identified by its ^1H NMR parameters. Note that the ratio exo:endo is unchanged between the halogeno compound and the reduced sulfone 8.

Reductions with Zn in HMPA as Solvent. The quantities of halo compound **1a** or **1b** and reducer were the same as described for the reduction reactions in methanol, but 5 mL of HMPA are used here as solvent. The temperature and time of reaction are indicated in Table II. At the end of the reaction we diluted with 10 mL of diethyl ether. The organic layer is washed two times with 20 mL of water, dried with magnesium sulfate, and concentrated under reduced pressure. The crude product is dissolved in exactly 5 mL of the standard solution of $C_{20}H_{42}$ (0.0025 mol L^{-1}) in dichloromethane. The yield in tricyclic compound **6** is measured by GC analysis using the calibration curve. It has been verified that, under the conditions of the reaction, the linear reduced compound **8** does not yield the tricyclic sulfone **6**.

Reductions in Deuterated Solvents. The chloro derivative **1b** has been reduced with Zn under the same conditions as the ones described above using 0.00005 mol of **1b** and 0.00025 mol of Zn. Solvents used for reaction m, 1 mL of CH_3OD, and for reaction n, 1 mL of $(CD_3)_2CO$. The identification of the deuterated tricyclic compound **9** (reaction m) and of the protonated tricyclic compound **6** (reaction n) has been realized with the help of coupled MS-GC.

Experiments performed in order to verify that the tricyclic reduced sulfone is not formed in the absence of reducer or directly from the intermediate carbanion.

(a) A solution of **1a** (38 mg) in 2.5 mL of CH_3OH is heated at 65 °C during 20 h. The recovered product is analyzed by ^1H NMR and GC. No trace of the compound **6** is detected.

(b) **8** (22.5 mg, 0.0001 mol) is heated during 6 h in 2 mL of CH_3OH containing 5.4 mg (0.0001 mol) of CH_3ONa. After hydrolysis and extraction the starting material is recovered without modification. (c) **8** (56.2 mg, 0.0025 mol) is dissolved in 5 mL of HMPA. The solution is degassed as for the reduction reactions. A solution of BuLi in hexane is added (169 μL of a solution 1.6 mol L^{-1}, 0.00027 mol). A pale yellow color appears. The solution is stirred during 3 h at room temperature. After the usual treatments, no trace of the tricyclic compound **6** is detected on GC analysis. The same result is observed when zinc (37.6 mg, 0.00057 mol) and $ZnCl_2$ (77.7 mg, 0.00057 mol) are added in the medium.

Salt Effects on the Reduction of 1a. **1a** (30.4 mg, 0.0001 mol) is dissolved in 2 mL of MeOH. Zn (30.1 mg, 0.0005 mol) and $NaPF_6$ (84 mg, 0.0005 mol) are added, and the solution is degassed as described above. Concentrated sulfuric acid (1 μL) is added, and the solution is refluxed during 22 h. After filtration, washing with MeOH followed by evaporation under reduced pressure, the crude product is dissolved in exactly 2 mL of the standard solution of $C_{20}H_{42}$ (0.0025 mol L^{-1}) in dichloromethane. The yield of tricyclic compound **6** measured by GC analysis using the calibration curve is 1%.

The same experiment was performed in HMPA as solvent (2 mL) with same quantities of reagents, but with stirring at room temperature during 22 h. After dilution with water, extraction with diethyl ether, drying of the organic layer with magnesium sulfate followed by evaporation of the solvent, the crude product is dissolved in exactly 2 mL of the standard solution of $C_{20}H_{42}$ (0.0025 mol L^{-1}) in dichloromethane. GC analysis indicates a yield of 5% in the tricyclic compound **6**.

Chloranil Effect on the Reduction of 1a. The same experiments as the ones described for salt effects were performed in MeOH and HMPA with chloranil in place of $NaPF_6$; 0.0001 mol and 0.0005 mol of chloranil were used successively. A 0.0001-mol portion of oxidant had no effect on the ratio **8**/**6** (98/2 in MeOH and 89/11 in HMPA). With 0.0005 mol of chloranil we did not detect the presence of the tricyclic compound **6** in the crude product, and a ^1H NMR analysis indicated the presence of the uncyclized compound **8** (a quantitative analysis was not possible).

