p-CH_3, ring opening competes to give dimethyl 2-(chloromethyl)-2-methyl-3-hydroxypropyl phosphate. The latter has been synthesized independently (see Experimental Section). Apparently, at low acid concentration, retention and ring opening involve a similar or common intermediate.

Systems analogous to the p-nitrophenyl esters have received some attention. Thus, the *trans*-2-phenylthio ester, $k = 0.9\ h^{-1}$ for a solution 0.1 M in ester and acid, gives after complete reaction 18% inversion, while a solution 0.1 M in ester and 0.8 M in acid, $k = 1.4\ h^{-1}$, gives 52% inversion. The 2,4-dinitrophenyl ester analogous to **4** yields, at low acid concentrations, only the methyl ester formed by retention, **3**, while at high acid concentrations inversion reaches a maximum of only 5%. The results in this latter case may reflect the very low basicity of the oxygen adjacent to phosphorus in the leaving group and its inability to undergo protonation.

It is reported that the acid-catalyzed hydrolysis of phosphinamides proceeds by inversion.[5] Similarly, we find the acid-catalyzed methanolysis of a 2-benzylamido analogue of **1** to give 85% inversion product, even at a low acid concentration, 0.1 M. In this instance the nitrogen atom must be a more basic site than phosphoryl oxygen and is perhaps protonated first.

Experimental Section

^1H NMR spectra were recorded on a Perkin-Elmer R-12B spectrophotometer and chemical shifts, reported in parts per million, measured relative to an internal tetramethylsilane standard with $CDCl_3$ as solvent. The ^1H NMR spectra of the methyl esters **2** and **3** have been published. Isomer ratios were obtained by integration of peaks due to 5-methyl hydrogens, cis methyl ester 0.958 and trans methyl ester 1.258. ^{13}C NMR spectra were recorded on a JEOL FX-100 spectrometer and the ^{31}P NMR spectra on an NT-150 spectrometer.

Materials. The preparation and properties of the 2-substituted-5-(chloromethyl)-5-methyl-2-oxo-1,3,2-dioxaphosphorinans have been reported in a prior publication.[1] Methanol was distilled before use and PTSA·H_2O dried under reduced pressure. All glassware was washed with distilled water and carefully dried before use.

Dimethyl 2-(Chloromethyl)-2-methyl-3-hydroxypropyl Phosphate. 2-Methyl-5-(chloromethyl)-5-methyl-2-oxo-1,3,2-dioxaphosphorinan (1.07 g, 0.005 mol) and potassium *tert*-butoxide (1.12 g, 0.01 mol) were dissolved in 25 mL of methanol. The mixture was allowed to stand for 48 h and then added to 150 mL of water. The solution was extracted with two 20-mL portions of methylene chloride and the combined extracts were dried over $MgSO_4$. After filtration, solvent was removed under reduced pressure and the residue was distilled, bp 130 °C (1.0 mm), 0.95 g (77.2%).

Anal. Calcd for $C_7H_6ClO_5P$: C, 34.15; H, 6.50; Cl, 14.23. Found: C, 34.32; H, 6.60; Cl, 14.17. The 2-methyl hydrogens and carbon absorbed as follows: ^1H NMR 1.03 (3 H); ^{13}C NMR 16.988; ^{31}P NMR (85% H_3PO_4 external standard) 2.23. All other peaks in the ^1H NMR and ^{13}C NMR spectra were easily assigned to the proposed structure.

Methanolysis of *trans*-2-(*p*-Nitrophenyl)-5-(chloromethyl)-5-methyl-2-oxo-1,3,2-dioxaphosphorinan. A methanolic solution of PTSA·H_2O (0.1 M) was added to the trans p-nitrophenyl ester **1** (0.32 g, 0.001 mol) to give a total volume of 10 mL. The solution was gently refluxed for 24 h and then diluted after cooling with 20 mL of CH_2Cl_2. The solution was washed well with two 100-mL portions of 0.1 M KOH and dried over anhydrous $MgSO_4$, and the solvent was removed under reduced pressure. The NMR of the residue was taken without further purification. Peaks due to 5-methyl hydrogens of the reactant (1.358 ppm) and aromatic protons are completely absent.

