Sulfur- and Selenium-Promoted Cyclization of Allenic Phosphonates and Phosphinates to Substituted 1,2-Oxaphosphol-3-enes; Stereochemical Consequences at Phosphorus. The Crystal and Molecular Structure of (*Z*)-3,5-Di-*tert*-butyl-2-methoxy-4-(phenylseleno)-1,2-oxaphosphol-3-ene 2-Oxide

Roger S. Macomber* and George A. Krudy

Department of Chemistry, University of Cincinnati, Cincinnati, Ohio 45221

Karl Seff*

Department of Chemistry, University of Hawaii, Honolulu, Hawaii 96822

L. E. Rendón-Diazmirón

Instituto de Investigaciones en Materiales, Universidad Nacional Autónoma de México, Mexico 04510, D.F., Mexico

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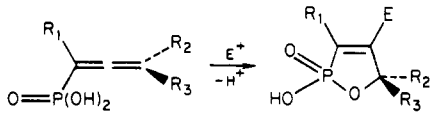
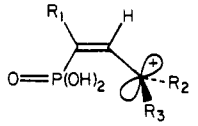
A series of allenic phosphonate esters (**4a–d**) and phosphinate **6** were reacted with benzeneselenyl chloride. Except for **4a**, which gave a simple 1,2-adduct, each ester afforded the corresponding 4-(phenylseleno)-1,2-oxaphosphol-3-ene (**11b–e**). Similar reaction of the esters with 2,4-dinitrobenzenesulfenyl chloride gave the corresponding 4-thio derivatives (**13**) in cases **4c**, **4d**, and **6**; **4a** and **4b** were unreactive. The diastereomers of **11b** were separated, and the structure of the *Z* isomer was established by X-ray crystallography. The stereochemistry of the cyclization and related reactions is discussed.

We have previously described how allenic phosphonic acids undergo cyclization to oxaphospholenes when treated with certain electrophiles.[1-6] Proton-catalyzed cyclizations



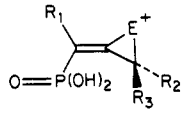
E = H;[1-3] Br;[4] HgOAc;[4] OH[5]

required both C-terminal substituents (R_2 and R_3) to be alkyl,[6] presumably to stabilize intermediate **1a**, which



1a

cannot enjoy allylic stabilization until it undergoes a 90° rotation. No such substituent limitations were encountered for the remaining electrophiles, which are believed to involve cyclic, configurationally fixed intermediates such as **1b**.[4] Indeed, the bromination of optically pure allenic

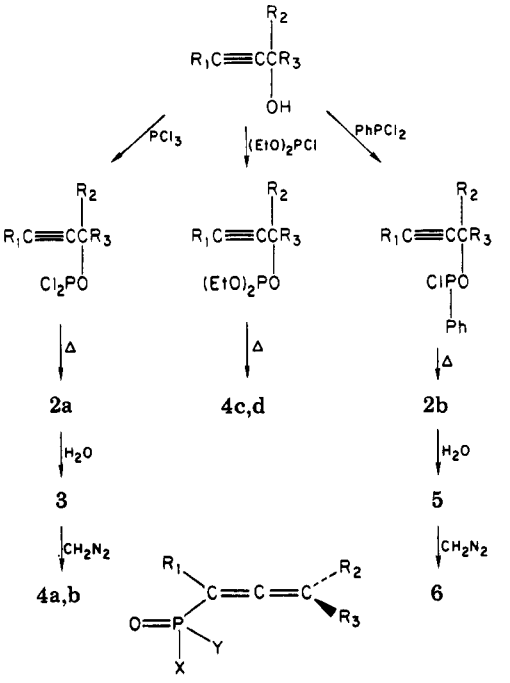


1b

phosphonic acid **3b** (Scheme I) proceeded with 41% stereospecificity, while oxymercuration occurred with 86% stereospecificity.[4]

To complement our earlier work in this area, we have examined the efficacy of sulfur and selenium electrophiles

Scheme I



2a, X = Y = Cl
2b, X = Ph; Y = Cl
3, X = Y = OH
3b, R_1 = R_3 = *t*-Bu; R_2 = H; X = Y = OH
4a, R_1 = R_2 = R_3 = H; X = Y = OMe
4b, R_1 = R_3 = *t*-Bu; R_2 = H; X = Y = OMe
4c, R_1 = H; R_2 = R_3 = Me; X = Y = OEt
4d, R_1 = H; R_2 + R_3 = $(CH_2)_5$; X = Y = OEt
5, R_1 = H; R_2 = R_3 = Me; X = Ph; Y = OH
6, R_1 = H; R_2 = R_3 = Me; X = Ph; Y = OMe

(1) Macomber, R. S. *J. Org. Chem.* **1971**, *36*, 2713.
(2) Elder, R. C.; Florian, L. R.; Kennedy, E. R.; Macomber, R. S. *J. Org. Chem.* **1973**, *38*, 4177.
(3) Macomber, R. S.; Kennedy, E. R. *J. Org. Chem.* **1976**, *41*, 3191.
(4) Macomber, R. S. *J. Am. Chem. Soc.* **1977**, *99*, 3072.
(5) Macomber, R. S. *J. Org. Chem.* **1978**, *43*, 1832.
(6) Macomber, R. S. *J. Org. Chem.* **1977**, *42*, 3297.

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Table I. Reactions of Allenic Phosphonyl Derivatives with Benzeneselenyl Chloride (7)

substrate	reaction time[a]/ temp/solvent	product	yield,[b] %
4a	420/46/$CHCl_3$	12a	46
4b	300/66/CH_3CN	(*E*)- and (*Z*)-11b[c]	67
4c	15/25/CH_2Cl_2	11c	67
4d	15/25/$CHCl_3$	11d	73
5	20/25/CH_2Cl_2	11e	66
6	60/25/$CHCl_3$	11e	61

[a] In min and °C. [b] After purification. [c] See text.

in promoting the cyclization to 4-heterosubstituted oxaphospholenes.

