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The Role Played by Phosphorus Hexacoordination in Driving the Stereochemical Outcome of a Phosphination Reaction

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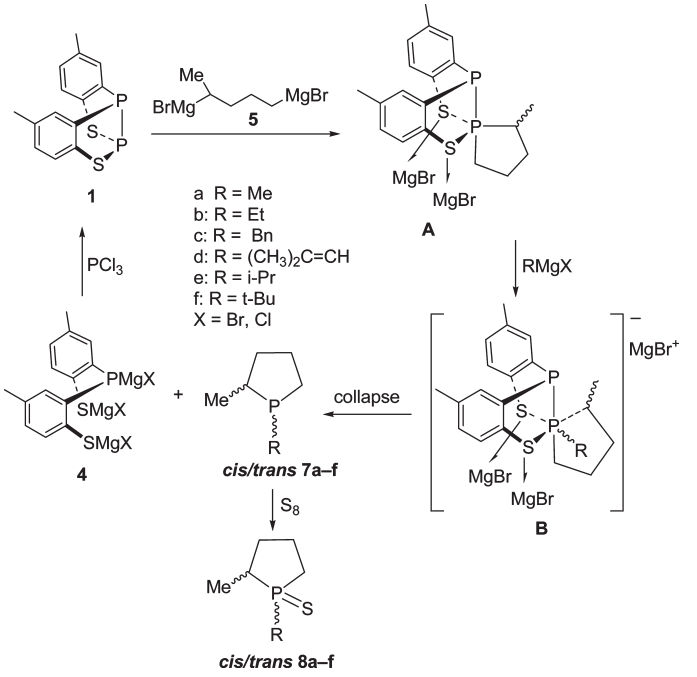

Asymmetric alkyl phospholanes have been diastereoselectively synthesized by addition of an unsymmetrical bis-Grignard reagent and of a mono-Grignard reagent to benzothiadiphosphole (**1**) and isolated as sulfides. The relative cis/trans ratio of the products depends on the steric hindrance of the mono-Grignard used. An accurate analysis of NMR and stereoselective data revealed the fundamental role played by hexacoordinated phosphorus intermediates in driving the stereochemical outcome of the reaction. The particular bicyclic and folded structure of reagent **1** strongly stabilizes hypercoordinated phosphorus species involved in the reaction and favors their formation. Pentacoordinate and metastable hexacoordinate phosphorus species have been detected and their evolution studied through ^{31}P NMR spectroscopy. The diastereoselective outcome of the reaction between reagent **1** and the couple bis-Grignard reagent **5**/mono-Grignard reagent has been explained through a pathway involving hexacoordination of the phosphorus as a key step.

Introduction

Organophosphorus compounds play a fundamental role in inorganic, organic, and applied chemistry, both as reaction intermediates and final products, and their presence is essential also in the biological field, because many life processes involve phosphorus-containing structures.

Most of the reactions occurring through organophosphorus intermediates are drived by the ability of the phosphorus to form hypercoordinate species, mainly penta- and hexacoordinate,

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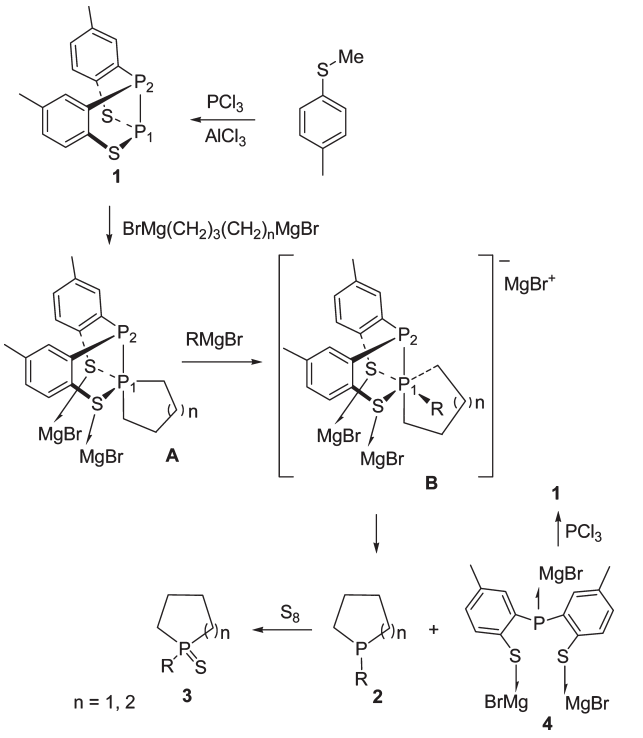
which are fluxional species because they may undergo positional changes among substituents. For example, phosphoryl transfer reactions, which are basic biological processes, are generally assumed to involve pentacoordinate intermediates that influence the outcome of the reactions.[1] The trigonal bipyramidal geometry represents the most common structure of pentacoordinate phosphorus intermediates. Their stability strongly depends on their structure; in particular, when it is possible, the formation of a cycle around the pentacoordinate phosphorus atom is favored over that of the corresponding acyclic intermediate by a factor of 10^6-10^8, as reported by Westheimer.[2] Sufficiently long-lived pentacoordinate intermediates can undergo stereomutation or positional interchange of the substituents at pentacoordinate phosphorus by a Turnstile rotation (TR)[3] or a resultwise equivalent Berry pseudorotation (BPR)[4] that are very rapid processes, since the energy barriers of pseudorotation are usually relatively low.[5] The relative position of the substituents in pentacoordinate compounds depends on their steric hindrance and apicophilicity. Apicophilicity is the relative preference of substituents to occupy the apical positions as opposed to the equatorial positions in trigonal bipyramidal (TBP) structures: a number of experimental results and theoretical calculations have indicated a general propensity of the more electronegative substituents to prefer the apical positions; in addition, bulky ligands prefer the equatorial positions.[6]

Once formed, pentacoordinate intermediates can undergo nucleophilic attack with formation of hexacoordinate intermediates[1e] but only a few examples of the latter have been reported so far, because often they are transient species, difficult to detect. To the best of our knowledge, the only reported examples of stable hexacoordinate phosphorus species[7] are, with rare exceptions,[7c,d] via nitrogen-, oxygen-, or sulfur-donation,[8a] or compounds formed by 1,3,2-diheterophosphacyclanes containing a phosphorus atom entering into the composition of one, two, or three rings, mainly four- or five-membered rings, and bound to heteroatoms such as oxygen or nitrogen.[8b,c]

SCHEME 1. Synthesis of Cyclic Phosphines from the Phosphorus Donor Reagent 1



In the past few years we reported an easy and practical one-pot method to synthesize phosphines using an unusual phosphorus donor compound, namely, 2,10-dimethyl[1,2,3]-benzothiadiphospholo[2,3-*b*][1,2,3]benzothiadiphospholo (**1**),[9] called the "butterfly reagent"[10] by us due to its folded structure.