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Methyl Effects in the Cyclization of γ-Epoxy Bis-Sulfones

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A quantitative study on the effects of methyl and *gem*-dimethyl groups in the intramolecular ring opening of epoxides by bis-sulfonyl carbanions is reported for the formation of cyclopropanes. Reaction rates are increased by methyl groups on the chain connecting the nucleophile with the oxirane and depressed by methyl substitution in the epoxide ring. When *gem*-dimethyl groups are present on the epoxide, ring opening is apparently inhibited. It will be shown that in this case the reaction is reversible and the apparent stabilization of the *gem*-dimethyl-substituted oxirane is actually due to a combination of effects on both the forward and the reverse reactions. On the basis of current theories on intramolecular reactions, it is suggested that release of ground-state strain and van der Waals repulsions in the transition state can account for the observed reactivity.

The ring closure of bifunctional molecules provides a powerful model for studying the factors that control intramolecular reactivity[2] and for testing, on simple systems, effects, such as proximity and orientation, that have been proposed for explaining the high efficiency of enzymatic catalysis.[3]

We have recently studied the effect of ring size in the intramolecular ring opening of ω-epoxy carbanions, and we have found a marked dependence of regioselectivity and rates upon the length of the chain connecting the nucleophile and the oxirane ring.[4] In this study we examine

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(2) (a) Capon, B. *Q. Rev. Chem. Soc.* **1965**, *18*, 45. (b) Capon, B.; McManus, S. P. *Neighboring Group Participation*; Plenum Press: New York, 1976; Vol. 1. (c) Mandolini, L. *Adv. Phys. Org. Chem.* **1986**, *22*, 1. (d) Illuminati, G.; Mandolini, L. *Acc. Chem. Res.* **1981**, *14*, 95.

(3) (a) Gandour, R. D. In *Transition States of Biochemical Processes*; Gandour, R. D., Schowen, R. L., Eds.; Plenum Press: New York, 1978; Chapter 14. (b) Menger, F. M. *Acc. Chem. Res.* **1985**, *18*, 128. (c) Page, M. I. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 449. (d) Fife, T. H. *Adv. Phys. Org. Chem.* **1975**, *11*, 1. (e) Bruice, T. C. *Annu. Rev. Biochem.* **1976**, *45*, 331. (f) Jencks, W. P. *Adv. Enzymol.* **1975**, *43*, 219. (g) Jenks, W. P. *Catalysis in Chemistry and Enzymology*; McGraw-Hill: New York, 1969.

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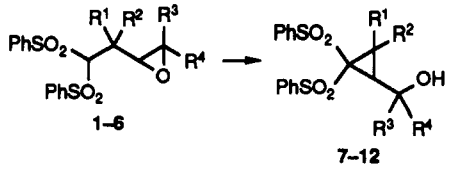
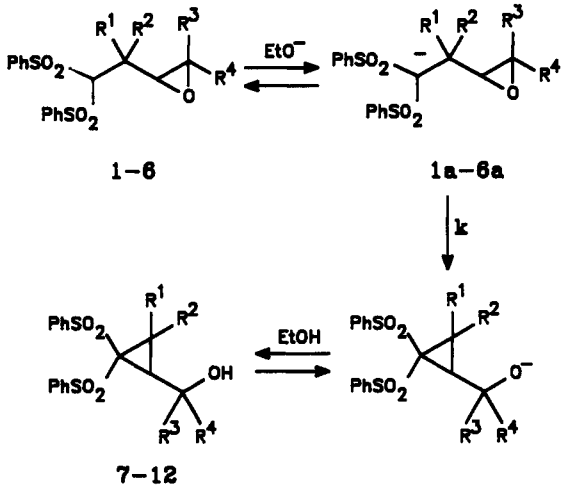
Table I. Cyclization of Epoxy Bis-Sulfones