An identical spectrum was obtained after rewashing a CH_2Cl_2 solution of the residue with aqueous KOH, drying, and removal of solvent. The workup procedure had no effect on product ratios. Other data reported in this article were obtained in an identical manner. The reactant and its concentration as well as the concentration of acid and reflux times were varied.

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this research. The ^{13}C and ^{31}P NMR spectra were supplied by the Colorado State University Regional NMR Center, supported by the National Science Foundation Grant No. CHE 78-18581.

Registry No. 1, 36912-37-5; 2, 28097-12-3; 3, 36912-27-3; 4, 36912-38-6; dimethyl (2-chloromethyl)-2-methyl-3-hydroxypropyl-phosphate, 74465-69-3; 2-methyl-5-(chloromethyl)-5-methyl-2-oxo-1,3,2-dioxaphosphorinan, 74465-70-6.

Ring-Closure Reactions. 17.[1] Kinetics of Formation of Meta- and Paracyclophane Diethers

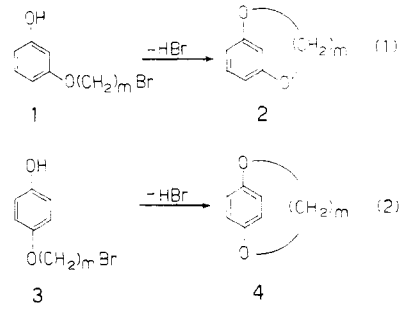
Antonella Dalla Cort, Luigi Mandolini,* and Bernardo Masci

Centro CNR di Studio sui Meccanismi di Reazione, Istituto di Chimica Organica dell'Università di Roma, 00185 Roma, Italy

Received February 12, 1980

The [n]cyclophanes are a stereochemically interesting group of compounds in which an aromatic moiety is incorporated into a ring structure by means of nonadjacent positions connected by a cyclic side chain of n atoms. Their distinguishing feature is that a substantial strain energy is expected to develop as n gets sufficiently small.[2] Qualitative evidence for this derives, for instance, from the increasing synthetic difficulties encountered when the cyclophane ring size becomes smaller.[3]

Our continuous interest in the quantitative aspects of intramolecular reactions, as well as the aim at providing an insight into the energetics of formation of cyclophane systems, led us to extend our previous investigation[4] on the kinetics of formation of meta- and paracyclophane diethers by intramolecular Williamson synthesis (eq 1 and 2). Since, as shown by Allinger's force-field calculations,[5]



the amount of strain energy of the smaller cyclophanes is such as to seriously discourage any effort to study the kinetics of formation of these rings, the present study is restricted to medium-sized cyclophane systems. We report the results of such an investigation, including the kinetics of formation of compounds **2**, m = 8, 9, 10, and 12, and

(1) Part 16: Catoni, G.; Galli, C.; Mandolini, L. *J. Org. Chem.* **1980**, *45*, 1906.

(2) (a) Smith, B. H. "Bridged Aromatic Compounds"; Academic Press: New York, 1964. (b) Greenberg, A.; Liebman, J. F. "Strained Organic Molecules"; Academic Press: New York, 1978; Chapter 3.

(3) (a) Lüttringhaus, A. *Justus Liebigs Ann. Chem.* **1937**, *528*, 181. (b) Lüttringhaus, A.; Ziegler, K. *Ibid.* **1937**, *528*, 155. (c) Lüttringhaus, A.; Eyring, G. *Ibid.* **1957**, *604*, 111.

(4) Mandolini, L.; Masci, B.; Roelens, S. *J. Org. Chem.* **1977**, *42*, 3733.