Compound **1** can be easily prepared by addition of PCl_3 and $AlCl_3$ to *p*-methylthioanisole[9] and it is able to donate one atom of phosphorus by reaction with Grignard reagents to give, depending on the reagents and reaction conditions, cyclic and acyclic secondary and tertiary phosphines.[10−12] Reagent **1** can be easily regenerated in situ by addition of PCl_3 to its residue **4**.[10−12] In particular, the reaction of compound **1** with a bis-Grignard reagent and a mono-Grignard reagent gave quantitative formation of cyclic tertiary phosphines **2**, which have been separated as sulfides **3** (Scheme 1). The reaction involves, as a first step, the formation of a cyclic pentacoordinate phosphorus intermediate like **A**, which we detected by ^{31}P NMR spectroscopy as it is highly stable due to the presence of three cycles

(1) (a) Holmes, R. R. *Acc. Chem. Res.* **2004**, *37*, 746–753. (b) Holmes, R. R.; Deiters, J. A. *Inorg. Chem.* **1994**, *33*, 3235–3238. For reviews on hypervalent phosphorus see: (c) Holmes, R. R.; *Pentacoordinated Phosphorus Structure and Spectroscopy*; ACS Monograph 175; American Chemical Society: Washington, DC, 1980; Vols. I and II. (d) Holmes, R. R. *Acc. Chem. Res.* **1998**, *31*, 535–542. (e) Wong, C. Y.; Kennepohl, D. K.; Cavell, R. G. *Chem. Rev.* **1996**, *96*, 1917–1951. (f) Kumara Swamy, K. C.; Satish Kumar, N. *Acc. Chem. Res.* **2006**, *39*, 324–333. (g) Röschenthaler, G.-V *Organophosph. Chem.* **2008**, *37*, 247–261.

(2) Westheimer, F. H. *Acc. Chem. Res.* **1968**, *1*, 70–78.

(3) In a turnstyle rotation (TR), permutation is postulated to occur by mutual counterrotation of a pair (one apical and one equatorial ligand) and of a trio (one apical and two equatorial ligands) with subsequent collapse to a new trigonal bipyramid. In four- and five-membered cyclic phosphoranes the ring must always play the role of the pair. The consequences of single and multiple TR processes follow from the application of the following rules. For TR, transpose the pair ligands and rotate the trio of ligands 120° in the direction that brings the trioapical ligand into the original position of the trioequatorial ligand, which remains equatorial in the isomerization. For $(TR)^2$, do not change the pair; rotate the trio as for TR. For $(TR)^3$, transpose the pair. For a discussion of the permutational isomerization of phosphoranes by the TR process, see ref 4b.

(4) (a) Berry, R. S. *J. Chem. Phys.* **1960**, *32*, 933–938. (b) Gillespie, P.; Ramirez, F.; Ugi, I.; Marquading, D. *Angew. Chem., Int. Ed.* **1973**, *12*, 91–119.

(5) Nakamoto, M.; Kojima, S.; Matsukawa, S.; Yamamoto, Y.; Akiba, K. *J. Organomet. Chem.* **2002**, *643−644*, 441–452.

(6) Matsukawa, S.; Kojima, S.; Kajiyama, K.; Yamamoto, Y.; Akiba, K.; Re, S.; Nagase, S. *J. Am. Chem. Soc.* **2002**, *124*, 13154–13170.

(7) (a) Constant, S.; Lacour, J. *Top. Curr. Chem.* **2005**, *250*, 1–41. (b) Kumara Swamy, K. C.; Kumaraswamy, S.; Said, M. A.; Kishore, R. S. K.; Herbst-Irmer, R.; Pülm, M. *Curr. Sci.* **2000**, *78*, 473–478. (c) Hellwinkel, D. *Angew. Chem., Int. Ed. Engl.* **1965**, *4*, 356. (d) Hellwinkel, D. *Chem. Ber.* **1965**, *98*, 576. (e) Pavan Kumar, K. V. P.; Phani Pavan, M.; Kumara Swamy, K. C. *Inorg. Chem. Commun.* **2009**, *12*, 544–547.

(8) (a) Holmes, R. R. *Chem. Rev.* **1996**, *96*, 927–950. (b) Cherkasov, R. A.; Polezhaeva, N. A. *Russ. Chem. Rev.* **1987**, *56*, 163–181. (c) Pavan Kumar, K. V. P.; Satish Kumar, N.; Kumara Swamy, K. C. *New J. Chem.* **2006**, *30*, 717–728.

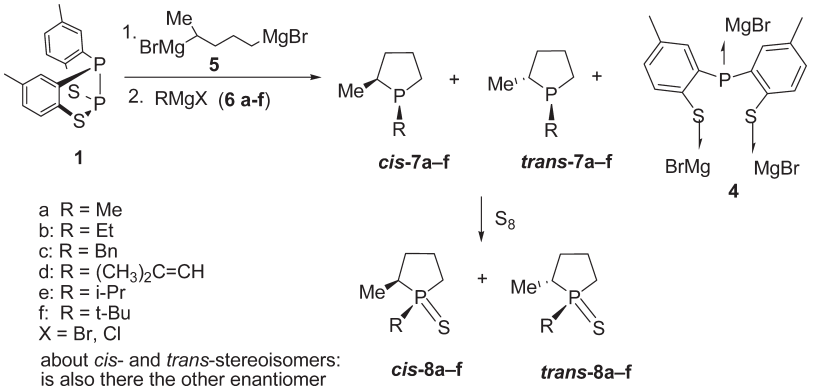
(9) (a) Baccolini, G.; Mezzina, E.; Todesco, P. E.; Foresti, E. *J. Chem. Soc., Chem. Commun.* **1988**, 304–305. (b) Baccolini, G.; Beghelli, M.; Boga, C. *Heteroatom Chem.* **1997**, *8*, 551–556.

(10) Baccolini, G.; Boga, C.; Mazzacurati, M. *J. Org. Chem.* **2005**, *70*, 4774–4777.

(11) (a) Baccolini, G.; Boga, C.; Negri, U. *Synlett* **2000**, 1685–1687. (b) Baccolini, G.; Boga, C.; Buscaroli, R. A. *Eur. J. Org. Chem.* **2001**, 3421–3424. (c) Baccolini, G.; Boga, C.; Galeotti, M. *Angew. Chem., Int. Ed.* **2004**, *43*, 3058–3060. (d) Baccolini, G.; Boga, C.; Mazzacurati, M.; Micheletti, G. *Chem.—Eur. J.* **2009**, *15*, 597–599.

(12) (a) Baccolini, G.; Boga, C.; Mazzacurati, M.; Sangirardi, F. *Org. Lett.* **2006**, *8*, 1677–1680. (b) Baccolini, G.; Boga, C.; Mazzacurati, M. *Eur. J. Org. Chem.* **2007**, 4529–4534.

