

Free Radical Chain Reactions of [1.1.1]Propellane with Three-Coordinate Phosphorus Molecules. Evidence for the High Reactivity of the Bicyclo[1.1.1]pent-1-yl Radical

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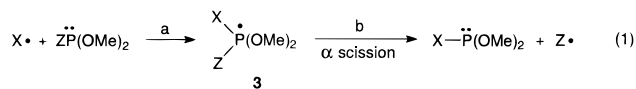
Abstract: Three-substituted bicyclo[1.1.1]pent-1-yl radicals (**5**), generated from additions of radicals to [1.1.1]propellane (**1**), are found to have high propensities to react with three-coordinate phosphorus molecules. For example, the 3-ethylbicyclo[1.1.1]pent-1-yl radical (**5d**) reacts with (EtO)₃P in a free-radical Arbuzov process to yield dimethyl 3-ethylbicyclo[1.1.1]pent-1-ylphosphonate (**13**). By contrast, the ethyl radical does not react with (EtO)₃P to yield EtP(O)(OEt)₂. However, the highly reactive phenyl radical yields PhP(O)(OEt)₂. Moreover, attack of the *n*-pentylbicyclo[1.1.1]pent-1-yl radical (**5b**) on *n*-C₅H₁₁P(OMe)₂ results in a free-radical substitution process that gives dimethyl 3-*n*-pentyl[1.1.1]bicyclopent-1-ylphosphonite (**7b**) and the primary alkyl radical *n*-C₅H₁₁•. Thus, **5** has a propensity to bond to three-coordinate phosphorus that is greater than that of a primary alkyl radical and similar to that of phenyl radical. Reaction of 2-benzyl-4-methyl-1,3,2-dioxaphospholane (**9**) with **5a** is found to proceed with predominant inversion of configuration at phosphorus. Furthermore, 3-phenylmethylbicyclo[1.1.1]pent-1-yl radical, **5a** (from reaction of benzyl radical with **1**), participates in reasonably efficient radical chain reactions with PhCH₂OP(OMe)₂ (**11**) and PhCH₂P(OMe)₂ (**6a**) (chain lengths 30–50) to provide structurally novel products of new radical-Arbuzov and radical-substitution reactions. Dimethyl 3-phenylmethylbicyclo[1.1.1]pent-1-ylphosphonate (**12**) from **11** and dimethyl 3-phenylmethylbicyclo[1.1.1]pent-1-ylphosphonite (**7a**) from **6a** incorporate the bicyclo[1.1.1]pent-1-yl moiety. The high propensity of various **5** to react with three-coordinate phosphorus molecules reflects the highly pyramidal nature of **5** which is accompanied by the increased *s*-character of the SOMO orbital of **5** and the strength of the phosphorus–carbon bond in the presumed phosphoranyl radical intermediates (**3** and **4**) formed. Figure 1 depicts the thermodynamics of three classes of free radical substitution and Arbuzov reactions with three-coordinate phosphorus molecules.

Introduction

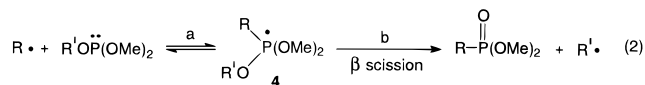
The strained hydrocarbon [1.1.1]propellane (**1**) and the highly pyramidal 3-substituted bicyclo[1.1.1]pent-1-yl radical (**2**), generated by addition of X• to **1**, have been the subject of numerous structural and chemical studies in recent years.^{1,2} Propellane **1** is of special interest because of the thermodynamic³ and kinetic⁷ ease of additions of free radicals to it. The tertiary alkyl product radical **2** has attracted attention because of its highly pyramidal structure and consequent potentially increased reactivity.⁸ Thus, **2** might be expected to form relatively strong bonds and feature reduced steric demands compared to those of unconstrained tertiary alkyl radicals. Comparisons of the reactivity of radical **2** with those of unstrained primary, secondary, and tertiary alkyl radicals are of particular interest.



The reactions of free radicals with three-coordinate phosphorus molecules present an attractive diagnostic system for the study of radical reactivity. The majority of these reactions undoubtedly proceed through intermediate phosphoranyl radicals (**3** and **4**),¹⁰ a great number of which, formed via oxidative



addition to phosphorus (reactions 1a, 2a), have been characterized by ESR spectroscopy.^{10b,d,e} A key process undergone by three-coordinate phosphorus molecules on reaction with radicals is substitution (eq 1) via α scission (path 1b) of the phosphoranyl



radical intermediate **3**. Another is the addition of a radical (path 2a) followed by β scission (path 2b) of an alkoxy group already attached to phosphorus. Reaction 2 has been termed a free-radical Arbuzov reaction,¹⁰ a name particularly appropriate when R• is an alkyl radical, although this reaction is also known for R• = Me₂N•¹¹ and Ph•.¹²

The rate constants for oxidative addition of radicals to three-coordinated phosphorus, the ease of the ensuing α and β scission reactions of **3** and **4**, and the overall thermodynamic ease of reactions 1 and 2 are correlated by the relative strengths of the new bonds to phosphorus formed in intermediates **2** and **3** and

(1) For recent reviews on the chemistry of small ring propellanes and the formation of bridgehead free radicals, see: (a) Kaszynski, P.; Michl, J. In *The Chemistry of the Cyclopropyl Group*; Rappoport, Z., Ed.; Wiley: New York, 1995; Vol. 2, p 773. (b) Szeimies, G. In *Advances in Strain in Organic Chemistry*; Halton, B., Ed.; JAI Press Ltd.: Greenwich, 1992; Vol. 2, p 1. (c) Walton, J. C. *Chem. Soc. Rev.* **1992**, 21, 104. (d) Wiberg, K. B. *Angew. Chem., Int. Ed. Engl.* **1986**, 25, 312. (e) Kaszynski, P.; Michl, J. In *Advances in Strain in Organic Chemistry*; Halton, B., Ed.; JAI Press: London, 1995; Vol. 4, p 283. (f) Tobe, Y. In *Carbocyclic Cage Compounds: Chemistry and Applications*; Osawa, E., Yonemitsu, O., Eds.; VCH: New York, 1992; p 125. (g) Wiberg, K. B. *Chem. Rev.* **1989**, 89, 975. (h) Ginsburg, D. In *The Chemistry of the Cyclopropyl Group*; Rappoport, Z., Ed.; Wiley: New York, 1987; Vol. 1, p 1193.

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those in the reactants and products.^{10a-d,f,13,14} Thus, radicals that form relatively strong bonds to phosphorus (alkoxy, thiyl, and phenyl radicals) add to trialkyl phosphites, (RO)₃P, *irreversibly* with second-order rate constants^{10a} of 3×10^8 – 5×10^9 M⁻¹ s⁻¹. By contrast ESR studies¹⁷ have demonstrated that methyl radicals add *reversibly* to a series of (RO)₃P (reaction 2a, R• = Me•) and only give β scission (reaction 2b) when R• is the relatively stable benzyl radical. The efficiency of reaction 1 depends on both the ability of X• to form a bond to

(2) For recent papers on the free radical chemistry of [1.1.1]propellane, see: (a) Scaiano, J. C.; McGarry, P. F. *Tetrahedron Lett.* **1993**, *34*, 1243. (b) Kaszynski, P.; Friedli, A. C.; Michl, J. *J. Am. Chem. Soc.* **1992**, *114*, 601. (c) Obeng, Y. S.; Laing, M. E.; Friedli, A. C.; Yang, H. C.; Wang, D.; Thulstrup, E. W.; Bard, A. J.; Michl, J. *J. Am. Chem. Soc.* **1992**, *114*, 9943. (d) Kaszynski, P.; McMurdie, N. D.; Michl, J. *J. Org. Chem.* **1991**, *56*, 307. (e) Wiberg, K. B.; Waddell, S. T. *J. Am. Chem. Soc.* **1990**, *112*, 2194. (f) Sadovaya, N. K.; Blokhin, A. V.; Surmina, L. S.; Tyurekhodzhaeva, M. A.; Koz'min, A. S.; Zefirov, N. S. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1990**, 2451. (g) Sadovaya, N. K.; Blokhin, A. V.; Tyurekhodzhaeva, M. A.; Grishin, Yu. K.; Surmina, L. S.; Koz'min, A. S.; Zefirov, N. S. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1990**, 716. (h) Kaszynski, P.; Friedli, A. C.; McMurdie, N. D.; Michl, J. *Mol. Cryst. Liq. Cryst.* **1990**, *191*, 193. (i) Hassenrueck, K.; Murthy, G. S.; Lynch, V. M.; Michl, J. *J. Org. Chem.* **1990**, *55*, 1013. (j) McGarry, P. F.; Johnston, L. J.; Scaiano, J. C. *J. Am. Chem. Soc.* **1989**, *111*, 3750. (k) McGarry, P. F.; Johnston, L. J.; Scaiano, J. C. *J. Org. Chem.* **1989**, *54*, 6133. (l) Murthy, G. S.; Hassenrueck, K.; Lynch, V. M.; Michl, J. *J. Am. Chem. Soc.* **1989**, *111*, 7262. (m) Bunz, U.; Polborn, K.; Wagner, H.-U.; Szeimies, G. *Chem. Ber.* **1988**, *121*, 1785. (n) Kaszynski, P.; Michl, J. *J. Am. Chem. Soc.* **1988**, *110*, 5225. (o) Kaszynski, P.; Michl, J. *J. Org. Chem.* **1988**, *53*, 4593. (p) Zefirov, N. S.; Sadovaya, N. K.; Surmina, L. S.; Godunov, I. A.; Koz'min, A. S.; Potekhin, K. A.; Maleev, A. V.; Struchkov, Yu. T. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1988**, 2648. (q) Wiberg, K. B.; Waddell, S. T.; Laidig, K. *Tetrahedron Lett.* **1986**, *27*, 1553.

(3) The strength of the central bond of [1.1.1]propellane (**1**), based on theoretical estimates and experimental measurements, is 60–70 kcal/mol⁴⁻⁶ which is close to that of cyclopropane. The value for the heat of addition of H₂ to the central C–C bond of [1.1.1]propellane (**1**) is –37.9 kcal/mol (Kozina, M. P.; Pimenova, S. M.; Lukyanova, V. A.; Surmina, L. S. *Dokl. Akad. Nauk SSSR* **1985**, 283, 661). The bond dissociation energy for the bridge head C–H bond of bicyclo[1.1.1]pentane is calculated to be 104.4 kcal.⁶

(4) Wiberg, K. B.; Walker, F. H. *J. Am. Chem. Soc.* **1982**, *104*, 5239. (5) Feller, D.; Davidson, E. R. *J. Am. Chem. Soc.* **1987**, *109*, 4133. (6) Wiberg, K. B.; Hadad, C. M.; Sieber, S.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1992**, *114*, 5820.

(7) A series of radicals, tertiary butoxy, phenylthiyl, triethylsilyl, benzene-complexed chlorine atom, and *p*-methoxybenzoyl add to [1.1.1]propellane (**1**) about 2–3 times more rapidly than they add to styrene. (Scaiano, J. C., private communication. Data given in ref 1a).

(8) Bicyclopentyl radical (**2**, X = H) is estimated from ESR measurements to have about 20% 2s character in the SOMO (A_{iso} ¹³C = 223 G at –196 °C.⁹

(9) Rhodes, C. J.; Walton, J. C.; Della, E. W. *J. Chem. Soc., Perkin Trans. 2* **1993**, 2125.

(10) For reviews of phosphoranyl radicals, see: (a) Bentrude, W. G. In *The Chemistry of Organophosphorus Compounds*; Hartley, F. R., Ed.; Wiley: Sussex, 1990; Vol. 1, p 531; (b) Bentrude, W. G. In *Reactive Intermediates*, Abramovitch, R. A., Ed.; Plenum: London, 1983; Vol. 3, p 199. (c) Bentrude, W. G. *Acc. Chem. Res.* **1982**, *15*, 117. (d) Roberts, B. P. In *Advances in Free Radical Chemistry*; Williams, G. H., Ed.; Heyden and Sons: London, 1980; Vol. 6, p 225. (e) Schipper, P.; Janzen, E. H. J. M.; Buck, H. M. *Top. Phosphorus Chem.* **1977**, *9*, 407. (f) Bentrude, W. G. In *Free Radicals*; Kochi, J. K., Ed.; Wiley-Interscience: New York, 1973; p 595.

(11) Bentrude, W. G.; Alley, W. D.; Johnson, N. A.; Murakami, M.; Nishikida, K.; Tan, H.-W. *J. Am. Chem. Soc.* **1977**, *99*, 4383.

