observed asymmetric induction in the anion-accelerated rearrangement of *cis*-**17** (Table 7, entry 1). As the amount of LiCl is increased from 1 to 6 equiv (Table 7, entries 2−4), the diastereomeric ratios improve from ∼2:1 to 9:1. No further increase in selectivity is observed with additional equivalents of LiCl (Table 7, entry 5). Note that LiDMSO prepared from *n*-BuLi and DMSO in THF also results in high relative asymmetric induction (Table 4, entry 6). Finally, added LiCl had no positive effect on the selectivity of the thermal rearrangement (Table 7, entry 8). The anion-accelerated rearrangement of *trans*-**17** also proceeded with high selectivity (Scheme 12).

2.5. Degradation and Assignment. To establish the relative configuration at the newly created stereogenic centers with that of the existing phosphorus center, CACR products (*S*)-(*l,l*)-**18** and (*S*)-(*u,u*)-**18** were degraded to optically active dimethyl methylsuccinates as shown in Scheme 13. Treatment of the keto oxazaphosphorinanes with KHMDS at −78 °C and trapping with *tert*-butyldimethylsilyl chloride afforded the silyl enol ether. Ozonolysis followed by an oxidative workup

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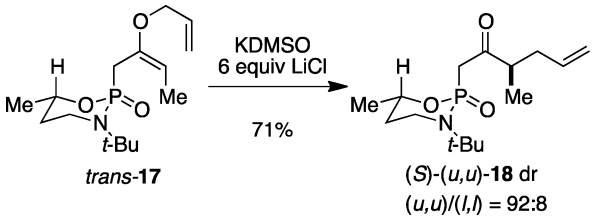
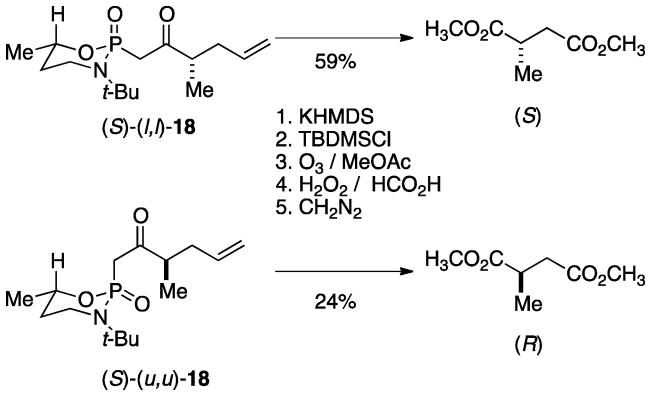
Scheme 12



provided an enantiomerically enriched sample of methylsuccinic acids which were esterified with diazomethane. The overall yields were 59% from *cis*-**18** and 24% from *trans*-**18**.

Scheme 13



The absolute configuration of the succinate esters could not be established by optical rotation because the absolute optical rotation of dimethyl methylsuccinate is quite small.[34] With only limited amounts of material in hand, the use of optical rotation became inappropriate. The enantiomeric succinates were instead distinguished by ^{1}H NMR spectroscopy in the presence of the chiral shift agent (*R*)-2,2,2-trifluoro-1-(9-anthryl)-ethanol.[35] The methyl ester regions of the spectra clearly show four singlets. Assignment of the major enantiomers followed from the ^{1}H NMR spectrum of a mixture of the racemic succinates enriched with authentic *R* succinate and the chiral shift agent. As shown in Scheme 13, *cis*-**18** produced the (*S*)-dimethyl methylsuccinate and *trans*-**18** produced the *R* enantiomer. These data, coupled with the known configurations of the vinyl ether double bond (*E*) and the phosphorus stereogenic center, allows the unambiguous assignment of the sense of the chairlike folding in the transition state during the rearrangement. Thus, the rearrangement of *cis*-**17** proceeds by bonding to the *Re* face of the allyl anion at C(1) (cf. Chart 4), whereas the *Si* face is preferred for *trans*-**17**.

2.6. Proposed Transition States. It is clear that auxiliary structure, anion structure, counterion effects, and conformational preferences are crucial to phosphorus-induced diastereoselectivity. Before developing any reasonable model for the rearrangement, it would be prudent to review the current understanding of the structure of such phosphorus-stabilized anions.

The combination of multinuclear, variable-temperature solution NMR studies, X-ray crystallographic analyses,[36] and computational studies[37] provide a very clear picture of the factors that influence the structure of these species. Anions derived from 1,3,2-diazaphosphorinanes and 1,3,2-dioxaphosphorinanes bearing both *P*-benzyl and *P*-isopropyl substituents display the following characteristics: (1) the anionic carbons are fully planarized (i.e., sp^2 hybridized) and are devoid of contacts to lithium, (2) the atoms of the anion are all aligned in nearly eclipsed conformations with respect to the P═O moiety such that the dihedral angle, O(1)−P(1)−C(1)−C(2) spans a mere 10° across all structures, (3) the lithium atoms are coordinated to the phosphoryl oxygens and to two or more solvent (THF) molecules, (4) the nitrogen atoms in the 1,3,2-diazaphosphorinanes are pyramidalized, and (5) rotational barriers around the P−C bonds are very low. Although phosphorus-stabilized allyl anions have been studied only computationally, our experimental observations are consistent with the results of those studies.

The currently preferred model proposed to explain relative diastereoselectivity in the carbanion-accelerated Claisen rearrangement incorporates the various steric and electronic components that have been established in the foregoing studies. The model, shown in Figure 2, possesses the following characteristics: (1) a planar carbanion in which the atoms are aligned parallel to the P═O bond, (2) chelation of a lithium ion between the phosphoryl and vinyl ether oxygens, and (3) a sterically directed, diastereofacial preference of chair conformers such that the allyloxy side chain folds away from the bulky nitrogen substituent. This model corresponds to the parallel anion model **vii** in Chart 2.

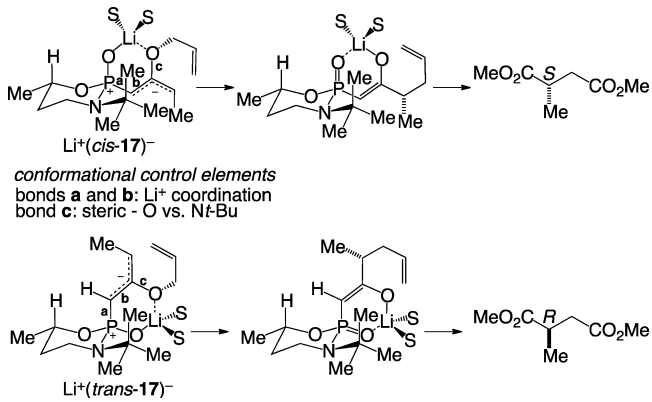


Figure 2. CACR transition state models for *cis*-**17** and *trans*-**17**.

In this model, the strong preference for the *ul* transition state in the anion-accelerated Claisen rearrangements of 1,3,2-oxazaphosphorinanes is a result of approach of the allyloxy side chain to the sterically less hindered side, i.e., away from the large *N*-*tert*-butyl group. The effect of the size of this group is dramatic as selectivity is completely lost in the *N*-methyl substrate **7ca** but slightly enhanced in the *N*-adamantyl substrate **7ba**. This model also comports with the high selectivity observed in the CACR of *trans*-**17**, which displayed an even higher level of diastereoselectivity than *cis*-**17**. The high diastereoselectivity observed with *trans*-**17** is particularly noteworthy. In a chairlike ring conformation, the allyl vinyl ether would have an axial orientation (Figure 1). Following the same logic, the fixed anion conformation and the biased folding of the allyl ether side chain away from the *N*-*tert*-butyl group leads to the correct prediction for the configuration of the rearrangement product. However, the higher selectivity for *trans*-**17** is puzzling and may hint that the ring conformations are not chairs but rather twist chairs with similar orientations of

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the allyl vinyl ether substituent because of the bulky N-*tert*-butyl group.

CONCLUSION

The carbanion-accelerated Claisen rearrangement allyl vinyl ethers bearing chiral 1,3,2-oxazaphosphorinanes takes place under extremely mild conditions (room temperature, 15 min) to afford γ,δ-unsaturated ketones with high levels of internal and relative diastereoselectivity. The internal diastereoselectivity followed the well-established paradigm of chairlike transition structures for these rearrangements. The relative diastereoselectivity with respect to the 1,3,2-oxazaphosphorinane ring was dependent upon the auxiliary structure and the reaction conditions. Lithium salts were shown to greatly enhance the diastereoselectivity which was interpreted to arise from chelation of the phosphoryl oxygen with the allyl vinyl ether oxygen in the stereodetermining transition structure. The size of the nitrogen substituent was shown to be critical for high diastereoselectivity. A model was constructed for the origin of high selectivity that was grounded in structural studies on phosphorus-stabilized anions.

EXPERIMENTAL SECTION[38]

Racemic 1,3,2-Oxazaphosphorinane 2-Oxides. *Methyl 3-(N-tert-Butyl-N-trifluoroacetyl)aminopropionate (**1a**).* A 15-mL, three-necked flask equipped with a stirring bar, septum, and N_2 inlet was charged with 5.08 g (25.2 mmol) of methyl 3-*tert*-butylaminopropionate and 25 mL of CH_2Cl_2. The mixture was placed in an ice bath, and 5.35 mL (37.9 mmol) of trifluoroacetic anhydride was added via syringe over 5 min. The reaction mixture was warmed to room temperature and stirred for 2 h. The solvent was removed by rotary evaporation, and the crude product purified by Kugelrohr distillation to give 5.30 g (84.3%) of amido ester **1a** as a colorless oil. Data for **1a**: bp 90 °C (0.3 mmHg); ^{1}H NMR (300 MHz) 3.71 (m, 2 H), 3.66 (s, 3 H), 2.60 (m, 2 H), 1.44 (s, 9 H); ^{13}C NMR (75.5 MHz) 170.5 (C(1)), 157.0 (q, J = 34.3, $CF_3C{=}O$)), 116.4 (q, J = 289.4, CF_3), 59.7 ($(CH_3)_3C$), 51.8 (OCH_3), 39.9 (q, J = 3.2, C(3)), 36.0 (C(2)), 27.8 ($(CH_3)_3C$); IR (neat) 2961 (m), 1742 (s), 1694 (s), 1482 (m), 1439 (s), 1422 (s), 1401 (m), 1383 (s), 1372 (s), 1327 (s), 1294 (m), 1266 (s), 1198 (s), 1123 (s), 1048 (s), 1026 (m), 986 (w), 899 (w), 804 (w); MS (70 eV) 240 (M^+ − 15, 38), 208 (38), 199 (38), 168 (30), 167 (1), 166 (20), 139 (11), 57 (100), 56 (15), 55 (42). Anal. Calcd for $C_{10}H_{16}F_3NO_3$ (225.25): C, 47.06; H, 6.32; N, 5.49; F, 22.33. Found: C, 47.04; H, 6.24; N, 5.56; F, 22.03.

*Methyl 3-[N-(1-Adamantyl)-N-trifluoroacetyl]aminopropionate (**1b**).* To a suspension of 1-adamantylamine (12.5 g, 80.2 mmol) in methanol (50 mL) at 0 °C was added methyl acrylate (8.02 mL, 88.2 mmol) over 20 min. The resulting mixture was stirred for 2.5 days at room temperature, and then the methanol was removed by rotary evaporation. The crude product was used without further purification. The amino ester (19.0 g, 80.2 mmol) was placed in a dry flask, dichloromethane (100 mL), 4-dimethylaminopyridine (0.49 g, 4.0 mmol), and triethylamine (13.4 mL, 92.2 mmol) were added sequentially, and the mixture was cooled to 0 °C. A solution of trifluoroacetic anhydride (13.0 mL, 92.2 mmol) in CH_2Cl_2 (25 mL) was added dropwise via addition funnel over 30 min. The solution was warmed to room temperature and stirred for 2 days. The mixture was then poured into Et_2O (250 mL), washed with satd aq $NaHCO_3$ solution (3 × 50 mL) and brine (50 mL), dried ($MgSO_4$), and filtered, and the solvents were removed by rotary evaporation. The crude product was purified by vacuum distillation to give 24.9 g (93% for two steps) of **1b** as a clear, colorless oil. Data for (**1b**): bp 160 °C (0.6 mmHg); ^{1}H NMR (500 MHz) 3.75−3.72 (m, 2 H), 3.70 (s, 3 H), 2.66−2.63 (m, 2 H), 2.19 (s, 6 H), 2.15 (s, br, 3 H), 1.73−1.66 (m, 6 H); ^{13}C NMR (125.8 MHz) 170.6 (C(1)), 156.8 (q, J = 34.3, $CF_3C{=}O$), 116.3 (q, J = 289.9, CF_3), 61.3 (adamantyl C), 51.8 (OCH_3), 39.0 (adamantyl CH_2CN), 38.8 (s, C(3)), 36.7 9(s, C(2)), 36.0 (s, adamantyl CH_2CH CH_2CN), 30.0 (s, adamantyl *C*H); MS (70 eV) 333 (M^+, 0.77), 136 (10), 135 (100), 134 (15). Anal. Calcd for $C_{16}H_{22}F_3NO_3$(333.35): C, 57.65; H, 6.65; N, 4.20; F, 17.10. Found: C, 57.43; H, 6.56; N, 4.25; F, 17.46.