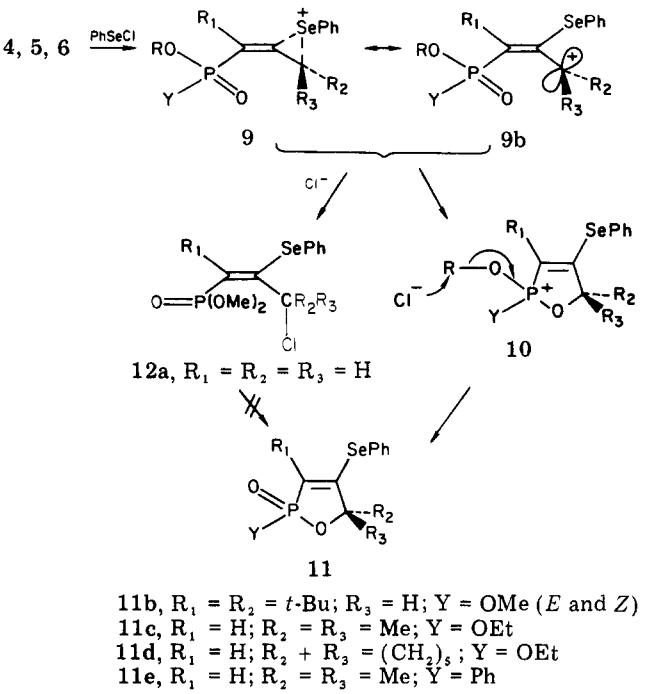
During the course of our work there have been reports of related studies in the Russian literature.[7] The majority of these papers described the reaction of several alkane and aromatic sulfenyl halides with a number of allenic phosphonates of general structure **4**. The Russian observations of electrophilic cyclizations to 4-substituted oxaphospholenes parallel our results, though they did not report any reactions involving 2,4-dinitrobenzenesulfenyl chloride. In the cases where $R_2 \neq R_3$,[7a,e] no attempts were made to separate the diastereomers of the product oxaphospholenes. Their investigation of selenium-promoted cyclizations[7d] was limited to esters related to **4b** and one ester where R_2 = Me and R_3 = Et. Again, no separation of the stereoisomers of the products was attempted. In none of this work were there descriptions of reactions of sulfur or selenium electrophiles with phosphinates.

Results

While the reaction of allenes with sulfur electrophiles has been studied over 2 decades,[8] only recently has the corresponding reaction with selenium electrophiles been examined.[9a] We chose as prototype substrates a series of allenic phosphoryl derivatives having either no (**4a**), one (**4b**), or two (**4c**, **4d**, **5**, **6**) C-terminal substituents, avoiding as much as possible those esters previously examined.[7] In our initial experiments we used the free acids (**3** and **5**), but we found that in most cases the corresponding esters **4** and **6** were superior substrates from the standpoint of solubility and ease of product isolation.

Methyl esters **4a**, **4b**, and **6** were prepared by reacting diazomethane with the corresponding allenic acids **3** and **5**,[10,11] which in turn were isolated from the reaction of the appropriate propargyl alcohol with phosphorus trichloride[1-3] or phenyldichlorophosphine.[12] Ethyl esters **4c** and **4d** were prepared directly from the propargyl alcohols by treatment with diethyl chlorophosphite[13] (Scheme I).

Scheme II



11b, $R_1 = R_2 = t$-Bu; R_3 = H; Y = OMe (*E* and *Z*)
11c, R_1 = H; $R_2 = R_3$ = Me; Y = OEt
11d, R_1 = H; $R_2 + R_3 = (CH_2)_5$; Y = OEt
11e, R_1 = H; $R_2 = R_3$ = Me; Y = Ph

Table II. Reactions of Allenic Phosphonyl Derivatives with 2,4-Dinitrobenzenesulfenyl Chloride (8)

substrate	reaction time[a]/ solvent	product	yield, %[b]
4a	7 (65 °C)/$CDCl_3$		0[c]
4b	8 (65 °C)/$CDCl_3$		0[c]
4c	6/CH_2Cl_2	13c	76
4d	7/CH_2Cl_2	13d	61
6	3/$CHCl_3$	13e	65

[a] In days and at 25 °C unless otherwise noted. [b] After purification by chromatography and recrystallization. [c] Only starting material by NMR and TLC.

The electrophiles examined, benzeneselenyl chloride (**7**) and 2,4-dinitrobenzenesulfenyl chloride (**8**), were selected on the bases of their previously reported reactions with allenes.[8,9a] Results with the selenium-induced cyclization are summarized in Table I (see Scheme II).[9b] At 25 °C these reactions were quite rapid for substrates (**4c**, **4d**, **5**, and **6**), which lead to cationic intermediates **9a** with tertiary carbocationic resonance forms (**9b**), but only ca. one-tenth as fast for the secondary case **4b**. Unsubstituted ester **4a** was the slowest to react and gave chlorine-containing 1,2-adduct **12a** rather than oxaphospholene. We assign it the *E* stereochemistry on the basis of the 1.5-Hz allylic proton–proton coupling and its similarity to certain sulfur analogues.[7c] Apparently with **4a** at no time does sufficient positive charge develop (as in **9b**) to direct the phosphoryl oxygen to attack the terminal carbon. Indeed, the addition of chloride may be in concert with attack by selenium. Because compounds similar to **12** where OH is substituted for Cl are known to cyclize spontaneously,[14] we attempted to cyclize **12a** by thermolysis[15] and hy-

(7) (a) Angelov, Kh. M.; Vachkov, K. V.; Ionin, B. I.; Kirilov, M. *Zh. Obsch. Khim.* **1979**, *49*, 2438. (b) Angelov, Kh. M.; Vachkov, K.; Kirilov, M.; Ionin, B. I.; Petrov, A. A. *Dokl. Bolg. Akad. Nauk.* **1979**, *32*, 611. (c) Pudovik, A. N.; Khusainova, N. G.; Berdnikov, E. A. *Dokl. Akad. Nauk SSSR* **1980**, *250*, 116. (d) Angelov, Kh. M.; Khristov, Kh. *Zh. Obsch. Khim.* **1980**, *50*, 1891. (e) Vassilev, G. N.; Kirilov, M.; Angelov, H. M.; Dimeheva, Z. D.; Vachkov, K. V. *Dokl. Bolg. Akad. Nauk* **1980**, *33*, 853. (f) Angelov, Kh. M.; Vachkov, K. *Tetrahedron Lett.* **1981**, 2517. Angelov, Kh. M.; Kirilov, M.; Vachkov, K. V.; Spassov, S. L. *Ibid.* **1980**, *21*, 3507. (g) Khusainova, N. G.; Naumova, L. V.; Berdnikov, E. A.; Pudovik, A. N. *Zh. Obshch. Khim.* **1982**, *52*, 1040.