SCHEME 2. Diastereoselective One-Pot Formation of Phospholanes 7 and Their Sulfides 8



around the P^1 atom. Subsequently, intermediate **A** undergoes nucleophilic attack by the second Grignard reagent with formation of a hexacoordinate specie like **B**, which rapidly collapses to give the tertiary phosphine **2** and the residue **4**.

It is important to remark that cyclic phosphines **2** are formed in nearly quantitative yield and this indicates, according to Westheimer,[2] that the formation of cyclic intermediates like **A** and **B** is strongly favored over that of acyclic species. In addition, the rigid structure of **1**, with its bicyclic condensed and folded system around the phosphorus, gives a further factor of stability to these hypervalent intermediates, each ring reducing the overcrowding of the molecule. Owing to this stability, we were able to detect, by ^{31}P NMR spectroscopy, penta- and hexacoordinate intermediates like **A** and **B**.[11b,12]

Up to now, many studies have reported that the outcome of the reactions involving phosphorus is governed by the formation of pentacoordinate intermediates. The ability of molecule **1** to stabilize also hypercoordinated phosphorus intermediates prompted us to verify whether hexacoordinate phosphorus intermediates also play a role in determining the stereochemical outcome of reactions involving phosphorus species.

For this purpose, we decided to study what happens when an unsymmetrical bis-Grignard reagent such as 1,4-bis-(bromomagnesio)pentane (**5**) is used. In this case the formation of a mixture of pentacoordinate intermediates is possible. Addition of a mono-Grignard reagent to these latter could give different hexacoordinate intermediates, resulting in different ratios of diastereomeric phospholanes such as **7**.

Results and Discussion

Asymmetric tertiary phosphines **7a**−**f** have been obtained in different diastereomeric cis/trans ratios by reaction between benzothiadiphosphole (**1**) and the unsymmetrical bis-Grignard reagent **5**, followed by addition of a mono-Grignard reagent (**6a**−**f**). The phosphines *cis*-**7a**−**f** and *trans*-**7a**−**f** (each as racemic mixture) were separated as sulfides **8a**−**f** by adding elemental sulfur[13] to the crude reaction mixture (Scheme 2) and fully characterized. For the sake of simplicity only one enantiomer of both cis and trans isomers is represented in Scheme 2, but each of them is produced as a racemic mixture.

TABLE 1. Yields and Diastereomeric Relative Ratios of Phosphine Sulfides 8a−f

RMgX	product (yield, %)[a]	dr (cis/trans)[b]
6a (R = methyl)	**8a** (60)	75:25
6b (R = ethyl)	**8b** (70)	70:30
6c (R = benzyl)	**8c** (65)	67:33
6d (R = 2,2-dimethylvinyl)	**8d** (35)	55:45
6e (R = isopropyl)	**8e** (63)	50:50
6f (R = *t*-butyl)	**8f** (62)	5:95

[a]Yields of pure isolated sulfides. [b]Calculated on sulfides by GC-MS.

The reaction course was monitored by GC-MS, showing the presence, in the reaction mixture, of two compounds characterized by the same molecular ion and mass fragmentation, corresponding to the two possible cis and trans isomers. The yields and the relative diastereomeric ratios of the products are collected in Table 1.

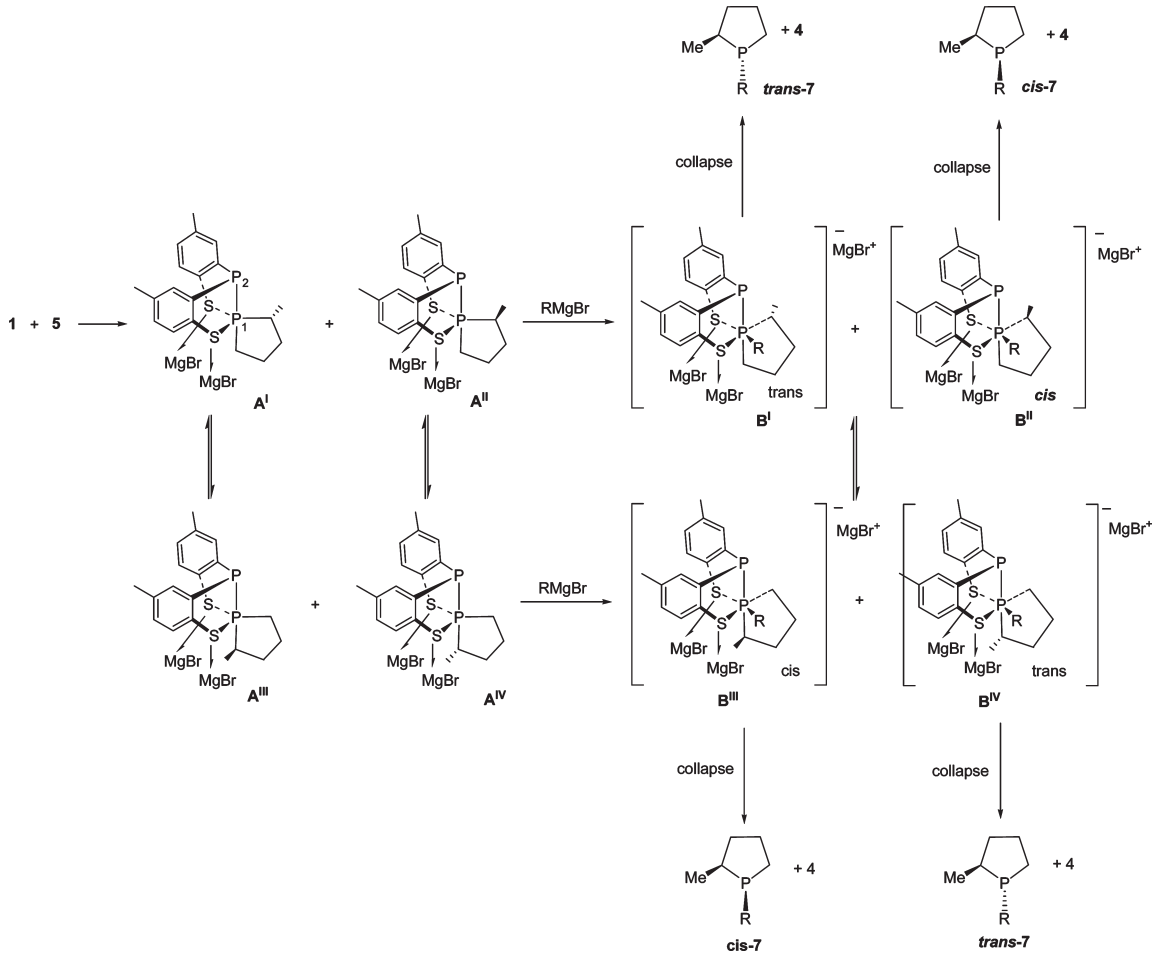
The cis or trans configuration of each diastereoisomer was established by means of ^1H NOE NMR experiments on samples containing both isomers. Because of the overlapping of many signals caused by the $^1H-^{31}P$ heteronuclear coupling, the NOE experiments were carried out under phosphorus decoupling conditions. A comparison between the relative GC-MS retention times and ^{31}P NMR chemical shifts of the two diastereoisomers with data obtained through NOE experiments showed that the trans isomer, in all cases, had both the lower retention time and the downfield ^{31}P resonance, with respect to the cis isomer.