(5) Allinger, N. L.; Sprague, J. T.; Liljefors, T. *J. Am. Chem. Soc.*, **1974**, *96*, 5100.

0022-3263/80/1945-3923$01.00/0

Table I. Kinetic Data for Ring-Closure Reaction of Potassium Salts of 1 and 3 in 99% Me_2SO at 25.0 °C

compd	m	k_{obsd}, s^{-1} [a]	yield, %[b]	k_{intra}[c]	effective molarity, M[d]	$\Delta G^{\neq}_{rel}$, kcal/mol[e]
1	8	3.4×10^{-4}	91[f]	3.1×10^{-4}	2.0×10^{-3}	1.40
	9	8.5×10^{-4}	93	7.9×10^{-4}	5.3×10^{-3}	0.43
	10	2.1×10^{-3}	86	1.8×10^{-3}	1.2×10^{-2}	0.36
	12	3.6×10^{-3} [g]	90	3.3×10^{-3}	2.2×10^{-2}	0.00
3	8	2.9×10^{-4}	87	2.5×10^{-4}	5.3×10^{-4}	1.89
	9	1.8×10^{-3}	89	1.6×10^{-3}	3.4×10^{-3}	0.78
	10	4.1×10^{-3}	89	3.6×10^{-3}	7.8×10^{-3}	0.30
	12	6.6×10^{-3} [h]	90	6.0×10^{-3}	1.3×10^{-2}	0.00
	16	7.0×10^{-3}	82	5.7×10^{-3}	1.2×10^{-2}	0.02

[a] Average from at least three independent runs. Reproducibility in a set of consecutive experiments was good (±3% or better). However, because of complications possibly due to trace impurities and/or to atmospheric oxygen in the extremely dilute phenoxide solutions used in the kinetic runs, experimental accuracy cannot reasonably be considered to be better than ±10%. See also footnotes *g* and *h*. [b] Spectrophotometric estimates. [c] Calculated as (% yield/100)k_{obsd}. [d] Calculated as k_{intra}/k_{inter}, where k_{inter} refers to proper intermolecular model reactions, namely, the alkylation with butyl bromide of the anions derived from resorcinol and hydroquinone monomethyl ethers (see ref 4). [e] Free energies of activation relative to those of the dodecamethylene compounds. [f] The yield was 88 ± 5% by VPC analysis (see Experimental Section). [g] The value previously reported[4] was $3.56 \pm 0.04 \times 10^{-3}$ s^{-1}. [h] The value previously reported[4] was $7.22 \pm 0.13 \times 10^{-3}$ s^{-1}.

4, m = 8, 9, 10, 12, and 16, from the anions of the corresponding ω-bromoalkoxyphenols 1 and 3, respectively, in Me_2SO–H_2O (99:1, v/v) at 25.0 °C.

The results of the kinetic experiments are listed in Table I. In both series the reactivity decreases regularly on decreasing the chain length, in qualitative agreement with earlier preparative experiments by Lüttringhaus,[3] who found that yields of ring compounds 2 and 4 fall rapidly in the smaller rings and become either very small or negligible when m is smaller than 8. Table I also shows the pertinent effective molarities (EM), calculated as k_{intra}/k_{inter}, where k_{inter} is based on a properly chosen intermolecular model reaction (see footnote *d* in Table I). The use of the EM values permits a direct comparison of reactivity data as it allows for the varying reactivity of the nucleophilic end in the different cyclization series.[4] EM data for the present work, together with related data for the formation under the same conditions of the isomeric catechol polymethylene ethers,[6] are plotted in Figure 1. Clearly a dramatic modification of the shape of the reactivity profile is caused by moving the junctions between the rigid aromatic moiety and the dioxapolymethylene bridge from the ortho to the meta and para positions. The steep reactivity drop, as observed upon decreasing the chain length in the cyclophane diethers, leads one to predict extremely low values for chains shorter than eight methylenes, which would require prohibitively low concentrations for rate measurements.