(8) See, for example: Jacobs, T. L.; Macomber, R. S.; Zunker, D. *J. Am. Chem. Soc.* **1967**, *89*, 7001. Jacobs, T. L.; Macomber, R. S. *J. Org. Chem.* **1968**, *33*, 2988. Garratt, D. G.; Beaulieu, P. L. *Can. J. Chem.* **1980**, *58*, 2737.

(9) (a) Garratt, D. G.; Beaulieu, P. L.; Morisset, V. M.; Ujjainwalla, M. *Can. J. Chem.* **1980**, *58*, 2745. Garratt, D. G.; Beaulieu, P. L.; Morisset, V. M. *Tetrahedron Lett.* **1980**, *21*, 129. (b) The process described in Scheme II may be more complex than depicted. The formation of other intermediates (e.g., episelenuranes and ion pairs) have been postulated[9a] to precede formation of the episelenium ion (e.g., **9**) in reactions with other allenes. While such intermediates would have a stereochemical impact on the formation of **9**, the stereochemistry of **11** would be independent of them. Our results, therefore, do not preclude the occurrence of these other intermediates.

(10) Macomber, R. S. *Synth. Commun.* **1977**, *7*, 405.

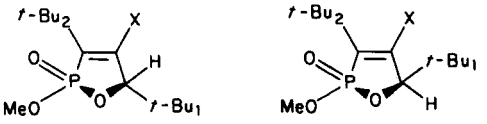
(11) Baverman, S.; Reisman, D. *Tetrahedron Lett.* **1977**, 1753. These authors did not report the spectral properties of **6**.

(12) Cherbuliez, E.; Jaccard, S.; Prince, R.; Rabinowitz, J. *Helv. Chim. Acta* **1965**, *48*, 632. Our method differs substantially from theirs, as described in the Experimental Section.

(13) Mark, V. *Tetrahedron Lett.* **1962**, 281.

(14) Machida, Y., Saito, I. *J. Org. Chem.* **1979**, *44*, 865.

Table III. NMR Parameters for (*Z*)- and (*E*)-11b, 14, and 15.[a] Stereoisomer Distribution as a Function of Conditions



Z *E*

conditions	11b, X = SePh		14, X = Br		15, X = H	
	(*Z*)-11b[e]	(*E*)-11b[f]	(*Z*)-14	(*E*)-14	(*Z*)-15	(*E*)-15
t-Bu$_1$	0.97	1.02	1.10	1.13	0.91	0.95
t-Bu$_2$	1.45	1.45	1.35	1.35	1.21	1.21
OCH$_3$ (*J*)	3.82 (11)	3.77 (11.5)	3.81 (11.5)	3.72 (12)	3.78 (11.5)	3.65 (12)
CH (*J*)	4.27 (11)	4.18 (11.5)	4.47 (8.5)	4.40 (9)	4.39 (5, 1.5)	4.30 (4.5, 1.5)
% acetonitrile[b]	35	65				
% chloroform[b]	50	50				
% via esterification[c] with CH_2N_2	48	52	43	57	44	56
% via bromination[c]			40	60		
% via methanolysis of 17[d]						100

[a] All spectra run in CCl_4 solution; chemical shifts in ppm downfield from Me_4Si. [b] See Experimental Section. [c] See ref 17. [d] Reference 1. [e] Phenyl protons appear at 7.33 ppm (s, 5 H). [f] Phenyl protons appear at 7.30 ppm (s, 5 H).

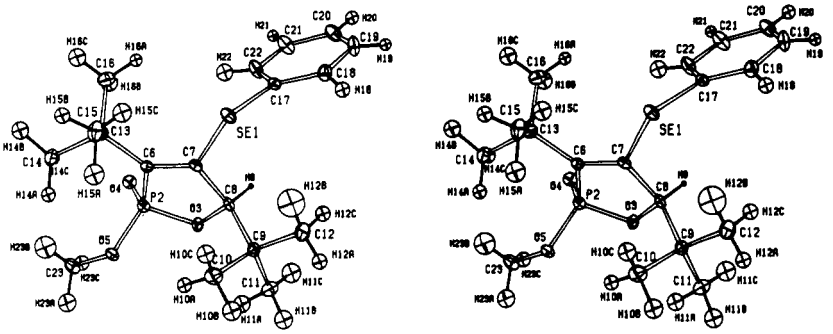
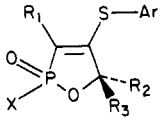


Figure 1. Stereoview of the (*Z*)-**11b** molecule. Ellipsoids of 10% probability are shown.[32]

drolysis. Unfortunately, **12a** was completely stable when heated to 110 °C for 36.25 h (in toluene) or when heated to 59 °C for 25 h in aqueous methanol (44:56), indicating the low solvolytic reactivity of the chloride and the low nucleophilicity of the phosphoryl oxygen toward C–Cl.

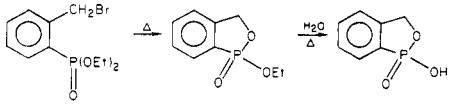
Results with the sulfur-induced cyclizations are summarized in Table II. Comparison of these data with those in Table I immediately indicates sulfenyl chloride **8** is far less reactive than benzeneselenyl chloride. Not only did reaction times increase by ca. 10^3 but esters **4a** and **4b** were completely inert even after extended periods of reflux. There is evidence[7c] that benzenesulfenyl chloride is comparable in reactivity to **7**, giving a chlorine-containing 1,2-adduct with **4a**. Nonetheless, the 4-thiooxaphospholenes (**13**) from **4c**, **4d**, and **6** were readily isolated.



Ar = 2,4-dinitrophenyl

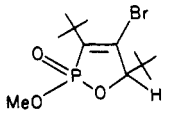
13c, R_1 = H; R_2 = R_3 = CH_3; X = OEt
13d, R_1 = H; R_2 + R_3 = $(CH_2)_5$; X = OEt
13e, R_1 = H; R_2 = R_3 = CH_3; X = Ph

(15) Compound i cyclizes when heated to 180 °C for 10 h in *o*-dichlorobenzene: Miles, J. A.; et al. *J. Org. Chem.* **1982**, *47*, 1677.