As shown in Table 1, the use of Grignard reagents **6a**−**d** gave the corresponding tertiary phosphine sulfides in cis/trans ratio slowly decreasing from 75/25 to 55/45 in parallel with the increase of the steric hindrance of the R group, whereas the use of a very bulky Grignard reagent, such as *tert*-butylmagnesium chloride (**6f**), caused a strong enhancement of the diastereoselectivity degree, but in the opposite sense with respect to that observed in cases **a**−**d**. A borderline situation occurred with isopropyl derivative **6e** that produced an equimolar amount of cis and trans isomers.

The inversion of the diastereoselection observed on going from *n*-alkyl to more bulky Grignard reagents might be explained considering the penta- and hexacoordinate phosphorus intermediates involved in the reaction and shown, in a simplified manner, in Scheme 3.

(13) For reactions of chiral phosphines with sulfur with retention of configuration see: (a) Young, D. P.; McEven, W. E.; Velez, D. C. *Tetrahedron Lett*. **1964**, *7*, 359−364 and references cited therein. (b) Omelańczuk, J.; Mikołajczyk, M. *J. Am. Chem. Soc*. **1979**, *101*, 7292–7294.

SCHEME 3. Simplified Proposed Pathways To Explain the Diastereoselective Outcome of the Reaction of Benzothiadiphosphole 1 with the Couple Bis-Grignard Reagent 5/Mono-Grignard Reagent



First, we take into consideration the formation of pentacoordinate intermediates. Since the bis-Grignard reagent **5** is unsymmetrical, in principle, its addition to reagent **1** can produce four possible pentacordinate intermediates $\mathbf{A^I}-\mathbf{A^{IV}}$, whose relative stereochemical relationships are as follows: intermediates $\mathbf{A^I}$ and $\mathbf{A^{II}}$ are enantiomeric forms, as well as $\mathbf{A^{III}}$ and $\mathbf{A^{IV}}$, while $\mathbf{A^I}$ and $\mathbf{A^{III}}$, as well as $\mathbf{A^{II}}$ and $\mathbf{A^{IV}}$, can be converted into one another through pseudorotation (TR or Berry) processes.[3,4]

Since there is an intramolecular overcrowding in trigonal-bipyramidal structures[14] the steric factors will have a considerable influence on the stability of such intermediates. In particular, one can state that $\mathbf{A^I}$ and $\mathbf{A^{II}}$ will be more favored than $\mathbf{A^{III}}$ and $\mathbf{A^{IV}}$, respectively, because in structures $\mathbf{A^I}$ and $\mathbf{A^{II}}$ the methyl substituent of the phospholane ring is bonded to the carbon atom arranged in the less sterically hindered equatorial position. As previously reported for the reaction between **1** and symmetrical bis-Grignard reagents,[11] also in the present case pentacoordinate species $\mathbf{A^I}-\mathbf{A^{IV}}$ are stabilized by the presence of three cycles around one phosphorus atom. This increases the lifetime of these species permitting us to detect them and to follow the reaction course through ^{31}P NMR spectroscopy. However, the interconversion rate of these isomers gives rise to only one averaged signal as two doublets at δ −10.7 ($^1J_{P-P}$ = 196 Hz) and δ −44.4 ($^1J_{P-P}$ = 196 Hz) ppm.

(14) Baccolini, G.; Todesco, P. E. *J. Org. Chem.* **1978**, *43*, 216–220.

Nevertheless, the relative stability of pentacoordinate intermediates $\mathbf{A^I}-\mathbf{A^{IV}}$ is not the factor responsible for the stereochemical outcome of our reactions, since in these pentacoordinate intermediates the substituent derived from the addition of the mono-Grignard reagent (which drives the diastereoselectivity observed) is not yet present.

An explanation of the results shown in Table 1 can only be made by considering the fate of these intermediates when the mono-Grignard reagent is added to them. The nucleophilic attack of the mono-Grignard reagent on the pentacoordinate phosphorus atom of intermediates $\mathbf{A^I}-\mathbf{A^{IV}}$ can generate four hexacoordinated diastereomeric forms $\mathbf{B^I}-\mathbf{B^{IV}}$, each together with its own enantiomeric form: these latter species, for the sake of simplicity, are neither shown in Scheme 3, nor considered in the following discussion. In intermediates $\mathbf{B^I}$ and $\mathbf{B^{IV}}$ the methyl substituent on the phospholane ring and the R group on the hypercoordinate phosphorus atom are in a trans relationship, while in $\mathbf{B^{II}}$ and $\mathbf{B^{III}}$ they are in a cis relative position and one can evince that trans forms are less hindered, and thus more stable, than cis ones. Hexacoordinate intermediates **B** spontaneously collapse, as already reported,[12b] giving racemic mixtures of *trans*- and *cis*-phospholanes in relative ratio depending on the mono-Grignard reagent added to the pentacoordinate precursor.

The possibility that one of the five-membered rings containing a P−S bond in $\mathbf{A^{I-IV}}$ is cleaved upon addition of the