The present comparison nicely illustrates that the operation of the so-called rigid-group effect[7] on cyclization rates is not only dependent on the geometry of the rigid group itself but also on the size of the ring to be formed. The effect tends to vanish when the length of the bridge is such as to render the given rings strainless large rings. This condition appears to be already met in the dodecamethylene diethers, as shown by the fact that the pertinent EM's lie well within a factor of two and show values in the normal range for large-ring formation in general.[4,8] Furthermore, the increase in the chain length m from 12 to 16 in the para series causes but a negligible effect on the cyclization rate, again suggesting that no further relief of strain accompanies the given structural change. Unfortunately, evidence as to the strain energies of medium-sized cyclophane systems from either thermochemical data or force-field calculations is not available. However, arguments based on the importance of torsional strains led Allinger[5] to suggest that "the strain in the *para*-cyclophanes will increase as n becomes greater than 10, until a maximum is reached, and then eventually decreases as the aliphatic bridge becomes large enough to avoid cross-ring interactions".

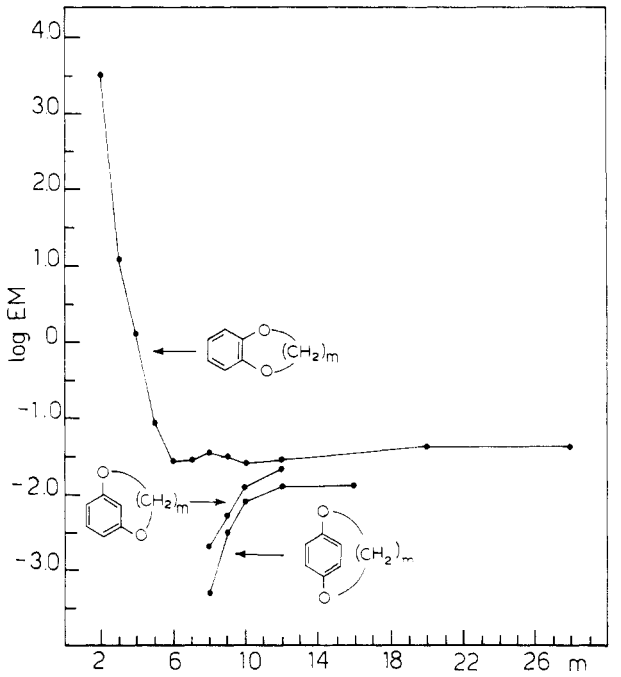


Figure 1. Plots of log EM vs. number of bridge methylenes for the formation of catechol, resorcinol, and hydroquinone polymethylene ethers by intramolecular nucleophilic substitution. Data from the present work and from ref 6.

Although no parameters of activation have been measured for the present reaction, the entropy loss upon cyclization can be safely expected to be greater the longer the chain,[8] thus favoring the formation of the smaller rings. The fact that just the opposite trend is actually observed provides a clear indication that the major contribution to the relative free energies of activation is enthalpic in nature, with a partial compensation of the entropy term acting in the opposite direction. Since the enthalpies of activation are expected to closely reflect the strain energies of the rings to be formed, as suggested in several in-

(6) Dalla Cort, A.; Illuminati, G.; Mandolini, L.; Masci, B. *J. Chem. Soc., Perkin Trans. 2*, in press.
(7) (a) Baker, W.; McOmie, J. F. W.; Ollis, W. D. *J. Chem. Soc.* **1951**, 200. (b) Ziegler, K. *Methoden Org. Chem. (Houben-Weyl)* **1955**, *4/2*, 729.
(8) Illuminati, G.; Mandolini, L.; Masci, B. *J. Am. Chem. Soc.* **1977**, *99*, 6308.