(12) (a) Fu, J.-J. L.; Bentrude, W. G. *J. Am. Chem. Soc.* **1972**, *94*, 7710. (b) Fu, J.-J. L.; Bentrude, W. G.; Griffin, C. E. *J. Am. Chem. Soc.* **1972**, *94*, 7717. (c) Kryger, R. G.; Lorand, J. P.; Stevens, N. R.; Herron, N. R. *J. Am. Chem. Soc.* **1977**, *99*, 7589. (d) Reference 11 and 12 are concerned with reactions of dimethylamino and phenyl radicals with trialkyl phosphites. (e) With phenylphosphonites (PhP(OR)₂) and diphenylphosphinites (Ph₂POR), a greater range of radicals promote free radical Arbuzov reactions, as summarized in ref 10. This may be related to the ligand- π structure^{10a} of phenyl-substituted phosphoranyl radicals which may be of increased stability compared to their TBP σ radical counterparts.

(13) Tables of first-order rate constants for reactions of radicals with three-coordinate phosphorus molecules are found in refs 10a–10d.

(14) This sort of understanding of the reactions of radicals with three-coordinate phosphorus molecules, in terms of three reaction classes, was first set forth in refs 15 and 16.

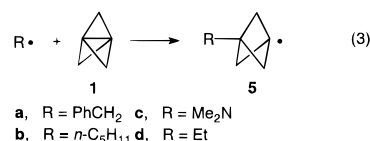
phosphorus, at least reversibly, and the relative energies of the P–Z and P–X bonds.

In the present study a comparison is made of the abilities of the 3-substituted bicyclo[1.1.1]pent-1-yl radical (**2** and **5**) and the radicals ethyl, isopropyl, and benzyl to undergo free radical Arbuzov (eq 2) and substitution (eq 1) processes with certain three-coordinate phosphorus molecules. This research is based on the known facile additions of a variety of radicals to **1** to give intermediate **5** (eq 3).^{1-3,7} The important conclusion of these studies is that 3-substituted bicyclo[1.1.1]pent-1-yl radicals have a propensity to undergo reactions 1 and 2 that is greater than that of primary radicals and closer to that of phenyl radicals. Furthermore, because of its high reactivity and ease of formation from **1**, the 3-substituted bicyclo[1.1.1]pent-1-yl radical (**5**) participates in two new free-radical chain reactions that yield novel insertion products (**7a–c**, **9**, and **12**) containing the bicyclo[1.1.1]pent-1-yl structural moiety.¹⁵

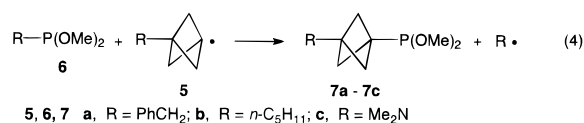
Results

Free Radical Substitution-Propellane Insertion Reactions.

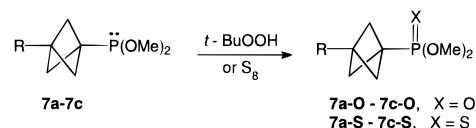
Tests of the abilities of 3-substituted bicyclo[1.1.1]pent-1-yl radicals (**5**), generated on addition of an alkyl radical (R•) to **1** (eq 3), to displace benzyl and *n*-pentyl radicals from phospho-



nites **5a** and **5b** (eq 4) were carried out under photoinitiation



conditions in 100 μ L of deoxygenated benzene solutions of GC-purified **1** (\approx 0.5 mmol) and excess **6** (0.7–1.4 mmol). The reaction with **5b** was initiated with di-*tert*-butyl peroxide (0.02 mmol) while that with **6a** was more efficient with the benzyl radical source, bis(phenylmethyl)diazene BPMDA (0.04 mm), as initiator. The yields of these reactions, based on consumed phosphonite, were determined by ³¹P NMR spectroscopy following oxidation of phosphonites **7a** and **7b** to the phosphonates (**7a-O** and **7b-O**) by *t*-BuOOH and are recorded in Table 1 along with the isolated yield (12%) of pure **7b-O**. (**7a-O** is the same as **12** formed in eq 5.) The yields are considered to



be conservative because of losses in transfers of the phosphonite solution to the reaction tube (see Experimental Section) and possible less-than-quantitative oxidation of products. Nonetheless, reasonable amounts of **7a** and **7b** as their oxides were obtained. A few percent of **7a-O** was isolated in pure form by HPLC. Major peaks in the ³¹P NMR spectra of the crude

(15) Bentrude, W. G.; Hansen, E. R.; Khan, W. A.; Min, T. B.; Rogers, P. E. *J. Am. Chem. Soc.* **1973**, *95*, 2286. Bentrude, W. G.; Rogers, P. E. *J. Am. Chem. Soc.* **1976**, *98*, 1674.

(16) Bentrude, W. G.; Fu, J.-J. L.; Rogers, P. E. *J. Am. Chem. Soc.* **1973**, *95*, 3625.

(17) Davies, A. G.; Griller, D.; Roberts, B. P. *J. Chem. Soc., Perkin Trans. 2* **1972**, 2224.

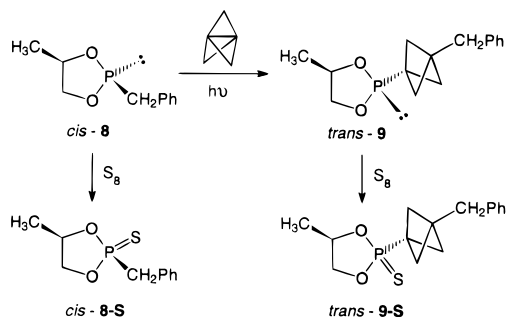
Table 1. Free Radical Chain Reactions of Three-Coordinate Phosphorus with [1.1.1]Propellane at 0 °C

reactant ^a	mmol	initiator	mmol	% conversion ^b	product	% yield ^c
6a	1.33	BPMDA	0.02	31	7a	46
<i>trans</i> - and <i>cis</i> - 8	1.23	BPMDA	0.02	49	9	40
11	1.38	BPMDA	0.03	28	12	61 (45)
6b	0.67	DTBP ^d	0.02	69	7b	69 (12)
6c ^h	0.77	TMT	0.5	15 ^e	7c	<i>f</i> (7)
(EtO) ₃ P ^h	11.9	Et ₂ N ₂	0.66	<i>f</i>	13	15 (6) ^g

^a **6a–6c** and **8** were converted to the oxide or sulfide, the products **7a** and **7b** to the oxides, and products **7c** and **9a** to the sulfides. ^b Determined by quantitative ³¹P NMR vs 0.317 M (MeO)₃PO in C₆D₆ as external standard. ^c By quantitative ³¹P NMR based on disappearance of starting compound. Numbers in parentheses indicate isolated yields. ^d Di-*tert*-butyl peroxide. ^e Estimated from crude ³¹P NMR. ^f Conversion too low to determine. ^g Yield based on total starting [1.1.1]propellane. ^h At 24 °C.

reactions mixtures could be reasonably assigned to **7a** (δ 172.6) and **7b** (δ 172.0). For **6a** assignments of ¹H NMR resonances for the nonaromatic protons in the crude product mixture also could be made by comparisons to resonances for purified analogs. Purified phosphonate **7b-O** was fully characterized by ¹H and ¹³C NMR spectroscopy and by both high and low resolution mass spectrometry (see later paragraph and Experimental Section). Isolated phosphonate **7a-O** was identified by comparison of its spectral properties and GC retention time to those of a sample of **7a-O** (**12**) that was obtained in greater quantities from the reaction of (MeO)₂POCH₂Ph with [1.1.1]-propellane (**1**) (see below, eq 5).

The stereochemistry of the displacement of the benzyl group by the 3-benzylbicyclo[1.1.1]pent-1-yl radical (**5a**, R = PhCH₂) was determined from the reaction of a 71:29 (*trans*:*cis*) ratio of starting diastereomers of phosphonite **8**¹⁹ to give phosphonites *cis*- and *trans*-**9**.²⁰ (A Kimax filter was employed to avoid photoisomerization of **8**.²¹) These reactions are illustrated below using *cis*-**8**. Major peaks assignable to these phosphonites were seen in the ³¹P NMR spectra of the crude product mixture at δ 183.3 (*cis*) and δ 177.7 (*trans*). An overall yield of 40% for



this process was determined (Table 1) by ³¹P NMR following

(18) Preliminary studies of the reactions of alkyl radicals with trialkyl phosphites and alkylphosphonites were carried out in this laboratory by E. R. Hansen and P. E. Rogers. For a preliminary report of a portion of the results reported in the present paper, see: Dockery, K. P.; Bentrude, W. G. *J. Am. Chem. Soc.* **1994**, *116*, 10332.

(19) The preparation and assignment of *cis* and *trans* geometries to **8** and its sulfides were reported previously from this group. Bentrude, W. G.; Tan, H.-W. *J. Am. Chem. Soc.* **1976**, *98*, 1850. *Cis* and *trans* designations refer to the relation of the ring methyl and alkyl substituent on phosphorus. The stereospecific conversion of three-coordinate phosphorus to the sulfide with retention of configuration is well established. (Young, D. P.; McEwen, W. E.; Velez, D. C.; Johnson, J. W.; Van-derWerf, C. A. *Tetrahedron Lett.* **1964**, 359. Horner, L.; Winkler, H. *Tetrahedron Lett.* **1964**, 175.)

(20) The assignment of *cis* and *trans* stereochemistries were made from the relative ³¹P chemical shifts, a previously established criterion.¹⁵

(21) Unpublished results from this laboratory.

Table 2. Mean Chain Lengths for the Reactions of **6a**, **7**, and **11** with [1.1.1]Propellane

compd	reactant ^a	% conversion ^b	% yield ^b	% D incorprtn ^c	product	chain length ^d
6a		50	36	1.6	7a	46
6a		41	37	1.8	7a	41
<i>trans</i> - and <i>cis</i> - 8		49	40	2.0 ^e	9	37
11		28	61	1.8	12	41
11		77	45	2.6	12	28

^a **6a** and its products were analyzed as the oxide, *trans*- and *cis*-**8** and their products as the sulfides. ^b By quantitative ³¹P NMR. ^c Determined by GC-EIMS (70 eV) from the product [M + 1]⁺/[M]⁺ ratio with labeled initiator BPMDA-*d*₂ vs the product [M + 1]⁺/[M]⁺ ratio with unlabeled BPMDA. ^d Determined from the ratio of unlabeled to labeled product and multiplying by 0.75 (75% D incorporation in BPMDA-*d*₂). ^e From the ratio of fragment *m/z* 92 to fragment *m/z* 91.

stereospecific retentive¹⁹ conversion of the diastereomers of **9** with S₈ to the sulfides, *cis*- and *trans*-**9-S**. The latter were found to be in *trans*:*cis* ratio of 38:62.¹⁹ The sulfides (**8-S**) of unreacted starting **8** (*trans*:*cis* ratio, 67:33) were purified as a mixture, *trans*:*cis* ratio, 67:33. *The predominant stereochemistry of this displacement reaction, therefore, is inversion.*

The small increase in percentage of *trans* product, compared to that predicted from the 71:29 *trans*:*cis* ratio of starting phosphonite **8**, could come from a slightly greater reactivity of the *cis* isomer or from a partial equilibration of the diastereomers of **8**. Both possibilities are consistent with the reduction in *trans*:*cis* ratio of the reactants from 71:29 to 67:33 over the course of the reaction. However, the *trans*:*cis* ratio of products **9-S**, 38:62, is far removed from the thermodynamic equilibrium *trans*:*cis* ratio known for **9** of about 65:35.¹⁹

The structure of **9-S** was determined spectroscopically. ¹H and ³¹P NMR spectra were obtained from very small amounts of pure individual diastereomers, while a pure *cis*/*trans* mixture of isomers yielded ¹³C NMR parameters and HRMS data (see later paragraph and Experimental Section).

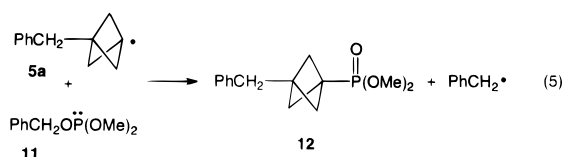
Since these insertion reactions are obviously radical chain processes, the mean kinetic chain lengths for the benzyl-radical induced reactions of [1.1.1]propellane (**1**) with phosphonite **6a** and cyclic phosphonite **8** were determined by use of deuterium-labeled BPMDA from which PhCHD[•] was generated photolytically. Reaction conditions and workup duplicated those for the reactions with unlabeled BPMDA. Data from these studies are found in Table 2. The percentage of product with deuterium incorporation was determined from the increase in the [M + 1] ion intensity in the mass spectrum relative to product from reaction using unlabeled BPMDA. (GC/MS on **7a-O**, *trans*- and *cis*-**9-S**). Equations 3 and 4 (R = PhCH₂) were assumed to be operative. The chain length was then calculated from the ratio, in the oxidized product mixture, of the *unlabeled* 3-benzylbicyclo[1.1.1]pent-1-ylphosphonate (**7a-O** or **9-S**) containing PhCH₂ to the *labeled* 3-benzylbicyclo[1.1.1]pent-1-ylphosphonate (**7a-O** or **9-S**) containing PhCHD. No deuterium incorporation into recovered starting material could be detected. Kinetic chain lengths of the order 30–50, recorded in Table 2, show these reactions to be reasonably efficient chain processes. (MS data on which Table 2 is based are found in the Supporting Information.)