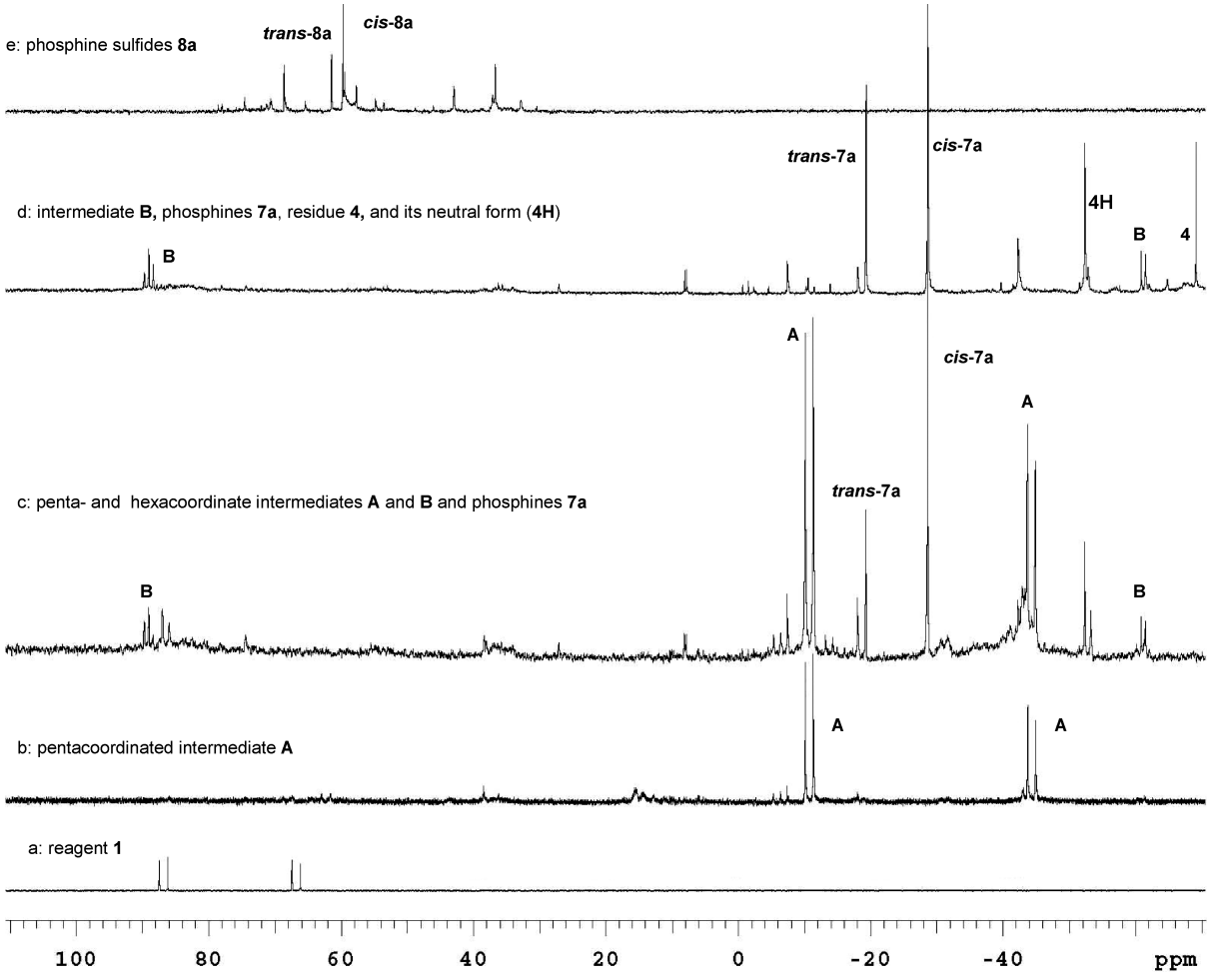


FIGURE 1. Monitoring over time the reaction course from compound **1** to phosphine sulfides **8a** through ^{31}P NMR spectroscopy of the crude reaction mixture in THF.

acyclic Grignard reagent to lead to another pentacoordinate species with breakage of a P−S bond cannot be completely excluded. In fact, we know that penta- and hexacoordinated species may be, in particular conditions, in equilibrium with their ionic forms and, consequently, the ^{31}P NMR signal will be an average of the two forms. However, in the present case, we think that the amount of ionic form for **B**-like species (δ_{31P} ca. −60 ppm) is very low because the hexacoordinate **B** species is stabilized by the presence of the further cycle formed after addition of the bis-Grignard reagent. With these considerations in mind, it is very probable that in the case of the hexacoordinate species bearing acyclic groups previously reported in ref 12b (δ_{31}P −48.7 ppm), not stabilized by this further ring, the equilibrium is shifted toward the ionic form, and, consequently, its signal is shifted downfield. In this manner the apparent disagreement between the two signals for the two different hexacoordinate species is explained.

The different diastereoselectivity observed on going from case **a** to case **f** can be explained as follows: In cases **a**−**d**, in which the steric hindrance of the R substituent is similar and not very high, trans and cis hexacoordinate intermediates can be formed in similar amount, but, once formed, the cis form, being less stable than the trans form, immediately collapses causing the shift of the equilibria,[15] depicted in Scheme 3, toward the formation of an additional amount of cis intermediate, thus providing a final major amount of cis-phosphine. On the other hand, in case **f**, when R = *t*-Bu, the high steric hindrance of this substituent causes formation of hexacoordinate intermediates in very different relative amounts, favoring the trans species $\mathbf{B^I}$ and $\mathbf{B^{IV}}$, which cannot equilibrate and rapidly collapse giving almost exclusively trans-phosphine **7f**. In the case of the isopropyl substituent (case **e**), all these factors offset each other to provide an equimolar amount of the two trans and cis diastereomeric phosphines **7e**.

This hypothesis not only explains the experimental results, but it has been verified monitoring the reaction course by means of ^{31}P NMR spectroscopy. As shown in Figure 1 for case **a** (R = Me), chosen as an example, after the addition of the bis-Grignard reagent **5** to a solution of compound **1** (Figure 1, spectrum a), the ^{31}P NMR spectrum of the crude reaction mixture showed (Figure 1, spectrum b) the disappearance of signals of starting compound **1** and the concomitant appearance of a new couple of doublets

(15) These equilibria are due to interconversion of hexacoordinated species, see: (a) Rodger, A.; Johnson, B. F. G. *Inorg. Chem.* **1988**, *27*, 3062–3064. (b) Alemany, P.; Alvarez, S.; Avnir, D. *Chem.—Eur. J.* **2003**, *9*, 1952–1957.

(16) Baccolini, G.; Boga, C.; Mazzacurati, M. *Tetrahedron* **2007**, *63*, 12595–12600.

(δ −10.7 ($^1J_{P-P}$ = 196 Hz) and δ −44.4 ppm ($^1J_{P-P}$ = 196 Hz) in the region of pentacoordinate species **A**-like.[11b,16]

Immediately after the addition of CH_3MgBr, the appearance of new signals, in low amount, ascribed to hexacoordinate intermediates, was detected (Figure 1, spectrum c), together with the signals of the diastereomeric tertiary cyclic phosphines **7a** (δ −19.3 and −28.6 ppm) derived from the spontaneous and rapid collapse of hexacoordinate species.

With time, we observed a slow decrease of signals corresponding to pentacoordinate intermediate and a concomitant gradual increase of signals belonging to the phosphines, until the situation depicted by spectrum d of Figure 1, where the height of the signals ascribed to hexacoordinate intermediates, even if low, remained unmodified until the end of the reaction, with concomitant increasing of the signals of the diastereomeric phosphines **7a** (in Figure 1, spectrum d shows also signals of the magnesium salt of the residue of **1**, and of its neutral form (labeled as **4H**)). Addition of an excess of elemental sulfur to the crude final reaction mixture caused (Figure 1, spectrum e) the shift of the signals of phosphines **7a** toward those of the corresponding sulfides **8a**.