stances,[8,9] it follows that the shape of the given reactivity profiles should be mainly determined by an increasingly greater strain in the smaller rings. Thus, the present data would suggest that the strain energies of the given cyclophane compounds regularly increase on decreasing the chain length, without any indication of the existence of a strain maximum, as predicted by Allinger[5] for the medium-sized [n]paracyclophanes. The presence of two oxygen atoms in our systems should be a relatively unimportant factor in this respect, since the reactivity profiles bear a close similarity to that displayed by the formation of a series of (2,5)-thiophenophan-1-ones by intramolecular acylation of ω-thienyl-2-alkanoic acids,[10] in spite of the different reaction type and of the presence of an all-carbon chain in the latter system.

Experimental Section

Most apparatuses were as before.[4] All materials used in this work, except those listed below, were reagent-grade commercial samples.

1,16-Dibromohexadecane was prepared by the symmetric anodic coupling of 9-bromononanoic acid[11] in a modification[12] of Woolford's procedure.[13] The cell was that previously described.[9] The compound was obtained in 30% yield, mp 51.5–52.5 °C, from hexane [lit.[13] mp 53.5–55.0 °C].

***m*- and *p*-(ω-Bromoalkoxy)phenols (1 and 3, respectively).** The 12-bromododecyl ethers 1, m = 12, and 3, m = 12, were available from a previous investigation.[4] All the other compounds were prepared by monoalkylation of resorcinol and hydroquinone with the proper α,ω-dibromoalkane in KOH/EtOH as previously reported.[4] Purification was made very difficult by the presence of several impurities, as shown by TLC analysis. Pure samples for analytical and kinetic purposes were obtained by repeated elutions on silica gel using several eluants until pure (TLC), followed by crystallization or microdistillation in vacuo with the ball tube. Low yields (3 to 20%) of isolated pure materials were obtained, since several fractions containing the given products in a low purity state were discarded. Consistent with the expected structures, all the compounds showed ^{1}H NMR spectra similar to those of the dodecamethylene homologues previously reported,[4] with the corrected peak intensity ratios. No extra peaks were present.

Physical constants and UV spectral data in 99% Me_2SO solution are given below. For the new compounds analytical data (Br content) are also reported. 1, m = 8: mp 29–31 °C; UV λ_{max} 278 nm (log ε 3.39); Br +0.5% of theory. 1, m = 9: $n^{26.5}_D$ 1.5288; UV λ_{max} 278 nm (log ε 3.36); Br −0.7% of theory. 1, m = 10: mp 49.5–50.5 °C from light petroleum/ether [lit.[3b] mp 56 °C]; UV λ_{max} 278 nm (log ε 3.40).

3, m = 8: mp 61.5–62.5 °C from CCl_4 [lit.[3a] mp 65 °C]; UV λ_{max} 297 nm (log ε 3.48); **3**, m = 10: mp 70–71 °C from CCl_4 [lit.[3a] mp 76–77 °C]; UV λ_{max} 297 nm (log ε 3.49); **3**, m = 16: mp 84–85 °C from hexane; UV λ_{max} 297 nm (log ε 3.48); Br −0.2% of theory.

1,10-Dioxa[10]metacyclophane (Resorcinol Octamethylene Ether) (2, *m* = 8). This compound was prepared by cyclization of 1, m = 8, in a modification of an earlier procedure reported for the preparation of hydroquinone dodecamethylene ether,[4] with the difference that the reaction was run at 35 °C, the addition of the reactants was carried out by means of two motor-driven syringes operated by a Sage Instrument syringe pump Model 355, and the total addition time was 30 h. After workup with light petroleum–water, column chromatography on silica gel with benzene afforded the pure title compound in 41% yield, mp 99–100.5 °C, after sublimation in vacuo. In the ^{1}H NMR spectrum (CCl_4) the four aromatic protons are shown as two multiplets with relative areas 3:1 at δ 6.35–6.75 and 6.9–7.15, respectively. The four OCH_2 protons appeared as a partially resolved triplet centered at δ 4.1, whereas the other methylene protons are shown as a broad multiplet at δ 1.3–2.3, with a prominent peak at δ 1.55; m/e 220 (M^+).