*Methyl- 3-(N-Methyl-N-trifluoroacetyl)aminopropionate (**1c**).* To a solution of *N*-methyl trifluoroacetamide (16.0 g, 123.4 mmol) and methyl acrylate (28.6 mL, 308.5 mmol) in *tert*-butyl alcohol (30 mL) was added potassium *tert*-butoxide (0.75 g, 6.17 mmol). The resulting solution was stirred at room temperature for 8.5 h. Acetic acid (0.2 mL) was added and the mixture stirred for an additional 1 h. The reaction mixture was then quenched with acetic acid (1.0 mL) and filtered through silica gel (3 in. column), and the column was washed with Et_2O (250 mL). The solvents were removed in vacuo, and the crude product was purified by vacuum distillation to yield 23.4 g (89%) of **1c** as a clear, colorless oil. Data for **1c**: bp 153−154 °C (75 mmHg); ^{1}H NMR (500 MHz) major rotamer 3.70−3.67 (m, 2 H), 3.69 (s, 3 H), 3.17 (s, 3 H), 2.65−2.63 (m, 2 H), minor rotamer 3.70−3.67 (m, 2 H), 3.70 (s, 3 H), 3.02 (s, 3 H), 2.65−2.63 (m, 2 H); ^{13}C NMR ($CDCl_3$, 125.8 MHz) major rotamer 171.5 (s, C(1)), 156.8 (q, J = 36.0, CF_3CO), 116.2 (q, J = 287.3, CF_3), 51.7 (OCH_3), 45.7 (C(3)), 35.5 (NCH_3), 31.2 (C(2)), minor rotamer 170.6 (C(1)), 156.6 (q, J = 36.1, $CF_3C{=}O$), 116.3 (q, J = 287.4, CF_3), 51.8 (s, OCH_3), 44.9 (C(3)), 34.3 (NCH_3), 32.8 (C(2)); IR (neat) 3378 (w), 2959 (m), 2361 (w), 1738 (s), 1688 (s), 1520 (m), 1497 (w), 1441 (s), 1387 (m), 1319 (s), 1248 (s), 1146 (s), 1096 (s), 1048 (m), 985 (w), 887 (w), 835 (w), 793 (w), 760 (s), 725 (w); MS (70 eV) 213 (M^+, 9), 182 (18), 181 (13), 153 (25), 140 (100), 116 (24), 102 (15), 84 (13), 69 (32), 59 (15), 55 (42). Anal. Calcd for $C_7H_{10}F_3NO_3$(213.15): C, 39.44; H, 4.73; N, 6.57; F, 26.74. Found: C, 39.81; H, 4.95; N, 6.60; F, 27.02.

*4-(tert-Butylamino)-2-methyl-2-butanol (**2a**).* A 250-mL, three-necked flask equipped with a mechanical stirrer, addition funnel (with septum and N_2 inlet), and thermometer was charged with 4.00 g (15.7 mmol) of amido ester **1a** and 100 mL of Et_2O. The mixture was cooled to 5 °C and the addition funnel charged with 36.2 mL (2.7 M, 99.7 mmol) of methylmagnesium bromide. The Grignard reagent was added dropwise over 30 min at 0−5 °C. The ice bath was removed, and the mixture was stirred for 3 h. The mixture was then cooled to 0 °C, and 50 mL of a satd aq K_2CO_3 solution was added. The mixture was diluted with 200 mL of a satd aq solution of Rochelle's salt. The aqueous layer was extracted with EtOAc (3 × 250 mL), the organic layers were dried ($MgSO_4$) and filtered, and the solvent was removed by rotary evaporation. The crude product was purified by Kugelrohr distillation to yield 1.47 g (58.8%) of **2a** as a clear, colorless oil, yield range 59−76%. Data for **2a**: bp 80 °C (0.3 mmHg); ^{1}H NMR (300 MHz) 2.86 (t, 2 H, J = 5.5), 1.57 (t, 2 H, J = 5.5), 1.21 (s, 6 H), 1.10 (s, 9 H); ^{13}C NMR (75.5 MHz) 71.0 (C(2)), 50.4 ($(CH_3)_3C$), 40.8 (C(3)), 38.7(C(2)), 29.6 (C(1), CH_3C(2)), 28.5 ($(CH_3)_3C$); IR (neat) 3276 (m), 2971 (s), 2932 (s), 2869 (m), 1717 (w), 1653 (w), 1480 (m), 1426 (m), 1391 (m), 1362 (s), 1267 (w), 1233 (m), 1215 (m), 1154 (m), 1086 (w), 1017 (w), 967 (w), 938 (w), 887 (w); MS (70 eV) 144 (M^+ − 15, 100), 126 (90), 88 (14), 86 (30), 81 (11), 70 (75), 58 (43), 57 (11). Anal. Calcd for $C_9H_{21}NO$ (159.28): C, 67.87; H, 13.29; N, 8.79. Found: C, 67.52; H, 13.28; N, 8.84.

*4-(N-Methylamino)-2-methyl-2-butanol (**2c**).* To a refluxing ethereal solution of methylmagnesium bromide (3.0 M, 75.1 mL, 225 mmol) under N_2 was added dropwise a solution of amido ester **1c** (8.0 g, 37.5 mmol) in Et_2O (40 mL) over 30 min. The resulting thick suspension was refluxed for 1 h and quenched with the dropwise addition of a satd aq solution of NH_4Cl (15 mL). Ether and absolute ethanol (100 mL each) were added, and the mixture was heated to reflux for 30 min. The mixture was then cooled and filtered through a plug of silica gel (5 g). After the silica gel was washed with absolute ethanol (150 mL), the combined filtrates were evaporated under reduced pressure. The residue was diluted with methanol, filtered, and purified by column chromatography (5−15% ammonia-saturated methanol in Et_2O) to give 2.30 g (52.3%) of **2c** as a clear, colorless oil. Data for **2c**: bp 66−68 °C (1.2 mmHg); ^{1}H NMR (500 MHz) 2.86 (t, 2 H, J = 5.8), 2.40 (s, 3 H), 1.58 (t, 2 H, J = 5.8), 1.22 (s, 6 H); ^{13}C NMR (125.8 MHz) 71.0 (C(2)), 48.4 (C(4)), 39.9 (C((3)), 36.1

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(NCH_3), 29.7 (C(1) and $H_3CC(2)$); IR (neat) 3293 (s, br, OH, NH), 2967 (s), 2930 (s), 2845 (s), 2799 (m), 1643 (w), 1474 (s), 1377 (s), 1362 (s), 1296 (w), 1266 (m), 1198 (m), 1171 (s), 1142 (m), 1111 (m), 1038 (w), 941 (m), 909 (m), 882 (m), 810 (m), 734 (m); MS (10 eV) 117 (M^+, 12), 102 (10), 84 (13), 59 (20), 58 (10), 44 (100); high-resolution MS calcd for $C_6H_{15}NO$ 117.1157, found 117.1155; TLC R_f 0.25 (Et_2O/MeOH (NH_3 satd), 3:1).

Synthesis of 2-Allenyl 1,3,2-Oxazaphosphorinane 2-Oxides. General Procedure 1. A 250-mL, three-necked, round-bottomed flask equipped with a stirring bar, septum, thermometer, and N_2 inlet was charged with 100 mL of CH_2Cl_2 and cooled to 0 °C. Phosphorus trichloride (13.7 mmol) and *N*-methylmorpholine (13.7 mmol) were added sequentially via syringe. After the mixture was stirred for 5 min, the appropriate propargylic alcohol (13.7 mmol) in 5 mL of CH_2Cl_2 was added via syringe (0−5 °C). After the mixture was stirred for 20 min, *N*-methylmorpholine (27.4 mmol) was added. After the mixture was stirred for 5 min, the appropriate amino alcohol (13.7 mmol) in 5 mL of CH_2Cl_2 was added. The reaction mixture was warmed to room temperature and stirred for 16 h. The mixture was diluted with 100 mL of water and extracted with CH_2Cl_2 (3 × 100 mL). The organic layers were washed with water and brine (1 × 50 mL each). The combined organic layers were dried ($MgSO_4$) and filtered, and the solvent was removed by rotary evaporation. Purification is given for each individual compound.

*3-tert-Butyl-2-(1′,2′-butadienyl)-6,6-dimethyl-2-oxo-1,3,2-oxazaphosphorinane (**5a**).* Following general procedure 1, the crude product was purified by column chromatography (hexane/acetone; 1:1) to give 2.05 g (58%) of allene **5a**. Data for **5a** are reported for a distilled sample: bp 175 °C (0.2 mmHg); ^{1}H NMR (300 MHz) 5.46−5.42 (m, 1 H), 5.30−5.20 (m, 1 H), 3.26−3.07 (m, 2 H), 1.94−1.80 (m, 2 H), 1.74−1.66 (m, 3 H), 1.44 (d, 3 H, *J* = 2.5), 1.38 (s, 12 H); ^{13}C NMR (75.5 MHz) 209.6 (C(2′)), 209.2 (C(2′)), 88.7 (d, *J* = 6.0, C(3′)), 86.3 (d, *J* = 6.9, C(3′)), 79.9 (d, *J* = 6.3, C(6)), 79.8 (d, *J* = 7.2, C(6)), 54.5 (d, *J* = 4.2, $(CH_3)_3C$), 28.6 ($(CH_3)_3C$), 12.2 (d, *J* = 7.3 C(4′)), 11.7 (d, *J* = 7.0, C(4′)); the following resonances could not be unambiguously assigned: 86.4, 86.3, 85.7, 85.5, 38.7, 38.5, 38.4, 38.3, 28.7, 28.5, 28.4; ^{31}P NMR (121.4 MHz) 9.26, 9.24; IR (neat) 2977 (s), 2874 (m), 2357 (w), 1952 (m), 1639 (w), 1466 (m), 1370 (s), 1291 (w), 1254 (s, P═O), 1208 (s), 1152 (s), 1102 (m), 1061 (s), 997 (s), 936 (m), 889 (m), 855 (m); MS (70 eV) 257 (M^+, 6.9), 243 (13), 242 (100), 204 (11), 201 (47), 186 (94), 174 (40), 148 (91), 146 (59), 145 (58), 84 (16), 70 (61), 69 (48), 58 (37), 57 (78), 56 (13), 55 (19), 53 (28), 43 (15), 42 (20), 41 (82), 39 (13), 31 (19); high-resolution MS calcd for $C_{13}H_{24}NO_2P$ 257.1542, found 257.1577; TLC R_f 0.40 (hexane/acetone, 1:1).

*3-tert-Butyl-6,6-dimethyl-2-(3′-methyl-1′,2′-butadienyl)-2-oxo-1,3,2-oxazaphosphorinane (**6**).* Following general procedure 1, the crude product was purified by column chromatography (hexane/acetone, 1:1) to give a 1.36 g (53.1%) of allene **6**. Data for **6** are reported for a distilled sample: bp 205 °C (0.15 mmHg); ^{1}H NMR (300 MHz) 5.55−5.47 (m, 1 H), 3.20−3.08 (m, 2 H), 2.04−1.94 (m, 2 H), 1.89−1.82 (m, 6 H), 1.57(s, 3 H), 1.48 (s, 12 H); ^{13}C NMR (75.5 MHz) 207.3 (C(2′)), 95.3 (d, *J* = 17.2, C(3′)), 86.7 (d, *J* = 182.9, C(1′)) 80.1 (d, *J* = 8.6, C(6)), 54.9 (d, *J* = 5.2, $(CH_3)_3C$), 38.9 (d, *J* = 13.7, C(4)), 38.8 (C(5)), 29.1 ($CH_3C(6)$), 28.9 ($(CH_3)_3C$), 28.8 ($CH_3C(6)$), 19.2 (d, *J* = 6.6, C(4′)), 18.7 (d, *J* = 7.7, $CH_3C(3')$); ^{31}P NMR (121.4 MHz) 9.6; IR (CCl_4) 2980 (s), 2940 (s), 2872 (m), 1964 (m, C═C═C), 1632 (w), 1559 (w), 1466 (m), 1445 (m), 1395 (m), 1385 (m), 1362 (s), 1291 (s), 1252 (s, P═O), 1235 (s), 1204 (s), 1152 (s), 1103 (m), 1061 (m), 999 (s), 932 (m), 889 (m); MS (70 eV) 271 (M^+, 11.5), 257 (1), 256 (76), 215 (73), 201 (11), 200 (94), 198 (15), 188 (28), 160 (56), 159 (75), 148 (99), 132 (15), 126 (12), 84 (24), 70 (73), 69 (50), 67 (29), 58 (49), 57 (80), 56 (11), 55 (19), 43 (38), 42 (20), 41 (100), 39 (19), 31 (27); high-resolution MS calcd for $C_{14}H_{26}NO_2P$ 271.1711, found 271.1706; TLC R_f 0.38 (hexane/acetone, 1:1).

