The β-(Phosphatoxy)alkyl Radical Rearrangement. Rate Constants, Arrhenius Parameters, and Structure Activity Relationships

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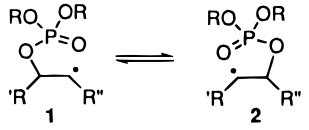
Abstract: Rate constants for the migration of a series of *p,p*-disubstituted β-(diarylphosphatoxy)alkyl migrations have been determined in benzene at reflux by competition against the benzeneselenol clock reaction. There is a strong linear correlation of log(k) with the Hammett σ_p but not with various $\sigma^\bullet$ parameters indicating that the migration occurs through a highly polarized transition state resembling an alkene radical cation loosely bound to a phosphate anion. The Arrhenius equation describing the migration of the β-phenyl-β-(diphenylphosphatoxy)ethyl radical in toluene was found to be $\log(k_R) = (10.2 \pm 0.8) - (7.0 \pm 1.0)/2.3RT$.

Introduction

β-(Phosphatoxy)alkyl radicals are implicated in the degradation of oligonucleotides by free radicals, including various antitumor antibiotics and hydroxyl radicals.[1] Exploration of the fundamental chemistry of this clearly important class of radicals with simple model systems has uncovered a previously unknown radical migration, the β-(phosphatoxy)alkyl rearrangement (**1** → **2**).[2,3] A series of stereochemically and deuterium labeled



probes revealed this rearrangement to proceed in benzene solution in a non-dissociative manner through two parallel, competing transition states representing formal 1,2- and 2,3-

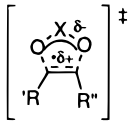


Figure 1. 5-Center-5-electron TS.

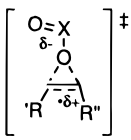


Figure 2. 3-Center-3-electron TS.

shifts [Figures 1 and 2, X = $P(OR)_2$], and to be in certain cases highly or even completely stereoselective.[2] Initially, Giese[3] and we[2] had predicted the existence of the β-(phosphatoxy)alkyl migration on the grounds of its probable relationship to the intriguing β-(acyloxy)alkyl, or Surzur/Tanner rearrangement.[4] Subsequently, we have shown this class of radical ester rearrangements to be somewhat general and to include the migration of nitrates and sulfonates,[5] and even the contraction and/or expansion of lactones.[6] We have postulated that each of these rearrangements occurs in apolar, aprotic solvents through the two parallel mechanisms of Figures 1 and 2 [X = $P(OR)_2$, CR, NO, S(O)R] with the distribution a factor of the particular system.[2a] The polarized nature of the 5-center-5-electron transition state for the β-(acyloxy)alkyl migration (Figure 1, X = CR) was first put forward by Beckwith and Ingold on the grounds that the rearrangement was accelerated by polar solvents and was more rapid for trifluoroacetates than for simple acetates.[7] Consideration of the structures of the

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(3) (a) Koch, A.; Giese, B. *Helv. Chim. Acta* **1993**, *76*, 1687. (b) Koch, A.; Lamberth, C.; Wettrich, F.; Giese, B. *J. Org. Chem.* **1993**, *58*, 1083.

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(7) (a) Barclay, L. R. C.; Lusztyk, J.; Ingold, K. U. *J. Am. Chem. Soc.* **1984**, *106*, 1793. (b) Saebo, S.; Beckwith, A. L. J.; Radom, L. *J. Am. Chem. Soc.* **1984**, *104*, 5119.

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cyclopentadienyl and cyclopropenyl radicals, as revealed by EPR-spectroscopy,[8,9] and of simple competition experiments showing the phosphatoxy migration to be several orders of magnitude faster than the acyloxy shift, led us to suggest that this polarization is general to both the 3- and 5-center shifts.[2a] We have now determined the migration rate constants of a series of *p*-substituted diphenyl phosphate esters and find that they fit to a simple correlation with the Hammett σ_p-parameter providing strong support for polarization of the transition states for migration as indicated in Figures 1 and 2.

Results and Discussion

Competition experiments in this laboratory in which **3** was allowed to react with tributyltin hydride under AIBN initiation in benzene at reflux revealed the diphenylphosphatoxy group to migrate stereospecifically to **4**, and to the exclusion of the acetoxy group, indicating a difference in rate constant of at least two orders of magnitude. More quantitative experiments in the Giese laboratory put the rate constant for the rearrangement of radical **5** to **6** at 8×10^6 s^{-1},[3a] as opposed to 5.2×10^2 s^{-1} for that of the corresponding acetate (**7** → **8**).[10] Combined with the earlier observation of Ingold on the effect of solvents on the rate of the acyloxy migration and the accelerating effect of electron-withdrawing substituents on the migrating ester in the same, these differences in rate constant strongly suggested a significant polar component to the transition states for the phosphatoxy migration. To test this hypothesis we set out to measure the rate constants for the rearrangement of a series of *β*-(phosphatoxy)alkyl migrations and to look for linear free energy relationships with either Hammett *σ*-parameters or, failing that, with the free radical equivalents as devised by several groups.