Anal. Calcd for $C_{14}H_{20}O_2$: C, 76.32; H, 9.15. Found: C, 76.32; H, 9.17.

Kinetics and Product Analyses. The mixed solvent (99% aqueous Me_2SO, v/v) and the KOH stock solution (2×10^{-2} M in 93% aqueous Me_2SO) used for the in situ generation of the anions derived from compounds 1 and 3 were prepared and handled as previously reported.[9] In all cases initial concentrations were at least one order of magnitude lower than the corresponding EM values (Table I) to minimize polymerization. The kinetics were followed spectrophotometrically at wavelengths corresponding to the absorption maxima of the conjugate bases of the substrates, namely, λ 309 and 337 nm for the resorcinol and hydroquinone derivatives, respectively. The decrease of optical density of the solutions was found to follow clean first-order behavior for at least 2 to 3 half-lives. Yield determinations in the kinetic runs were carried out spectrophotometrically in the usual manner.[4,6] Further product analysis for the cyclization of 1, m = 8, was carried out as follows. A 1.2×10^{-4} M solution (50 mL) of the potassium salt of 1, m = 8, in 99% Me_2SO was kept at room temperature for 24 h. After workup with water–pentane, the residue was analyzed by VPC (internal standard) on a 1.5-m column packed with 2% SE-30 plus 0.4% FFAP on silanized Chromosorb W, 60–80 mesh, operated at 166 °C. The yield of cyclic product **2**, m = 8, was 88 ± 5%.

(9) Galli, C.; Illuminati, G.; Mandolini, L.; Tamborra, P. *J. Am. Chem. Soc.* **1977**, *99*, 2591.
(10) Galli, C.; Illuminati, G.; Mandolini, L. *J. Org. Chem.* **1980**, *45*, 311.
(11) Galli, C.; Illuminati, G.; Mandolini, L. *J. Am. Chem. Soc.* **1973**, *95*, 8374.
(12) Galli, C.; Giovannelli, G.; Illuminati, G.; Mandolini, L. *J. Org. Chem.* **1979**, *44*, 1258.
(13) Woolford, R. G. *Can. J. Chem.* **1962**, *40*, 1846.

Communications

(Trimethylsilyl)allenes as Propargylic Anion Equivalents: Synthesis of Homopropargylic Alcohols and Ethers

Summary: (Trimethylsilyl)allenes react with ketones, aldehydes, and acetals in the presence of titanium tetrachloride to yield homopropargylic alcohols and ethers.

Sir: Substitution and addition reactions involving propargylic anion equivalents provide a potentially important synthetic route to acetylenic compounds. The utility of organometallic derivatives of type 1 in such methodology

$$\underset{\textbf{1a}}{R_1C{\equiv}CCR_2R_3M} \rightleftarrows \underset{\textbf{1b}}{R_1MC{=}C{=}CR_2R_3}$$

unfortunately is limited by the tendency of these ambident nucleophiles to combine with electrophiles to produce both allenic and acetylenic products.[1,2] For example, organo-

(1) Klein, J. In "The Chemistry of the Carbon–Carbon Triple Bond"; Patai, S., Ed.; Wiley: New York, 1978; pp 343–381.
(2) Alkylation of lithio-1-(trimethylsilyl)propyne yields acetylenic products, but reaction of this reagent with other electrophiles leads to mixtures of allenes and acetylenes: Corey, E. J.; Kirst, H. *Tetrahedron Lett.* **1968**, 5041. Kirst, H. Ph.D. Dissertation, Harvard University, Cambridge, MA, 1971. Ganem, B. *Tetrahedron Lett.* **1974**, 4467.

0022-3263/80/1945-3925$01.00/0