In case **b** (R = Et), the ^{31}P NMR spectrum (see the Supporting Information) showed two couples of doublets in the region of hexacoordinate species[17] [δ 89.4 (d, J = 113 Hz), δ −61.2 (d, J = 113 Hz) ppm; and δ 85.3 (d, J = 103 Hz), δ −57.0 (d, J = 103 Hz) ppm] which might correspond to the two most stable diastereoisomeric forms **B** or, more likely, to averaged signals of trans (**B**$^{\mathbf{I}}$ and **B**$^{\mathbf{III}}$) and cis (**B**$^{\mathbf{II}}$ and **B**$^{\mathbf{IV}}$) species. In case **a** (R = Me) only one doublet was detected (δ 83.4 ppm (d, J = 115 Hz); δ −61.2 ppm (d, J = 115 Hz)) probably belonging to the trans species.

In case **f**, when *t*-BuMgCl was added to the solution containing the pentacoordinate specie, only one couple of doublets, in very low amount, appeared in the ^{31}P NMR spectrum, together with the signals of tertiary phosphines **7f** (with a huge excess of the signal belonging to *trans*-**7f**) and of compound **4**. Probably in this case the signal of the hexacoordinate intermediate precursor of cis-phosphine is present in an amount so small as not to be detectable. In all cases, after addition of elemental sulfur to the final reaction mixture, ^{31}P NMR spectrum showed mainly signals related to cis/trans-phosphine sulfides **8**.

Conclusion

In conclusion, the addition to benzothiadiphosphole **1** of an unsymmetrical bis-Grignard reagent and a mono-Grignard reagent gives tertiary phosphines, isolated as sulfides, in different cis/trans diastereomeric ratio, depending on the mono-Grignard used. The particular bicyclic and folded structure of reagent **1** strongly stabilize hypercoordinated phosphorus intermediates involved in the reaction and favor their formation. In the present case, it has been possible to detect, by ^{31}P NMR spectroscopy, both pentacoordinate and metastable hexacoordinate species and to follow their evolution during the course of the reaction. An accurate analysis of spectroscopic data and stereoselectivity data permits the fundamental role played by the hexacoordination of phosphorus on the stereochemical outcome of the reaction to be defined.

(17) (a) Quin, L. D.; Williams, A. J. *Practical Interpretation of P-31 NMR Spectra and Computer Assisted Structure Verification*; Advanced Chemistry Development, Inc.: Toronto, Canada, 2004; Chapter 12, pp 83−85. (b) Fluck, E.; Heckmann, G. Empirical Methods for Interpreting Chemical Shifts of Phosphorus Compounds. In *Phosphorus-31 NMR Spectroscopy in Stereochemical Analysis Organic Compounds and Metal Complexes*; Verkade, J. G., Quin, L. D., Eds.; VCH Publihers: Deerfield Beach, FL, 1987; Chapter 2.

Experimental Section

Synthesis for Tertiary Cyclic Phosphine Sulfides: General Procedure. Bis-Grignard reagent **5** (0.333 mmol), prepared from the corresponding bromide and magnesium turnings, was added to a solution of benzothiadiphosphole **1** (0.102 g, 0.333 mmol) in anhydrous THF (3 mL) under dry argon. After about 10 min, mono-Grignard reagent (RMgX, 0.400 mmol) was added. After about 30−40 min, sulfur (0.500 mmol) was added to obtain phosphine sulfides. After 5−10 min, the reaction mixture was treated with water. Extraction with CH_2Cl_2, treatment with anhydrous Na_2SO_4, and concentration under vacuum gave a mixture of the phosphine sulfides. Phosphine sulfides were purified by bulb-to-bulb distillation and/or by flash chromatography on silica gel column (eluent: dichloromethane).

1,2-Dimethylphospholane 1-sulfide (8a): colorless oil, bp 140−160 °C (0.1 mmHg, mixture of cis and trans isomers). *cis*-**8a**: ^1H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 2.40−1.90 (m s, 3H; C*H*CH_3 and CH_2P), 1.90−1.76 (m, 2H; CH_2), 1.65 (d, ^2J(H,P) = 12.3 Hz, 3H; CH_3P), 1.46−1.30 (m, 1H), 1.24 (dd, ^3J(H,P) = 17.3 Hz, ^3J(H,H) = 7.1 Hz, 3H; CH_3CHP), 0.98−0.84 ppm (m, 1H); ^{13}C NMR (100.56 MHz, $CDCl_3$, 25 °C) δ = 41.4 (d, ^1J(C,P) = 54.3 Hz; CHP), 34.0 (d, ^2J(C,P) = 12.2 Hz; CH_2), 33.5 (d, ^1J(C,P) = 52.1 Hz; CH_2P), 23.1 (d, ^2J(C,P) = 3.9 Hz; CH_2), 20.6 (d, ^1J(C,P) = 53.5 Hz; CH_3P), 12.3 ppm (d, ^2J(C,P) = 1.6 Hz; *C*H_3CHP); ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 60.2 ppm (m); MS (70 eV) *m*/*z* (%) 148 (M^+, 100), 133 (32), 120 (41), 115 (29), 106 (30), 94 (14), 78 (34), 63 (47). *trans*-**8a**: ^1H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 2.40−1.90 (m s, 3H; C*H*CH_3 and CH_2P), 1.90−1.76 (m, 2H; CH_2), 1.77 (d, ^2J(H,P) = 12.6 Hz, 3H; CH_3P), 1.46−1.30 (m, 1H), 1.25 (dd, ^3J(H,P) = 17.7 Hz, ^3J(H,H) = 6.9 Hz, 3H; CH_3CHP), 0.98−0.84 ppm (m, 1H); ^{13}C NMR (100.56 MHz, $CDCl_3$, 25 °C) δ 35.5 (d, ^1J(C,P) = 50.1 Hz; CHP), 34.8 (d, ^1J(C,P) = 51.3 Hz; CH_2P), 32.7 (d, ^2J(C,P) = 14.9 Hz; CH_2), 22.3 (d, ^2J(C,P) = 3.1 Hz; CH_2), 21.5 (d, ^1J(C,P) = 47.5 Hz; CH_3P), 14.1 ppm (s; *C*H_3CHP); ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 61.9 ppm (m); MS (70 eV) *m*/*z* (%) 148 (M^+, 100), 133 (28), 120 (39), 115 (15), 106 (50), 94 (19), 78 (48), 63 (42). Elemental analysis calcd for $C_6H_{13}PS$: C 48.62, H 8.84. Found: C 48.44, H 8.81.