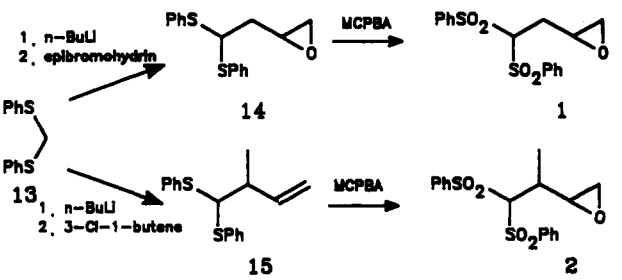
epoxide	R^1	R^2	R^3	R^4	cyclopropane	yield, %	k,[a] s^{-1}	k_{rel}	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, cal mol^{-1} K^{-1}
1	H	H	H	H	7	97	0.0144	1	13.6	−21
2	CH_3	H	H	H	8	98	0.0245	1.7	17.4	−7
3	CH_3	CH_3	H	H	9	98	0.329	23	10.9	−24
4	H	H	CH_3	H	10	99[b]	0.000558	0.039	21.9	0
5	H	H	H	CH_3	11	99[b]	0.0116	0.81	15.1	−16
6	H	H	CH_3	CH_3	12	–[c]	–[c]	–	–	–

[a] In sodium ethoxide/ethanol at T = 25.0 ± 0.1 °C. [b] Overall; 25:75 mixture of 10 and 11 from a 27:73 mixture of 4 and 5. [c] No reaction; 6 recovered unchanged (97%).

Scheme I



Scheme II



the effect of methyl substitution in a series of γ-epoxy bis-sulfones (1–6) that undergo base-promoted isomerization to (hydroxymethyl)cyclopropanes (7–12) by way of a concerted ring opening–ring closure (Scheme I, Table I). Several groups have reported on the synthesis of cyclopropanes by cyclization of γ-epoxy carbanions,[5] but substituent effects on reactivity have not been systematically studied before in this reaction.

It has been known for a long time that ring–chain equilibria can be shifted by alkyl substituents toward cyclic isomers.[6] The effect, which is particularly pronounced in geminally substituted compounds, was first explained by Ingold and Thorpe[7] and is confirmed by a large body of data.[8,9]

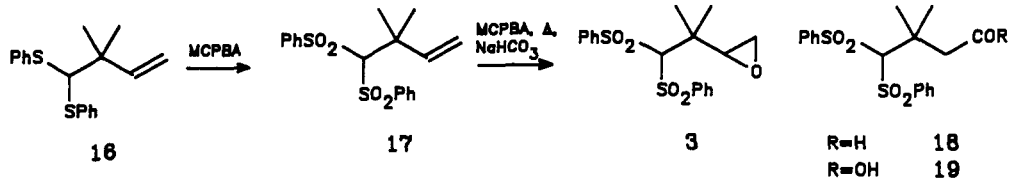
This effect is by no means confined to equilibria, but it can operate also on rates[8] and is well documented in a number of studies on reactions leading to five- and six-membered rings.[3,8] Acceleration of intramolecular pericyclic reactions has been reported,[10] and the *gem*-dimethyl effect has also been studied in the formation of medium and large rings.[11]

Quantitative data on methyl effects in the formation of smaller rings are scarce. Engberts and co-workers have shown that the intramolecularly carboxyl catalyzed hydrolysis of carboxy-*N*-methyl-*N*-phenylmethanesulfonamides,[12] which proceeds through a four-membered cyclic intermediate, is accelerated by alkyl substituents on the central carbon. Very large methyl effects have been observed in the S_N2 ring closure of halohydrins leading to oxiranes and oxetanes,[8] and a large acceleration upon *gem*-dimethyl substitution was also found by Stirling in the base-catalyzed ring closure of 3-bromopropyl sulfones.[13] Stirling has also shown recently that the reverse effect (anti Thorpe–Ingold) operates in reactions in which small rings are opened: the base-catalyzed ring fission of sulfonylmethyl oxiranes, cyclopropanes and oxetanes is retarded by *gem*-dimethyl substituents in the ring.[14]

Epoxy bis-sulfones 1–6 are particularly suitable for a kinetic investigation on the effects of methyl substitution. Substituent effects on both ring closure and ring opening can be studied in the same series. The mechanism is unambiguously S_N2; ring closure is concerted with ring opening and takes place in the rate-determining step. The effects of substituents on rate constants and activation parameters can thus be compared and are free from contributions due to complex reaction mechanisms and multistep processes.