*3-Adamantyl-2-(1′,2′-butadienyl)-6,6-dimethyl-2-oxo-1,3,2-oxazaphosphorinane (**5b**).* To a refluxing ethereal solution of methylmagnesium bromide (3.0 M, 84.0 mL, 252 mmol) under N_2 was added a solution of **1b** (14.0 g, 42.0 mmol) in Et_2O (50 mL) over 30 min. The solution was heated reflux for 1.5 h further and then quenched by the dropwise addition of a satd aq NH_4Cl solution (10 mL). Ether and absolute ethanol (150 mL each) were added, and the mixture was stirred for 1 h and filtered through a pad of Celite. After the precipitate was washed with absolute ethanol (250 mL), the combined filtrates were evaporated under reduced pressure. The residue was diluted with saturated methanolic ammonia in Et_2O (1:1, 250 mL), filtered, and twice purified by column chromatography (5−15% saturated methanolic ammonia in Et_2O) to give 6.52 g (65.4%) of 4-[*N*-(1-adamantyl)amino]-2-methyl-2-butanol (**2b**).

To a solution of phosphorus trichloride (0.84 mL, 9.69 mmol) in CH_2Cl_2 (50 mL) at 0 °C under N_2 was added dropwise *N*-methylmorpholine (1.12 mL, 10.1 mmol) over 5 min. After the mixture was stirred for 5 min, (±)-3-butyn-2-ol (0.73 mL, 9.69 mmol) was added dropwise over a 5 min period. After the mixture was stirred for an additional 30 min, *N*-methylmorpholine (2.24 mL, 20.2 mmol) was added. After an additional 5 min, a solution of **2b** (2.0 g, 8.43 mmol) in CH_2Cl_2 (40 mL) was added by cannula over a 20 min period. The resulting mixture was stirred for 20 h and poured into Et_2O (400 mL). The mixture was washed with water (30 mL), 1 N HCl (30 mL), and brine (30 mL). The organic phase was then dried ($MgSO_4$), filtered, and concentrated in vacuo. The crude product was purified by column chromatography (EtOAc) to give 2.32 g (70.4%) of **5b** as a clear, colorless oil. Data for **5b**: ^{1}H NMR (500 MHz) major diastereomer 5.50−5.44 (m, 1 H), 5.31−5.24 (m, 1 H), 3.27−3.20 (m, 1 H), 3.143−3.07 (m, 1 H), 2.10 (d, 3 H, *J* = 10.8), 2.09 (s, 3 H), 1.95 (d, 3 H, *J* = 10.8), 1.76−1.71 (m, 3 H), 1.63 (s, 6 H), 1.45 (s, 3 H), 1.35 (s, 3 H), minor diastereomer 5.50−5.44 (m, 1 H), 5.31−5.24 (m, 1 H), 3.27−3.20 (m, 1 H), 3.14−3.07 (m, 1 H), 2.10 (d, 3 H, *J* = 10.8), 2.09 (s, 3 H), 1.95 (d, 3 H, *J* = 10.8), 1.76−1.71 (m, 3 H), 1.63 (s, 6 H), 1.46 (s, 3 H), 1.36 (s, 3 H); ^{13}C NMR (125.8 MHz) 210.0 (C(2′)), 209.6 (C(2′)), 80.3−80.2 (m, C(6)), 55.92 (adamantyl C), 55.90 (adamantyl C), 41.05 (adamantyl CH_2CN), 40.99 (adamantyl CH_2CN), 39.45−39.35 (m, C(5)), 37.1 (C(4)), 36.1 (adamantyl CH_2CH CH_2CN), 29.6−29.5 (m, $CH_3C(6)$ and adamantyl CH) 28.91 ($CHC(6)$), 28.87 ($CH_3C(6)$), 12.9 (d, *J* = 7.0, C(4′)), 12.3 (d, *J* = 7.0, C(4′)); the following peaks could not be unambiguously assigned: 88.9, 88.8, 87.4, 86.1, 86.0, 85.7, 85.6; IR (neat) 2977 (s), 2909 (2), 2851 (s), 1952 (m, C═C═C), 1453 (m), 1370 (s), 1298 (m), 1242 (s, P═O), 1204 (s), 1150 (s), 1115 (m), 1094 (s), 995 (s), 930 (m), 891 (m), 808 (s), 776 (m), 752 (m), 706 (m), 669 (m); MS (70 eV) 335 (M^+, 7.4), 280 (10), 279 (24), 136 (11), 135 (100), 106 (10), 93 (16), 79 (19), 55 (11), 53 (13); high-resolution MS calcd for $C_{19}H_{30}O_2NP$ 335.2015, found 335.2016; TLC R_f 0.24 (EtOAc).

*N-Methyl-2-(1′,2′-butadienyl)-6,6-dimethyl-2-oxo-1,3,2-oxazaphosphorinane (**5c**).* From **2c** (5.1g, 32.0 mmol) following general procedure 1, the crude product was purified by column chromatography (hexane/acetone, 3/2) to give 6.54 g (79%) of **5c** as a clear, colorless oil. Data for **5c**: ^{1}H NMR (500 MHz) major diastereomer 5.38−5.35 (m, 1 H), 5.32−5.25 (m, 1 H), 3.21−3.08 (m, 2 H), 2.72 (d, 3 H, *J* = 9.4), 1.95−1.91 (m, 2 H), 1.76−1.71 (m, 3 H), 1.48 (s, 3 H), 1.41 (s, 3 H), minor diastereomer 5.38−5.35 (m, 1 H), 5.32−5.25 (m, 1 H), 3.21−3.08 (m, 2 H), 2.72 (d, 3 H, *J* = 9.4), 1.95−1.91 (m, 2 H), 1.76−1.71 (m, 3 H), 1.48 (s, 3 H), 1.40 (s, 3 H); ^{13}C NMR (125.8 MHz) major diastereomer 209.5 (C(2′)), 85.5−84.5 (C(3′)), 82.4 (d, *J* = 205.8, C(1′), 81.5 (C(6)), 45.7 (C(4)), 35.8 (C(5)), 34.6 (NCH_3), 28.4 ($CH_3C(6)$), 27.5 ($CH_3C(6)$), 12.1 ($CH_3C(4')$), minor diastereomer 209.3 (C(2′)), 85.5−84.5 (C(3′)), 82.3 (d, *J* = 190.2, C(1′)), 81.5 (C(6)), 45.8 (C(4)), 35.8 (C(5)), 34.6 (NCH_3), 28.4 ($CH_3C(6)$), 27.5 ($CH_3C(6)$), 12.3 ($CH_3C(4')$); ^{31}P NMR (121.5 MHz) 11.9, 11.8; IR (neat) 2977 (m), 2490 (w), 1950 (m, C═C═C), 1649 (w), 1470 (m), 1372 (m), 1298 (s), 1248 (s, P═O), 1223 (s), 1157 (m), 1227 (s), 1061 (m), 997 (s), 970 (s), 878 (m), 808 (m), 785 (m), 750 (s); MS (70 eV) 215 (M^+, 22), 162 (31), 160 (55), 159 (57), 144 (10), 123 (16), 98 (19), 95 (11), 69 (52), 44 (100); high-resolution MS calcd for $C_{10}H_{18}NO_2P$ 215.1071, found 215.1073; TLC R_f 0.18 (4.5% *i*-PrOH in CH_2Cl_2).

Synthesis of Allyl Vinyl Ethers. General Procedure 2. A 15-mL, 3-necked flask equipped with stirring bar, septa, and N_2 inlet was charged with NaH dispersion (50%, 0.48 mmol). The NaH dispersion

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was rinsed with hexane (3 × 1 mL/0.1 g NaH) and suspended in 3.0 mL of THF. *t*-Butyl alcohol (0.96 mmol) and the appropriate allyl alcohol (0.48 mmol) were added sequentially. After stirring for 10 min, a solution of the allene (0.40 mmol) in 1.0 mL of THF was added via syringe, The reaction was monitored by TLC. Upon completion, the reaction was quenched with 5 mL of water and extracted with Et_2O (3 × 15 mL). The organic layers were washed with brine (15 mL), dried ($MgSO_4$), filtered, and the solvent removed by rotary evaporation. Purification is given for each individual compound.

*(E)-3-tert-Butyl-6,6-dimethyl-2-oxo-[2′-(2-propenyloxy)-2′-butenyl]-1,3,2-oxazaphosphorinane (**7aa**).* Following General Procedure 2, the crude product was purified by radial chromatography (hexane/acetone, 5:1) to give 155 mg (64%) of **7aa**. Data for **7aa**: ^{1}H NMR (300 MHz) 6.00−5.88 (m, 1 H), 5.29 (dd, 1 H, *J* = 1.3, 17.4), 5.19 (dd, 1 H, *J* = 1.1, 10.4, 4.54−4.46 (m, 1 H), 4.20−4.08 (m, 2 H), 3.15−2.93 (m, 3 H)), 2.61−2.50 (m, 1 H), 1.89−1.77 (m, 2 H), 1.62−1.51 (m, 3 H), 1.48 (s, 3 H), 1.37 (s, 9 H), 1.26 (s, 3 H); ^{1}H NMR (500 MHz); ^{13}C NMR (75.5 MHz) 149.8 (d, *J* = 12.2, C(2′)), 133.8 (*C*H=CH$_2$), 116.9 (CH=*C*H$_2$), 93.9 (d, *J* = 10.2, C(3′)), 79.2 (d, *J* = 8.2, C(6)), 67.8 (OCH$_2$), 55.1 ((CH$_3$)$_3$*C*), 39.4 (C(4)), 39.3 (C(5)), 35.2 (d, *J* = 134.6, C(1′)), 29.7 (d, *J* = 8.0, CH$_3$*C*(6)), 29.1 ((*C*H$_3$)$_3$C), 28.9(*C*H$_3$C(6)), 12.3 (C(4′)); ^{31}P NMR (121.4 MHz) 20.5; IR (neat) 2980 (s), 2934 (s), 2874 (m), 1665 (s), 1466 (s), 1399 (m), 1387 (m), 1372 (s), 1362 (m), 1348 (m), 1293 (s), 1256 (s), 1231 (s), 1202 (s), 1152 (s), 1102 (s), 1063 (m), 997 (s), 926 (s), 889 (m); MS (70 eV); 315 (M$^+$, 1.42), 300 (13), 274 (22), 242 (15), 218 (25), 186 (15), 174 (18), 162 (100), 150 (33), 148 (36), 146 (12), 126 (15), 84 (16), 80 (14), 70 (73), 69 (29), 58 (36), 57 (46), 56 (10), 55 (16), 53 (11) 42 (14), 41 (73), 39 (14); high-resolution MS calcd for $C_{16}H_{30}NO_3P$ 315.1975, found 315.1969; TLC R_f 0.45 (hexane/acetone, 1:1). Anal. Calcd for $C_{16}H_{30}NO_3P$ (315.20): C, 60.93; H, 9.59; N, 4.44; P, 9.82. Found: C, 60.72; H, 9.49; N, 4.53; P, 9.88.

*(E)-3-tert-Butyl-6,6-dimethyl-2-oxo-[(E)-2′-(2-propenyloxy)-1′-butenyl]-1,3,2-oxaza-phosphorinane (**8aa**).* Following General Procedure 2, the crude product was purified by column chromatography (hexane/acetone, 1.5:1) to give 175 mg (71%) of **8aa**. Data for **8aa** are reported for a recrystallized sample: mp 60−62 °C; ^{1}H NMR (300 MHz) 5.99−5.86 (m, 1 H), 5.34−5.20 (m, 2 H), 4.54 (d, 1 H, *J* = 7.5), 4.23 (d, 2 H, *J* = 5.1), 3.25−3.05 (m, 2 H), 2.66−2.45 (m, 2 H), 2.09−2.00 (m, 1 H), 1.86−1.79 (m 1 H), 1.51 (s, 3 H), 1.30 (s, 12 H), 1.09 (t, 3 H, *J* = 7.5); ^{13}C NMR (75.5 MHz) 171.7 (d, *J* = 19.7, C(2′)). 132.5 (CH=CH$_2$), 117.4 (CH=*C*H$_2$), 92.5 (d, *J* = 195.4, C(1′)), 78.9 (d, *J* = 7.5, C(6)), 67.9 (OCH$_2$), 54.7 ((CH$_3$)$_3$*C*), 40.1 (d, *J* = 8.1, C(4)), 39.3 (C(5)), 29.9 (CH$_3$*C*(6)), 29.4 (d, *J* = 5.3, CH$_3$*C*(6)), 29.0 ((CH$_3$)$_3$*C*), 25.5,(C(3′)), 11.4 (C(4′)); ^{31}P NMR (121.4 MHz) 15.8; IR (CCl_4) 2977 (s), 2940 (s), 2874 (m), 1615 (s, C=C), 1464 (m), 1394 (m), 1385 (m), 1370 (s), 1362 (m), 1343 (m), 1287 (s), 1248 (s), 1225 (s, P=O), 1186 (s), 1150 (s), 1094 (s), 1059 (m), 1015 (s), 968 (s), 926 (s), 887 (s); MS (70 eV) 315 (M$^+$, 19.2), 301 (15), 300 (89), 260 (11), 258 (11), 244 (32), 242 (19), 204 (46), 203 (16), 174 (11), 148 (15), 134 (12), 126 (76), 84 (13), 70 (100), 69 (11), 58 (31); TLC R_f 0.45 (hexane/acetone, 1:1). Anal. Calcd for $C_{16}H_{30}NO_3P$ (315.40): C, 60.93; H, 9.59; N, 4.44; P, 9.82. Found: C, 60.92; H, 9.65; N, 4.26; P, 9.73.