Dialkylamino groups have been shown to be readily displaced from phosphorus by *tert*-butoxy radicals¹⁵ which undoubtedly form strong phosphorus–oxygen bonds. Reaction of phosphoramidite **6c** with [1.1.1]propellane (**1**), under conditions of photoinitiation by tetramethyltetrazine (Me₂NN=NNMe₂) at 0 °C, gave only trace amounts of insertion product **7c**, presumably generated by attack of **5c** (R = Me₂N) on phosphoramidite **6c** (eqs 3 and 4). However, at higher temperatures (24 °C), use

of near-stoichiometric amounts of initiator (0.77 mmol **6c**, 0.60 mmol tetramethyltetrazine) and higher dilution in C₆D₆ gave insertion product **7c**, isolated as the sulfide (**7c-S**) (85% purity). The initial product **7c** was evident in the crude reaction mixture from its ³¹P NMR resonance at δ 171.9. The isolated yield of **7c** in Table 5 (7%) takes into account its 85% purity and is a rough estimate at best in view of the very low conversion of phosphoramidite **6c**. ¹H NMR parameters from the 85% pure **7c-S** sample were readily assignable by comparisons to analogous compounds, **7b-O**, **9-S**, and **12**. GC-MS fragmentation patterns and HRMS confirmed the assignment (see later paragraph and Experimental Section).

Free-Radical Arbuzov-Propellane Insertion Reactions.

The potential reaction of 3-substituted bicyclo[1.1.1]pent-1-yl intermediate **5a** (R = PhCH₂), formed via eq 3, with benzyl dimethyl phosphite (**11**) to yield adduct phosphonate **12** (eq 5) was explored. The optimal conditions determined for this reaction involved photoinitiation by BPMDA, rather than di-*tert*-butyl peroxide, and use of excess **11** (Table 1). Both ³¹P NMR (61%) and isolated (45%) yields of **12** are quite good.



Insertion product **12**, a solid, was thoroughly characterized by ³¹P, ¹H, and ¹³C NMR spectroscopy, GC-MS fragmentation patterns, and HRMS (see later paragraph and Experimental Section). When the reaction was run with an excess of [1.1.1]-propellane (**1**) (0.57 mmol of **11**, approx. 1 mmol of **1**), the crystalline bis adduct (**10-O**) was isolated in 8% yield (11% NMR yield). By contrast the substitution-insertion reactions, discussed earlier, of **6a** and **6b** with [1.1.1]propellane (**1**) to yield **7a** and **7b** (eq 4) gave bis adducts, e.g., phosphonite **10** (reactions of **1** with **6a**), in only barely detectable amounts (GC/MS evidence only). (See Experimental Section and later paragraph for characterization of **10-O**.)

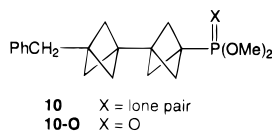
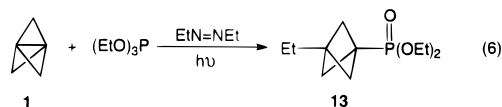


Table 2 records the kinetic chain length for formation of **12**, again determined by use of deuterated BPMDA. The chain mechanism assumed is the repeating steps of eqs 3 (R = PhCH₂) and 5 and again is reasonably efficient. (The involvement of a phosphoranyl radical in reaction 5 will be discussed below.) The lower number (28) determined at higher conversions of phosphite **11** probably reflects the decrease in rate of chain-carrying step 5 as the concentration of **11** decreases, and other processes compete more effectively for 3-substituted bicyclo[1.1.1]pent-1-yl radical **5a**.

A less efficient radical-Arbuzov trapping of **5** by a phosphite ((EtO)₃P) is seen in the overall reaction 6 (presumed intermediate **5d**, R = Et). Under conditions that were successful for reaction 5 (Table 1), **no 13 could be detected**. The use of (EtO)₃P as solvent at 0 °C likewise did not give insertion product **13**. Large quantities of a waxy material were formed, along with what may be polymeric phosphonates. Use of azobisethane instead of di-*tert*-butyl peroxide, however, was successful when the reaction was carried out at 24 °C instead of 0 °C. Additionally, more dilute conditions were employed along with



excess phosphite (phosphite/**1** approximately 12) and a lower phosphite/azobisethane ratio. Isolable amounts of phosphonate **13** were obtained. The ³¹P NMR yield, about 15% (6% isolated), was based on total starting [1.1.1]propellane (**1**) instead of (EtO)₃P, because the very low conversion of the phosphite could not be accurately measured.

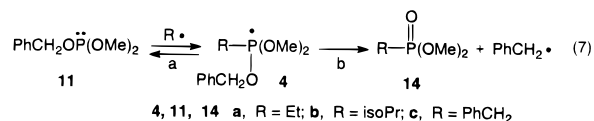
Finally, a reaction parallel to eq 6 was carried out at 0 °C with (MeO)₃P (40 mmol) in 30 mL of an ether solution of crude [1.1.1]propellane (**1**) using BPMDA (0.85 mmol) as the radical source. Insertion product, phosphonate **12** (identified by comparison of spectral data to those of **12** from reaction of **6a** with **1**) was generated in low, undetermined yield along with some bis adduct **10-O** (R = PhCH₂). A large amount of bibenzyl also was formed. This is clearly a nonchain process. Furthermore, the analog of **12** with methyl in place of benzyl apparently also was formed (GC-MS evidence only).

Evidence for Product Structure from NMR and MS Data.

Detailed listings of ³¹P, ¹³C, and ¹H NMR data for the insertion products **7-O**, **9-S**, **10-O**, **12**, and **13** are found in the Experimental Section and fully support the structures written. Indicative of the incorporation of the bicyclo[1.1.1]pentyl ring system were the ¹H chemical resonances for the methylene groups of that ring at δ 1.72–1.94 that featured three-bond couplings to phosphorus of 0.9–1.3 Hz. Molecules containing a methylene group attached to the bridgehead carbon, i.e., **7a-O**, **9-S**, **12**, and **13** (substituent at C3 = CH₂CH₃, CH₂C₆H₅), resulting from addition of ethyl or benzyl radicals to [1.1.1]-propellane (**1**) (eq 3), displayed 0.7–1.5 Hz five-bond proton-phosphorus couplings. The ring methylene carbon resonances of the insertion products all appeared at δ about 50 ppm with ²J_{CP} ≈ 2 Hz. Bridgehead carbons (C1, C3) were distinguished by large couplings to phosphorus (¹J_{CP} ≈ 150 Hz, ³J_{CP} ≈ 50 Hz). The products **7b-O**, **9-S**, **10-O**, and **12** displayed long-range ⁴J_{P-C} couplings, transmitted through the bicyclo[1.1.1]pentyl framework, of 25.8–26.9 Hz.

The EI/MS fragmentation patterns for **7a-O**, **7b-O**, **7c-S**, **9-S**, **12**, and **13** strongly supported their structures. Peaks assignable to the 3-substituted bicyclo[1.1.1]pent-1-yl ion, the (MeO)₂P(O) or (EtO)₂P(O) ion, and the 3-substituents were seen in each case and often had intensities 10–25% or more of the base peak. The spectral parameters, NMR and MS, compare well to those found for many other molecules containing the bicyclo[1.1.1]pentyl structural unit.²

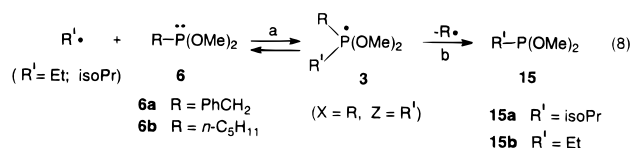
Nonchain Reactions of Alkyl Radicals with Trialkyl Phosphites and Phosphonites 6a and 6b. In order to better evaluate the propensities of 3-substituted bicyclo[1.1.1]pent-1-yl radicals, formed via reaction 3, to participate in free radical substitution (eq 4) and Arbuzov (eq 5) reactions with those of other radicals, parallel comparison reactions of primary and secondary alkyl radicals and benzyl radicals were carried out. Equation 7 depicts the potential *nonchain free radical Arbuzov reaction* of alkyl radicals with dimethyl benzyl phosphite (**11**) to yield dimethyl alkylphosphonates **14a-c**, presumably via phosphoranyl radical **4**. When deoxygenated benzene solutions,



0.23 M in both azobisethane and **11**, were irradiated at 24 °C

through Pyrex, a 90% yield of **14a** (R = Et) resulted, based on consumed phosphite **11** (18%), along with generous amounts of bibenzyl. This finding is clearly consistent with the operation of the two-step process depicted by eq 7 which is analogous to process 2. Significantly, the benzyl radicals generated *failed to take part in a potential chain reaction analogous to 7 but with R = PhCH₂*. Thus, no dimethyl benzylphosphonate (**14c**) was noted (³¹P NMR, GLC). By contrast to the case with azobisethane, the parallel photogeneration of isopropyl radicals from azobisisopropane (0.28 M) in a 0.35 M benzene solution of phosphite **11** did not yield dimethyl isopropylphosphonate (**14b**) or any other new phosphorus-containing molecule (³¹P NMR).¹⁸ Furthermore, the photolysis of azobisethane (0.27 M) in benzene solution 0.28 M in (MeO)₃P or (EtO)₃P led to no new phosphorus-containing products (e.g., EtP(O)(OMe)₂ or EtP(O)(OEt)₂) or evidence for consumption of the phosphites (³¹P NMR) by any other reaction.

However, isopropyl radicals, photogenerated in deoxygenated benzene, were reactive with phosphonite **6a** in a substitution process, eq 8 (R' = isoPr), to generate dimethyl isopropylphosphonite (**15a**) with bibenzyl as biproduct. The yield of dimethyl isopropylphosphonite **15a**, based on conversion of **6a** (69%), was 36% (³¹P NMR of the unoxidized product mixture, tri-*n*-propyl phosphate internal standard). Ethyl radicals also reacted cleanly (³¹P NMR) with dimethyl benzylphosphonite (**6a**) according to eq 8 to form dimethyl ethylphosphonate **15b**. (The



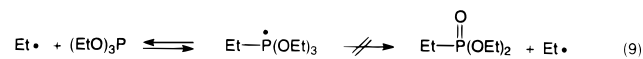
yield of **15b** was not determined.) However, the isopropyl radical failed to replace the presumably more strongly bound, less stable *n*-pentyl radical from the *n*-pentylphosphonite **6b** to form isopropylphosphonite **15a**.

Discussion

Nonchain Radical Substitution and Arbuzov Reactions of Alkylphosphonites and Phosphites. These processes are expressed in terms of the assumed phosphoranyl radicals, **3** and **4**, by eqs 7 (Arbuzov) and 8 (substitution). For these processes to proceed, the intermediates **3** and **4** must be accessible kinetically, and the overall reactions must be thermodynamically favorable. The results reported above established an ability to effect overall Arbuzov reaction or substitution, reactions for radicals R (eq 7) and R' (eq 8) of Et > *i*-Pr > PhCH₂.

Thus, in the radical Arbuzov reactions (eq 7), ethyl radical reacts readily with PhOCH₂OP(OMe)₂ (**11**) to generate dimethyl ethylphosphonate (**14a**). However, the benzyl radical, generated on β scission of **4**, fails to react analogously with PhCH₂OP(OMe)₂ (**11**) to yield PhCH₂P(O)(OMe)₂ (**14c**). Similarly, isopropyl radicals, generated independently in the presence of phosphite **11**, do not give *i*-PrP(O)(OMe)₂ (**14b**). Clearly β scission of intermediate **4**, when R = Et, is rapid enough to compete with the reverse of step 7a (α scission) to regenerate **11** and ethyl radical. When R is an *i*-Pr or benzyl radical, β-scission of **4** to yield phosphonate **14b** or **14c** does not compete with a more rapid α scission which now gives more stable radicals, isopropyl and benzyl. The fact that exchange of deuterium labeled benzyl radical with **6a** (eq 8) is not observed makes questionable the ability of the very stable benzyl radical to bond to three-coordinate phosphorus to form either **3** or **4**.

The failure of ethyl radical to react in radical-Arbuzov fashion with (EtO)₃P, when its reaction with **11** (eq 7) occurs so readily, can be easily understood in terms of the relatively slow β scission of the phosphoranyl radical of sequence 9 (analogous to reaction 7) which cannot compete with α scission to reform ethyl radical and the phosphite. These results give chemical confirmation to previously reported ESR studies of the reversible



addition of methyl radical to PhCH₂OP(OMe)₂, (MeO)₃P and (EtO)₃P. Only PhCH₂OP(OMe)₂ gave evidence of β scission, i.e., the rapid formation of benzyl radical (eq 7, R = Me•), though reversible phosphoranyl radical formation was noted in other cases.¹⁷ For the process (EtO)₃P → EtP(O)(OEt)₂ ΔH° has been measured (-25 kcal/mol).²² However, kinetic factors preclude its catalysis by ethyl radicals.