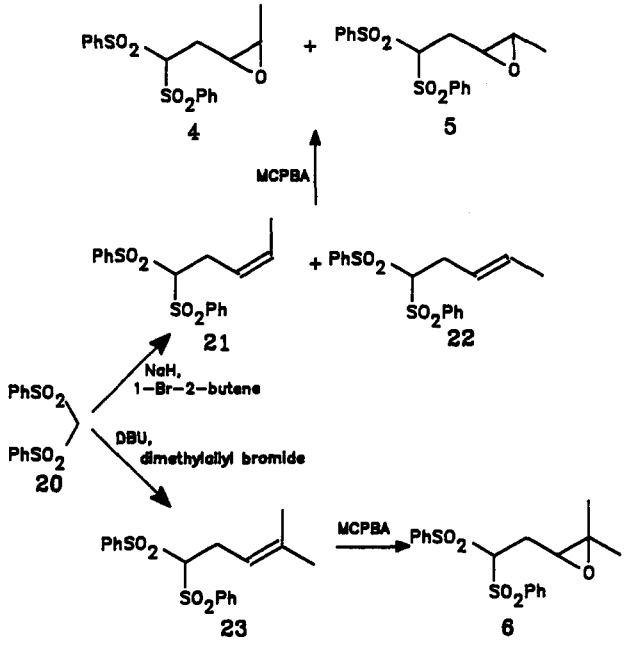
(4) Benedetti, F.; Fabrissin, S.; Gianferrara, T.; Risaliti, A. *J. Chem. Soc., Chem. Commun.* **1987**, 406.
(5) (a) Stork, G.; Cohen, J. F. *J. Am. Chem. Soc.* **1974**, *96*, 5270. (b) Corbel, B.; Durst, T. *J. Org. Chem.* **1976**, *41*, 3448. (c) Decesare, J. M.; Corbel, B.; Durst, T.; Blount, J. F. *Can. J. Chem.* **1981**, *59*, 1415. (d) Turcant, A.; Le Corre, M. *Tetrahedron Lett.* **1979**, 789. (e) Gaoni, Y. *J. Org. Chem.* **1982**, *47*, 2564. (f) Gaoni, Y. *Tetrahedron Lett.* **1981**, 4339.
(6) Early work is reviewed in the following: Eliel, E. L. *Stereochemistry of Carbon Compounds*; McGraw-Hill: New York, 1962; pp 196–197.
(7) (a) Beesley, R. M.; Ingold, C. K.; Thorpe, J. F. *J. Chem. Soc.* **1915**, *107*, 1080. (b) Ingold, C. K. *J. Chem. Soc.* **1921**, *119*, 305.
(8) Kirby, A. J. *Adv. Phys. Org. Chem.* **1980**, *17*, 183.
(9) Valters, R. E.; Flitsch, W. *Ring-Chain Tautomerism*; Plenum Press: New York, 1985.
(10) (a) Jung, M. E.; Gervay, J. *Tetrahedron Lett.* **1988**, 2429. (b) Harfenist, M.; Thom, E. *J. Org. Chem.* **1972**, *37*, 841.
(11) Galli, C.; Giovannelli, G.; Illuminati, G.; Mandolini, L. *J. Org. Chem.* **1979**, *44*, 1258.
(12) Jager, J.; Graafland, T.; Schenk, H.; Kirby, A. J.; Engberts, J. B. F. N. *J. Am. Chem. Soc.* **1984**, *106*, 139.
(13) Issari, B.; Stirling, C. J. M. *J. Chem. Soc., Perkin Trans. 2*, **1984**, 1043.
(14) (a) Griffiths, G.; Stirling, C. J. M. *Heterocycles* **1989**, *28*, 89. (b) Hughes, S.; Griffiths, G.; Stirling, C. J. M. *J. Chem. Soc., Perkin Trans. 2* **1987**, 1253. (c) Piras, P. P.; Stirling, C. J. M. *J. Chem. Soc., Perkin Trans. 2* **1987**, 1265. (d) Stirling, C. J. M. *Isr. J. Chem.* **1981**, *21*, 111.