The various substrates and authentic product samples were prepared either as previously described (**9**, **14**, **19**)[2a] or by reaction of the appropriate ethyl diaryl phosphite with iodine, to give the diaryl iodophosphate,[11] followed by addition of styrene bromohydrin or 1-, or 2-phenylethanol (**15**−**18**, **20**−**23**). The diethyl phosphates (**24**−**26**) were also prepared in order to assess the rate of migration of a simple dialkyl phosphate group. The kinetics were conducted by the radical clock method[12] using quenching of the unrearranged primary alkyl radicals by benzeneselenol as the metronomic standard.[13] This particular clock reaction was introduced by Newcomb for the determination of picosecond radical kinetics[14] but we have prefered to use our recent adaptation in which a fixed, catalytic amount of PhSeH introduced as PhSeSePh is constantly regenerated by slow addition of 1 molar equiv of tributyltin hydride as this avoids the preparation and handling of PhSeH and allows the reaction to be driven to completion while maintaining pseudo-first-order conditions.[15] The ratios of reduction to migration products at each of the different concentrations of PhSeH (PhSeSePh) used are collected in Table 1 for substrates **9**−**13** and in Table 2 for **24**. Plotting of the ratio of reduction to migration products against [PhSeH] gave, for each substrate, a straight line whose gradient is equal to k_H/k_R, where k_H is the rate constant for the reduction of primary

Chart 1

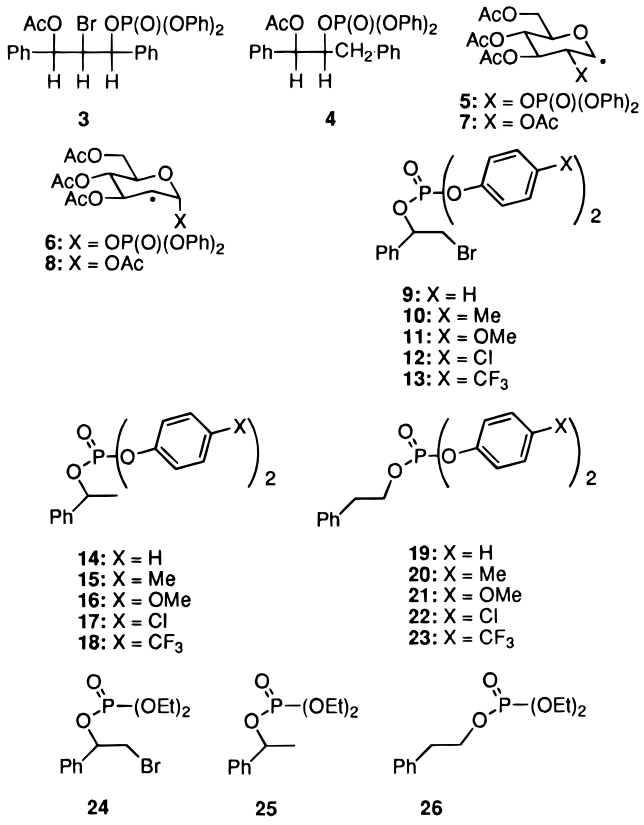

Table 1. Kinetic Data

mol % PhSeSePh	[PhSeSePh] ($M \times 10^3$)	ratio of reduction to migration				
		9, H	**10**, Me	**11**, OMe	**12**, Cl	**13**, CF_3
4.0	0.39		1.94			
5.0	0.49	1.43		1.76		
6.0	0.59		2.51			
8.0	0.78	1.57	3.90	2.23	0.54	
10.0	0.98	2.57	4.78	3.12	0.63	
12.0	1.17		5.33	3.95	0.75	
14.0	1.37	3.17		4.62	0.85	
16.0	1.56	3.71		5.54	0.97	0.32
18.0	1.76	4.46			1.14	
24.0	2.37					0.43
32.0	3.16					0.55
40.0	3.95					0.63
50.0	4.94					0.87

Table 2. Kinetic Data for **24**

mol % PhSeSePh	[PhSeSePh] ($M \times 10^5$)	ratio red/mig[a]
2.0	3.98	10.9
3.0	5.97	13.9
4.0	7.96	16.6
5.0	9.95	20.7
6.0	11.94	22.8

[a] Ratio of reduction to migration.

(8) (a) Sutcliffe, R.; Lindsay, D. A.; Griller, D.; Walton, J. C.; Ingold, K. U. *J. Am. Chem. Soc.* **1982**, *104*, 4674. (b) Schreiner, K.; Berndt, A. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 698.

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(12) (a) Ingold, K. U.; Griller, D. *Acc. Chem. Res.* **1980**, *13*, 317. (b) Newcomb, M. *Tetrahedron* **1993**, *49*, 1151.

(13) In using this method, we make the reasonable assumption that the rate of the clock reaction is not significantly affected by the presence of the *β*-phosphatoxy group and its substituents.