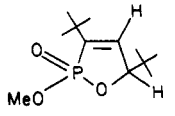


i

The cyclization of **4b** is particularly interesting from the standpoint of stereochemistry. The relevant spectral properties of the two diastereomers[16] of product **11b** and those of the related esters **14**[17] and **15**[1] are summarized in

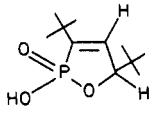


14



15

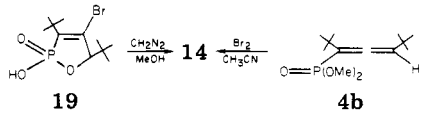
Table III. The exact structure of the higher melting diastereomer[16] of **11b** was determined by single-crystal X-ray analysis (see Experimental Section) to be the *Z* isomer[18] as shown in Figure 1. A comparison of the bond lengths and angles of (*Z*)-**11b** (see supplementary tables) with those of 4-protio analogue **16**[2] shows that the re-



16

(16) Each diastereomer exists as a *d,l* pair.

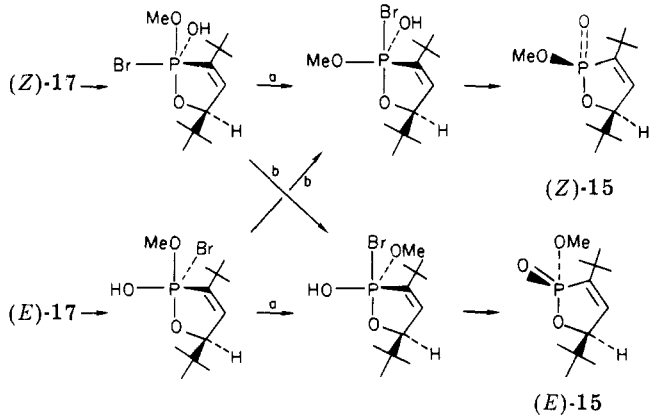
(17) Diastereomers of **14** were prepared by two independent routes: (a) esterification of **19**[4] with diazomethane,[10] and (b) bromination of diester **4b**.



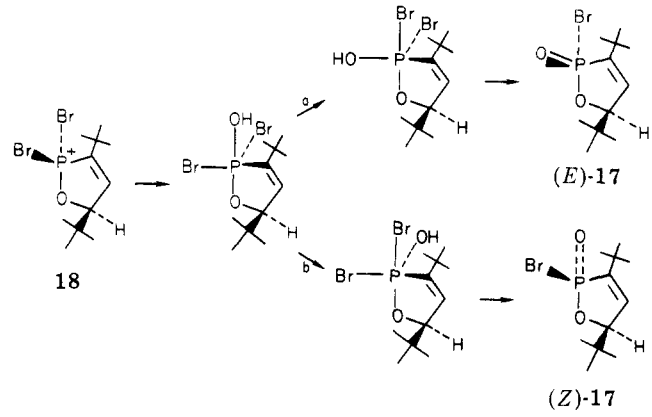
19 **4b**

(18) The *Z* isomer is so designated because OCH_3 has higher priority than $P^+–O^-$.

Scheme III



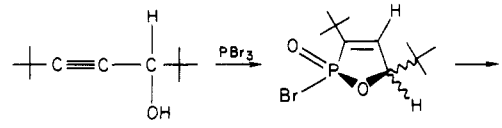
Scheme IV



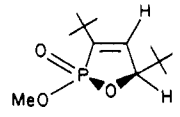
placement of the 4-hydrogen by the much bulkier phenylseleno group, as well as conversion of the phosphonic acid to its methyl ester, leaves the oxaphospholene ring skeleton essentially unperturbed. The mean difference between the 5 ring bonds of (*Z*)-**11b** and **16** is 0.01 Å; the mean difference in the 5 internal angles of the ring is 0.6°, these differences being just slightly larger than the experimental uncertainty in the values.

Comparison of the ^{1}H NMR spectral parameters for the *E* and *Z* isomers of **11b** (Table III) makes the stereochemical assignments for the diastereomers of **14** and **15** quite straightforward. In each case the *Z* isomer has more shielded *t*-Bu_1 (0.04 ± 0.01 ppm) and the *less* shielded OCH_3 (0.09 ± 0.04 ppm) and methine hydrogen (0.08 ± 0.01 ppm). This suggests that the substituent position *Z* to the phosphoryl oxygen is consistently *deshielded* relative to the *E* position. In addition, a (*Z*)-*t*-Bu_1 is deshielding to the transannular methoxy group, relative to an (*E*)-*t*-Bu_1.

In our original report on the formation of the oxaphospholene ring system,[1] we reported that **17** was formed as a single diastereomer[16] and that its methanolysis led to a single diastereomer[16] of ester **15**.[19a] We can now identify



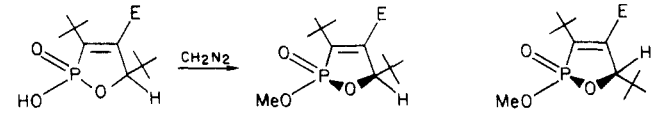
17



Z-**15**

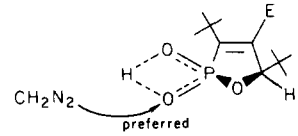
that methyl ester[1] as the *E* isomer. This requires that the formation of **17** be stereoselective and that its methanolysis be stereospecific, but without knowing the exact stereochemistry of **17** it is not yet possible to determine whether the methanolysis involves retention or inversion at phosphorus. Nonetheless, one can assert that the trigonal-bipyramidal (TBP) intermediates involved in these reactions[20,21] must interconvert stereospecifically (a or b but not both, Scheme III). If these TBP interconversions do involve ring opening–ring closing sequences,[20,21] path b (Scheme III) would be operative, with conversion of (*Z*)-**17** to (*E*)-**15** (net inversion). Moreover, that the presumed[1] precursor of **17** (**18**, which is achiral at phosphorus) hydrolyzed stereoselectivity to *either* (*Z*)-**17** *or* (*E*)-**17**[18] requires that either path a or b (Scheme IV) is operative, but *not* both. Following the above argument, we would predict that **17** has the *Z* stereochemistry, with path b (Scheme IV) being favored. Alternatively, it is possible that direct $S_N2(P)$ displacements with the nucleophile attacking trans to *t*-Bu_1 would convert **18** to (*Z*)-**17** to (*E*)-**15**.