1-Ethyl-2-methylphospholane 1-sulfide (8b): colorless oil, bp 145−155 °C (0.1 mmHg, mixture of cis and trans isomers). *cis*-**8b**: ^1H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 2.50−1.60 (m.s, 7H; CH and CH_2), 1.60−1.23 (m, 4H), 1.35 (dd, ^3J(H,P) = 16.3 Hz, ^3J(H,H) = 7.4 Hz, 3H; CH_3CHP), 1.09−0.50 ppm (m, 1H); ^{13}C NMR (100.56 MHz, $CDCl_3$, 25 °C) δ 42.0 (d, ^1J(C,P) = 51.5 Hz; CH), 34.3 (d, ^2J(C,P) = 10.9 Hz; CH_2), 31.5 (d, ^1J(C,P) = 50.3 Hz; CH_2), 23.1 (d, ^2J(C,P) = 3.4 Hz; CH_2), 22.1 (d, ^1J(C,P) = 45.7 Hz; CH_2), 12.4 (d, ^2J(C,P) = 1.6 Hz; *C*H_3CHP), 6.4 ppm (d, ^2J(C,P) = 4.7 Hz; *C*H_3CH_2P); ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 68.7 ppm (m); MS (70 eV) 162 (M^+, 93), 134 (100), 119 (11), 106 (19), 100 (14), 92 (26), 63 (35). *trans*-**8b**: ^1H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 2.50−1.60 (m s, 7H; CH and CH_2), 1.60−1.38 (m, 4H), 1.40 (dd, ^3J(H,P) = 17.5 Hz, ^3J(H,H) = 7.6 Hz, 3H; CH_3CHP), 1.09−0.50 ppm (m, 1H); ^{13}C NMR (100.56 MHz, $CDCl_3$, 25 °C) δ 36.6

(d, J = 9.9 Hz; CH_2), 33.7 (d, ^1J(C,P) = 51.0 Hz; CH), 33.0 (d, ^1J(C,P) = 50.9 Hz; CH_2), 26.9 (d, ^1J(C,P) = 48.3 Hz; CH_2), 23.4 (d, ^2J(C,P) = 4.3 Hz; CH_2), 14.4 (s, CH_3), 6.9 ppm (d, ^2J(C,P) = 4.3 Hz; CH_3CH_2P); ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 71.6 ppm (m); MS (70 eV) m/z (%) 162 (M^+, 84), 134 (100), 119 (10), 106 (15), 100 (12), 92 (35), 63 (36). Elemental analysis calcd for $C_7H_{15}PS$: C 51.82, H 9.32. Found: C 51.90, H 9.35.

1-Benzyl-2-methylphospholane 1-sulfide (8c): colorless oil, bp 145−165 °C (0.1 mmHg, mixture of cis and trans isomers). *cis*-**8c**: ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 7.37−7.25 (m s, 5H; Ph), 3.20 (dd, J = 14.4 Hz, J = 14.4 Hz, 1H; CH_2Ph), 3.11 (dd, J = 13.7 Hz, J = 8.9 Hz, 1H; CH_2Ph), 2.44−0.82 (m s, 7H), 1.32 ppm (dd, ^3J = 16.1 Hz, ^3J = 6.9 Hz, 3H; CH_3CHP); ^{13}C NMR (100.56 MHz, $CDCl_3$, 25 °C) δ 131.5 (d, J(C,P) = 7.9 Hz; C), 130.4 (d, J(C,P) = 4.8 Hz; CH), 128.8 (d, J(C,P) = 2.4 Hz; CH), 127.5 (d, J(C,P) = 3.2 Hz; CH), 42.8 (d, ^1J(C,P) = 50.9 Hz; CH), 37.6 (d, ^1J(C,P) = 39.2 Hz; CH_2), 34.2 (d, ^2J(C,P) = 10.4 Hz; CH_2), 30.5 (d, ^1J(C,P) = 50.6 Hz; CH_2), 23.0 (d, ^2J(C,P) = 4.7 Hz; CH_2), 12.4 ppm (d, ^2J(C,P) = 1.6 Hz; CH_3); ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 65.6 ppm (m); MS (70 eV) m/z (%) 224 (M^+, 93), 133 (99), 91 (100), 63 (30). *trans*-**8c**: ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 7.38−7.25 (m s, 5H; Ph), 3.36 (d, J = 13.7 Hz, 2H; CH_2Ph), 2.44−0.82 ppm (m s, 7H), 1.14 ppm (dd, ^3J = 17.6 Hz, ^3J = 6.9 Hz, 3H; CH_3CHP); ^{13}C NMR (100.56 MHz, $CDCl_3$, 25 °C) δ 132.1 (d, J(C,P) = 7.9 Hz; C), 129.9 (d, J(C,P) = 4.8 Hz; CH), 128.9 (d, J(C,P) = 3.3 Hz; CH), 127.6 (d, J(C,P) = 3.3 Hz; CH), 42.2 (d, ^1J(C,P) = 41.0 Hz; CH_2), 34.4 (d, ^2J(C,P) = 10.4 Hz; CH_2), 33.3 (d, ^1J(C,P) = 51.7 Hz; CH_2), 33.1 (d, ^1J(C,P) = 50.6 Hz; CH), 23.6 (d, ^2J(C,P) = 4.4 Hz; CH_2), 14.2 ppm (CH_3); ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 68.1 ppm (m); MS (70 eV) m/z (%) 224 (M^+, 81), 133 (94), 91 (100), 63 (27). Elemental analysis calcd for $C_{12}H_{17}PS$: C 64.26, H 7.64. Found: C 64.14, H 7.67.