(14) (a) Newcomb, M.; Varick, T. R.; Ha, C.; Manek, M. B.; Yue, X. *J. Am. Chem. Soc.* **1992**, *114*, 8158. (b) Martin-Esker, A. A.; Johnson, C. C.; Horner, J. H.; Newcomb, M. *J. Am. Chem. Soc.* **1994**, *116*, 9174.

(15) Crich, D.; Jiao, X.-Y.; Yao, Q.; Harwood, J. S. *J. Org. Chem.* **1996**, *61*, 2368.

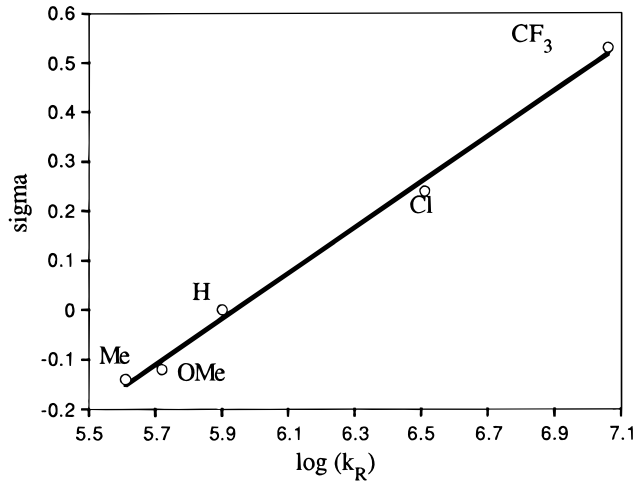

Figure 3. Hammett plot i.

Table 3. Rate and σ Constants

subs	*p*-substituent	slope[a] ($\times 10^{-3}$)	k_R[a] ($s^{-1} \times 10^{-6}$)	log-(k_R)	σ_p (Hammett)	$\sigma^\bullet$ (Arnold)
9	H	2.41 ± 0.78	0.80	5.90	0.00	0.00
10	Me	4.64 ± 1.28	0.41	5.61	−0.14	0.015
11	OMe	3.64 ± 0.85	0.53	5.72	−0.12	0.018
12	Cl	0.60 ± 0.10	3.20	6.51	0.24	0.011
13	CF_3	0.17 ± 0.06	11.6	7.06	0.53	−0.009
24		154 ± 24	0.012			

[a] Errors are at the 95% confidence interval (3.2σ).

alkyl radicals by PhSeH and k_R is the rate constant for the rearrangement in question. Substitution of 1.9×10^9 $M^{-1}s^{-1}$, calculated at 80 °C from the Arrhenius function [$\log(k_H) = 10.4 - 1.8/2.3RT$], for k_H gave the rate constants k_R in Table 3.

It is immediately evident from inspection of Table 3 that the nature of the substituent R in the migrating group OP(=O)-$(OR)_2$ has a significant effect on the rate of the β-(phosphatoxy)-alkyl radical migration. Thus, within the series of *p*-substituted diaryl phosphates (**9**−**13**) rate constants differ by a factor of as much as 29 (cf. **10** and **13**). It is also apparent that even the slowest diaryl phosphate migration measured is some 30-fold more rapid than that of the diethyl phosphate **24**. Within the series **9**−**13** $\log(k_R)$ was found to vary in a linear fashion with the Hammett σ_p parameter[16] (Table 3, Figure 3). On the other hand, no correlation whatsoever was found on plotting $\log(k_R)$ against the EPR-derived, Arnold $\sigma^\bullet$ parameter[17] (Table 3) for the stabilization of benzyl radicals by *para* substituents or other radical σ-parameters, such as that of Jackson[18] based on the decomposition of a series of dibenzylmercury compounds.[19] The lack of correlation of $\log(k_R)$ with $\sigma^\bullet$ scales and the strong one with σ_p, leading to a reaction coefficient ρ of 2.1, indicates that the β-(phosphatoxy)alkyl radical migration occurs through highly polarized transition states in which significant negative charge resides on the phosphate moiety. We therefore believe that Figures 1 and 2 [X = $P(OR)_2$] are reasonable qualitative representations of the 5-center-5-electron and 3-center-3-electron

(16) Taken from Exner, O. in *Correlation Analysis in Chemistry*; Chapman, N. B., Shorter, J., Eds.; Plenum Press: New York, 1978; Chapter 10.

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(19) (a) For a discussion of the pros and cons of the various $\sigma^\bullet$ scales in the literature see: Jackson, R. A. In *Substituent Effects in Radical Chemistry*; Viehe, H. G., Janousek, Z., Merényi, R., Eds.; Reidel Publishing: Dordrecht, 1986; p 325. (b) For recent work on $\sigma^\bullet$ scales see: Jiang, X. K.; Ji, G. Z. *J. Org. Chem.* **1992**, *57*, 6052 and references cited therein.