Treatment of phosphonic acids **16**,[2] **19**,[4] and **20b** (vide infra), which are achiral at phosphorus owing to prototropy,[2,3] with diazomethane[10] led cleanly to the corre-

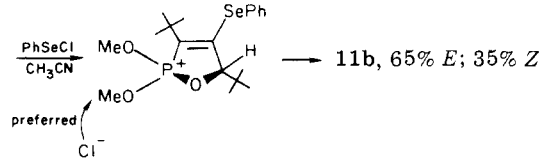


	E, %	*Z*, %
16, E = H		
19, E = Br		
20b, E = SePh	56	44
	57	43
	52	48

sponding methyl esters as stable[19b] mixtures of diastereomers, with a consistent preference for the *E* isomer. Because this reaction does *not* involve TBP's, it is clear that the diazomethane has a slight preference for approach trans to the bulky *t*-Bu_1.



Returning to the selenium-mediated cyclization of **4b**, the diastereomer ratio again favored the *E* isomer when the reaction was carried out in polar acetonitrile, but a 50:50 mixture was formed during the (much slower) reaction in chloroform. Here again the intermediate (**10b**) is achiral at phosphorus (though retaining chirality of carbon[4]), as was **18**. The conversion of **10b** to **11b** involves



10b

Arbuzov-type S_N2 cleavage at methoxy carbon[20-22] by

(19) (a) Examination by ^{1}H NMR of crude **17** before purification shows a single diastereomer. (b) Esters (*E*)- and (*Z*)-**15** were completely stable in CD_3OD containing 1.5 molar equiv of trifluoroacetic acid (**5d**, 65 °C), showing neither methoxy exchange nor epimerization.

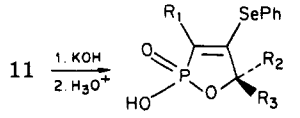
(20) Macomber, R. S.; Krudy, G. A.; Amer, M. Z. *J. Org. Chem.*, previous paper in this issue.

(21) These interconversions probably do not involve simple pseudorotation but rather a series of ring opening–ring closing reactions. See also: Macomber, R. S. *J. Am. Chem. Soc.*, in press.

(22) Macomber, R. S.; Krudy, G. A. *J. Org. Chem.* **1981**, *46*, 4038.

chloride. The observed diastereomer ratio in acetonitrile requires that this attack occurs preferentially cis to t-Bu_1. That this preference disappears in chloroform can be attributed to the weaker solvation (hence higher reactivity and less selectivity) of chloride ion and **10b** than in the more polar acetonitrile.

Finally, we have found that the 4-selenooxaphospholene esters can be hydrolyzed to the corresponding phosphonic acids, as has been found in similar systems.[14,15,20-22] Thus, a mixture of (*Z*)- and (*E*)-**11b** underwent basic hydrolysis to a single product **20b** in 73% yield; **11c** hydrolyzed to **20c** in 91% yield. The latter hydrolysis was ten times faster than the former. Apparently the bulky t-Bu_2 inhibits nucleophilic attack necessary for hydrolysis of phosphorus.[20-22]



20b, $R_1 = R_3 = t$-Bu; $R_2 = H$
20c, $R_1 = H$; $R_2 = R_3 = Me$

Experimental Section

General procedures and instrumentation were as previously described.[1-6] Details on the preparation of three of the starting materials can be found in the literature: **4a**,[3] **4c**,[13] **4d**.[13] ^1H NMR chemical shifts in ppm downfield from internal Me_4Si.

Dimethyl (2,2,6,6-Tetramethyl-3,4-heptadien-3-yl)phosphonate (4b). Ethereal diazomethane was added to a solution of 164 mg (0.71 mmol) of 2,2,6,6-tetramethyl-3,4-heptadiene-3-phosphonic acid (**3b**)[2,3] until the color persisted for 5 min. Rotary evaporation left 184 mg (100%) of **4b**: ^1H NMR (CCl_4)[23] 1.09 (s, 9 H), 1.30 (s, 9 H), 3.80 (d, 13 Hz, 3 H), 3.82 (d, 13 Hz, 3 H), 5.23 ppm (d, J = 13 Hz, 1 H); IR (CCl_4) 2960 (s), 2900 (s), 2865 (s), 1950 (m), 1740 (m), 1475 (m), 1380 (m), 1260 (s), 1190 (w), 1070 (s), 1040 (s), 990 (w), 965 (w), 865 (s), 845 (s), 760 (vs), 695 (w), 652 (w), 605 (w), 572 (s) cm^{-1}. Exact mass calcd for $C_{13}H_{25}O_3P$: 260.1543. Found: 260.1634.

Phenyl (3-Methyl-1,2-butadienyl)phosphinic Acid (5). With a small gas dispersion tube, dry nitrogen (200 mL/min) was passed through a stirred solution of 9.21 g (0.11 mol) of 2-methyl-3-butyn-2-ol in 60 mL of dichloromethane, maintained at 25 °C in a water bath. Over 10 min, a solution of 20.77 g (0.12 mol) of dichlorophenylphosphine in 42 mL of dichloromethane was added dropwise. With nitrogen flow continuing, the solution was stirred for 3.0 h. Rotary evaporation left a colorless liquid, which was added dropwise to 50 mL of water at 0 °C. During the addition sodium bicarbonate (4.5 g, 5.4 mmol) was added portionwise. The mixture was briefly warmed to 35 °C, and the crude product was collected by filtration. Recrystallization (70:30 $EtOH/H_2O$) gave 16.77 g (74%) of **5** as colorless needles: mp 80.5–82.5 °C (lit.[12] 79–80 °C); ^1H NMR ($CDCl_3$) 1.55 (dd, J = 3, 7 Hz, 6 H), 5.38 (m, 1 H), 7.28–7.97 (m, 5 H), 12.57 ppm (br s, 1 H).

Methyl Phenyl(3-methyl-1,2-butadienyl)phosphinate (6).[11] Ethereal diazomethane was added to a solution of 209 mg (1.0 mmol) of phosphinic acid **5** in 3 mL of methanol until the color persisted for 1 min. Rotary evaporation left 223 mg (100%) of **6**, which was used without further purification: ^1H NMR ($CDCl_3$) 1.63 (dd, J = 7.5, 4 Hz, 6 H), 3.73 (d, J = 12 Hz, 3 H), 5.42 (m, 1 H), 7.37–8.03 ppm (m, 5 H).