*(E)-3-tert-Butyl-6,6-dimethyl-2-oxo-[2′-((E)-2-butenyloxy)-2′-butenyl]-1,3,2-oxazaphosphorinane (**7ab**).* Following General Procedure 2, the crude product was purified by column chromatography (hexane/acetone, 1:1) to give 59.0 mg (46%) of **7ab**. Data for **7ab**: ^{1}H NMR (300 MHz) 5.77−5.60 (m, 2 H), 4.52−4.48 (m, 1 H), 4.11−4.06 (m, 2 H), 3.13−2.94 (m, 3 H), 2.57 (dd, 1 H, *J* = 18.1, 15.2), 1.87−1.82 (m, 2 H), 1.71 (d, 3 H, *J* = 5.8) 1.62 (d, 3 H, *J* = 6.7, 4.5), 1.50 (s), 1.39 (s, 9 H), 1.28 (d, 3 H, *J* = 1.1); ^{13}C NMR (75.5 MHz) 149.8 (d, *J* = 15.5, C(2′)), 129.4 (CH=*C*HCH$_3$), 126.7 (CH=*C*HCH$_3$), 93.7 (d, *J* = 9.9, C(3′)), 79.2 (d, *J* = 9.6, C(6)), 67.5 (OCH$_2$), 55.1 ((CH$_3$)$_3$*C*), 39.3 (d, *J* = 7.2, C(4)), 35.1 (d, *J* = 133.5, C(1′)), 29.7 (CH$_3$*C*(6)), 29.1 ((*C*H$_3$)$_3$C), 28.8 (*C*H$_3$C(6)), 17.7 (CH$_3$CH=CH), 12.3 (C(4′)); ^{31}P NMR (121.4 MHz) 19.2; IR (neat) 2977 (s), 2587 (w), 1719 (w), 1665 (s, C=C), 1464 (m), 1397 (m), 1372 (m), 1293 (s), 1256 (s, P=O), 1231 (s), 1200 (s), 1152 (s), 1102 (s), 1065 (m), 997 (s), 926 (m), 901 (m), 847 (m); MS (70 eV) 329 (M$^+$, 10.2), 314 (16), 275 (14), 274 (74), 273 (15), 219 (39), 218 (39), 218 (62), 204 (24), 190 (13), 188 (11), 164 (27), 163 (70), 162 (100), 151 (66), 150 (36), 148 (15), 134 (16), 125 (11), 84 (14), 70 (21), 58 (11); high-resolution MS calcd for $C_{17}H_{32}NO_3P$ 329.2120, found 329.2121; TLC R_f 0.43 (hexane/acetone, 1:1).

*(E)-3-tert-Butyl-6,6-dimethyl-2-oxo-[2′-((E)-2-butenyloxy)-1′-butenyl]-1,3,2-oxaza-phosphorinane (**8ab**).* Following General Procedure 2, the crude product was purified by column chromatography (hexane/acetone, 1:1) to afford 230 mg (69%) of **8ab**. Data for **8ab**: bp 200 °C (0.5 mmHg); ^{1}H NMR (300 MHz) 5.83−5.56 (m, 2 H), 4.55 (d, 1 H, *J* = 7.6), 4.17 (d, 2 H, *J* = 5.9), 3.27−3.07 (m, 2 H). 2.66−2.47 (m, 2 H). 2.11−2.03 (m, 1 H), 1.88−1.81 (m, 1 H), 1.72 (d, 3 H, *J* = 5.7), 1.53 (s, 3 H), 1.33 (s, 12 H), 1.10 (t, 3 H, *J* = 7.5); ^{13}C NMR (75.5 MHz) 171.8 (d, *J* = 19.5, C(2′)), 130.0 (*C*H=CHCH$_3$), 125.3 (CH=*C*HCH$_3$), 91.7 (d, *J* = 195.3, C(1′)), 78.7 (d, *J* = 8.6, C(6)), 67.9 (OCH$_2$), 54.6 (d, *J* = 4.7, (CH$_3$)$_3$*C*), 40.0 (d, *J* = 7.5, C(4)), 39.2 (C(5)), 29.8 (*C*H$_3$C(6)), 29.3 (d, *J* = 5.6, *C*H$_3$C(6)), 28.9 ((*C*H$_3$)$_3$C), 25.5 (C(3′)), 17.6 (*C*H$_3$CH=CH), 11.4 (C(4′)); ^{31}P NMR (121.4 MHz) 16.0; IR (neat) 2975 (s), 2876 (m), 2361 (w), 1709 (w), 1613 (s, C=C), 1464 (m), 1370 (m), 1347 (m), 1289 (m), 1250 (s. P=O), 1223 (s), 1186 (s), 1152 (s), 1094 (s), 1063 (m), 1017 (m), 967 (s), 932 (m), 889 (m); MS (70 eV) 330 (M$^+$ + 1, 11.4), 329 (M$^+$, 30.5), 314 (46), 273 (15), 272 (20), 260 (46), 258 (24), 256 (11), 246 (12), 219 (15), 218 (55), 217 (20), 216 (13), 206 (13), 205 (13), 204 (55), 202 (19), 192 (18), 190 (25), 188 (18), 164 (91), 163 (30), 162 (15), 160 (10), 152 (23), 151 (19), 148 (34), 135 (13), 134 (52), 127 (10), 126 (100), 84 (42), 83 (11), 70 (99), 58 (41), 55 (10); high-resolution MS calcd for $C_{17}H_{32}NO_3P$ 329.2120, found 329.2124; TLC R_f 0.43 (hexane/acetone, 1:1).

*(E)-3-Adamantyl-6,6-dimethyl-2-oxo-[2′-(2-propenyloxy)-2′-butenyl]-1,3,2-oxazaphosphorinane (**7ba**).* From **5b** (3.8 g, 11.3 mmol) following general procedure 2, the crude product was purified by column chromatography (petroleum/acetone ether, 3:1) to give 1.52 g (34%) of **7ba** as a clear, colorless oil. Data for **7ba**: ^{1}H NMR (500 MHz) 6.02−5.94 (m, 1 H), 5.31 (dd, 1 H, *J* = 17.1, 1.5), 5.20 (d, 1 H, *J* = 10.5), 4.53−4.49 (m, 1 H), 4.21−4.11 (m, 2 H), 3.19−3.14 (m, 1 H), 3.03 (dd, 1 H, *J* = 11.4), 2.07 (s, 3 H), 1.97 (d, 3 H, *J* = 11.4), 1.86−1.81 (m, 1 H), 1.71 (s, 6 H), 1.66−1.60 (m, 1 H), 1.63 (dd, 3 H, *J* = 6.5, 4.4), 1.51 (s, 3 H), 1.27 (s, 3 H); ^{13}C NMR (125.8 MHz) 149.7 (d, *J* = 12.9, C(2′)), 133.9 (*C*H=CH$_2$), 117.0 (CH=*C*H$_2$), 94.0 (d, *J* = 10.3, C(3′)), 79.2 (d, *J* = 9.9, C(6)), 67.8 (OCH$_2$), 56.0 (d, *J* = 10.3, C(3′)), 41.0 (adamantyl *C*H$_2$CN), 40.0 (d, *J* = 6.6, C(5)), 37.3 (d, *J* = 2.1, C(4)); 36.3 (adamantyl *C*H$_2$CH CH$_2$CN), 35.5 (d, *J* = 131.8, C(1′)), 29.7 (s, adamantyl *C*H), 29.6 (CH$_3$*C*(6)), 29.5 (CH$_3$*C*(6)), 12.3 (s, C(4′)); IR (neat) 2977 (m), 2909 (s), 2853 (s), 2681 (w), 2448 (w), 1665 (s), 1456 (m), 1404 (m), 1387 (m), 1362 (m), 1300 (m), 1248 (s, P=O), 1200 (s), 1148 (s), 1100 (s), 992 (s), 926 (s), 891 (m), 849 (s), 776 (m); MS (70 eV) 393 (M$^+$, 1.3), 352 (13), 136 (11), 135 (100), 106 (11), 93 (11), 79 (11). Anal. Calcd for $C_{22}H_{36}NO_3P$ (393.50): C, 67.15; H, 9.22; N, 3.56; P, 7.87. Found: C, 67.41; H, 9.28; N, 3.45; P, 7.82; TLC R_f 0.31 (EtOAc).

*(E)-N-Methyl-6,6-dimethyl-2-oxo-[2′-(2-propenyloxy)-2′-butenyl]-1,3,2-oxazaphosphorinane (**7ca**).* From **5c** (700 mg, 3.25 mmol) following general procedure 2, the crude product was purified by column chromatography (CH_2Cl_2/*i*-PrOH, 19:1) to give 356 mg (40%) of **7ca** as a clear, colorless oil. Data for **7ca**: ^{1}H NMR (500 MHz) 6.01−5.90 (m, 1 H), 5.32 (dd, 1 H, *J* = 17.2, 1.4), 5.21 (dd, 1 H, *J* = 10.5, 1.4), 4.60−4.51 (m, 1 H), 4.20−4.08 (m, 2 H), 3.20−2.90 (m, 2 H), 2.90−2.75 (m, 2 H), 2.72 (d, 3 H, *J* = 8.8), 1.94−1.66 (m, 2 H), 1.62 (dd, 3 H, *J* = 6.7, 4.5), 1.50 (s, 3 H), 1.33 (d, 3 H, *J* = 1.6); ^{13}C NMR (125.8 MHz) 149.1 (d, *J* = 13.4, C(2′)), 133.4 (*C*H=CH$_2$), 116.7 (CH=*C*H$_2$), 94.1 (d, *J* = 10.2, C(3′)), 80.9 (d, *J* = 8.7, C(6)), 67.4 (OCH$_2$), 45.8 (C(4)), 35.9 (C(5)), 34.9 (NCH$_3$), 33.5 (d, *J* = 46.0, C(1′)), 30.2 (*C*H$_3$C(6)), 26.0 (CH$_3$*C*(6)), 11.9 (C(4′)); ^{31}P NMR (121.5 MHz) 22.2; IR (neat) 2980 (m), 2926 (m), 2442 (w), 2357 (w), 2220 (w), 1968 (w), 1667 (m), 1470 (w), 1387 (m), 1348 (w), 1300 (m), 1252 (s, P=O), 1196 (m), 1127 (s), 1100 (m), 1065 (m), 997 (s), 974 (s), 926 (m), 882 (m), 847 (m), 777 (m), 712 (m); MS (70 eV) 273 (M$^+$, 1.7), 176 (15), 162 (40), 160 (28), 159 (16), 98

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(52), 71 (11), 69 (23), 57 (93), 44 (100), 43 (14); high-resolution MS calcd for $C_{13}H_{24}NO_3P$ 273.1494, found 273.1495; TLC R_f 0.21 (CH_2Cl_2/*i*-PrOH 19:1).

*(E)-3-tert-Butyl-6,6-dimethyl-2-oxo-[2′-((E)-2-butenyloxy)-3′-methyl-2′-butenyl]-1,3,2-oxazaphosphorinane (**11**).* Following general procedure 2, the crude product was purified by column chromatography (hexane/2-propanol, 10:1) to give 130 mg (51%) of **11**. Data for **11**: ^{1}H NMR (300 MHz) 5.72−5.60 (m, 2 H), 4.10−3.96 (m, 2 H), 3.13−3.04 (m, 2 H), 2.89 (dd, 1 H, *J* = 18.9, 15.6), 2.62 (dd, 1 H, *J* = 15.9, 15.5), 1.83 (t, 2 H, *J* = 6.3), 1.68 (d, 3 H, *J* = 7.5), 1.67−1.62 (m, 6 H), 1.48 (s, 3 H), 1.37(s, 9 H), 1.25 (s, 3 H); ^{13}C NMR (75.5 MHz) 142.6 (d, *J* = 12.5, C(2′)), 127.7 (CH═$CHCH_3$), 123.8 (CH═$CHCH_3$), 117.5 (d, *J* = 11.0, C(3′)), 78.8 (d, *J* = 8.7, C(6)), 69.2 (OCH_2), 54.7 ((CH_3)$_3$C), 38.7 (C(4)), 38.6 (C(5)), 32.5 (d, *J* = 142.7, C(1′)), 29.3 (CH_3C(6)), 29.0 ((CH_3)$_3$C), 28.9 (CH_3C(6)), 19.1 (CH═$CHCH_3$), 16.8 (CH_3C(3′)), 16.7 (CH_3C-(3′)); ^{31}P NMR (121.4 MHz) 20.5; IR (neat) 2973 (s), 2926 (s), 2732 (m), 1676 (w), 1609 (w), 1464 (m), 1387 (m), 1370 (m), 1293 (s), 1254 (s, P═O), 1196 (s), 1152 (s), 1094 (s), 1065 (m), 997 (s), 928 (m), 889 (m); MS (70 eV) 343 (M+, 3.38), 328 (26), 289 (11), 288 (28), 286 (12), 233 (28), 232 (29), 190 (18), 177 (46), 176 (42), 165 (56), 164 (19), 149 (11), 148 (100), 147 (12), 126 (26), 86 (17), 84 (15), 70 (28), 58 (14); high-resolution MS calcd for $C_{18}H_{34}NO_3P$ 343.2276, found 343.2278; TLC R_f 0.45 (hexane/acetone, 1:1).