2-Methyl-1-(2-methylprop-1-en-1-yl)phospholane 1-sulfide (8d): colorless oil, mixture of cis and trans isomers. *cis*-**8d**: ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 5.62 (d, ^2J(H,P) = 24.0 Hz; =CHP), 2.60−1.86 (m, 3H; CH and CH_2), 2.30 (dd, J = 2.5 Hz, J = 1.0 Hz, 3H; CH_3CH=), 1.91 (dd, J = 1.1 Hz, J = 1.1 Hz, 3H; CH_3CH=), 1.70−1.58 (m, 2H), 1.48−1.24 (m, 1H), 1.29 (dd, ^2J(H,P) = 18.0 Hz, ^3J(H,H) = 6.3 Hz, 3H; CH_3CHP), 1.00−0.78 ppm (m, 1H); ^{13}C NMR (100.56 MHz, $CDCl_3$, 25 °C) δ 133.3 (d, ^2J(C,P) = 10.5 Hz; $(CH_3)_2C$=), 114.6 (d, ^1J(C,P) = 72.3 Hz; C=CHP), 43.8 (d, ^1J(C,P) = 55.2 Hz; CHP), 35.7 (d, ^1J(C,P) = 55.1 Hz; CH_2), 34.1 (d, ^2J(C,P) = 10.3 Hz; CH_2), 28.8 (d, ^3J(C,P) = 16.2 Hz; CH_3C=CHP), 23.4 (d, ^2J(C,P) = 4.6 Hz; CH_2), 22.0 (d, ^3J(C,P) = 7.9 Hz; CH_3=CHP), 13.1 ppm (d, ^2J(C,P) = 1.7 Hz; CH_3CHP); ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 51.4 ppm (m); MS (70 eV) m/z (%) 188 (M^+, 100), 173 (11), 155 (15), 133 (31), 117 (9), 99 (21), 86 (21), 63 (36). *trans*-**8d**: ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 5.53 (d, ^2J(H,P) = 24.4 Hz; =CHP), 2.58−1.84 (m, 3H; CH and CH_2), 2.20 (dd, J = 2.4 Hz, J = 1.1 Hz, 3H; CH_3CH=), 1.95 (dd, J = 1.2 Hz, J = 1.2 Hz, 3H; CH_3CH=), 1.70−1.56 (m, 2H), 1.46−1.22 (m, 1H), 1.23 (dd, ^2J(H,P) = 16.8 Hz, ^3J(H,H) = 6.7 Hz, 3H; CH_3CHP), 1.02−0.76 ppm (m, 1H); ^{13}C NMR (100.56 MHz, $CDCl_3$, 25 °C) δ 133.4 (d, ^2J(C,P) = 11.0 Hz; $(CH_3)_2C$H=), 120.5 (d, ^1J(C,P) = 73.6 Hz; C=CHP), 36.7 (d, ^1J(C,P) = 54.9 Hz; CH_2), 36.6 (d, ^1J(C,P) = 54.6 Hz; CH), 34.3 (d, ^2J(C,P) = 10.0 Hz; CH_2), 28.2 (d, ^3J(C,P) = 16.2 Hz; CH_3=CHP), 23.0 (d, ^2J(C,P) = 4.0 Hz; CH_2), 21.9 (d, ^3J(C,P) = 8.0 Hz; CH_3=CHP), 14.2 ppm (s, CH_3CHP); ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 53.9 ppm (m); MS (70 eV) m/z (%) 188 (M^+, 100), 173 (11), 155 (12), 133 (29), 119 (9), 99 (12), 86 (14), 63 (33). Elemental analysis calcd for $C_9H_{17}PS$: C 57.42, H 9.10. Found: C 57.21, H 9.13.

1-Isopropyl-2-methylphospholane 1-sulfide (8e): colorless oil, bp 145−165 °C (0.1 mmHg, 1:1 mixture of cis and trans isomers); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 2.40−2.20 (m, 2H), 2.16−1.85 (m, 4H), 1.70−1.33 (m, 2H), 1.32−1.15 ppm (m, 9H); ^{13}C NMR (100.56 MHz, $CDCl_3$, 25 °C) δ 42.9 (d, ^1J(C,P) = 49.0 Hz; CH), 34.9 (d, ^2J(C,P) = 5.5 Hz; CH_2), 34.8 (d, ^2J(C,P) = 5.0 Hz; CH_2), 32.8 (d, ^1J(C,P) = 49.9 Hz; CH), 32.4 (d, ^1J(C,P) = 49.9 Hz; CH_2), 31.0 (d, ^1J(C,P) = 49.5 Hz; CH_2), 30.9 (d, ^1J(C,P) = 46.4 Hz; CH), 26.8 (d, ^1J(C,P) = 44.6 Hz; CH), 23.7 (d, ^2J(C,P) = 4.2 Hz; CH_2), 22.7 (d, ^2J(C,P) = 4.0 Hz; CH_2), 17.0 (d, ^2J(C,P) = 2.5 Hz; CH_3), 16.9 (d, ^2J(C,P) = 1.8 Hz; CH_3), 16.5 (d, ^2J(C,P) = 1.9 Hz; CH_3), 15.8 (d, ^2J(C,P) = 2.4 Hz; CH_3), 14.7 (CH_3), 13.5 ppm (d, ^2J(C,P) = 1.7 Hz; CH_3). *cis*-**8e**: ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 76.4 ppm (m); MS (70 eV) m/z (%) 176 (M^+, 59), 134 (100), 119 (11), 106 (15), 100 (14), 92 (15), 63 (26). *trans*-**8e**: ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 79.5 ppm (m); MS (70 eV) m/z (%) 176 (M^+, 56), 134 (100), 119 (10), 106 (13), 100 (14), 92 (15), 63 (21). Elemental analysis calcd for $C_8H_{17}PS$: C 54.51, H 9.72. Found: C 54.43, H 9.69.

1-*tert*-Butyl-2-methylphospholane 1-sulfide (8f): colorless oil, bp 180−200 °C (0.1 mmHg, mixture of cis and trans isomers). *cis*-**8f**: ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 2.45−2.12 (m, 2H), 2.12−1.82 (m, 2H), 1.68−1.51 (m, 2H), 1.42 (dd, J = 15.1 Hz, J = 7.3 Hz, 3H), 1.31 (d, J = 15.5 Hz, 9H), 1.01−0.78 ppm (m, 1H); ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 83.0 ppm (m); MS (70 eV) m/z (%) 190 (M^+, 39), 134 (100), 119 (10), 100 (13), 92 (30), 69 (22), 63 (31), 57 (66). *trans*-**8f**: ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C, TMS) δ 2.50−2.40 (m, 1H), 2.22−2.13 (m, 1H), 2.14−2.00 (m, 2H), 1.93−1.53 (m, 2H), 1.26 (dd, J_1 = 16.4 Hz, J_2 = 7.0 Hz, 3H), 1.24 (d, J = 15.7 Hz, 9H), 1.01−0.78 ppm (m, 1H); ^{13}C NMR (100.56 MHz, $CDCl_3$, 25 °C) δ 35.1 (d, ^2J(C,P) = 9.0 Hz; CH_2), 33.7 (d, ^1J(C,P) = 44.1 Hz; C), 31.3 (d, ^1J(C,P) = 48.9 Hz; CH_2), 30.0 (d, ^1J(C,P) = 47.6 Hz; CH), 24.9 (d, ^2J(C,P) = 1.5 Hz; CH_3), 24.5 (d, J(C,P) = 3.3 Hz; CH_2), 15.0 ppm (CH_3); ^{31}P NMR (161.89 MHz, $CDCl_3$, 25 °C, ext. H_3PO_4) δ 86.1 ppm (m); MS (70 eV) m/z (%) 190 (M^+, 37), 134 (100), 119 (23), 92 (23), 101 (22), 64 (79), 57 (67). Elemental analysis calcd for $C_9H_{19}PS$: C 56.81, H 10.06. Found: C 56.87, H 10.09.

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Supporting Information Available: General experimental details, additional spectroscopic data, and copies of ^{1}H NMR, ^{13}C NMR, and ^{31}P NMR spectra of compounds **8a**−**f**. This material is available free of charge via the Internet at http://pubs.acs.org.