Dimethyl (3-Chloro-2-(phenylseleno)-1-(*E*)-propenyl)phosphonate (12a). Benzeneselenyl chloride (716 mg, 3.7 mmol) in 12 mL of chloroform was added to a stirred solution of 542 mg (3.7 mmol) of **4a** in 10 mL of chloroform at 46 °C under nitrogen. The mixture was stripped of solvent after 7 h at 46 °C, and the residue was subjected to flash chromatography. The product with R_f 0.51 (EtOAc) was distilled (Kugelrohr) to give 574 mg (46%) of yellow oil: bp 153–155 °C (0.15 mmHg); ^1H NMR ($CDCl_3$) 3.83 (d, J_{PH} = 11 Hz, 6 H), 4.00 (overlapping dd,[24] $J_{PH} = J_{HH}$ = 1.5 Hz, 2 H), 6.48 (t, J_{PH} = 14, J_{HH} = 1.5 Hz, 1 H), 7.23–7.83 ppm (m, 5 H); IR ($CHCl_3$) 3000 (m), 2955 (w), 2850 (w), 1575 (w), 1555 (w), 1475 (w), 1460 (w), 1440 (w), 1420 (w), 1240 (m, br), 1180 (sh), 1030 (s, br), 1000 (sh), 885 (w), 830 (m), 590 (m) cm^{-1}; MS (70 eV), m/e 342 (M^+ for ^{35}Cl, ^{80}Se), 185/183, (M – SePh; 1/2.9), 28 (base).

(*Z*)- and (*E*)-3,5-Di-*tert*-butyl-2-methoxy-4-(phenylseleno)-1,2-oxaphosphol-3-ene 2-Oxide ((*E*)-11b and (*Z*)-11b). Benzeneselenyl chloride (204 mg, 1.01 mmol) in 4.5 mL of acetonitrile was added to a stirred solution of 217 mg (0.83 mmol) of **4b** in 1.5 mL of acetonitrile, and the mixture was heated to 66 °C for 5 h. NMR showed quantitative conversion to a mixture of 65% Z and 35% E. Rotary evaporation left a red oil, which was chromatograhed on silica ($CHCl_3$/EtOAc, 20:1 (v/v)) to yield separate diastereomeric products. Both isomers were recrystallized from isopropyl ether. The combined mass of pure (*E*)- and (*Z*)-**11b** was 224 mg (67%). (*Z*)-**11b** (less polar): 79 mg; mp 123–125 °C; ^1H NMR (CCl_4) see Table III; IR (CCl_4) 2980 (m), 1555 (w), 1470 (m), 1365 (w), 1255 (s), 1050 (s), 1035 (sh), 1000 (s), 895 (w), 870 (m), 830 (w), 690 (w), 680 (w), 570 (w) cm^{-1}; MS (70 eV), m/e 402 (M^+ for ^{80}Se), 57 (base). Anal. Calcd for $C_{18}H_{27}O_3PSe$: C, 53.86; H, 6.78. Found: C, 53.90; H, 6.71. A crystal of this isomer was subjected to X-ray analysis (vide infra). (*E*)-**11b** (more polar): 145 mg; mp 117–119 °C; ^1H NMR (CCl_4) see Table III; IR (CCl_4) 3060 (w), 1480 (s), 1440 (m), 1390 (w), 1360 (m), 1320 (m), 1250 (s), 1040 (s), 1030 (s), 990 (s), 890 (w), 865 (s), 825 (m), 690 (m), 570 (w) cm^{-1}; MS (70 eV), m/e 402 (M^+ for ^{80}Se), 41 base. Anal. Calcd for $C_{18}H_{27}O_3PSe$: C, 53.86; H, 6.78. Found: C, 54.00; H, 6.67. When chloroform, rather than acetonitrile, was used as solvent the reaction required 4 days at reflux and a 1:1 diastereomer mixture was produced.

5,5-Dimethyl-2-ethoxy-4-(phenylseleno)-1,2-oxaphosphol-3-ene 2-Oxide (11c). Benzeneselenyl chloride (1.2 g, 6.3 mmol) in 12 mL of methylene chloride was added dropwise to a stirred solution of **4c** (1.29 g, 6.3 mmol) in 10 mL of methylene chloride at room temperature. The yellow mixture was stirred for 15 min, and the solvent was removed, leaving 2.30 g (2.09 theoretical) of crude product. Distillation afforded 1.40 g (67%) of **11c** as an oil: bp 150–152 °C (0.2 mmHg) (lit.[7d] 148–149 °C (0.5 mmHg); ^1H NMR ($CDCl_3$) 1.28 (t, J_{HH} = 7 Hz, 3 H), 1.60 (s, 3 H), 1.66 (s, 3 H), 4.07 (dq, J_{PH} = 10, J_{HH} = 7 Hz, 2 H), 5.28 (d, J_{PH} = 28 Hz, 1 H), 7.47 (m, 5 H).[25]

2-Ethoxy-5,5-pentamethylene-4-(phenylseleno)-1,2-oxaphosphol-3-ene 2-Oxide (11d). Benzeneselenyl chloride (368 mg, 1.9 mmol) in 12 mL of chloroform was added to a stirred solution of 433 mg (1.8 mmol) of **4d** in 10 mL of $CHCl_3$ at room temperature. The yellow mixture was stirred for 15 min, and the solvent was removed, leaving 706 mg (668 mg theoretical) of a yellow waxy solid. Recrystallization (methyl cyclohexane/dichloromethane) gave 486 mg (73%) of colorless **11d** in two crops: mp 145.5–147.0 °C; ^1H NMR ($CDCl_3$) 1.28 (t, J_{HH} = 7 Hz, 3 H), 1.57–2.00 (m, 10 H), 4.04 (dq, J_{PH} = 9.5, J_{HH} = 7 Hz, 2 H), 5.27 (d, J = 28.5 Hz, 1 H), 7.33–7.73 ppm (m, 5 H); IR ($CHCl_3$) 3010 (m), 2950 (m), 2870 (w), 1510 (m), 1475 (w), 1270 (s), 1250 (s), 1050 (s), 970 (vs), 910 (m), 900 (s) cm^{-1}; MS (70 eV), m/e 372 (M^+ for ^{80}Se), 105 (base). Anal. Calcd for $C_{16}H_{21}O_3PSe$: C, 51.76; H, 5.70. Found: C, 51.60; H, 5.86.