Anion-Accelerated Claisen Rearrangement. *A. KH/LiCl/DMSO. General Procedure 3.* A three-necked, 15-mL flask equipped with a stirring bar, septa, and a vacuum/N_2 inlet was charged with 35% KH dispersion (0.68 mmol). The dispersion was rinsed with hexane (3 × 0.5 mL/0.1 g of KH), and DMSO (3.0 mL) was added. After stirring until H_2 evolution ceased (∼10 min), LiCl (6 equiv) was added all at once (if necessary), followed by stirring for an additional 10 min. Then a solution of allyl vinyl ether (0.30 mmol) in THF (1.0 mL) was added via syringe. The reaction was monitored by TLC. Upon completion, the reaction mixture was quenched with water (10 mL) and extracted with ether (3 × 15 mL). The organic layers were washed with water (3 × 15 mL) and brine (1 × 15 mL). The combined organic layers were dried over $MgSO_4$ and filtered, and the solvent was removed by rotary evaporation. Purification is given for each individual compound.

B. n-BuLi/DMSO/THF. A 15-mL, three-necked, round-bottomed flask equipped with a septum, stirring bar, thermometer, and N_2 inlet was charged with 2.5 mL of THF and 1.5 mL of DMSO. *n*-BuLi (1.6 M in hexane, 0.46 mmol) was added dropwise via syringe to produce a clear, colorless solution. After the mixture was stirred for 5 min, a solution of allyl vinyl ether in 1 mL of THF was added via syringe. The solution was stirred at room temperature until judged complete by TLC. The reaction was quenched with water (5 mL) and extracted with Et_2O (3 × 15 mL). The organic layers were washed with water (3 × 5 mL) and brine (1 × 15 mL each). The combined organic layers were dried over $MgSO_4$ and filtered, and the solvent was removed by rotary evaporation. Purification is given for each individual compound.

C. LiDMSO/THF. Thermal Claisen Rearrangement. General Procedure 4. The allyl vinyl ether (0.10 mmol) THF (1.5 mL/mmol) was placed in a high-pressure sealed vial and heated at 100 °C until starting material was consumed as judged by TLC. The contents of the vial were transferred to a pear-shaped flask with ether, and the solvent was removed in vacuo.

*(R,S)-(Pl,3′l)-3-tert-Butyl-6,6-dimethyl-2-(3′-methyl-2′-oxo-5′-hexenyl)-2-oxo-1,3,2-oxazaphosphorinane ((l)-**12aa**).* Anionic (general procedure 3A): radial chromatography (hexane/acetone, 3:1) afforded 74.0 mg (81%) of **12aa**; thermal: radial chromatography (hexane/acetone, 3:1) afforded 90.7 mg (90%) of **12aa**. Data for (*l*)-**12aa** and (*u*)-**12aa**: ^{1}H NMR (500 MHz) major diastereomer (*l*)-**12aa** 5.76−5.69 (m, 1 H), 5.07−5.02 (m, 2 H), 3.39 (dd, 1 H, J_{P-H} = 21.5, J_{H-H} = 13.5), 3.18−3.05 (m, 2 H), 2.93 (dd, 1 H, J_{P-H} = 21.5, J_{H-H} = 13.5), 2.92−2.87 (m, 1 H), 2.43−2.37 (m, 1 H), 2.09−2.03 (m, 1 H), 2.00−1.95 (m, 1 H), 1.88−1.84 (m, 1 H), 1.51 (s, 3 H), 1.37 (s, 9 H), 1.30 (s, 3 H), 1.09 (d, 3 H, J = 7.2). Minor diastereomer (*u*)-**12aa**: 5.76−5.69 (m, 1 H), 5.07−5.02 (m, 2 H), 3.40 (dd, 1 H, J_{P-H} = 21.5, J_{H-H} = 13.5), 3.18−3.05 (m, 2 H), 2.93 (dd, 1 H, J_{P-H} = 21.5, J_{H-H} = 13.5), 2.92−2.87 (m, 1 H), 2.43−2.37 (m, 1 H), 2.09−2.03 (m, 1 H), 2.00−1.95 (m, 1 H), 1.88−1.84 (m, 1 H), 1.51 (s, 3 H), 1.37 (s, 9 H), 1.30 (s, 3 H), 1.06 (d, 3 H, *J* = 7.0); ^{13}C NMR (125.8 MHz) 206.6 (d, *J* = 7.0, C(2′)), 135 (C(5′)), 116.7 (C(6′)), 80.5 (d, *J* = 7.9, C(6)), 55.2 ((CH_3)$_3$*C*), 46.7 (d, *J* = 118.3, C(1′)), 45.7 (C(3′)), 40.0(d, *J* = 7.1, C(4)), 39.3 (C(5)), 36.2 (C(4′)), 29.9 (CH_3C(6)), 29.2 (d, *J* = 7.0, CH_3C(6)), 28.8 ((CH_3)$_3$C), 16.0 (CH_3C(3′)); ^{31}P NMR (121.4 MHz) 47: 15.9, 48: 15.8; IR (neat) 3077 (w), 2975 (s), 2934 (s), 1705 (s, C═O), 1642 (w), 1460 (m), 1397 (m), 1291 (s), 1254 (s, P═O), 1194 (s), 1102 (m), 1063 (m), 992 (s), 920 (s), 891 (m), 868 (m); MS (70 eV) 315 (M^+, 5.52), 301 (15), 300 (100), 259 (12), 258 (30), 244 (23), 242 (11), 232 (20), 204 (27), 192 (24), 174 (12) 148 (15), 135 (13), 126 (28), 109 (12), 84 (17) 70 (98), 58 (44); TLC R_f 0.39 (benzene/acetone, 2:1). Anal. Calcd for $C_{16}H_{30}NO_3P$ (315.40): C, 60.93; H, 9.59; N, 4.44; P, 9.82. Found: C, 60.92; H, 9.34; N, 4.61; P, 10.09.

*(R,S)-(Pl,3′l)-3-Adamantyl-6,6-dimethyl-2-(3′-methyl-2′-oxo-5′-hexenyl)-2-oxo-1,3,2-oxazaphosphorinane ((l)-**12ba**).* Anionic Rearrangement (*n*-BuLi). From **7ba** (194 mg, 0.490 mmol), the crude product was purified by column chromatography (acetone/hexane, 2:1) to give 164 mg (74.2%) of **12ba** as a clear, colorless oil. Thermal Rearrangement. From **7ba** (270 mg, 0.69 mmol), the crude product was purified by column chromatography (hexane/acetone, 7/3) to give 251 mg (93.0%) of **12ba**. Data for **12ba**: ^{1}H NMR (500 MHz) major 5.76−5.69 (m, 1 H), 5.04 (d, 1 H, *J* = 15.9), 5.01 (d, 1 H, *J* = 10.1), 3.41 (dd, 1 H, *J* = 13.4, 11.1), 3.26−3.18 (m, 1 H), 3.01−2.87 (m, 3 H), 2.43−2.37 (m, 1 H), 2.12−1.83 (m, 3 H), 2.10 (d, 3 H, *J* = 11.8), 2.09 (s, 3 H), 1.92 (d, 3 H, *J* = 11.8), 1.64 (s, 6 H); 1.52 (s), 1.28 (s), 1.09 (d, 3 H, *J* = 7.1), minor 5.76−5.69 (m, 1 H), 5.05 (d, 1 H, *J* = 15.9), 5.02 (d, 1 H, *J* = 10.1), 3.42 (dd, 1 H, *J* = 13.4, 13.4), 3.26−3.18 (m, 1 H), 3.01−2.87 (m, 3 H), 2.43−2.37 (m, 1 H), 2.12−1.83 (m, 3 H), 2.10 (d, 3 H, *J* = 11.8), 2.09 (s, 3 H), 1.92 (d, 3 H, *J* = 11.8), 1.64 (s, 6 H), 1.52 (s), 1.28 (s), 1.07 (d, 3 H, *J* = 6.8); ^{13}C NMR (125.8 MHz) 206.6 (d, *J* = 6.8, C(2′)), 135.7 (C(5′)), 116.6 (C(6′)), 8.04 (d, *J* = 8.8, C(6)), 56.1 (d, *J* = 2.5, adamantyl C), 47.0 (d, *J* = 117.5, C(1′)), 45.9 (C(3′)), 41.0 (s, adamantyl CH_2CN), 40.6 (d, *J* = 5.3, C(5)), 37.1 (s, C(4)), 36.2 (s, C(4′)), 36.1 (s, adamantyl CH_2CH CH_2CN), 30.2 (CH_3C(6)), 29.6 (adamantyl *C*H), 29.2 (d, *J* = 6.9, CH_3C(3′)); ^{31}P NMR (121.5 MHz) 16.5, 16.4; IR (neat) 2977 (s), 2909 (s), 1707 (s, C═O), 1640 (w), 1456 (m), 1387 (m), 1372 (m), 1298 (m), 1244 (s, P═O), 1196 (s), 1148 (s), 1115 (m), 1096 (s), 992 (s), 928 (s), 891 (m), 868 (m), 818 (m), 768 (w); MS (70 eV) 343 (M^+, 8.9), 258 (22), 136 (11), 135 (100), 106 (37), 93 (21), 79 (17), 69 (13), 67 (10); high-resolution MS calcd for $C_{22}H_{36}NO_3P$ 393.2421, found 393.2427; TLC R_f 0.29 (hexane/acetone, 2:1).

*(R,S)-(P1,3′1)-N-Methyl-6,6-dimethyl-2-(3′-methyl-2′-oxo-S′-hexenyl)-2-oxo-1,3,2-oxazaphosphorinene (**12ca**).* Anionic Rearrangement (Li^+DMSO^-). From **7ca** (125 mg, 0.460 mmol) following general procedure 4, the crude product was purified by column chromatography (CH_2Cl_2/*i*-PrOH, 19:1) to yield 78 mg (62%) of **12ca** as a clear, colorless oil. Thermal rearrangement. From **7ca** (88 mg, 0.32 mmol) the crude product was purified by column chromatography (CH_2Cl_2/*i*-PrOH, 19:1) to give 76 mg (86%) of **12ca**. Data for **12ca**: ^{1}H NMR (500 MHz) major 5.72−5.63 (m, 1 H), 4.99 (d, 1 H, *J* = 16.0), 4.97 (d, 1 H, *J* = 9.2), 3.18−2.97 (m, 4 H), 2.84−2.78 (m, 1 H), 2.66 (d, 3 H, *J* = 9.6), 2.37−2.32 (m, 1 H), 2.08−2.01 (m, 1 H), 1.90−1.84 (m, 1 H), 1.79−1.74 (m, 1 H), 1.46 (s, 3 H), 1.32 (s, 3 H), 1.05 (d, 3 H, *J* = 6.4), minor 5.72−5.63 (m, 1 H), 4.99 (d, 1 H, *J* = 16.0), 4.97 (d, 1 H, *J* = 9.2), 3.18−2.97 (m, 4 H), 2.84−2.78 (m, 1 H), 2.662 (d, 3 H, *J* = 9.7), 2.37−2.32 (m, 1 H), 2.08−2.01 (m, 1 H), 1.90−1.84 (m, 1 H), 1.79−1.74 (m, 1 H), 1.46 (s, 3 H), 1.32 (s, 3 H), 1.03 (d, 3 H, *J* = 6.6); ^{13}C NMR (125.8 MHz) major 206.6 (d, *J* = 6.9, C(2′)), 135.3 (C(5′)), 116.9 (C(6′)), 82.12 (d, *J* = 5.9, C(6)), 46.4 (C(3′)), 46.0 (C(4)), 43.7 (d, *J* = 18.3, C(1′)), 36.7 (C(5)), 36.7 (C(4′)), 35.1 (NCH_3), 29.9 (CH_3C(6)), 26.8 (CH_3C-(6)), 15.5 (CH_3C(3′)), minor 206.5 (d, *J* = 7.2, C(2′)), 135.3 (C(5′)), 116.9 (C(6′)), 82.06 (d, *J* = 4.5, C(6)), 46.4 (C(3′)), 46.0 (C(4)), 43.7 (d, *J* = 118.3, C(1′)), 36.7 (C(5)), 36.7 (C(4′)), 36.5 (CH_3N), 29.9 (CH_3C(6)), 26.8 (CH_3C(6)), 15.2 (CH_3C(3′)); ^{31}P NMR (121.5 MHz) 17.05, 16.96; IR (neat) 2979 (s), 2932 (s), 2469 (w), 1705 (s, C═O), 1640 (w), 1458 (m), 1389 (m), 1374 (m), 1298 (s),

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1252 (s, P═O), 1194 (s), 1125 (s), 1063 (s), 1036 (m), 997 (2), 972 (s), 926 (m), 882 (s), 808 (w), 712 (w); MS (70 eV) 273 (M^+, 2.4), 174 (11), 162 (63), 160 (34), 159 (32), 98 (40), 69 (50), 44 (100); high-resolution MS calcd for $C_{13}H_{24}NO_3P$ 273.1496, found 273.1495; TLC R_f 0.18 (CH_2Cl_2/*i*-PrOH, 19:1).