Both ethyl and isopropyl radicals replace benzyl radical in PhCH₂P(OMe)₂ (**6a**) in a radical substitution process, eq 8. This is a reasonable result in terms of the overall thermodynamics of process 8 with these combinations of R and R' radicals. It also likely means that isopropyl radical is able to bond to **11** and **6a** to form both **4** and **3**, respectively. However, only in reaction 8 is the scission step (α-scission, eq 8, 3 → 15a) rapid enough to give product formation in competition with reversal of the formation of **3** and **4**. Indeed, α scission is often more rapid than competing β scission options for phosphoranyl radicals.³ The failure of isopropyl radical to replace *n*-pentyl radical from phosphonite **6b** to afford **15a** is totally consistent with the unfavorable thermodynamics of the overall process and the faster α scission reforming reactants (reverse of reaction 8a).

The kinetics and thermodynamics of formation of **3** and **4**, of course, are closely intertwined in that for a reversible endothermic process, the activation free energy is at least as great as the free energy change for the reaction. Thus it was noted that the *thermoneutral* exchange of benzyl groups was not observed when deuterium-labeled benzyl radical was generated in the presence of PhCH₂P(OMe)₂ (**6a**). Likely, the formation of **3** (R = R' = PhCH₂) is thermodynamically and kinetically unfavorable.

Earlier work from this laboratory showed that a facile radical Arbuzov reaction ensues (reaction 7) with PhCH₂OP(OMe)₂ when R = Me₂N but not with (MeO)₃P and (EtO)₃P.¹¹ Clearly, the dimethylamino radical (like the ethyl radical) bonds sufficiently well to add reversibly to phosphorus; but product formation requires rapid subsequent β scission. Phenyl radical, however, forms a strong bond with phosphorus. Phosphites of all kinds undergo radical Arbuzov reactions, as exemplified by sequence 2, when R = Ph and R' = Me. We have shown the formation of **4** to be highly irreversible for R = Ph.¹⁶

There are then three general classes of reactions of free radicals with three-coordinate phosphorus.¹⁴ When the radical bonds too weakly to phosphorus (e.g., benzyl), no reaction ensues. When the bonding is reversible (e.g., ethyl and dimethylamino), a sufficiently rapid α or β scission step will trap the intermediate phosphoranyl radical to generate stable product. Irreversible formation of the phosphoranyl radical intermediate by radicals such as phenyl that form very strong bonds to phosphorus gives product even in the absence of particularly rapid α or β scission step. Irreversible oxidative addition occurs with alkoxy, thyl, and phenyl radicals and is

(22) Lewis, E. S.; Colle, K. S. *J. Org. Chem. Soc.* **1981**, *46*, 4369. An earlier estimate of -44 kcal/mol was based on measured and calculated heats of formation from the literature.^{12b}

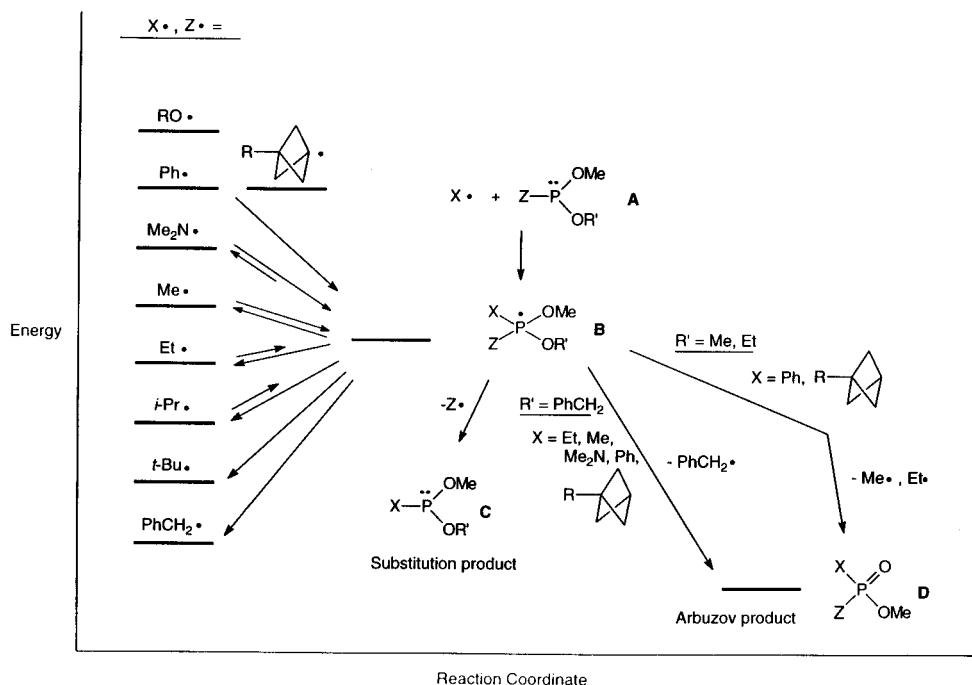
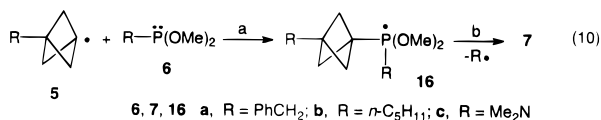


Figure 1. Free-radical Arbusov and substitution reactions. Energetics of phosphoranyl radical formation and subsequent α and β scissions.

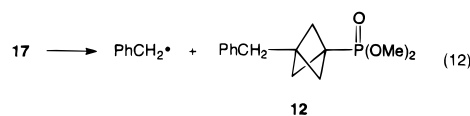
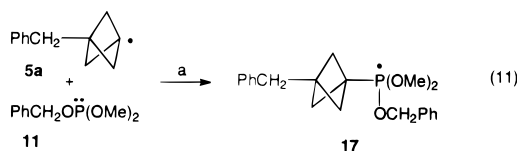
then followed by α scission (substitution) or β scission with transfer of attacking oxygen or sulfur (oxidation). These ideas are depicted energetically in Figure 1, which includes both substitution and Arbusov processes using a single reactant **A**, and will be discussed more thoroughly below.^{14,23}

Free-Radical Chain Substitution-Insertion and Arbusov-Insertion Reactions. The above studies of free-radical reactions of dimethyl benzylphosphonite (**6a**) and *n*-pentylphosphonite (**6b**) and the free-radical Arbusov reactions of trialkyl phosphites provide a background against which to assess the propensity of 3-substituted bicyclo[1.1.1]pent-1-yl radicals (**5**) to undergo analogous reactions. The observed radical insertion-substitution processes that incorporate the bicyclo[1.1.1]pent-1-yl moiety into **7** are reasonably depicted by a chain sequence, reactions 3 and 10. The results in Table 1 show that radical **5** is able to attack phosphorus (eq 10a) to displace not only benzyl radical to give **7a** but also the primary *n*-pentyl radical to yield **7b**. This means that the new phosphorus–carbon bond formed in **7b** is not only stronger than the phosphorus–carbon bond to the benzyl substituent broken in **6a** but is even *stronger than the n-pentyl-phosphorus bond in 6b*. For **7a** a mean chain length of about



45 was measured (Table 2), along with a similar number, close to 30, for the analogous reactions of *cis*- and *trans*-**8**. Reactions 3 and 10 are evidently both reasonably efficient.

Equations 3, 11, and 12 account nicely for the reaction of **1** with PhCH₂OP(OMe)₂ in the radical Arbusov-insertion process that provides **12** (reaction 5). Like the reaction of **6a** via process 8, reactions 11 and 12 are quite efficient, as indicated by the measured mean chain length of 30–40. Evidently, both α scission (step 10b) and β scission (step 12) are rapid when the relatively stable benzyl radical is formed. The benzyl radical



then reacts readily with [1.1.1]propellane (**1**) to give **5a** in chain carrying reaction 3.²⁵ Remarkably, as in the substitution reaction (eq 8), the *tertiary* 3-benzylbicyclo[1.1.1]pent-1-yl radical (**5a**) evidently forms a stronger bond to phosphorus in **17** than does the unreactive *secondary* isopropyl radical and, by this comparison, a bond *at least* comparable in strength to that formed by ethyl radical. (Recall that the isopropyl radical fails to react with PhCH₂OP(OMe)₂ (eq 7, R = *i*-Pr), while ethyl radical gives the phosphonate EtP(O)(OMe)₂; and radical **5d** with (EtO)₃P yields phosphonate **13**.) In the chain reactions of both **6a** (via eq 3 and 10) and **11** (via eq 3, 11, and 12), a relatively stable benzyl radical that is unreactive toward three-coordinate phosphorus is trapped by addition to [1.1.1]propellane (**1**) to give a reactive radical (**5a**) able to propagate a free-radical chain process by oxidative addition to phosphorus.¹⁰ *These constitute novel processes to give modest yields of structurally unusual products, 7 and 12.* In fact bis adduct **10-O**, which incorporates two molecules of [1.1.1]propellane (**1**), results on reaction of PhCH₂OP(OMe)₂ **11** but not PhCH₂P(OMe)₂ **6a**. This indicates that attack by 3-benzylbicyclo[1.1.1]pent-1-yl radical **5a** on the phosphorus of **6a** and subsequent α scission, are more efficient than attack on PhCH₂OP(OMe)₂ **11** followed by β scission. This result also is consistent with the trapping of the isopropyl radical by PhCH₂P(OMe)₂ **6a** but not by PhCH₂OP(OMe)₂ **11**.

Additional evidence that the 3-substituted bicyclo[1.1.1]pent-1-yl radical forms an especially strong bond to phosphorus is

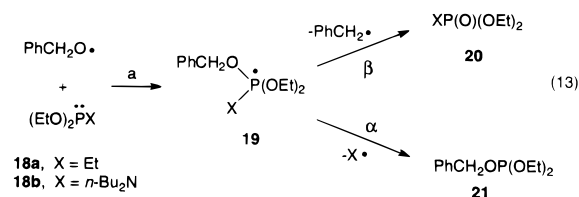
(24) Tables of average bond strengths for these substituents are recorded in ref 10 a–c, f, and 16.

(25) The addition of PhCH₂Br to [1.1.1]propellane (**1**), presumably involving attack benzyl radical on [1.1.1]propellane (**1**), is well documented although yields were not reported.^{2a,n}

(23) For earlier presentations of figures similar to Figure 1 that represent the potential reactions of free radicals with three-coordinate phosphorus molecules, including substitution, oxidation, and free-radical Arbusov, see refs 10a,b,c,f, 15, and 16.

the observed reaction (eq 10, R = Me₂N) at room temperature of 3-(dimethylamino)bicyclo[1.1.1]pent-1-yl radical **6c** (R = Me₂N) with (MeO)₂PNMe₂ (**6c**) to displace dimethylamino radical. This provides substitution-insertion product **7c** (R = Me₂N) in a process that requires the phosphorus–carbon bond of **7c** to be stronger than the phosphorus–nitrogen bond broken in **6c**.

For comparison, the experimentally determined average bond strength of the phosphorus–carbon bond in Et₃P is 62 kcal/mol²⁴ and that of the phosphorus–nitrogen bond in (Me₂N)₃P is 69 kcal/mol.^{24,26} This difference in bond strengths also is reflected in the relative rates of α -scission in the phosphoranyl radical derived from addition (eq 13) of benzyloxy radical to (EtO)₂Pet (**18a**) and (EtO)₂PNBu_{2-n} (**18b**). For **18a** the ratio of **20** (β scission) to **21** (α scission) is 0.19. The same ratio (**20/21**) for **18b** is 1.7. On the premise that the weaker bond would undergo α scission more rapidly, it is apparent that the P–Et bond is weaker than the P–NBu₂ bond. The difference in the efficiencies of the reactions of *n*-C₅H₁₁P(OMe)₂ (**6b**) and Me₂NP(OMe)₂ (**6c**) with [1.1.1]propellane (**1**) is likely due to the difference in bond strengths (i.e., *n*-C₅H₁₁-P < Me₂N-P). Thus, *n*-C₅H₁₁P(OMe)₂ (**6b**) undergoes a much more efficient reaction with [1.1.1]propellane (**1**) than does Me₂NP(OMe)₂ **6c**. A *tert*-butoxy radical from photolysis of di-*tert*-butyl peroxide

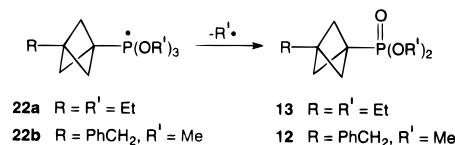


18a, X = Et
18b, X = *n*-Bu₂N

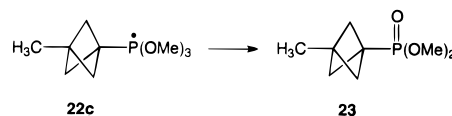
displaces *n*-pentyl radical from **6b** to initiate the process. In the chain reaction represented in steps 3 and 10, the *n*-pentyl radical is again readily generated on α scission of phosphoranyl radical **16b**, even at 0 °C. By contrast, the reaction of Me₂NP(OMe)₂ (**6c**) with [1.1.1]propellane (**1**) requires a higher temperature (24 °C) and a high flux of dimethylamino radicals from near-stoichiometric amounts of Me₂NN=NNMe₂ to give reasonable quantities of the 3-(dimethylamino)bicyclo[1.1.1]pent-1-ylphosphonate (**7c**) in a process with a short kinetic chain length at best. The higher temperature, along with dilute reaction conditions, ultimately allows the α scission of the P–N bond of phosphoranyl radical **16c** to compete with the dominant formation of polymer observed under normal conditions (0 °C and higher concentrations of [1.1.1]propellane (**1**)). Nevertheless, the tertiary bicyclo[1.1.1]pent-1-yl radical **5c** was able to displace the dimethylamino radical (eq 10, R = Me₂N). Clearly, bicyclo[1.1.1]pent-1-yl substituent **5** forms a stronger bond to three-coordinate phosphorus than do the *n*-pentyl and dimethylamino groups.