Table 4. Determination of Arrhenius Parameters for **9** → **19**

1000/*T*	temp (K)	[PhSeH] (M)	ratio **19/14**	k_H (M^{-1} s^{-1})	k_R (s^{-1})	log(k_R)
2.83	353			2.2×10^9	[a] 8.0×10^5	5.9
3.04	329	2.93×10^{-4}	0.66	1.6×10^9	3.1×10^5	5.5
3.19	313	2.93×10^{-4}	0.31	1.4×10^9	1.3×10^5	5.1
3.57	280	2.93×10^{-4}	0.18	9.8×10^8	5.1×10^4	4.7
4.03	248	2.93×10^{-4}	0.05	6.5×10^8	9.5×10^3	4.0
4.33	231	2.93×10^{-4}	0.02	4.9×10^8	2.9×10^3	3.5

[a] Taken from Table 3 (in benzene).

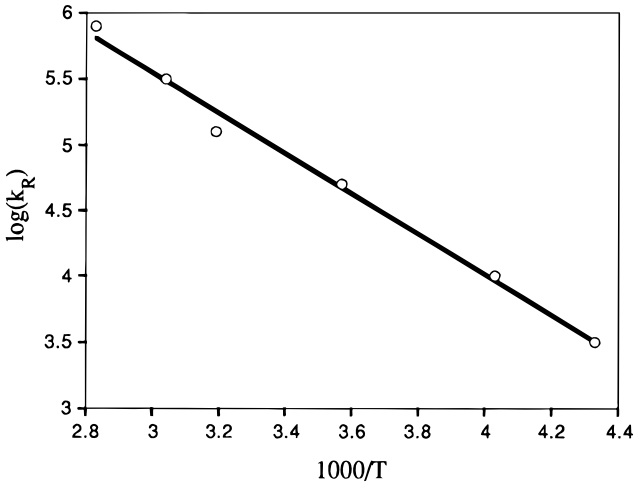
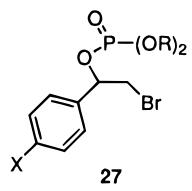


Figure 4. Arrhenius plot i.

migrations, respectively. In the light of these conclusions, a related study with **27** in which the migrating ester is kept constant and a substituent (X) varied should reveal a correlation between the electron donating ability of X and the migration rate. Indeed, Beckwith and Duggan have carried out such a series of experiments for the acyloxy migration, including a detailed ^{17}O-NMR analysis of the mechanism (1,2 vs 2,3) as a function of X, and do find the anticipated correlation.[20] Of course, the polar transition states advanced here and represented in Figures 1 and 2 are only separated from tight radical cation−anion pairs by a small margin. It is to be expected that this threshold will be crossed, and radical cation−anion pairs become true intermediates, as the ability of the two fragments to support charge increases and as the solvent polarity is augmented. In the extreme, as demonstrated by the work of Giese with the radical **28** in allyl alcohol as solvent,[21] it should be possible to trap radical cation intermediates with external nucleophiles.



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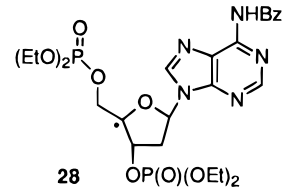

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By conducting the rearrangement of **9** over an 120 °C range of temperature (Table 4, Figure 4) the Arrhenius parameters for the one example were determined to be $\log(k_R) = (10.2 \pm 0.8) - (7.0 \pm 1.0)/2.3RT$.[22] While this equation is certainly useful for predicting the rate constant for the migration at a given temperature, it must be emphasized that it describes the sum of the 3-center-3-electron and the 5-center-5-electron

(20) Beckwith, A. L. J.; Duggan, P. J. Private communication.

(21) Giese, B.; Beyrich-Graf, X.; Burger, J.; Kesselheim, C.; Senn, M.; Schäfer, T. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1742.

(22) . Errors are at the 95% confidence interval (3.2σ).

processes. As such we have preferred not to draw conclusions about the nature of either transition state from this hybrid equation.

Finally, it is of some interest to reflect on the absolute magnitude of the rate constants presented in Table 3 in relation to those of prototypical radical rearrangements used in many synthetic schemes. Thus, although it is commonly acknowledged that β-ester functions do not compete effectively with the prototypical 5-hexenyl to cyclopentylmethyl ($k = 1.4 \times 10^6$ s^{-1} at 80 °C)[23] or cyclopropylmethyl to homoallyl (3.7×10^8 s^{-1} at 80 °C)[24] rearrangements, we see that a degree of caution is indicated when the ester is a diaryl phosphate, or we suspect a nitrate or sulfonate ester whose migration would yield a relatively stabilized radical.