5,5-Dimethyl-2-phenyl-4-(phenylseleno)-1,2-oxaphosphol-3-ene 2-Oxide (11e). Benzeneselenyl chloride (234 mg, 1.2 mmol) in 7 mL of chloroform was slowly added to a stirred solution of 249 mg (1.1 mmol) **6** in 5 mL of chloroform at room temperature. After addition, during which the color of **7** was discharged, the mixture was stirred for 1 h at room temperature. Removal of the solvent left a solid, which was subjected to flash chromatography and recrystallized twice from methylcyclohexane to afford 244 mg (61%) of **11e**: mp 100.5–102.0 °C; ^1H NMR (CCl_4) 1.63 (s, 3 H), 1.77 (s, 3 H), 5.42 (d, J_{PH} = 29 Hz, 1 H), 7.3–7.87 ppm (m, 10 H); IR ($CHCl_3$) 3075 (vw), 3000 (s), 1555 (s), 1445 (m), 1260 (s), 1230 (s, br), 1180 (m), 1140 (sh), 1120 (s), 970 (s), 945 (s), 890 (vs), 840 (m), 580 (s) cm^{-1}; MS (70 eV), m/e 364 (M^+ for ^{80}Se), 77 (base). Anal. Calcd for $C_{17}H_{17}O_2PSe$: C, 56.21; H, 4.72. Found: C, 56.20; H, 4.97. Alternatively, a solution of 160 mg (0.84 mmol) of benzeneselenyl chloride in 5 mL of methylene

(23) The ^{13}C spectrum of this compound was previously described: Krudy, G. A.; Macomber, R. S. *J. Org. Chem.* **1978**, *43*, 4656.
(24) J_{PH} obtained by decoupling.
(25) Previous description of the spectrum[7d] is similar to ours, though we find the CH_2O absorption at 4.07, *not* 2.04 ppm.

chloride was added dropwise to a stirred solution of 160 mg (0.77 mmol) of **5** in 10 mL of methylene chloride. The mixture was stirred at room temperature for 20 min, washed with saturated aqueous sodium bicarbonate, dired over magnesium sulfate, concentrated to ca. 1.5 mL, and flash chromatographed to remove diphenyl diselenide. Recrystallization from methyl cyclohexane gave 184 mg (66%) of **11e** identical in all respects with the material prepared by the previously described method.

5,5-Dimethyl-2-ethoxy-4-((2,4-dinitrophenyl)thio)-1,2-oxaphosphol-3-ene 2-Oxide (13c). A solution of 2.55 g (10.9 mmol) of 2,4-dinitrobenzenesulfenyl chloride in 35 mL of CH_2Cl_2 was added dropwise to a cooled (10 °C) stirred solution of 2.21 g (10.8 mmol) of **4c** in 50 mL of CH_2Cl_2 over a period of 18 min. The resulting mixture was stirred for 6 days at room temperature, filtered, and evaporated, leaving 4.23 g of red oil, which crystallized on standing. Recrystallization from ethyl acetate afforded 3.06 g (76%) of **13c** in two crops: mp 162–164 °C; ^1H NMR ($CDCl_3$) 1.30 (t, J_{HH} = 7 Hz, 3 H), 1.58 (s, 3 H), 1.63 (s, 3 H), 4.17 (dq, J_{PH} = 10, J_{HH} = 7 Hz, 2 H), 5.90 (d, J_{PH} = 25 Hz, 1 H), 7.97 (d, J_{HH} = 9 Hz, 1 H), 8.50 (dd, J_{HH} = 9, J_{HH} = 2 Hz, 1 H), 8.98 ppm (d, J_{HH} = 2 Hz, 1 H); IR ($CHCl_3$) 3100 (w), 3000 (m), 1595 (s), 1565 (s), 1535 (vs), 1460 (w), 1385 (w), 1375 (sh), 1340 (vs), 1270 (vs), 1245 (sh), 1185 (m), 1145 (m), 1040 (vs), 980 (vs), 905 (s), 850 (sh), 835 (s), 585 (m) cm^{-1}; MS (70 eV), m/e 374 (M^+), 191 (base). Anal. Calcd for $C_{13}H_{15}N_2O_7PS$: C, 41.71; H, 4.05. Found: C, 41.81; H, 4.13.

2-Ethoxy-5,5-pentamethylene-4-((2,4-dinitrophenyl)thio)-1,2-oxaphosphol-3-ene 2-Oxide (13d). Under nitrogen, a solution of 1.17 g (5.0 mmol) of 2,4-dinitrobenzenesulfenyl chloride in 25 mL of CH_2Cl_2 was added dropwise to a cooled (0 °C) stirred solution of 1.06 g (4.3 mmol) of **4d** in 25 mL of CH_2Cl_2. After 7 days of stirring at room temperature, the solvent was stripped, leaving a red oil that was subjected to flash chromatography. The yellow product was recrystallized (EtOAc/methylcyclohexane) to yield 1.09 g (61%) of **13d**: mp 143–144.5 °C; ^1H NMR ($CDCl_3$) 1.35 (t, J_{HH} = 7 Hz, 3 H), 1.80 (s, $\nu_{1/2}$ = 11 Hz, 10 H), 4.17 (dq, J_{PH} = 10, J_{HH} = 7 Hz, 2 H), 5.97 (d, J_{PH} = 26 Hz, 1 H), 7.95 (d, J_{HH} = 9 Hz, 1 H), 8.45 (dd, J_{HH} = 9, J_{HH} = 2 Hz, 1 H), 8.93 (d, J = 2 Hz, 1 H); IR ($CHCl_3$) 3000 (w), 2940 (w), 1600 (m), 1530 (m), 1340 (vs), 1270 (m), 1245 (m), 1030 (m), 975 (s), 900 (m), 830 (w) cm^{-1}; MS (70 eV), m/e 414 (M^+), base, 55. Anal. Calcd for $C_{16}H_{19}N_2O_7PS$: C, 46.37; H, 4.62. Found: C, 46.52; H, 4.81.