Most dramatic, however, is the ability of the 3-ethylbicyclo[1.1.1]pent-1-yl radical (**5d**, R = Et), generated under dilute conditions from near stoichiometric quantities of azobisethane, to react with (EtO)₃P at 24 °C to form **13**. This requires the 3-ethylbicyclo[1.1.1]pent-1-yl radical (**5d**) to bind tightly, and presumably irreversibly, to phosphorus in phosphoranyl radical **22a** so that generation of ethyl radicals via β scission of the O–Et bond can take place at 24 °C. The higher temperature (24 °C) facilitates the β scission of **22a**. (As a model for this

process, the β scission of (EtO)₄P• at 0 °C has a rate constant¹⁷ of only 3 × 10² s⁻¹.) Moreover, 3-benzylbicyclo[1.1.1]pent-1-yl radical **5a** (R = PhCH₂), formed on photolysis of stoichiometric amounts of BPMDA in the presence of [1.1.1]propellane (**1**), reacted with (MeO)₃P, even at 0 °C, to yield small amounts of insertion product **12**. This requires β scission of the even stronger O–Me bond of phosphoranyl radical **22b**. Though this β scission is relatively slow, the methyl radicals from **22b** initiated formation of minor amounts of phosphonate **23** via phosphoranyl radical **22c**.



Free radical Arbuzov reactions of (MeO)₃P and (EtO)₃P with ethyl radicals, as noted above, do not occur. Normally, only phenyl radicals carry out such a reaction (eq 2, R = Ph, R' = Me¹²). Phenyl radicals, which are σ radicals with the odd electron in an sp² hybridized orbital, no doubt form relatively strong bonds to phosphorus in the intermediate phosphoranyl radical.^{12d,e} Moreover, the latter, based on ESR evidence, is



electronically best represented by structure **24** with the odd electron in a π^* orbital.²⁷ Such a ligand- π^{10d} phosphoranyl radical may have intrinsic stability greater than that of the more usual near-trigonal bipyramidal species like **3** and **4** of the present study. The oxidative addition of 3-ethylbicyclo[1.1.1]pent-1-yl radicals (**5d**) to triethyl phosphite to give phosphoranyl radical **22a** followed by its β scission to generate phosphonate **13**, finds precedent in the recently reported reaction of 3-(methoxycarbonyl)bicyclo[1.1.1]pent-1-yl radicals with (EtO)₃P at 30 °C to give a 28% yield of **25**.^{2d}



The above results show the propensity of a 3-substituted bicyclo[1.1.1]pent-1-yl radical to add oxidatively to three-coordinate phosphorus to be similar to that of a phenyl radical. This behavior is a reflection of the high degree of *s* character in the bridgehead orbital containing the odd electron which results from the pyramidal nature of this strained radical. Indeed, ESR measurements of ¹³C hyperfine splittings at the bridgehead carbon of the bicyclo[1.1.1]pent-1-yl radical allow assignment of 20% 2*s* character to the orbital bearing the odd electron and lead to an estimation of 100° for the bridgehead C–C–C bond angle for this highly pyramidal species.^{8,9} Bicyclo[1.1.1]pent-1-yl radicals, therefore, differ markedly from *tert*-butyl radicals which are estimated by theoretical calculations²⁸ and ESR measurements²⁹ to be bent only 11–24° from planarity.^{27,28} Furthermore, theoretical and experimental evidences have been presented for the increased strength of bonds formed to the bridgehead carbon of various bicyclo[1.1.1]-

(26) A somewhat higher average bond strength (and in our view an unreasonably high one) is calculated using a more recent heat of formation of the dimethylamino radical. Golden, D.; Solly, R. K.; Gac, N. A.; Benson, S. W. *J. Am. Chem. Soc.* **1972**, *94*, 363.

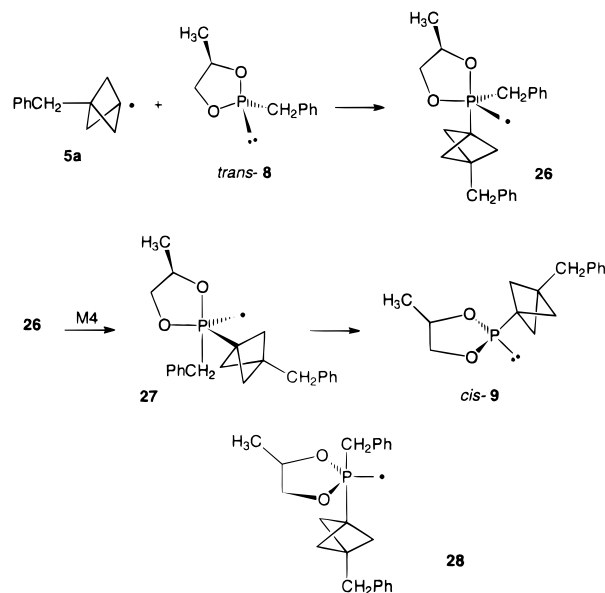
(27) (a) Davies, A. G.; Maxwell, J. P.; Roberts, B. P. *J. Chem. Soc., Chem. Commun.* **1974**, 973. (b) Boeckstein, G.; Jansen, E. H. J. M.; Buck, H. M. *J. Chem. Soc., Chem. Commun.* **1974**, 118.

pentanes.^{1d,2d,6,30} This is undoubtedly true also of bonds formed to phosphorus in phosphoranyl radical intermediates and in their products of α and β scission. These factors, combined with potentially reduced steric interactions with the phosphorus center, give the bicyclo[1.1.1]pent-1-yl radical a thermodynamic and presumably also kinetic propensity toward reaction with three-coordinate phosphorus that is greater than that of other alkyl radicals (primary, secondary, or tertiary) and commensurate with that of the phenyl radical.

Energetics and Kinetics of Reactions of Free Radicals with Three-Coordinate Phosphorus. The approximate relative energetics of addition of free radicals to three-coordinate phosphorus and the alternative α and β scission routes available to the phosphoranyl radical formed are shown in Figure 1.^{14,23} A reactant, **A**, is employed that combines processes 1 and 2, substitution and free-radical Arbuzov reactions, through a single phosphoranyl radical intermediate, **B**. The average P–X bond strengths for several PX_3 are known experimentally:²⁴ X = MeO, 84 kcal/mol; X = Ph, 77 kcal/mol; X = NMe₂, 69 kcal/mol; X = Et, 62 kcal/mol. This allows the radicals to be ordered along the energy axis such that the approximate thermodynamic ease of generation of a given radical (**Z**[•]) by its replacement by a particular attacking radical (**X**[•]) is indicated. For the carbon radicals methyl through benzyl, the ordering comes from relative radical stabilities and presumed consequent energies of the bonds formed to phosphorus in **A** and **C**, even though average bond strength values are available only for Me₃P (67 kcal/mol) and Et₃P (62 kcal/mol).²⁴ No attempt is made to precisely space the energies of the various **Z**[•] or **X**[•]. However, for addition of methyl radical to (EtO)₃P, ΔH° has been determined to be –7 kcal/mol,¹⁷ a value used to guide the placement of the methyl radical (and hence the others relative to it) along the energy axis with respect to the phosphoranyl radical **B**. We previously estimated the highly irreversible oxidative addition of a phenyl radical to a phosphite to be exothermic by 10–13 kcal/mol.¹⁶ The assumption is made that variations in X and Z attached to **B** will not greatly affect its energy. Figure 1 then allows one to compare the thermodynamics of formation of phosphoranyl radical **B** by oxidative addition of various **X**[•] to **A** followed by loss of **Z**[•] (α scission) to give **C** (radical substitution product) or β scission to give **D** (radical Arbuzov product). The difficulty of forming **B** by oxidative addition of the more stable radicals to **A** is readily apparent.

Depicted by Figure 1 are the *three classes of reactivity* mentioned above.^{14,23} Relatively stable radicals (isopropyl, *tert*-butyl, and benzyl) bond weakly or *not at all* to phosphorus in **B**. The failure, shown in this study, of isopropyl to replace *n*-pentyl (thermodynamically unfavorable) and benzyl to replace benzyl (energetically inaccessible **B**) are consistent with Figure 1. The *second* class of radicals, dimethylamino, methyl, and ethyl, form stronger bonds to phosphorus, but bonding is *reversible* and only leads to free radical Arbuzov product when R' is benzyl whereupon rapid β scission ensues. Substitution potentially can occur if the radical to be displaced is lower on the energy scale than the attacking radical (e.g., dimethylamino radical should readily replace an alkyl radical.) The replacements of benzyl by isopropyl and ethyl radicals and failure of isopropyl radical to displace *n*-pentyl, reported in the present research, are in accord with Figure 1. Those radicals that form

Scheme 1



very strong bonds to phosphorus (alkoxy, phenyl, and 3-*substituted* bicyclo[1.1.1]pent-1-yl) constitute a *third* class, those that react *irreversibly* and give radical-Arbuzov product even when the alkyl radical formed on β scission is less stable than benzyl (e.g., ethyl or methyl) and is formed more slowly. The 3-*substituted* bicyclo[1.1.1]pent-1-yl radical (**5**) is grouped with the phenyl radical in Figure 1. These radicals, of course, readily replace those below them on the energy scale in substitution processes, as exemplified in this study by the reactions of **5** with **6a–c**.

Stereochemistry of Free Radical Displacement-Insertion.

The predominant inversion stereochemistry of the reactions of *cis*- and *trans*-2-benzyl-5-methyl-1,3,2-dioxaphospholanes (*cis*- and *trans*-**8**) to form the displacement-insertion products *cis*- and *trans*-**9** is completely consistent with the known inversion stereochemistry of other radical substitutions at phosphorus that were reported earlier by the Bentrude group.³¹ A rationale for this outcome is depicted in Scheme 1. Radical **5a** is introduced into trigonal bipyramidal **26** axially in keeping with conclusions from ESR studies of α scission reactions (the microscopic reverse).³² The benzyl group is then moved to the axial position (**27**) from which it leaves (α scission) to yield product (*cis*-**9**). The overall result is substitution with inversion at phosphorus. The isomerization of **26** to **27** is of mode 4, as defined by variable temperature ESR studies³ of the kinetics of such processes when phosphorus is included in a 1,3-dioxaphospholane ring. Theoretical calculations also support mode 4 low-barrier processes for at least certain phosphoranyl radicals.³³ A straightforward inline process via **28** also would proceed with inversion at phosphorus. However, the stereochemical consequences of initial formation of intermediate **26** must be considered because of the known *thermodynamic* preference of such rings to be attached in apical–equatorial fashion³ which also may be true kinetically.

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Conclusions

The above results demonstrate the great ease of reaction of 3-substituted bicyclo[1.1.1]pentyl radicals (**5**) with three coordinate phosphorus. E.g., free radical Arbuzov reactions with $(\text{EtO})_3\text{P}$, that only occur with the very reactive phenyl radical, are found for **5**. The replacement of a primary radical, the *n*-pentyl, by **5** further shows the propensity of these highly pyramidal tertiary radicals (**5**) to bond to three-coordinate phosphorus. Moreover, [1.1.1] propellane (**1**) is able to trap free radicals (eq 3) to give 3-substituted bicyclo[1.1.1]pentyl radicals (**5**) that participate in chain carrying reactions 4 and 5 as part of reasonably efficient radical chain processes (chain lengths 30–50). Reactions 4 and 5 involve the key α scission step of radical substitution (eq 10b) and β scission step of the free radical Arbuzov process (eq 12) and yield novel products, e.g., **7** and **12**, featuring the insertion of the bicyclo[1.1.1]pentane structure. These chain processes are enabled by the ability of **5** to form strong bonds to three-coordinate phosphorus molecules (eqs 10a and 11a). The propensities of various radicals, including **5**, to bond to three-coordinate phosphorus and promote radical substitution or radical-Arbuzov reactions are summarized in Figure 1 in which three reactivity classes of radicals are depicted.