Experimental Section

General Protocol for Preparation of 10−13, 15−18, 20−23. 2-Bromo-1-phenylethyl Bis(4′-methylphenyl) Phosphate (10). 4-Methylphenol (1.51 g, 14 mmol) in THF (20 mL) was added to a stirred suspension of sodium hydride (0.60 g, 60% in mineral oil, 15 mmol) in THF (10 mL) under Ar at 0 °C resulting, after 15 min, in a clear solution. A solution of ethyl dichloro phosphite (0.97 g, 6.6 mmol) in THF (20 mL) was then added dropwise and the reaction mixture subsequently stirred for 1.5 h at room temperature. The resulting solution was passed through a short silica gel column, eluting with ether, then concentrated under vacuum. Chromatography on silica gel (eluent: hexane/ethyl acetate 4/1) gave ethyl bis(4′-methylphenyl) phosphite (1.89 g, 99%) as a colorless oil. ^{1}H-NMR δ 1.33 (3 H, t, J = 7.1 Hz), 2.30 (6 H, s), 4.20 (2 H, q, J = 7.1 Hz), 6.98 (2 H, d, J = 8.0 Hz), 7.10 (2 H, d, J = 8.4 Hz); ^{13}C-NMR δ 16.7, 20.7, 58.5, 120.0 (d, J = 7.6 Hz), 130.1, 133.1, 149.3 (d, J = 3.6 Hz); ^{31}P-NMR δ 129.82. Iodine (1.32 g, 5.2 mmol) was added to a stirred solution of the above prepared phosphite (1.50 g, 5.2 mmol) in dichloromethane (15 mL) at −30 °C under Ar. After 15 min the so-formed phosphorylating agent was added to a mixture of styrene bromohydrin (1.05 g, 5.20 mmol) and pyridine (1.63 g, 20.6 mmol) in dichloromethane (15 mL), stirred under Ar at −30 °C. The reaction mixture was then allowed to come to 0 °C and then diluted with dichloromethane (40 mL) and washed with saturated NH_4Cl (20 mL), saturated $Na_2S_2O_3$ (20 mL), and brine (20 mL). The organic layer was dried on $MgSO_4$, concentrated, and purified by chromatography on silica gel (eluent: hexane/ethyl acetate 4/1) to give the title compound as a colorless oil. ^{1}H-NMR δ 2.27 (3 H, s), 2.32 (3 H, s), 3.59 (1 H, ddd, J = 2.1, 5.4, 10.9 Hz), 3.70 (1 H, dd, J = 7.0, 10.9 Hz), 5.69 (1 H, dd, J = 5.5, 7.0 Hz), 6.8−7.3 (13 H, m); ^{13}C-NMR δ 20.66, 20.72, 34.7 (d, J = 8.2 Hz), 80.5 (d, J = 5.5 Hz), 119.7 (d, J = 4.6 Hz), 119.9 (d, J = 4.4 Hz), 123.0, 126.7, 129.1, 130.1, 134.7, 134.9, 136.8, 148.1 (d, J = 6.5 Hz), 148.2 (d, J = 6.5 Hz); ^{31}P-NMR δ −11.7; IR ν 3037, 2963, 1507, 1454, 1289, 1193, 993, 708, 596 cm^{-1}. Anal. Calcd for $C_{22}H_{22}BrO_4P$: C, 57.28; H, 4.81. Found: C, 57.15; H, 4.76.

2-Bromo-1-phenylethyl Bis(4′-methoxyphenyl) Phosphate (11). ^{1}H-NMR δ 3.59 (1 H, ddd, J = 2.1, 5.4, 10.9 Hz), 3.70 (1H, dd, J = 6.9, 11.0 Hz), 3.74 (3 H, s), 3.78 (3 H, s), 5.67 (1 H, dt, J = 5.4, 7.1 Hz), 6.8−7.4 (13 H, m); ^{13}C-NMR δ 34.8 (d, J = 8.5 Hz), 55.55, 55.60, 80.5 (d, J = 3.4 Hz), 114.5, 114.6, 120.9 (d, J = 4.4 Hz), 121.1 (d, J = 4.5 Hz), 126.7, 128.6, 129.2, 136.9 (d, J = 3.2 Hz), 143.9 (d, J = 7.7 Hz), 144.0 (d, J = 7.6 Hz); ^{31}P-NMR δ −11.08; IR ν 3065, 2958, 1594, 1456, 1289, 1178, 1031, 700, 597 cm^{-1}. Anal. Calcd for $C_{22}H_{22}BrO_6P$: C, 53.56; H, 4.50. Found: C, 53.14; H, 4.41.

2-Bromo-1-phenylethyl Bis(4′-chlorophenyl) Phosphate (12). ^{1}H-NMR δ 3.58 (1 H, ddd, J = 2.8, 4.7, 11.1 Hz), 3.71 (1 H, dd, J = 7.8, 11.1 Hz), 5.7 (1 H, dd, J = 4.8, 7.8 Hz), 6.8−7.4 (13 H, m); ^{13}C-NMR δ 34.5 (d, J = 8.9 Hz), 81.4 (d, J = 5.2 Hz), 121.3 (d, J = 4.7 Hz), 121.6 (d, J = 4.6 Hz), 126.7, 128.8, 129.5, 129.6, 129.8, 130.8, 131.0, 136.5, 148.5 (d, J = 7.6 Hz), 148.8 (d, J = 7.6 Hz); ^{31}P-NMR δ −12.2; IR ν 3093, 3066, 2966, 1588, 1487, 1287, 1196, 998, 700, 647, 595 cm^{-1}. Anal. Calcd for $C_{20}H_{16}BrCl_2O_4P$: C, 47.84; H, 3.21. Found: C, 47.65; H, 3.28.