5,5-Dimethyl-2-phenyl-4-((2,4-dinitrophenyl)thio)-1,2-oxaphosphol-3-ene 2-Oxide (13e). Under nitrogen, a solution of 902 mg (3.9 mmol) of 2,4-dinitrobenzenesulfenyl chloride in 35 mL of $CHCl_3$ was added dropwise to a cooled (0 °C), stirred solution of 846 mg (3.8 mmol) of **6** in 25 mL of $CHCl_3$. The resulting yellow mixture was stirred for 3 days at room temperature, and the solvent was stripped to leave 1.69 g of orange semisolid, which was redissolved in CCl_4, filtered, and evaporated to dryness, leaving 1.53 g of yellow solid. The crude product was recrystallized twice (methylcyclohexane/EtOAc) to give 1.00 g (65%) of **13e** in two crops: mp 111.5–113.5 °C; ^1H NMR ($CDCl_3$) 1.75 (s, 3 H), 1.86 (s, 3 H), 5.97 (d, J_{PH} = 28 Hz, 1 H), 7.37–7.73 (m, 5 H), 8.02 (d, J_{HH} = 9 Hz, 1 H), 8.43 (dd, J_{HH} = 9, J_{HH} = 2 Hz, 1 H), 8.88 ppm (d, J = 2 Hz, 1 H); IR ($CHCl_3$) 3100 (vw), 3000 (m), 1600 (s), 1530 (s), 1490 (w), 1395 (vs), 1260 (m), 1230 (br), 1140 (sh), 1125 (m), 1050 (w), 975 (m), 960 (m), 900 (s), 840 (s), 690 (w), 580 (m) cm^{-1}; MS (40 eV), m/e 406 (M^+), 28 (base). A satisfactory elemental analysis could not be obtained.

3,5-Di-*tert*-butyl-2-hydroxy-4-(phenylseleno)-1,2-oxaphosphol-3-ene 2-Oxide (20b). Potassium hydroxide (0.27 g, 5 mmol) was added to a solution of 223 mg (0.56 mmol) of a mixture of (*Z*)- and (*E*)-**11b** in 10 mL of methanol and the mixture refluxed for 4 days. The mixture was stripped of solvent and the residue redissolved in H_2O. Acidification with 0.1 N HCl gave 202 mg (215 theoretical) of crude **20b**, which was recrystallized from ethyl acetate to afford 157 mg (73%) in two crops: mp 186.5–189 °C; ^1H NMR ($CDCl_3$) 1.03 (s, 9 H), 1.55 (s, 9 H), 4.35 (d, J = 11 Hz, 1 H), 7.35 (s, 5 H), 11.23 (s, 1 H); IR ($CHCl_3$) 3060 (sh), 3100–2500 (br), 2980 (s), 2900 (sh), 2880, 2460–2000 (br), 1800–1600 (br), 1570 (m), 1550 (s) 1470 (s), 1430 (w), 1390 (w), 1360 (m), 1320 (w), 1300 (w), 1220 (br), 1180 (s), 1040 (s), 1020 (sh), 990 (vs), 910 (s), 860 (s), 690 (m), 680 (m), 650 (w), 560 (m) cm^{-1}; MS (70 eV), m/e, 388 (M^+ for ^{80}Se), 57 (base). Anal. Calcd for $C_{17}H_{25}O_3PSe$: C, 52.72; H, 6.51. Found: C, 52.92; H, 6.61.

5,5-Dimethyl-2-hydroxy-4-(phenylseleno)-1,2-oxaphosphol-3-ene 2-Oxide (20c). A suspension of 407 mg (1.2 mmol) of 5,5-dimethyl-2-ethoxy-4-(phenylselenyl)-1,2-oxaphosphol-3-ene 2-oxide (**11c**) in 5 mL of H_2O was refluxed for 9 h, and the solvent was completely removed. The residue was recrystallized from acetone to afford 333 mg (91%) of **20c** in two crops: mp 219–220.5 °C; ^1H NMR ($CDCl_3$) 1.60 (s, 6 H), 5.25 (d, J = 28 Hz, 1 H), 7.3–7.7 (m, 5 H), 11.0 (s, 1 H); IR ($CHCl_3$) 3100–2500 (v br), 2960 (w), 2460–2020 (br), 1770–1540 (br), 1540 (s), 1460 (w), 1425 (w), 1370 (w), 1355 (w), 1240 (s), 1200 (br), 1160 (s), 1130 (m), 980 (vs), 960 (sh), 930 (s), 875 (s), 840 (m), 675 (w), 600 (w) cm^{-1}; MS (70 eV), m/e 304 (M^+ for ^{80}Se), 182 (base). Anal. Calcd for $C_{11}H_{13}O_3PSe$: C, 43.58; H, 4.32. Found: C, 43.60; H, 4.32.

Crystallographic Analysis. An automated Syntex $P\bar{1}$ diffractometer with graphite-monochromatized Mo Kα radiation (Kα_1, λ = 0.70930 Å, Kα_2, λ = 0.71359 Å) was used to study a single crystal of (*E*)-**11b** of extreme dimensions 0.12 × 0.12 × 0.15 mm at 23 °C. Each reflection was scanned at 2°/min from 0.8° below Kα_1 to 0.8° above Kα_2 by the θ–2θ technique. Three standard reflections, remeasured every 100 reflections, varied little during the course of data collection. All intensities were corrected for Lorentz and polarization effects.[26] Weights used in least-squares refinement were the reciprocal squares of $\sigma(F_o)$, which were derived from counting statistics. Of the 3487 unique reflections measured, only those 1967 for which $I > 2\sigma(I)$ were used. The atomic scattering factors for Se^0,P^0,O^0,C^0 (valence),[27] and H (bonded)[28] were used; all but hydrogen were modified to include the real and imaginary parts of the anomalous dispersion correction.[29]

The structure was solved by Patterson and Fourier methods.[30] All 27 hydrogen-atom positions were observed on difference Fourier functions. Full-matrix least-squares refinement[31] of all atoms, using isotropic temperature factors for hydrogens and anisotropic ones for the rest, converged to reliability indices, R = 0.054 and R_w = 0.037. The goodness-of-fit was 1.35. The two largest peaks on the final difference function were less than 0.5 e Å^{-3} in height and were located less than 1.1 Å from Se at chemically implausible positions.

Crystal data for (*Z*)-11b: $C_{18}H_{27}O_3PSe$, M_r 401.34, monoclinic, $P2_1/c$, a = 11.909 (2) Å, b = 18.520 (4) Å, c = 9.542 (2) Å, β = 111.18 (1)°, V = 1962.4 (6) Å^3 at 25 °C, $F(000)$ = 832, ρ_{obsd} (flotation) = 1.35 (1) g cm^{-3}, ρ_{calcd} (Z = 4) = 1.358 g cm^{-3}, μ(Mo Kα) = 19.8 cm^{-1}.

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Supplementary Material Available: Tables of final atomic coordinates and thermal parameters and bond lengths and bond angles (3 pages). Ordering information is given on any current masthead page.

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