Experimental Section

Materials. Ether (Et_2O) and tetrahydrofuran (THF) were distilled from sodium/benzophenone under nitrogen. Benzene (Baker Phortrex) was used as received. Acetonitrile was distilled over calcium hydride under nitrogen. Benzene- d_6 (C_6D_6) was degassed prior to use by purging with argon. Triethyl phosphite and trimethyl phosphite were distilled from sodium prior to use. *Cis*- and *trans*-**7**, bis(phenylmethyl)diazene,³⁴ azobisethane (Et_2N_2),³⁵ azobisisopropane (*i*- Pr_2N_2),³⁶ and tetramethyltetrazene (TMT)³⁶ were prepared by literature procedures. Et_2NPCI_2 , *i*- Pr_2NPCI_2 , $(\text{MeO})_2\text{PNEt}_2$, and *i*- $\text{Pr}_2\text{NP}(\text{OMe})_2$ were prepared by standard methods.³⁷ In the **Supporting Information Available** may be found details of the nearly routine preparations of [2,2'-*H*]bis(phenylmethyl)diazene, **6a**, **6b**, **6c**, **11**, and **15b**. Unless otherwise noted, all distillations were performed using a short-path apparatus.

Physical Methods. Melting points were obtained on a Thomas Hoover Capillary Melting Point apparatus and are uncorrected. ^1H , ^2H , ^{13}C , and ^{31}P NMR spectra were obtained on Varian XL-300 and Unity 300 NMR spectrometers. Some ^{31}P NMR spectra were taken on a Varian FT-80 NMR. The 125 MHz ^{13}C NMR spectra were measured on a Varian VXR-500 NMR spectrometer. Chemical shifts (δ) are recorded in parts per million with respect to tetramethylsilane (0.00) with the solvent as an internal standard for the ^1H , ^2H , and ^{13}C NMR spectra: (C_6HD_5) (^1H) 7.15, (^{13}C) 128.0; CHCl_3 (^1H) 7.24, (^{13}C) 77.0; C_6DH_5 (^2H) 7.15). A capillary of external 85% H_3PO_4 in C_6D_6 or CDCl_3 served as reference for the ^{31}P NMR spectra. GC-EIMS (70 eV) analyses were done on a Hewlett-Packard 5971A Mass Selective Detector utilizing a 5890 Series II Gas Chromatograph equipped with a 30 m X 0.25 mm HP-5 on fused silica capillary column. Other low resolution EIMS (70 eV) along with HRMS (EI, 70 eV) data were obtained on a Finnegan MAT 95 gas chromatograph/mass spectrometer. Intensities (parentheses) are reported as a percent of the base peak intensity. The molecular ion is designated as $[\text{M}]^+$. Because of the small scale of the reactions, HRMS rather than elemental analyses were obtained for new compounds.

HPLC separations and product isolations (isocratic) were done with a Waters 590 solvent delivery system and either an ISCO V⁴ UV or

Waters Differential Refractometer detector using Waters μ Porasil (25 \times 0.46 cm) and Rainin Microsorb Dyanmax 60A silica columns (25 \times 2.14 cm).

[1.1.1]Propellane (1) was prepared in ether according to the procedure of Szeimies et al.³⁸ from the reaction of 1,1-dibromo-2,2-bis(chloromethyl)cyclopropane (ca. 20 mmol scale) with methyl lithium (ca. 40 mmol). Volatile products, including [1.1.1]propellane (**1**), were distilled at 30–40 mmHg (water aspirator) into a flask cooled to -78°C in which crude [1.1.1]propellane (**1**) was stored prior to purification. Neat [1.1.1]propellane (**1**), employed in preparing most of the reaction solutions, was isolated by preparative GLC on 15% Apiezon L or 15% SE-30 on Chromosorb W utilizing a 25 ft \times 1/4 in. column operated at ambient temperature. A 3–5 mL portion of the ether solution of crude [1.1.1]propellane, warmed to warm temperature, was injected directly on column via a 5.00 mL Hamilton gastight Teflon luerlock syringe. Neat [1.1.1]propellane (10–30 mg/injection) was collected at -78°C .

General Procedure for the Reactions of Three-Coordinate Phosphorus Molecules with [1.1.1]Propellane. All operations with the exception of weighings were done in a glove bag under a N_2 atmosphere. Liquid transfers were made by syringe techniques. Thus, 1–2 mmol by weight of the three-coordinate phosphorus compound were transferred to a vial to which was added a solution of 0.05 mmol of initiator in 100 μL of degassed C_6D_6 . By way of a Hamilton 250 μL Teflon plunger luerlock syringe, 30–50 μL of neat [1.1.1]propellane (30–50 μL), isolated by preparative GLC, was added to a nitrogen-flushed quartz test tube (12 mm \times 40 mm), fitted with a rubber septum, and maintained at -78°C under a N_2 sweep. For reactions for which yields (based on [1.1.1]propellane) were determined, the quartz test tube was immediately reweighed to determine the amount of [1.1.1]propellane added. Quick transfers and weighings helped to minimize introduction of water by condensation as well as thermal oligomerization of the [1.1.1]propellane. The solution of the three-coordinate phosphorus compound and initiator was transferred from the vial to the quartz test tube maintained at -78°C . The solution was warmed to melting, agitated to insure thorough mixing, and irradiated for 1 h at 0°C (450 W medium pressure Hg lamp, filtered through a Kimax sleeve).

General Procedure for Oxidation of Reaction Products. Following irradiation the reaction mixture was transferred in a N_2 -swept glove bag to a round bottom flask, diluted to 10 mL with benzene, fitted with a stir bar, a rubber septum, and nitrogen inlet, and cooled to 0°C . Via syringe, 1.1 equiv of *tert*-butyl hydroperoxide (3.0 M in 2,2,4-trimethylpentane) was added. The solution was stirred for 1 h at 0°C , and the solvent was removed in vacuo.

General Procedure for Sulfur-Oxidation of Reaction Products. To a round bottom flask were added 15 mL of degassed benzene, 3 equiv of S_8 , and 100 μL of NEt_3 . The flask was cooled to 0°C under a sweep of nitrogen with stirring. The crude photolysis mixture, diluted with benzene to approximately 1 mL, was added to the above stirred solution via a cannula. After 1 h, the reaction mixture was filtered, and the solvent was removed in vacuo.

General Procedure for Determination of Yields by ^{31}P NMR (Table 5). The residue was diluted to 2.00 mL in a volumetric flask with C_6D_6 . Unreacted and product three-coordinate phosphorus compounds were converted to the oxides as above. Yields, based on starting three coordinate phosphorus-containing material consumed, were determined by quantitative ^{31}P NMR vs a 0.317 M solution of trimethyl phosphate in C_6D_6 inserted into the NMR tube as an external standard (sealed in a capillary tube). Relative peak areas for proton-coupled spectra were measured under conditions of 60 s delay times. A series of phosphorus compounds, over a range of known concentrations, were employed to obtain a sensitivity factor of 0.42 ± 0.03 mmol/mL which was multiplied by the area ratio and the number of milliliters of solution to obtain mmol of each phosphorus compound. The yields are considered to be conservative, as some of the starting phosphorus compound is inevitably lost in transfer, resulting in lowered recovery of unreacted starting material. The oxidations may be less than quantitative as well. Avoidance of an internal standard allowed products to be isolated more readily from the same solution used for quantitation

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by ^{31}P NMR. Isolated yields, given below and in Table 5, are also based on converted three-coordinate reactant as determined by ^{31}P NMR.

For example, a solution of bis(phenylmethyl)diazene (BPMDA) (4.8 mg, 0.023 mmol), benzyl dimethyl phosphite, **11** (113 mg, 0.57 mmol), excess [1.1.1]propellane (60–70 μL , approx. 1 mmol), and 100 μL of C_6D_6 was irradiated for 1 h at 0 $^\circ\text{C}$.³⁹ The photolysis mixture was diluted to 2.00 mL with C_6D_6 . The ^{31}P NMR spectrum showed the presence of two product peaks, identified as the mono- and bis-bicyclo[1.1.1]pentylphosphonate adducts **12** and **10-O**, in addition to starting phosphite and a small amount of benzyl phosphate, resulting from oxidation. Yields, determined by quantitative ^{31}P NMR, were 45% (0.20 mmol) for the mono adduct **12** and 11% (0.048 mmol) for the bisadduct **10-O**, based on disappearance of starting phosphite. Product isolation by flash chromatography (100% ethyl acetate), followed by HPLC (100% ethyl acetate), gave 29.4 mg (0.11 mmol, 25% isolated yield) of **12** and 11.1 mg (0.033 mmol, 8% isolated yield) of **10-O**. Product dimethyl 1-(3-(phenylmethyl)bicyclo[1.1.1]pentyl)phosphonate (**12**): mp 45–46 $^\circ\text{C}$; ^{31}P NMR (121.4 MHz, CDCl_3) δ 22.51; ^{31}P NMR (121.4 MHz, C_6D_6) δ 22.71; ^1H NMR (299.9 MHz, CDCl_3) δ 1.91 (d, 6 H, CCH_2C , $^3J_{\text{HP}} = 1.1$ Hz), 2.74 (d, 2 H, CCH_2Ph , $^5J_{\text{HP}} = 1.4$ Hz), 3.69 (d, 6 H, OCH_3 , $^3J_{\text{HP}} = 10.7$ Hz), 7.03–7.34 (m, 5 H); ^1H NMR (299.9 MHz, C_6D_6) δ 1.81 (d, 6 H, CCH_2C , $^3J_{\text{HP}} = 1.0$ Hz), 2.42 (d, 2 H, CCH_2Ph , $^5J_{\text{HP}} = 1.2$ Hz), 3.40 (d, 6 H, OCH_3 , $^3J_{\text{HP}} = 10.5$ Hz), 6.82–7.20 (m, 5 H). ^{13}C NMR (75.4 MHz, C_6D_6) δ 32.80 (d, PCCH_2C , $^1J_{\text{CP}} = 161.0$ Hz), 39.50 (d, CCH_2Ph , $^4J_{\text{CP}} = 26.2$ Hz), 44.60 (d, PCCH_2C , $^3J_{\text{CP}} = 35.5$ Hz), 51.24 (d, CCH_2C , $^2J_{\text{CP}} = 2.4$ Hz), 51.58 (d, OCH_3 , $^2J_{\text{CP}} = 6.1$ Hz), 126.33, 128.58, 129.08, 138.57 (*ipso*-Ph); GC-EIMS (70 eV) *m/z* (rel intensity) 266 [$\text{M}]^+$ (36), 265 [$\text{M} - 1]^+$ (15), 251 [$\text{M} - \text{CH}_3]^+$ (32), 189 [$\text{M} - \text{Ph}]^+$ (60), 175 [$\text{M} - \text{PhCH}_2]^+$ (6), 156 (39), 155 [$\text{M} - 111]^+$ (100), 141 (51), 115 (29), 109 [$(\text{CH}_3\text{O})_2\text{PO}]^+$ (21), 91 (49), 79 (31), 77 (9), 65 (24). $\text{C}_{14}\text{H}_{19}\text{O}_3\text{P}$: HRMS (calcd) 266.1072, (obsd) 266.1073. Product dimethyl 3-[3'-(phenylmethyl)-1,1'-bicyclo[1.1.1]pentyl]phosphonate (**10-O**): mp 106–108 $^\circ\text{C}$; ^{31}P NMR (121.4 MHz, C_6D_6) δ 22.46; ^1H NMR (299.9 MHz, C_6D_6) δ 1.27 (s, 6 H, CCCH_2C), 1.84 (d, 6 H, PCCH_2C , $^3J_{\text{HP}} = 1.2$ Hz), 2.55 (s, 2 H, CCH_2Ph), 3.40 (d, 6 H, OCH_3 , $^3J_{\text{HP}} = 10.5$ Hz), 6.86–7.44 (m, 5 H); ^{13}C NMR (125.7 MHz, C_6D_6) δ 31.31 (d, PCCH_2C , $^1J_{\text{CP}} = 160.0$ Hz), 39.13 (s, $\text{CCH}_2\text{CCH}_2\text{Ph}$), 39.45 (s, CCH_2Ph), 39.68 (d, CCH_2CC , $^4J_{\text{CP}} = 29.9$ Hz), 44.13 (d, CCH_2CC , $^3J_{\text{CP}} = 32.6$ Hz), 48.83, 50.35 (d, PCCH_2C , $^2J_{\text{CP}} = 1.9$ Hz), 51.87 (d, OCH_3 , $^2J_{\text{CP}} = 6.5$ Hz), 126.16, 128.47, 129.20, 139.68 (s, *ipso*-Ph); GC-EIMS (70 eV) *m/z* (rel intensity) 331 [$\text{M} - 1]^+$ (1), 317 [$\text{M} - \text{CH}_3]^+$ (2), 255 [$\text{M} - \text{Ph}]^+$ (2), 241 [$\text{M} - \text{PhCH}_2]^+$ (4), 177 (12), 149 (23), 131 (37), 115 (17), 91 [$\text{PhCH}_2]^+$ (100), 77 [$\text{Ph}]^+$ (9); $\text{C}_{19}\text{H}_{24}\text{O}_3\text{P}$ [$\text{M} - 1]^+$: HRMS [$\text{M} - 1]^+$ (calcd) 331.1463, (obsd) 331.1460.