2-Bromo-1-phenylethyl Bis(4′-(trifluoromethyl)phenyl) Phosphate (13). ^{1}H-NMR δ 3.60 (1 H, ddd, J = 3.2, 4.4, 11.2 Hz), 3.73 (1 H, dd, J = 8.3, 11.2 Hz), 5.71 (1 H, dt, J = 4.4, 8.1 Hz), 7.0−7.7 (13 H, m); ^{13}C-NMR δ 34.3 (d, J = 9.5 Hz), 82.0 (d, J = 5.5 Hz), 120.3 (d, J = 5.1 Hz), 120.6 (d, J = 5.1 Hz), 123.7 (dq, J = 4.4, 271.9 Hz), 126.6, 127.1, 127.2, 128.9, 129.7, 136.3, 152.3 (d, J = 6.5 Hz), 152.6 (d, J = 6.5 Hz); ^{31}P-NMR δ −12.85; IR ν 3070, 2970, 1512, 1326, 1127, 1068, 700, 594 cm^{-1}. Anal. Calcd for $C_{22}H_{16}BrF_6O_4P$: C, 46.42; H, 2.83. Found: C, 46.40; H, 2.79.

2-Bromo-1-phenylethyl Diethyl Phosphate (24). Iodine (0.83 g, 3.3 mmol) was added to a solution of triethyl phosphite (0.56 g, 3.58 mmol) in dichloromethane (2 mL) at 0 °C under Ar. After 5 min the clear, colorless solution was allowed to warm to room temperature and then added dropwise over 5 min to a solution of styrene bromohydrin (0.60 g, 3.0 mmol) and pyridine (0.94 g, 12 mmol) in dichloromethane (5 mL) at room temperature. After being stirred for 10 min, the reaction mixture was diluted with ether (50 mL), washed with 25% $NaHSO_4$ (3 × 5 mL) and 10% sodium hydrogen phosphate buffer (pH 7, 5 mL), dried ($MgSO_4$), and concentrated under vacuum. Column chromatography (eluent: hexane/ethyl acetate 3/1) afforded the title compound (0.42 g, 41%) as a colorless oil. ^{1}H-NMR δ 1.12 (3 H, dt, J = 1.0, 7.1 Hz), 1.26 (3 H, dt, J = 1.0, 7.1 Hz), 3.59 (1 H, ddd, J = 2.2, 4.9, 10.9 Hz), 3.69 (1 H, dd, J = 7.4, 10.9 Hz), 3.88 (2 H, dq, J = 3.0, 7.2 Hz), 4.09 (2 H, ddq, J = 7.2, 10.1, 16.0 Hz), 5.47 (1 H, dt, J = 5.0, 7.6 Hz), 7.3−7.3 (5 H, m); ^{13}C-NMR δ 15.8 (d, J = 9.4 Hz), 15.9 (d, J = 9.9 Hz), 35.3 (d, J = 8.0 Hz), 63.7 (d, J = 5.8 Hz), 64.0 (d, J = 5.5 Hz), 78.9 (d, J = 4.9 Hz), 126.5, 128.5, 129.0, 137.6; ^{31}P-NMR δ −1.73; IR ν 3033, 2978, 1455, 1272, 1031, 986, 797, 701, 590 cm^{-1}. Anal. Calcd for $C_{12}H_{18}BrO_4P$: C, 42.75; H, 5.38. Found: C, 42.81; H, 5.36.

1-Phenylethyl Bis(4′-methylphenyl) Phosphate (15). This secondary benzylic phosphate was stable to the neutral migration conditions (Bu_3SnH, benzene, 80 °C) and also to the standard conditions for preparation of an authentic sample; unfortunately any attempt at purification by silica gel chromatography with a variety of neutral and basified solvents led to decomposition. The essential spectral characteristics are therefore taken from a crude preparation of an authenic sample. ^{1}H-NMR δ 1.63 (3 H, dd, J = 1.0, 6.5 Hz), 2.28 (3 H, s), 2.31 (3 H, s), 5.68 (1 H, quint, J = 6.6 Hz), 6.89−7.34 (13 H, m).

1-Phenylethyl Bis(4′-methoxyphenyl) Phosphate (16). This secondary benzylic phosphate was stable to the neutral migration conditions (Bu_3SnH, benzene, 80 °C) and also to the standard conditions for preparation of an authentic sample; unfortunately any attempt at purification by silica gel chromatography with a variety of neutral and basified solvents led to decomposition. The essential spectral characteristics are therefore taken from a crude preparation of an authenic sample. ^{1}H-NMR δ 1.63 (3 H, d, J = 6.7 Hz), 3.76 (3 H, s), 3.78 (3 H, s), 5.67 (1 H, quint, J = 6.6 Hz), 6.71−7.36 (13 H, m).