*(R,S)-(Pl,3′l,4′u)-3-tert-Butyl-6,6-dimethyl-2-(3′,4′dimethyl-2′-oxo-5′-hexenyl)-2-oxo-1,3,2-oxazaphosphorinane ((l)-**12ab**).* Anionic (general procedure 3A): radial chromatography (hexane/acetone, 1:1) afforded 40.1 mg (80%) of **12ab**; thermal: radial chromatography (hexane/acetone, 1:1) afforded 32.5 mg (84%) of **12ab**. Data for **12ab** are reported for a distilled sample: bp 150 °C (0.05 mmHg); ^{1}H NMR (500 MHz) *syn*-(*l*)-**12ab**: 5.81−5.74 (m, 1 H), 5.01−4.96 (m, 2 H), 3.27 (dd, 1 H, J_{P-H} = 17.7, J_{H-H} = 13.7), 3.16−3.11 (m, 2 H), 2.98 (dd, 1 H, J_{P-H} = 16.9, J_{H-H} =13.7), 2.81−2.77 (m, 1 H), 2.55−2.51 (m, 1 H), 1.99−1.93 (m, 1 H), 1.88−1.84 (m, 1 H), 1.50 (s, 3 H), 1.36 (s, 9 H), 1.30 (s, 3 H), 1.04 (d, 3 H, J = 7.1), 0.95 (d, 3 H, J = 6.9); minor diastereomer *syn*-(*u*)-**12ab**: 5.81−5.74 (m, 1 H), 5.01−4.96(m, 2 H), 3.46 (dd, 1 H, J = 18.7, 13.3), 3.16−3.11 (m, 2 H), 2.90 (dd, 1 H, J = 16.9, 13.7), 2.81−2.77 (m, 1H), 2.55−2.51 (m, 1H), 1.99- 1.93 (m, 1H), 1.88- 1.84 (m, 1 H), 1.50 (s, 3 H), 1.37 (s, 9 H), 1.30 (s, 3 H), 0.99 (d, 3 H, J = 6.9), 0.93 (d, 3 H, J = 6.8); ^{13}C NMR (125.8 MHz) 206.6 (d, J = 4.9, C(2′)), 142 (C(5′)), 114 (C(6′)), 80.5 (d, J = 66.1, C(6)), 55.3 ($(CH_3)_3C$), 51.3 (C(3′)), 47.0 (d, J = 120.2 C(1′)), 40.0 (C(4)), 39.3 (C(5)), 38.7 (C(4′)), 30.0 ($CH_3C(6)$), 29.1 ($(CH_3)_3C$) 15.3 ($CH_3C(3')$), 12.3 ($CH_3C(4')$); ^{31}P NMR (101.3 MHz) 15.2; IR (neat) 2977 (s), 2878 (m), 1705 (s, C═O), 1638 (w), 1456 (m), 1456 (m), 1397 (m), 1372 (s), 1291 (s), 1254 (s, P═O), 1196 (s), 1150 (s), 1100 (m), 1063 (m), 995 (s), 918 (m), 891 (m), 868 (m); MS (70 eV) 329 (M^+, 16.5), 315 (26), 314 (100), 273 (25), 272 (43), 258 (20), 256 (10), 246 (16), 218 (18), 206 (27), 205 (10), 190 (16), 189 (13), 188 (11), 148 (12), 126 (33), 124 (12), 109 (10), 86 (22), 84 (21), 70 (65), 58 (25); high-resolution MS calcd for $C_{17}H_{32}NO_3P$ 329.2120, found 329.2128; TLC R_f 0.40 (benzene/acetone, 2:1).

*(R,S)-(Pl,3′l,4′l)-3-tert-Butyl-6,6-dimethyl-2-(3′,4′dimethyl-2′-oxo-5′-hexenyl)-2-oxo-1,3,2-oxazaphosphorinane ((u)-**12ab**).* Anionic (general procedure 3A): radial chromatography (hexane/acetone, 3:1) afforded 48.7 mg (60%) of (*u*)-**12ab**. Data for (*u*)-**12ab** are given for a distilled sample: bp 150 °C (0.05 mmHg); ^{1}H NMR (500 MHz) 5.67−5.60 (m, 1 H), 5.02−4.96 (m, 2 H), 3.45 (dd, 1 H, J_{P-H} = 18.1, J_{H-H} =13.5), 3.17−3.04 (m, 2 H), 2.87 (dd, 1H, J_{P-H} = 16.7, J_{H-H} = 13.5), 2.91−2.83 (m, 1 H), 2.52−2.48 (m, 1 H), 2.01−1.95 (m, 1 H), 1.88−1.84 (m, 1 H), 1.52 (s, 3 H), 1.38 (s, 9 H), 1.30 (s, 3 H), 1.04 (d, 3 H, J = 8.6), 1.01 (d, 3 H, J = 8.6); ^{13}C NMR (125.8 MHz) 206.9 (d, J = 7.4, C(2′)), 140.3 (C(5′)), 115.0 (C(6′)), 80.5 (d, J = 7.8, C(6)), 55.3 ($(CH_3)_3C$), 51.3 (C(3′)), 48.5 (d, J = 118.4, C(1′)), 40.1 (C(4′)), 39.4 (C(4)), 39.4 (C(5)), 30.0 ($CH_3C(6)$), 29.2 ($CH_3C(6)$), 29.0 ($(CH_3)_3C$), 18.0 ($CH_3C(3')$), 12.6 ($CH_3C(4')$); ^{31}P NMR (121.4 MHz) 16.1; IR (neat) 2975 (s), 2878 (m), 1703 (s, C═O), 1639 (m), 1456 (m), 1397 (m), 1372 (s), 1291 (s), 1252 (s, P═O), 1190 (s), 1150 (s), 1100 (m), 1063 (s), 995 (s), 918 (s), 891 (s), 868 (m); MS (70 eV) 329 (M^+, 16.2), 315 (18), 314 (100), 273 (19), 272 (39), 258 (15), 246 (15), 218 (15), 206 (24.0), 190 (12), 126 (24), 84 (15), 70 (46), 58 (18); high-resolution MS calcd for $C_{17}H_{32}NO_3P$ 329.2120, found 329.2122; TLC R_f 0.40 (benzene/acetone, 2:1).

*(R,S)-(Pl,4′u)-3-tert-Butyl-6,6-dimethyl-2-(3′,3′,4′trimethyl-2′-oxo-5′-hexenyl)-2-oxo-1,3,2-oxazaphosphorinane (**13**).* Anionic (general procedure 3A): radial chromatography (hexane/acetone, 1:1) afforded 89.5 mg (94%) of **13**; thermal: radial chromatography (hexane/acetone, 1:1) afforded 50.0 mg (65.8%) of **13**. Data for **13** are reported for a distilled sample: bp 160 °C (0.05 mmHg); ^{1}H NMR (500 MHz) Major diastereomer: 5.68−5.60 (m, 1 H), 5.09−5.00 (m, 2 H), 3.53 (dd, 1 H, J_{P-H} = 17.5, J_{H-H} = 15.7), 3.31−3.26 (m, 1 H), 3.16−3.10 (m, 1 H), 2.80 (dd, 1 H, J_{P-H} = 17.9, J_{H-H} = 15.7), 2.46−2.43 (m, 1 H), 1.97−1.88 (m, 2 H), 1.51 (s, 3 H), 1.38 (s, 9 H), 1.27 (s, 3 H), 1.11 (s, 3 H), 1.04 (s, 3 H), 0.93 (d, 3 H, J = 6.7). Minor diastereomer: 5.68−5.60 (m, 1 H), 5.09−5.00 (m, 2 H), 3.54 (dd, 1 H, J_{P-H} = 17.5, J_{H-H} = 15.7), 3.31−3.26 (m, 1 H), 3.16−3.10 (m, 1 H), 2.79 (dd, 1 H, J_{P-H} = 17.9, J_{H-H} = 15.7), 2.46−2.43 (m, 1 H), 1.97−1.88 (m, 2 H), 1.51 (s, 3 H), 1.36 (s, 9 H), 1.27 (s, 3 H), 1.11 (s, 3 H), 1.04 (s, 3 H), 0.89 (d, 3 H, J = 6.8); ^{13}C NMR (75.5 MHz) 208.4 (d, J = 8.2, C(2′)), 140.6 (C(5′)), 115.6 (C(6′)), 80.3 (d, J = 9.3, C(6)), 55.0 (d, J = 4.8, $(CH_3)_3C$), 51.2 (C(3′)), 44.0, (C(4′)), 42.7 (d, J = 127.5, C(1′)), 40.1 (d, J = 7.0, C(4)), 39.1 (C(5)), 30.1 ($CH_3C(6)$), 29.4 (d, J = 7.0, $CH_3C(6)$), 29.0 ($(CH_3)_3C$); 21.4 ($CH_3C(3')$), 20.4 ($CH_3C(3')$), 14.9 ($CH_3C(4')$); ^{31}P NMR (121.4 MHz) 16.1; IR (neat) 2975 (s), 1701 (s, C═O), 1636 (w), 1466 (m), 1389 (m), 1372 (m), 1291 (s), 1254 (s, P═O), 1233 (s), 1200 (s), 1103 (w), 1065 (m), 997 (s), 920 (s), 891 (m), 853 (w); MS (70 eV) 343 (M^+, 7.91), 329 (13), 328 (68), 300 (11), 287 (10), 286 (46), 232 (10), 220 (13), 190 (22), 148 (16), 126 (22), 110 (49), 88 (10), 86 (65), 84 (100), 75 (14), 70 (22), 58 (13); high-resolution MS calcd for $C_{18}H_{34}NO_3P$ 343.2276, found 343.2288; TLC R_f 0.40 (benzene/acetone, 2:1).

*Enantiomerically Enriched 1,3,2-Oxazaphosphorinane 2-Oxides. (S)-3-tert-Butyl-3-hydroxybutyramide ((S)-**14**).* The enantiomeric composition of ethyl (*S*)-3-hydroxybutanoate was measured by two methods. Optical rotation gave an enantiomeric excess of 97% ($[\alpha]^{28}_{589}$ = +42.5 (*c* 1.4; $CHCl_3$)). Analytical gas chromatographic separation of the Mosher esters[26] gave an enantiomeric excess of 96% (cOV-17, 165 °C, t_R = 14.5 (minor diastereomer), t_R = 14.9 (major diastereomer)). A 100-mL, 3-necked, flask equipped with septum, stirring bar, thermometer, and N_2 inlet was charged with 7.95 mL (75.7 mmol) of *tert*-butylamine and cooled to 0 °C. Trimethylaluminum (2 M in toluene, 37.8 mL, 75.7 mmol) was added slowly via syringe (0 °C − 10 °C). The mixture was warmed to room temperature for 30 min. After the mixture was cooled to 0 °C, 5.00 g (37.8 mmol) of ethyl (*S*)-3-hydroxybutanoate was added dropwise via syringe (0 to 10 °C). The mixture was warmed to room temperature and stirred for 20 h. The mixture was cooled to 0 °C, and water (50 mL) was added dropwise. CAUTION: Upon the initial addition of water (<1 mL), there is an induction period of several minutes followed by rapid, exothermic evolution of methane. The mixture was acidified to pH∼ 6 with 2 N HCl, filtered through a Buchner funnel and continuously extracted with Et_2O for 20 h. The organic layer was dried (K_2CO_3) and filtered, and the solvent removed by rotary evaporation. The crude product was purified by column chromatography to afford 4.33 g (71.9%) of (*S*)-**14** as white solid. Data for (*S*)-**14** are given for a recrystallized sample: mp 89−90 °C; $[\alpha]^{28}_{589}$ = +14.2 (*c* 1.4; $CHCl_3$); ^{1}H NMR (300 MHz), 5.53−5.37 (m, 1 H), 4.21−4.10 (m, 1 H), 3.92 (d, J = 2.9, 1 H), 2.28−2.14 (m, 2 H), 1.35 (s, 9 H), 1.20 (d, 3 H, J = 6.2); ^{13}C NMR (75.5 MHz) 171.9 ((1)), 64.7 (C(3)), 51.2 ($(CH_3)_3C$), 44.4 (C(2)), 28.7 ($(CH_3)_3C$), 22.6 (C(4)); IR (CCl_4) 3443 (m), 2971 (s), 1744 (w), 1698 (m), 1671 (s, C═O), 1511 (m), 1455 (m), 1420 (m), 1393 (w), 1366 (m), 1250 (w), 1198 (s), 1167 (s), 1142 (s), 928 (w); MS (70 eV) 159 (M^+, 11.0), 144 (24), 86 (12), 59 (18), 58 (100), 57 (17). Anal. Calcd for $C_8H_{17}NO_2$ (159.23): C, 60.35; H, 10.76; N, 8.80. Found: C, 60.65; H, 10.99; N, 8.79.

*(S)-4-(tert-Butylamino)-4-oxobutan-2-yl 3,5-Dinitrophenyl Carbamate ((S)-**14′**).* Compound (*S*)-**14′** was prepared by the method of Pirkle.[29] Data for (*S*)-**14′**: ^{1}H NMR (300 MHz) 9.59−9.54 (m, 1 H), 8.84−8.81 (m, 2 H) 8.56−8.52 (m, 1 H) 6.84−6.79 (m, 1 H) 5.36−5.21 (m, 1 H) 2.53 (dd, 1 H, J = 7.2, 19.8), 2.38 (dd, 1 H, J = 7.2, 19.8),1.33 (d, 3 H, J = 7.8 Hz), 1.29 (s, 9 H); HPLC (column B; hexane/EtOAc, 4:1; 2 mL/min) t_R (*S*)-54, 10.50 min; >99.5%.