The same procedures were used to determine the ^{31}P yields of the reactions of **6a**, **6b**, **6c**, **11**, and $(\text{EtO})_3\text{P}$. Only reactant quantities and oxidant (*tert*-BuOOH or S_8) are given below. Product isolation was by flash chromatography on silica gel under nitrogen followed by HPLC on silica gel with EtOAc as elutant for both chromatographies unless otherwise specified. UV or RI detection was used in the isolations by HPLC.

Dimethyl 1-(3-(Phenylmethyl)bicyclo[1.1.1]pentyl)phosphonate (12) from Reaction of 11 with [1.1.1]Propellane. The reaction mixture from the reaction of excess **11** (276.2 mg, 1.38 mmol), BPMDA (5 mg, 0.02 mmol), [1.1.1]propellane (~ 0.5 mmol), and 110 μL of C_6D_6 gave 45 mg (0.17 mmol, 45% isolated yield based on conversion of **11**, 61% crude yield, ^{31}P NMR) of product **12** as a colorless white solid. (Little or no **10-O** was detected by ^{31}P NMR.) Spectral data were identical to those for **12** recorded above.

Reaction of Dimethyl Benzylphosphonite (6a) with [1.1.1]Propellane. The product mixture (from **6a** (244 mg, 1.33 mmol), BPMDA (9 mg, 0.04 mmol), [1.1.1]propellane (0.5 mmol), and 200 μL of C_6D_6) was treated with *tert*-BuOOH and purified by flash chromatography on silica gel (EtOAc). A portion of this material was then subjected

to two HPLC (on silica) purifications (EtOAc, UV detection) to give 6 mg of the insertion product **1** as a colorless oil with NMR and MS spectra identical to those for **12** reported above. From the crude reaction mixture, prior to oxidation, the resonances for dimethyl 1-(3-(phenylmethyl)-bicyclo[1.1.1]pentyl)phosphonite (**7a**) could be readily assigned: ^{31}P NMR (121.4 MHz, C_6D_6) δ 172.49; ^1H NMR (299.9 MHz, C_6D_6) δ 1.72 (d, 6 H, PCCH_2C , $^3J_{\text{HP}} = 0.9$ Hz), 2.57 (s, 2 H, CCH_2Ph), 3.40 (d, 6 H, OCH_3 , $^3J_{\text{HP}} = 11.0$ Hz), aromatic protons obscured by overlap.

Reaction of *trans*- and *cis*-8 with [1.1.1]Propellane. The reaction mixture (e.g., from *trans*- and *cis*-8 (71:29 *trans:cis* starting ratio by ^{31}P NMR) (240.5 mg, 1.23 mmol), BPMDA (5.6 mg, 0.03 mmol), [1.1.1]propellane (~ 0.5 mmol), and 110 μL of C_6D_6) was treated with sulfur (see Table 5 for ^{31}P yield data) to give the products *cis*- and *trans*-**9-S** in a ratio of 62:38 *cis:trans* (by ^{31}P NMR). Starting material was recovered as the sulfides *trans*- and *cis*-**8-S** (67:33 *trans:cis* by GLC). The sulfides were then passed through silica gel (methylene chloride), followed by two HPLC purifications (hexanes:ethyl acetate, 90:10). A difficult separation of the isomers gave approximately 2 mg of pure **9-S** in 90/10 *cis:trans* ratio (^{31}P NMR and GLC) and approximately 1 mg of the pure *trans* isomer, *trans*-**9-S**. These samples yielded good ^{31}P and ^1H NMR data, while ^{13}C NMR data were obtained from fractions containing 9 mg of the *cis* and *trans* isomers in a 3:1 ratio (^{13}C NMR). *cis*-**9** ^{31}P (121.4 MHz, C_6D_6) δ 183.26 (crude reaction mixture). *trans*-**9** ^{31}P (121.4 MHz, C_6D_6) δ 177.65 (crude reaction mixture). *cis*-**9-S** ^{31}P NMR (121.4 MHz, C_6D_6) δ 106.86; ^1H NMR (299.9 MHz, C_6D_6) δ 0.58 (d, 3 H, CHCH_3 , $^3J_{\text{HH}} = 6.2$ Hz), 1.72 (d, 6 H, CCH_2C , $^3J_{\text{HP}} = 1.2$ Hz), 2.37 (d, 2 H, CCH_2Ph , $^5J_{\text{HP}} = 1.5$ Hz), 2.88 (m, 1 H), 3.56 (m, 1 H), 3.97–4.06 (m, 1 H), 6.78–7.44 (m, 5 H, C_6H_5); ^{13}C NMR (125.7 MHz, C_6D_6) δ 17.95 (d, CHCH_3 , $^3J_{\text{CP}} = 7.9$ Hz), 39.25 (d, CCH_2Ph , $^4J_{\text{CP}} = 26.9$ Hz), 39.85 (d, PCCH_2C , $^1J_{\text{CP}} = 96.1$ Hz), 43.55 (d, PCCH_2C , $^3J_{\text{CP}} = 39.3$ Hz), 51.33 (d, PCCH_2C , $^2J_{\text{CP}} = 2.5$ Hz), 72.71 (d, OCH_2 , $^2J_{\text{CP}} = 2.7$ Hz), 74.50 (d, OCHCH_3 , $^2J_{\text{CP}} = 1.5$ Hz), 138.51 (*ipso*), remaining phenyl resonances masked by C_6D_6 triplet (^{13}C NMR spectrum of 3:1 *cis:trans* mixture); GC-EIMS (70 eV) *m/z* (rel intensity) 294 [$\text{M}]^+$ (1), 261 [$\text{M} - \text{SH}]^+$ (11), 203 [$\text{M} - \text{PhCH}_2]^+$ (33), 157 [3-phenylmethyl bicyclo[1.1.1]pentyl] $^+$ (69), 156 [$\text{M} - 138]^+$ (100), 155 (44), 145 (19), 141 (75), 105 (24), 91 (75), 77 [$\text{Ph}]^+$ (13), 65 (49), 41 (48); $\text{C}_{15}\text{H}_{19}\text{O}_2\text{PS}$: HRMS (90/10 *cis:trans* mixture) (calcd) 294.0844, (obsd) 294.0836. *trans*-**9-S**: ^{31}P NMR (121.4 MHz, C_6D_6) δ 106.43; ^1H NMR (299.9 MHz, C_6D_6) δ 0.80 (d, 3 H, CHCH_3 , $^3J_{\text{HH}} = 6.2$ Hz), 1.72 (d, 6 H, PCCH_2C , $^3J_{\text{HP}} = 1.3$ Hz), 2.37 (d, 2 H, CCH_2Ph , $^5J_{\text{HP}} = 1.2$ Hz), 3.24–3.42 (m, 2 H), 3.56 (m, 1 H), 3.64–3.78 (m, 1 H), 6.80–7.44 (m, 5 H, C_6H_5); ^{13}C NMR (125.7 MHz, C_6D_6) δ 18.57 (d, CHCH_3 , $^3J_{\text{CP}} = 6.1$ Hz), 39.28 (d, CCH_2Ph , $^4J_{\text{CP}} = 26.9$ Hz), 39.89 (d, PCCH_2C , $^1J_{\text{CP}} = 96.3$ Hz), 43.17 (d, PCCH_2C , $^3J_{\text{CP}} = 39.1$ Hz), 51.33 (d, PCCH_2C , $^2J_{\text{CP}} = 2.5$ Hz), 71.82 (d, OCH_2 , $^2J_{\text{CP}} = 2.1$ Hz), 76.16 (d, OCHCH_3 , $^2J_{\text{CP}} = 2.3$ Hz), 138.56 (*ipso*), remaining phenyl resonances masked by C_6D_6 triplet.

Reaction of Dimethyl *n*-Pentylphosphonite (6b) with [1.1.1]-Propellane. The solution of products from reaction of **6b** (109 mg, 0.665 mmol), [1.1.1]propellane (~ 0.5 mmol), di-*tert*-butyl peroxide (3 μL , 2 mg, 0.02 mmol), in 100 μL of C_6D_6 was oxidized with *tert*-butyl hydroperoxide, purified by flash chromatography on silica gel (EtOAc), and separated by HPLC on silica gel (EtOAc) to give 13 mg (0.053 mmol) of the insertion product **7b-O** as a colorless oil (12% yield, based on **6b** consumed (^{31}P NMR). Product dimethyl 1-(3-*n*-pentylbicyclo[1.1.1]pentyl)phosphonite **7b**: ^{31}P NMR (121.4 MHz, C_6D_6) δ 171.98 (crude reaction mixture). Product dimethyl 1-(3-*n*-pentylbicyclo[1.1.1]pentyl)phosphonate (**7b-O**): ^{31}P NMR (121.4 MHz, C_6D_6) δ 22.20; ^1H NMR (299.9 MHz, C_6D_6) δ 0.86 (t, 3 H, CH_2CH_3 , $^3J_{\text{HH}} = 7.1$ Hz), 0.96–1.26 (m, 8 H, $(\text{CH}_2)_4$), 1.87 (d, 6 H, PCCH_2C , $^3J_{\text{HP}} = 1.2$ Hz), 3.44 (d, 6 H, OCH_3 , $^3J_{\text{HP}} = 10.6$ Hz); ^{13}C NMR (75.4 MHz, C_6D_6) δ 14.21, 22.90, 25.96, 32.17 (s), 32.17 (d, PCCH_2C , $^1J_{\text{CP}} = 159.8$ Hz), 32.26 (d, $\text{PCCH}_2\text{CCH}_2$, $^4J_{\text{CP}} = 25.8$ Hz), 44.83 (d, PCCH_2C , $^3J_{\text{CP}} = 33.1$ Hz), 51.41 (d, PCCH_2C , $^2J_{\text{CP}} = 2.2$ Hz), 51.86 (d, OCH_3 , $^2J_{\text{CP}} = 6.5$ Hz); GC-EIMS (70 eV) *m/z* (rel intensity) 246 [$\text{M}]^+$ (0.5), 245 [$\text{M} - 1]^+$ (4), 231 [$\text{M} - \text{CH}_3]^+$ (1), 217 [$\text{M} - \text{Et}]^+$ (3), 203 [$\text{M} - n\text{-Pr}]^+$ (9), 189 [$\text{M} - n\text{-Bu}]^+$ (100), 175 [$\text{M} - n\text{-C}_5\text{H}_{11}]^+$ (13), 157 (22), 137 [3-*n*-pentylbicyclo[1.1.1]pentyl] $^+$ (6), 109 [$(\text{CH}_3\text{O})_2\text{PO}]^+$ (23), 107 (19), 94 (17), 93 (38), 79 (50); $\text{C}_{12}\text{H}_{22}\text{O}_3\text{P}$ [$\text{M} - 1]^+$: HRMS [$\text{M} - 1]^+$ (calcd) 245.1306, (obsd) 245.1302.

(39) Use of Kimax filtered light avoids the photo-Arbusov isomerization of benzyl phosphites studied in this laboratory. Omelanzuk, J.; Sopchik, A. E.; Lee, S.-G.; Akutagawa, K.; Cairns, S. M.; Bentrude, W. G. *J. Am. Chem. Soc.* **1988**, *110*, 6908. Cairns, S. M.; Bentrude, W. G. *Tetrahedron Lett.* **1989**, *30*, 1025; Bentrude, W. G.; Mullah, K. B. *J. Org. Chem.* **1991**, *56*, 7218.