1-Phenylethyl Bis(4′-chlorophenyl) Phosphate (17). This secondary benzylic phosphate was stable to the neutral migration conditions (Bu_3SnH, benzene, 80 °C) and also to the standard conditions for preparation of an authentic sample; unfortunately any attempt at purification by silica gel chromatography with a variety of neutral and basified solvents led to decomposition. The essential spectral characteristics are therefore taken from a crude preparation of an authenic sample. ^{1}H-NMR δ 1.65 (3 H, dd, J = 1.0, 6.5 Hz), 5.67 (1 H, quint, J = 6.9 Hz), 6.70−7.35 (13 H, m).

1-Phenylethyl Bis(4′-trifluoromethylphenyl) Phosphate (18). This secondary benzylic phosphate was stable to the neutral migration conditions (Bu_3SnH, benzene, 80 °C) and also to the standard conditions for preparation of an authentic sample; unfortunately any attempt at purification by silica gel chromatography with a variety of neutral and basified solvents led to decomposition. The essential spectral characteristics are therefore taken from a crude preparation of an authenic sample. ^{1}H-NMR δ 1.68 (3 H, dd, J = 1.0, 6.5 Hz), 5.72 (1 H, quint, J = 6.8 Hz), 7.07−7.62 (13 H, m).

2-Phenylethyl Bis(4′-methylphenyl) Phosphate (20). ^{1}H-NMR δ 2.31 (6 H, s), 3.00 (2 H, t, J = 7.1 Hz), 4.41 (2 H, q, J = 7.1 Hz), 7.01−7.31 (13 H, m); ^{13}C-NMR δ 20.7, 36.6 (d, J = 7.6 Hz), 69.3 (d, J = 6.5 Hz), 119.7 (d, J = 4.7 Hz), 126.7, 128.5, 129.0, 130.1, 134.8,

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136.7, 148.3 (d, $J = 7.6$ Hz); ^{31}P-NMR δ −10.91; IR ν 3031, 2959, 1507, 1455, 1293, 1193, 1056, 749 cm^{-1}. Anal. Calcd for $C_{22}H_{23}O_4P$: C, 69.10; H, 6.06. Found: C, 69.01; H, 6.09.

2-Phenylethyl Bis(4′-methoxyphenyl) Phosphate (21). ^{1}H-NMR δ 3.00 (2 H, t, $J = 7.0$ Hz), 3.78 (6 H, s), 4.41 (2 H, q, $J = 7.1$ Hz), 6.78−7.30 (13 H, m); ^{13}C-NMR δ 36.6 (d, $J = 6.5$ Hz), 55.6, 69.3 (d, $J = 6.5$ Hz), 114.6, 120.9 (d, $J = 4.5$ Hz), 126.8, 128.5, 129.0, 136.8, 144.1 (d, $J = 7.6$ Hz), 156.8; ^{31}P-NMR δ −10.30; IR ν 3003, 2959, 1503, 1465, 1292, 1189, 1073, 833 cm^{-1}. Anal. Calcd for $C_{22}H_{23}O_6P$: C, 63.76; H, 5.59. Found: C, 63.29; H, 5.63.

2-Phenylethyl Bis(4′-chlorophenyl) Phosphate (22). ^{1}H-NMR δ 3.01 92 H, t, $J = 6.8$ Hz), 4.44 (2 H, q, $J = 6.9$ Hz), 7.0−7.3 (13 H, m); ^{13}C-NMR δ 36.5 (d, $J = 7.1$ Hz), 69.7 (d, $J = 6.4$ Hz), 121.6 (d, $J = 4.8$ Hz), 126.7, 128.6, 129.0, 129.8, 130.8, 136.4, 148.8 (d, $J = 6.5$ Hz); ^{31}P-NMR δ −11.56; IR ν 3092, 2958, 1588, 1484, 1304, 1197, 1057, 782 cm^{-1}. Anal. Calcd for $C_{20}H_{17}Cl_2O_4P$: C, 56.75; H, 4.05. Found: C, 56.50; H, 4.14.

2-Phenylethyl Bis(4′-(trifluoromethyl)phenyl) Phosphate (23). ^{1}H-NMR δ 3.04 (2 H, t, $J = 6.7$ Hz), 4.50 (2 H, q, $J = 6.7$ Hz), 7.2−7.6 (13 H, m); ^{13}C-NMR δ 36.5 (d, $J = 7.3$ Hz), 70.1 (d, $J = 6.3$ Hz), 120.3 (d, $J = 5.1$ Hz), 123.7 (q, $J = 272.5$ Hz), 127.0, 127.26, 127.30, 128.6, 129.0, 136.3, 152.6 (d, $J = 7.4$ Hz); ^{31}P-NMR δ −12.32; IR ν 3068, 2965, 1498, 1299, 1169, 1068, 847, 799 cm^{-1}. Anal. Calcd for $C_{22}H_{17}F_6O_4P$: C, 53.89; H, 3.49. Found: C, 53.96, H, 3.50.