*Preparation of (S)-4-N-tert-Butylamino-2-butanol ((S)-**15**).* A 500-mL, three-necked flask equipped with an addition funnel, thermometer, stirring bar, and an N_2 inlet was charged with 120 mL (1.0 M, 120 mmol) of BH_3·THF and was cooled to 3−5 °C. A solution of the amide (*S*)-52 (6.81 g, 42.8 mmol) dissolved in 50 mL of THF was added dropwise via addition funnel (3−7 °C). The mixture was stirred at *3−10 °C for 2.5 h* and then warmed to room temperature and stirred for an *additional 5 h*. The mixture was cooled to 5 °C, and 150 mL of 6 N HCl was cautiously added (N.B.: The first 5 mL was added 3−5 drops at a time maintaining the internal temperature <7 °C. The remainder was added dropwise (<20 °C) being careful to avoid a violent exothermic evolution of gas). The mixture was warmed to room temperature and stirred for 30 min and then cooled to 3−5 °C. KOH pellets were added cautiously until pH = 11, maintaining a

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temperature below 40 °C. The aqueous layer, which contained some solid KOH, was extracted with 250 mL of Et_2O. Water was then added to dissolve the solid KOH, and the homogeneous aqueous layer was extracted with Et_2O (3 × 250 mL). The combined organic fractions were dried (K_2CO_3), filtered, and concentrated by rotary evaporation. The crude product was purified by Kugelrohr distillation to afford 5.85 g (94.3%) of (*S*)-**53** as a clear, colorless oil. Data for (*S*)-**15**: bp 55 °C (0.15 mmHg); ^{1}H NMR (300 MHz) 3.99−3.92 (m, 1 H), 2.99 (dt, 1 H, *J* = 11.7, 4.0), 2.67 (td, 1 H, *J* = 11.4, 2.8), 1.67−1.59 (m, 1 H), 1.44−1.30 (m, 1 H), 1.15 (d, 3 H, *J* = 7.3), 1.09 (s, 9 H)); ^{13}C NMR (75.5 MHz) 69.2 (C(2)), 50.1 ($(CH_3)_3C$), 41.0 (C(4)), 37.4 (C(3)), 28.4 ($(CH_3)_3C$), 23.3 (C(1)); IR (neat) 3278 (s), 2965 (s), 2928 (s), 2867 (s), 1655 (w), 1480 (s), 1443 (s), 1391 (m), 1364 (s), 1335 (m), 1231 (s), 1215 (s), 1138 (s), 1121 (s), 1094 (m), 1030 (m), 976 (m), 911 (m); MS ((70 eV) 145 (M^+, 0.69), 130 (100), 112 (22), 72 (17), 70 (17), 58 (16). Anal. Calcd for $C_8H_{19}NO$ (145.25): C, 66.15; H, 13.18; N, 9.65. Found: C, 66.12; H, 13.23; N, 9.71.

*(S)-(Pl,6l)-3-tert-Butyl-2-(1′,2′-butadienyl)-6-methyl-2-oxo-1,3,2-oxazaphosphorinane (cis-**16**) and (R)-(P l,6 u)-3-tert-Butyl-2-(1′,2′-butadienyl)-6-methyl-2-oxo-1,3,2-oxazaphosphorinane (trans-**16**).* A 250-mL, three-necked flask equipped with stirring bar N_2 inlet, thermometer, and septum was charged with 100 mL of dry CH_2Cl_2 and cooled to −5 °C. Phosphorus trichloride (1.20 mL, 13.8 mmol) and *N*-methylmorpholine (1.51 mL, 13.8 mmol) were added sequentially via syringe. After the mixture was stirred for 5 min, a solution of (±)-3-butyn-2-ol (1.08 mL, 13.8 mmol) in 5 mL of CH_2Cl_2 was added via syringe (0−5 °C). After the mixture was stirred for 20 min, *N*-methylmorpholine (3.01 mL, 27.6 mmol) was added. After the mixture was stirred for an additional 5 min, a solution of (*S*)-*N*-*tert*-butyl-4-amino-2-butanol (1.08 mL, 13.8 mmol) in 5 mL of CH_2Cl_2 was added. The reaction mixture was warmed to room temperature and stirred for 6 h. The mixture was diluted with 100 mL of water and extracted with CH_2Cl_2 (3 × 100 mL). The organic layers were washed with water and brine (1 × 50 mL each). The combined organic layers were dried ($MgSO_4$) and filtered, and the solvent was removed by rotary evaporation. The crude product was twice purified by column chromatography (hexane/acetone, 3:1) to give 650 mg (19.5%) of *trans*-**16** and 1.82 g (54.3%) of *cis*-**16** as clear colorless oils. Data for *cis*-**16** are reported for a distilled sample: bp 160 °C (0.03 mmHg); ^{1}H NMR (300 MHz) 5.47−5.39 (m, 1 H), 5.38−5.23 (m, 1 H), 4.62−4.49 (m, 1 H), 3.31−3.03 (m, 2 H), 2.09−1.93 (m, 1 H), 1.76−1.61 (m, 4 H), 1.35 (s, 9 H), 1.32 (d, 3 H, *J* = 6.3); ^{13}C NMR (75.5 MHz) 210.6 (C(2′)), 210.3 (C2′)), 54.7(($CH_3)_3C$), 40.3 (C(4)), 34.2 (C(5)), 29.1 (($CH_3)_3C$), 29.0 (($CH_3)_3C$), 12.5 (d, *J* = 6.9, CH_3C(6)), 12.1 (d, *J* = 7.0, CH_3C(6)). The following resonances could not be unambiguously assigned: 87.6, 87.5, 86.3, 86.1, 85.9, 85.7, 85.2, 71.9, 71.8, 71.7, 22.0, 21.9; ^{31}P NMR (121.4 MHz), 13.1, 12.9; IR (neat) 2975 (s), 1952 (s, C═C═C), 1653 (w), 1445 (m), 1366 (s), 1279 (s), 1254 (s, P═O), 1204 (s), 1129 (s), 1044 (s), 1013 (s), 990 (s), 949 (s), 895 (m), 828 (m), 808 (m); MS (70 eV) 243 (M^+, 3.20), 229 (12), 228 (100), 187 (49), 186 (26), 174 (16), 164 (11), 148 (10), 146 (14), 145 (14), 134 (12), 70 (20), 58 (29), 57 (12), 55 (10); high-resolution MS calcd for $C_{12}H_{22}NO_2P$ 243.1388, found 243.1385; TLC R_f 0.30 (hexane/acetone, 3:1). Data for *trans*-**16** are reported for a distilled sample: bp 160 °C (0.03 mmHg); ^{1}H NMR (500 MHz) 5.44−5.39 (m, 1 H), 5.33−5.26 (m, 1 H), 4.35−4.30 (m, 1 H), 3.32−3.23 (m, 1 H), 3.08−3.00 (m, 1 H), 1.80−1.73 (m, 5 H), 1.35 (s, 9 H), 1.34−1.32 (m, 3 H); ^{13}C NMR (125.8 MHz), 210.6 (C(2′)), 210.3 (C(2′)), 55.7 (($CH_3)_3C$), 42.4 (C(4)), 34.9 (C(5)), 29.4 (($CH_3)_3C$). The following resonances could not be unambiguously assigned: 85.9, 85.8, 85.7, 84.7, 84.5, 84.2, 83.1, 82.9, 75.1, 75.0, 74.9, 22.5, 22.4, 13.2, 13.1, 13.0; ^{31}P NMR (121.4 MHz), 9.1, 8.9; IR (neat) 2975 (s), 2724 (w), 1949 (s, C═C═C), 1638 (m), 1557 (w), 1474 (w), 1366 (s), 1321 (m), 1281 (s), 1256 (s, P═O), 1204 (s), 1152 (s), 1111 (s), 1046 (s), 1016 (s), 989 (s), 893 (s), 853 (s), 810 (s); MS (70 eV) 243 (M^+, 4.59), 229 (13), 228 (100), 187 (41), 186 (14), 145 (13), 134 (13); high-resolution calcd for $C_{12}H_{22}N_2P$ 243.1388, found 243.1387; TLC R_f 0.39 (hexane/acetone, 3:1).

*(S)-(Pl,6l)(E)-3-tert-Butyl-6-methyl-2-oxo[2′-(2-propenyloxy)-2′-butenyl]-1,3,2-oxazaphosphorinane (cis-**17**).* A 100 mL, three-necked flask equipped with stirring bar, septa, and N_2 inlet was charged with 50% NaH dispersion (221 mg, 4.60 mmol). The NaH dispersion was rinsed with hexane (3 × 2 mL) and suspended in 40 mL of dry THF. After 5 min, *tert*-butyl alcohol (930 μL, 9.86 mmol) and allyl alcohol (307 μL, 4.52 mmol) were added sequentially via syringe. After 10 min, a solution of *cis*-**16** (1.00 g, 4.11 mmol) in 2 mL of THF was added via syringe. After an additional 15 min, the reaction was quenched with 10 mL of water and extracted with EtOAc (50 mL). The water layer was separated and further extracted with CH_2Cl_2 (3 × 50 mL). The organic layers were washed with brine (1 × 10 mL), combined, dried ($MgSO_4$), and filtered, and the solvent was removed by rotary evaporation. The crude product was purified by column chromatography (hexane/acetone, 2:1) to give 670 mg (54.0%) of *cis*-**17** as a white solid. Data for *cis*-**17**: mp 42−44 °C; ^{1}H NMR (300 MHz) 6.02−5.89 (m, 1 H), 5.30 (dd, 1 H, *J* = 17.5, 1.2), 5.18 (dd, 1 H, *J* = 10.4, 1.0); 4.57−4.45 (m, 2 H), 4.21−4.09 (m, 2 H), 3.15−2.95(m, 3 H), 2.63 (dd, 1 H, *J* = 17.1, 15.4), 2.01−1.91 (m, 1 H), 1.65−1.51 (m, 4 H), 1.37 (s, 9 H), 1.27 (d, 3 H, *J* = 6.4); ^{13}C NMR (75.5 MHz) 149.2 (d, *J* = 6.4, C(2′)), 133.7 (CH═CH_2), 116.9 (CH═CH_2), 94.3 (d, *J* = 10.6, C(3′)), 70.3 (d, *J* = 7.9, C(6)), 67.8 (OCH_2), 55.1 (d, *J* = 4.9, $(CH_3)_3C$), 40.5 (C(4)), 34.4 (C(5)), 34.1 (d, *J* = 131.7, C(1′)), 29.4 (($CH_3)_3C$), 22.3 (d, *J* = 9.0, CH_3C(6)), 12.2 (C(4′)); ^{31}P NMR (121.4 MHz) 24.4; IR (CCl_4) 2977 (m), 2932 (m), 1667 (m), 1458 (w), 1401 (w), 1364 (w), 1347 (w), 1277 (m), 1258 (s, P═O), 1233 (s), 1202 (s), 1146 (m), 1127 (m), 1102 (m), 1044 (m), 1009 (m), 992 (m), 947 (m), 893 (w); MS (70 eV) 301 (M^+, 2.9), 286 (14), 260 (52), 204 (100), 162 (36), 110 (24), 70 (11); high-resolution MS calcd for $C_{15}H_{28}NO_3P$ 301.1807, found 301.1799; TLC R_f 0.35 (hexane/acetone, 1:1).