Reaction of Dimethyl Dimethylphosphoramidite (6c) with [1.1.1]-Propellane. Under the above conditions (0.5 mmol of **6c**, 1 mmol of [1.1.1]propellane (**1**), 0.1 mmol of tetramethyltetrazene at 0 °C), only trace amounts of product **7c** resulted (³¹P NMR). Alternatively, the photolysis was done at 24 °C with larger amounts of C₆D₆: **6c** (106 mg, 0.774 mmol), tetramethyltetrazene (70 μL, 0.6 mmol), [1.1.1]-propellane (~1 mmol), in 500 μL of C₆D₆. The reaction products were treated with S₈. Separation of the sulfides by flash chromatography on silica gel (elution with hexanes:ethyl acetate, 1:1, then ethyl acetate), monitored by GLC, gave thiophosphonate **7c-S** (2 mg, 85% pure by GLC) as a colorless oil. (Co-evaporation of the residual EtOAc with benzene was necessary to prevent decomposition of **7c-S**): Product dimethyl 1-(3-dimethylaminobicyclo[1.1.1]pentyl)phosphonite (**7c**): ³¹P NMR (121.4 MHz, C₆D₆) δ 171.88 (crude reaction mixture). Product dimethyl 1-(3-(dimethylamino)bicyclo[1.1.1]pentyl)phosphonothioate (**7c-S**) (sulfide of **7c**): ³¹P NMR (121.4 MHz, C₆D₆) δ 93.07; ¹H NMR (299.9 MHz, C₆D₆) δ 1.91 (s, 6 H, N(CH₃)₂), 1.94 (d, 6 H, PCCH₂C, ³J_{HP} = 1.0 Hz), 3.42 (d, 6 H, OCH₃, ³J_{HP} = 13.4 Hz); GC-EIMS (70 eV) *m/z* (rel intensity) 235 [M]⁺ (0.2), 234 [M - 1]⁺ (1), 220 [M - CH₃]⁺ (5), 202 [M - SH]⁺ (29), 188 (11), 125 [(MeO)₂PS]⁺ (7), 110 [3-(dimethylamino)bicyclo[1.1.1]pentyl]⁺ (100), 108 (22), 70 (20); C₉H₁₈NO₂PS: HRMS (calcd) 235.0796, (obsd) 235.0779.

Reaction of 3-(Phenylmethyl)bicyclo[1.1.1]pent-1-yl Radicals from BPMDA and [1.1.1]Propellane with Trimethyl Phosphite. Formation of 12 and 10-O. A rubber septum fitted Pyrex tube was charged with a 30 mL of a solution of crude [1.1.1]propellane in ether (~1–2% by weight, 4–6 mmol [1.1.1]propellane, not purified by GC isolation), 178 mg (0.85 mmol) of BPMDA, and 5.0 mL (4.8 g, 38 mmol) of P(OMe)₃. The solution, sparged with nitrogen from a syringe needle, was irradiated at 0 °C for 1.5 h with light from a 450 W medium pressure Hg lamp. Volatile materials were removed in vacuo. ³¹P NMR and GC-EIMS analysis showed the presence of several phosphonate products, including adducts **12** and **10-O**. (The major product was bibenzyl (GC and GC-EIMS).) The residue from solvent removal was purified by flash chromatography followed by HPLC (25 × 0.46 cm column) to give 2 mg (0.008 mmol, 1% yield based on BPMDA) of phosphonate **12** (85% pure by GC and ¹H NMR): identification by comparison to ³¹P NMR and ¹H NMR spectral data, GC-retention time, and GC-EIMS data of authentic samples of **12** isolated from reactions of **6a** and **11** with [1.1.1]propellane (see above). Also identified in the crude reaction mixture (GC-EIMS) were **10b** and presumed dimethyl 1-(3-methylbicyclo[1.1.1]pentyl)phosphonate (**23**): GC-EIMS (70 eV) *m/z* (rel intensity) 190 [M]⁺ (3), 189 [M - 1]⁺ (35), 175 [M - CH₃]⁺ (25), 157 (12), 143 (13), 110 (23), 81 [3-methylbicyclo[1.1.1]pentyl]⁺ (15), 80 (41), 79 (100).

Reaction of Triethyl Phosphite with [1.1.1]Propellane. Under the above conditions for the reactions of **6a**, **6b**, and **11** with [1.1.1]propellane (irradiation of 1–2 mmol of P(OEt)₃, 0.5 mmol of [1.1.1]propellane, and 0.1 mmol Et₂N₂ initiator, in 100 μL of C₆D₆, 0 °C), a waxy polymer was formed. A relatively dilute solution in a serum-capped tube with significantly more initiator (3.0 mL of benzene, neat [1.1.1]propellane (60–70 μL, ~1 mmol), P(OEt)₃ (1.97 g, 11.9 mmol), and Et₂N₂ (70 μL, 57 mg, 0.66 mmol) (total solution volume = 5.2 mL) was irradiated at 24 °C (450 W medium pressure Hg lamp filtered through a Pyrex sleeve). The progress of the reaction was followed by ³¹P NMR and GC analysis of 300 and 500 μL aliquots of solution withdrawn after 1.5 and 12 h of irradiation, respectively. Solvent was removed from the remaining solution in vacuo. The residue was diluted to 2.00 mL in a volumetric flask. The amount of phosphonate **13** in the crude mixture was determined by quantitative ³¹P NMR to be 0.15 mmol (corrected for the 0.800 μL of solution removed from the original 5.2 mL reaction mixture), ca. 15% yield based on [1.1.1]propellane. Product purification by flash chromatography (EtOAc) followed by HPLC (EtOAc) yielded 14.5 mg (0.063 mmol, ca. 6% yield based on [1.1.1]propellane) of diethyl 1-(3-ethylbicyclo[1.1.1]pentyl)phosphonate (**13**) as a colorless oil: ³¹P NMR (121.4 MHz, C₆D₆) δ 20.11; ¹H NMR (299.9 MHz, C₆D₆) δ 0.63 (t, 3 H, CCH₂CH₃, ³J_{HH} = 7.5 Hz), 1.08 (t, 6 H, OCH₂CH₃, ³J_{HH} = 7.1 Hz), 1.17 (dq, 2 H, CCH₂CH₃, ⁴J_{HP} = 0.7 Hz, ³J_{HH} = 7.4 Hz), 1.85 (d, 6 H, PCCH₂C, ³J_{HP} = 1.2 Hz), 3.97 (m, 4 H, OCH₂CH₃); ¹³C NMR (75.4 MHz, C₆D₆) δ 10.04 (s, CCH₂CH₃), 16.72 (d, OCH₂CH₃, ³J_{CP} = 5.2 Hz), 25.23 (d, CCH₂CH₃, ⁴J_{CP} = 25.9 Hz), 32.37 (d, PCCH₂C, ¹J_{CP} = 160.8 Hz), 45.27 (d, PCCH₂C, ³J_{CP} =

33.2 Hz), 50.57 (d, PCCH₂C, ²J_{CP} = 2.1 Hz), 61.26 (d, OCH₂CH₃, ²J_{CP} = 6.2 Hz); GC-EIMS (70 eV) *m/z* (rel intensity) 232 [M]⁺ (0.4), 231 [M - 1]⁺ (3), 217 [M - CH₃]⁺ (12), 203 [M - Et]⁺ (7), 189 [M - 43]⁺ (14), 175 [M - 57]⁺ (24), 161 (66), 137 [(EtO)₂PO]⁺ (2), 111 (21), 95 [3-ethylbicyclo[1.1.1]pentyl]⁺ (24), 94 (60), 93 (100), 91 (19), 81 (25), 79 (62), 77 (19), 65 (21); C₁₁H₂₀O₃P [M - 1]⁺: HRMS [M - 1]⁺ (calcd) 231.1150, (obsd) 231.1146.

Reaction of Ethyl Radicals with Benzyl Dimethyl Phosphite. A 5.00 mL solution of benzyl dimethyl phosphite (**11**) (233 mg, 1.17 mmol), azobisethane (97 mg, 1.13 mmol), and tri-*n*-propyl phosphate (73 mg, 0.326 mmol) as internal standard in C₆D₆ was prepared under nitrogen, and portions were added to two 12 mm Pyrex NMR tubes (~0.7 mL each) that were then degassed at 10⁻³ mmHg with 4 freeze-pump-thaw cycles, flame sealed, and irradiated for 14 h (medium-pressure 450 W Hg lamp, Kimax filter sleeve). The ³¹P NMR spectrum showed the presence of dimethyl ethylphosphonate, confirmed by GC and GC-EIMS, in addition to starting phosphite and phosphate internal standard. By quantitative ³¹P NMR (proton-coupled, 60 s repetition rate), the yield of EtP(O)(OEt)₂ was determined to be 90%, based on 18% conversion of starting material. No phosphonate was formed in a nonirradiated control reaction. The ¹H NMR spectrum showed evidence for the formation of *n*-butane, ethane, and ethylene.

Reaction of Ethyl radicals with Triethyl Phosphite and Trimethyl Phosphite. Analogously, aliquots of a stock 5.00 mL solution of 1.37 mmol of the appropriate three-coordinate phosphorus compound (triethyl phosphite or trimethyl phosphite), 1.14 mmol Et₂N₂, and 0.283 mmol tri-*n*-propyl phosphate, in C₆D₆ were irradiated for 12 h. The ³¹P NMR spectrum showed the presence of only the starting phosphite and the phosphate internal standard and in the initial ratio.

Reaction of Isopropyl Radicals with Benzyl Dimethyl Phosphite (11). Irradiation in completely analogous fashion of aliquots of a 5.00 mL solution of benzyl dimethyl phosphite (**11**) (352 mg, 1.76 mmol), azobisisopropane (157 mg, 1.40 mmol), and tri-*n*-propyl phosphate (129 mg, 0.576 mmol) in C₆D₆ for 12 h gave no evidence by ³¹P NMR spectroscopy for the formation of a phosphonate or consumption of starting phosphite.

Reaction of Isopropyl Radicals with Dimethyl *n*-Pentylphosphonite (6b). Similarly, aliquots of a 5.00 mL solution of dimethyl *n*-pentylphosphonite (**6b**) (157.5 mg, 0.960 mmol, 0.192 M), azobisisopropane (151.4 mg, 1.32 mmol, 0.264 M), and tri-*n*-propyl phosphate (84.2 mg, 0.76 mmol, 0.0752 M) in C₆H₆ were irradiated for 14 h (medium-pressure 450 W Hg lamp, Kimax filter sleeve). The ³¹P NMR spectrum showed only the presence of the starting *n*-pentylphosphonite (**6b**) and the phosphate internal standard in the initial ratio.

Reaction of Isopropyl Radicals with Dimethyl Benzylphosphonite (6a). As above, aliquots of a 5.00 mL solution of dimethyl benzylphosphonite (**5a**) (231.8 mg, 1.26 mmol, 0.252 M), azobisisopropane (129.7 mg, 1.14 mmol, 0.228 M), and tri-*n*-propyl phosphate (73.8 mg, 0.330 mmol, 0.0659 M) in C₆H₆ were irradiated in Pyrex NMR tubes for 14 h (medium-pressure 450 W Hg lamp, Kimax sleeve). A new resonance at δ 191.79 was observed in the ³¹P NMR spectrum, consistent with the formation of an alkylphosphonite. The ³¹P NMR yield of the presumed dimethyl isopropylphosphonite (**15a**) was 0.32 mmol (36% yield based on 69% conversion of starting **6a**).

Reaction of Ethyl Radicals with Dimethyl Benzylphosphonite (6a). A nitrogen flushed solution of dimethyl benzylphosphonite (**5a**) (198 mg, 1.08 mmol), azobisethane (38 mg, 0.44 mmol), in 0.6 mL of benzene in a 5 mm Pyrex NMR, capped with a septum and wrapped with parafilm, was irradiated at 24 °C for 12 h as above. ³¹P NMR (32.2 MHz) showed only the resonance of starting **5a** (δ 180.5) and a single new resonance (δ 188.1) assigned to dimethyl ethylphosphonite (**15b**) (δ 188.2 from a sample of **15b** prepared independently from methanolysis of EtP(NEt₂)₂,³⁷ lit. **15b**,³⁷ δ 188.3); area ratio, **6a**:**15b**, 87:13. The yield of **15b** was not quantitated.

Labeling Studies Using [2,2'-²H]Bis(phenylmethyl)diazene (BPMDA-*d*₂) as an Initiator. The general procedures outlined above for reaction of unlabeled BPMDA with **6a**, *trans*- and *cis*-**8**, and **11** were followed. The amount of ²H incorporation in the products was determined from the percentage increase in product [M + 1]⁺ peaks relative to natural abundance [M + 1]⁺ reference peaks observed using unlabeled initiator. The intensities of the [M + 1]⁺ peaks were expressed as a percentage of the molecular ion [M]⁺. Each of the

experiments was run twice, i.e., with two different sources of unlabeled BPMDA. The chain lengths were determined by multiplication of the peak ratios of unlabeled to labeled product by 0.75 (75% ^2H incorporation in the initiator). GC-EIMS data showed no evidence for ^2H incorporation in recovered starting material analyzed after oxidation to the oxide or sulfide (**6a-O**), *trans*- and *cis*-**8-S**). The GC-EIMS data used to determine the reaction kinetic chain lengths are contained in Tables 10–12).

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Supporting Information Available: Tables containing EIMS data for the deuterium labeling experiments on **6a**, **8**, and **11** or the incorporation of deuterium label into bibenzyl and preparations of **6a**, **6b**, **6c**, **8**, **11**, and deuterated BPMDA (6 pages). See any current masthead page for ordering and Internet access instructions.

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