1-Phenylethyl Diethyl Phosphate (25).[25] This compound was prepared analogously to **24**. ^{1}H-NMR δ 1.18 (3 H, dt, $J = 1.0$, 7.1 Hz), 1.28 (3 H, dt, $J = 1.0$, 7.1 Hz), 1.63 (3 H, d, $J = 6.5$ Hz), 3.92 (2 H, dq, $J = 0.6$, 7.1 Hz), 4.05 (2 H, m), 5.47 (1 H, dq, $J = 6.6$, 7.1 Hz), 7.27−7.40 (5 H, m); ^{13}C-NMR δ 15.9 (d, $J = 6.5$ Hz), 16.0 (d, $J = 6.5$ Hz), 24.2 (d, $J = 5.5$ Hz), 63.5 (2C, d, $J = 5.5$ Hz), 76.6 (d, $J = 5.5$ Hz), 125.9, 128.1, 128.4, 141.7 (d, $J = 5.5$ Hz); ^{31}P-NMR δ −1.12.

2-Phenylethyl Diethyl Phosphate (26).[26] This compound was prepared analogously to **24**. ^{1}H-NMR δ 1.28 (6 H, dt, $J = 1.3$, 7.1 Hz), 2.99 (2 H, t, $J = 7.0$ Hz), 4.02 (4 H, dq, $J = 1.1$, 7.1 Hz), 4.23 (2 H, q, $J = 7.1$ Hz), 7.20−7.33 (5 H, m); ^{13}C-NMR δ 15.9 (d, $J = 6.6$ Hz), 36.6 (d, $J = 6.9$ Hz), 63.5 (d, $J = 5.7$ Hz), 67.7 (d, $J = 6.0$ Hz), 126.5, 128.3, 137.0; ^{31}P-NMR δ −0.49.

Kinetics of Rearrangement of 9. General Method for Determination of Rearrangement Kinetics. A stock solution of **9** (0.866 g) in benzene (40 mL) was prepared and 4 mL (0.2 mmol) transferred to each of seven 50-mL round-bottomed Pyrex flasks. A stock solution of PhSeSePh (0.05 g) made up to 25 mL in benzene was then used to add 5, 6, 8, 12, 14, 16, or 18 mol % of PhSeSePh to these flasks. An amount of Bu_3SnH corresponding to that of PhSeSePh was added to each flask and the volume made up to 20 mL with benzene. A steady stream of Ar was then passed through each flask for several minutes. Each flask was brought to reflux, with stirring under Ar, while Bu_3SnH (0.070 g) and AIBN (1.6 mg) in benzene (1 mL) was added dropwise with a motor-driven syringe pump over 2.3 h. Reflux was continued for a further 1 h before the solvent was removed *in vacuo* and the residue examined by ^{1}H-NMR. In each case the substrate was completely consumed. Integration of the H-1 resonance in **14** and the H-2 resonance in **19** gave the ratio of (reduction/migration) **14**/**19** as recorded in Table 1. The spectral data for **14** and **19** were identical to those recorded in the literature.[2a] The total volume change in the course of the reaction, owing to the addition of Bu_3SnH, was essentially negligable at 5%. In calculating the molar concentration of PhSeSePh and also of PhSeH a mean volume of 20.5 mL was taken.

Kinetics of Rearrangement of 24. Five flasks were made up, using stock solutions, containing **24** (33.71 mg, 0.1 mmol), PhSeSePh (2, 3, 4, 5, or 6 mol %), and Bu_3SnH (2, 3, 4, 5, or 6 mol %) in benzene (50 mL). A steady stream of Ar was then passed through each flask for several minutes. Each flask was then brought to reflux, with stirring under Ar, while Bu_3SnH (0.035 g) and AIBN (0.8 mg) in benzene (0.5 mL) was added dropwise with a motor-driven syringe pump over 2.3 h. Reflux was continued for a further 1 h before the solvent was removed *in vacuo* and the residue examined by ^{1}H-NMR. In each case the substrate was completely consumed. Integration of the H-1 resonance in **25** and the H-2 resonance in **26** gave the ratio of (reduction/migration) **25**/**26** as recorded in Table 2. The total volume change in the course of the reaction, owing to the addition of Bu_3SnH, was essentially negligible at 1%.

Determination of the Arrhenius Function for Rearrangement of 9. A stock solution of **9** (0.8664 g) in toluene (40 mL) was prepared and 4 mL (0.2 mmol) transferred to each of five 50-mL round-bottomed flasks. A stock solution of PhSeSePh (0.05 g) in toluene (50 mL) was made up and 1.87 mL (0.006 mmol) added to each flask, followed by Bu_3SnH (2.1 mL of a 0.003 M solution in toluene, 0.0072 mmol). Each flask was then made up to 20 mL with toluene and purged with a steady stream of Ar for several minutes. In turn, each flask was equilibrated at the required temperature (Table 4) and irradiated with a 100-W medium-pressure Hg lamp (through Pyrex) while Bu_3SnH and AIBN in toluene (1 mL of a stock solution containing 0.700 g, 2.41 mmol of Bu_3SnH and 0.0164 g, 0.1 mmol of AIBN in a total of 10 mL) was added with the syringe pump over 2.3 h. After the addition the irradiation was continued for a further 1 h before the solvent was removed under vacuum and the residue examined by ^{1}H-NMR to give the data recorded in Table 4. The data for 80 °C were taken from Table 1.

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