*(S)-(Pu,6l)(E)-3-tert-Butyl-6-methyl-2-oxo-[2′-(2-propenyloxy)-2′-butenyl]-1,3,2-oxazaphosphorinane (trans-**17**).* A 15 mL, three-necked flask equipped with stirring bar, septa, and N_2 inlet was charged with 50% NaH dispersion (97.1 mg, 2.02 mmol). The NaH dispersion was rinsed with hexane (3 × 1 mL) and suspended in 16 mL of dry THF. After 5 min, *tert*-butyl alcohol (380 μL, 4.03 mmol) and allyl alcohol (137 μL, 2.01 mmol) were added sequentially via syringe. After an additional 5 min, a solution of allene *trans*-**16** (407 mg, 1.67 mmol) in 1 mL of THF was added via syringe. After being stirred at room temperature for 15 min, the reaction was quenched with 10 mL of water and extracted with EtOAc (75 mL). The aqueous layer was separated and further extracted with CH_2Cl_2 (3 × 50 mL). The organic layers were washed with brine (1 × 10 mL), combined, dried ($MgSO_4$), and filtered, and the solvent was removed by rotary evaporation. The crude product was purified by column chromatography (hexane/acetone, 2:1) to give 220 mg (30.0%) of *trans*-**17** as a white solid. Data for *trans*-**17**: mp 72−75 °C; ^{1}H NMR (500 MHz) 5.99−5.93 (m, 1 H), 5.31 (d, 1 H, *J* = 17.4), 5.20 (d, 1 H, *J* = 10.3), 4.58−4.55 (m, 1 H), 4.44−4.40 (m, 1 H), 4.21−4.15 (m, 2 H), 3.28−3.20 (m, 1 H), 3.05−2.95 (m, 1 H), 2.99 (dd, 1 H, *J* = 17.9, 15.1), 2.69 (dd, 1 H, *J* = 16.5, 15.7), 1.80−1.68 (m, 5 H), 1.35 (s, 9 H), 1.31 (d, 3 H, *J* = 6.2); ^{13}C NMR (125.8 MHz) 163.0 (C(2′)), 133.6 (CH═CH_2), 117.2 (CH═CH_2), 94.6 (d, *J* = 11.4, C(3′)), 76.0 (d, *J* = 6.0, C(6)), 67.9 (OCH_2), 55.6 (($CH_3)_3C$), 42.1 (C(4)), 35.1 (C(5)), 32.5 (d, *J* = 120.5, C(1′)), 29.5 (($CH_3)_3C$), 22.8 (d, *J* = 7.6, CH_3C(6)), 12.2(C(4′); ^{31}P NMR (121.4 MHz) 19.9; IR (CCl_4) 2977 (s), 2936 (m), 2870 (m), 1711 (w), 1667 (m), 1553 (m), 1458 (m), 1399 (m), 1385 (m), 1366 (m), 1346 (w), 1281 (s), 1260 (s, P═O), 1202 (s), 1102 (s), 1048 (s), 1017 (s), 992 (s), 930 (m), 893 (m); MS (70 eV) 301 (M^+, 6.16), 286 (54), 260 (55), 245 (12), 204 (100), 176 (15), 174 (12), 162 (36), 148 (10), 135 (36), 134 (15), 112 (20), 70 (27); high-resolution MS calcd for $C_{15}H_{28}NO_3P$ 301.1807, found 301.1816; TLC R_f 0.44 (hexane/acetone, 1:1).

*(S)-(Pl,6l,3′l)-3-tert-Butyl-6-methyl-2-(3′-methyl-2′-oxo-5′-hexenyl)-2-oxo-1,3,2-oxazaphosphorinane (S)-(l,l)-**18**.* Anionic (general procedure 3A): radial chromatography (hexane/acetone, 1:1) afforded 470 mg (78.3%) of *cis*-57. Anionic (general procedure 3B): radial chromatography (hexane/acetone, 1:1) afforded 28.5 mg (65.2%) of (*S*)-(*l,l*)-**18**. Data for (*S*)-(*l,l*)-**18** are reported for a distilled sample: bp 160 °C (0.5 mmHg); ^{1}H NMR (300 MHz) major diastereomer: 5.80−5.67 (m, 1 H), 5.09−5.00 (m, 2 H), 4.60−4.54 (m, 1 H), 3.38

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(dd, 1 H, J = 17.8, 13.3) 3.21−2.90 (m, 4 H), 2.46−2.35 (m, 1 H), 2.16−2.01 (m, 2 H), 1.70−1.59 (m, 1 H), 1.38 (s, 9 H), 1.30 (d, 3 H, J = 6.0), 1.10 (d, 3 H, J = 6.8); minor diastereomer: 5.80−5.67 (m, 1 H), 5.09−5.00 (m, 2 H), 4.60−4.54 (m, 1 H), 3.39 (dd, 1 H, J = 17.8, 13.3) 3.21−2.90 (m, 4 H), 2.46−2.35 (m, 1 H), 2.16−2.01 (m, 2 H), 1.70−1.59 (m, 1 H), 1.38 (s, 9 H), 1.30 (d, 3 H, J = 6.0), 1.08 (d, 3 H, J = 6.6); ^{13}C NMR (75.5 MHz) 206.5 (d, J = 6.8, C(2′)), 135.7 (CH═CH_2), 116.7 (CH═CH_2), 70.7 (d, J = 7.1, C(6)), 55.3 (d, J = 3.2, $(CH_3)_3C$), 46.3 (C(3′)), 45.5 (d, J = 116.1, C(1′)), 40.1 (C(4′)), 36.4 (C(5)), 34.5 (d, J = 3.5, C(4)), 29.3 ($(CH_3)_3C$), 22.2 (d, J = 2.2, $CH_3C(6)$), 16.0 ($CH_3C(3')$); ^{31}P NMR (121.4 MHz) 19.2; IR (neat) 2975 (s), 2934 (m), 1707 (s, C═O), 1642 (w), 1458 (m), 1399 (m), 1366 (m), 1277 (s), 1254 (s, P═O), 1198 (s), 1125 (s), 1044 (s), 990 (s), 947 (m), 893 (m), 870 (m), 810 (m); MS (70 eV) 301 (M^+, 5.1), 286 (76), 244 (33), 228 (12), 192 (39), 174 (19),148 (12), 124 (21), 112 (48), 93 (12), 70 (100), 55 (26), 41 (44); high-resolution MS calcd for $C_{15}H_{28}NO_3P$ 301.1807, found 301.1810; TLC R_f 0.28 (benzene/acetone, 2:1).

*(S)-(Pu,6l,3′u)-3-tert-Butyl-6-methyl-2-(3′-methyl-2′-oxo-5′-hexenyl)-2-oxo-1,3,2-oxaza-phosphorinane (S)-(u,u)-**18**.* Anionic (General Procedure 3.A.): radial chromatography (hexane/acetone, 1:1) afforded 35.4 mg (70.8%) of (*S*)-(*u,u*)-**18** as a colorless oil. Data for (*S*)-(*u,u*)-**18** are reported for a distilled sample: bp 160 °C (0.5 mmHg); ^{1}H NMR (500 MHz) major diastereomer: 5.78−5.70 (m, 1 H), 5.07−5.00 (m, 2 H), 4.44−4.37 (m, 1 H), 3.35−3.25 (m, 1 H), 3.30 (dd, 1 H, J = 17.0, 13.0), 3.11−3.00 (m, 3 H), 2.47−2.42 (m, 1 H), 2.13−2.07 (m, 1 H), 1.86−1.73 (m, 2 H), 1.34 (s, 1 H), 1.34−1.31 (m, 3 H), 1.12 (d, 3 H, J = 7.1); minor diastereomer: 5.78−5.70 (m, 1 H), 5.07−5.00 (m, 2 H), 4.44−4.37 (m, 1 H), 3.35−3.25 (m, 1 H), 3.30 (dd, 1 H, J = 17.0, 13.0), 3.11−3.00 (m, 3 H), 2.47−2.42 (m, 1 H), 2.13−2.07 (m, 1 H), 1.86−1.73 (m, 2 H), 1.34 (s, 1 H), 1.34−1.31 (m, 3 H), 1.11 (d, 3 H, J = 7.1); ^{13}C NMR (125.8 MHz) 207.2 (C(2′)), 135.7 (C(5′)), 116.8 (C(6′)), 67.1 (d, J = 9.8, C(6)), 56.0 ($(CH_3)_3C$), 43.7 (d, J = 105.4, C(1′)), 36.5 (C(4′)), 35.2 (C(5′)), 29.4 ($(CH_3)_3C$), 22.6 (d, J = 7.3, $CH_3C(6)$), 16.1($CH_3C(3')$); ^{31}P NMR (121.4 MHz) 14.7; IR (neat) 2977 (s), 1703 (s, C═O), 1642 (w), 1458 (w), 1368 (m), 1283 (s), 1256 (s, P═O), 1196 (m), 1152 (w), 1109 (m), 1043 (s), 1017 (s), 992 (s), 972 (m), 893 (m), 862 (w); MS (70 eV); 301 (M^+, 5.25), 287 (16), 286 (100), 244(17), 192(16), 112 (24), 70 (34); high-resolution MS calcd for $C_{15}H_{28}NO_3P$ 301.1807, found 301.1811; TLC R_f 0.35 (benzene/acetone, 2:1).

Degradation and Assignment of Rearrangement Products. Silyl Enol Ethers. General Procedure 5. A 15-mL, three-necked flask equipped with septa, stirring bar, and N_2 inlet was charged with a solution of the Claisen rearrangement product (20.2 mg, 0.0613 mmol) in 0.5 mL of THF. The solution was cooled to −78 °C. A solution of potassium hexamethyldisilazide in THF (0.815 M, 165 μL, 0.134 mmol) was added via syringe. After 2 min, a solution of *tert*-butyldimethylsilyl chloride in THF (22.8 mg, 0.151 mmol) was added via syringe. After being stirred for 30 min at −78 °C, the solution was warmed to room temperature, transferred to a centrifuge tube, and centrifuged for 5 min at 5000 rpm. The supernatant was transferred to a round-bottomed flask and the solvent removed. The resulting silyl enol ether was carried on without further purification.

Preparation of Dimethyl Succinates from Degradation. A 15 mL, three-necked flask equipped with stirring bar, thermometer, and ozone inlet and outlet tubes (outlet tube connected to a bubbler containing a 0.1 N KI solution) was charged with 3 mL of methyl acetate and cooled to −10 °C. A solution of the silyl enol ether (0.0613 mmol) in 1 mL of methyl acetate was added via syringe. Ozone was bubbled through the solution until the blue color persisted. Hydrogen peroxide (30%, 0.5 mL) and formic acid (88%, 1 mL) were then added sequentially. The solution was stirred at room temperature for 16 h and then the solvents were removed in vacuo. The residue was taken up in 3% NaOH and extracted with Et_2O (2 × 15 mL). The water layer was acidified with 2 N H_2SO_4 and continuously extracted with Et_2O for 16 h. The Et_2O layer was dried (Na_2SO_4) and filtered, and the solvents were removed. The resulting 2,3-dimethylsuccinic acids were esterified by treatment with an ethereal solution of diazomethane. The dimethyl 2,3-dimethylsuccinates were compared to authentic *meso*-and *d,l*-succinates by capillary GC analysis. The syn diastereomer was the major diastereomer present. GC (COV-17; 80 °C isothermal) t_R (*d,l*), 9.95 min; t_R (*meso*), 11.14 min.

*(S)[Pl,6l,3′l)-3-tert-Butyl-6-methyl-2-(3′-methyl-2′-(tert-butyldimethylsiloxy)-1,5-hexadienyl)-1,3,2-oxazaphosphorinane (cis-**19**).* General Procedure 5. Data for *cis*-**19**: ^{1}H NMR (300 MHz) 5.80−5.71 (m, 1 H), 5.08−5.01 (m, 2 H), 4.61 (d, 1 H, J = 15.4), 4.15−4.10 (m, 1 H), 3.29−3.20 (m, 1 H), 2.83−2.91 (m, 1 H), 2.42−2.38 (m, 1 H), 2.23−2.18 (m, 1 H), 2.15−2.07 (m, 1 H), 1.34 (s, 9 H) 1.29 (d, 3 H, J = 6.0), 1.08 (d, 3 H, J = 8.1), 0.97 (s, 9 H), 0.30 (s, 3 H), 0.23 (s, 3 H). Ozonolysis/esterification of *cis*-**19** afforded 17.3 mg (59.3%) of dimethyl (*S*)-(+)-methylsuccinate as assigned above. The ^{1}H NMR spectrum was identical to that from an authentic sample of the racemate.

*(R)[Pl,6u,3′l)-3-tert-Butyl-6-methyl-2-(3′-methyl-2′-(tert-butyldimethylsiloxy)-1,5-hexadienyl)-1,3,2-oxazaphosphorinane (trans-**19**).* General Procedure 5. Data for *trans*-**19**: ^{1}H NMR (300 MHz) 5.82−5.70 (m, 1 H), 5.10−5.01 (m, 2 H), 4.66 (d, 1 H, J = 15.4), 4.62−4.53 (m, 1 H), 3.19−3.04 (m, 1 H), 2.45−2.35 (m, 1 H), 2.42−2.38 (m, 1 H), 2.23−2.18 (m, 1 H), 2.15−2.07 (m, 1 H), 1.34 (s, 9 H) 1.33 (d, 3 H, J = 6.1), 1.08 (d, 3 H, J = 6.1), 0.99 (s, 9 H), 0.27 (s, 6 H). Ozonolysis/esterification of *trans*-**19** afforded 3.7 mg (24.1%) of dimethyl (*R*)-(+)-methylsuccinate as assigned above. The ^{1}H NMR spectrum was identical to that from an authentic sample of the racemate.

Chiral Shift Agent (CSA) Study of Dimethyl (R)- and (S)-Methylsuccinates. To a solution of the appropriate dimethyl methylsuccinate (0.25 M) in $CDCl_3$ was added (*R*)-2,2,2-trifluoro-1-(9-anthryl)ethanol in increments of 1.0 equiv until separation was observed by ^{1}H NMR spectroscopy (500 MHz). The methoxy groups are diagnostic: for dimethyl (*R*)-methylsuccinate 3.649 and 3.625 (2 s); for dimethyl (*S*)-methylsuccinate 3.646 and 3.620 (2 s). These assignments were verified by spiking with an authentic sample of dimethyl (*R*)-methyl succinate.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

General experimental procedures along with copies of ^{1}H and ^{13}C NMR spectra along with a listing of crystal and positional parameters, bond lengths, bond angles, and torsional angles for *cis*-**17** and *trans*-**17**. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

The authors declare no competing financial interest.

‡Dedicated to the memory of Professor Robert E. Ireland whose greatest legacy inspired this work.

§Deceased July 13, 1988.

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