Scheme III



16 17 3 18 19

Scheme IV



4 5 21 22 20 23 6

Results

Epoxides. All the bis-sulfonyl epoxides of this work except **1** were prepared by oxidation of the corresponding bis(phenylsulfonyl)- or bis(phenylthio)alkenes (Schemes II–IV). Oxidation of the bis-sulfide **16**[15] (Scheme III) with excess m-CPBA, at room temperature, failed to give the expected product **3**, yielding instead the bis-sulfonyl alkene **17**. Epoxidation of this alkene proceeded smoothly in refluxing chloroform, buffered with sodium hydrogen carbonate in order to prevent the acid-catalyzed rearrangement of **3** to the aldehyde **18** and further oxidation to **19**. Oxidation of the 1:3 mixture of *cis*- and *trans*-alkenes **21** and **22**, from the alkylation of the bis-sulfone **20** with 1-bromo-2-butene (Scheme IV), gave a 1:3 mixture of cis and trans epoxides **4** and **5** which could not be separated.

Products. The epoxides **1–5**, at room temperature, in sodium ethoxide/ethanol, gave the corresponding bis-sulfonyl cyclopropanes **7–11** in high yield (Scheme I, Table I). The *gem*-dimethyl derivative **6** failed to react under the standard conditions of this work and was recovered unchanged even after prolonged heating in concentrated sodium ethoxide. Reactions are regiospecific, giving only cyclopropanes irrespective of the substitution pattern.[5] From the mixture of cis and trans isomers **4** and **5** was obtained a mixture of diastereomeric alcohols **10** and **11**; the two alcohols, in the same ratio as the starting epoxides, were separated by flash chromatography.

Mechanism. In the basic medium, bis-sulfones **1–6** are rapidly converted into the corresponding carbanions[16] (Scheme I). Due to the high acidity of geminal bis-sulfones, with pK_a values ranging from 11 to 14,[17] this preequilibrium lies well to the carbanion side, provided that the base is present in excess. The rate constant k for cyclization can thus be evaluated by monitoring the disappearance of the UV absorption band of the carbanion at 290 nm; results are in Table I.

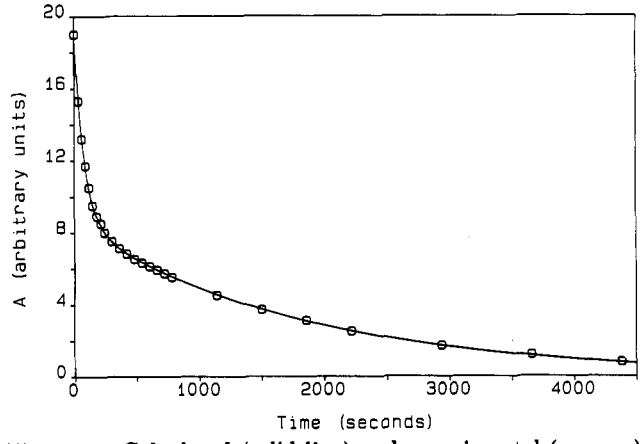


Figure 1. Calculated (solid line) and experimental (squares) absorption vs time curve for the cyclization of a mixture of epoxides **4** and **5**. The curve is calculated with $k = 0.000\,558\ s^{-1}$ for **4** and $k = 0.0116\ s^{-1}$ for **5**.

Since it was not possible to separate the cis and trans epoxides **4** and **5**, the rate constants for cyclization of the two isomers were obtained from kinetic experiments run with the 1:3 mixture of the two. The experimental absorption vs time curves result from the convolution of two exponential decays, each corresponding to one isomer. The two rate constants were estimated from the initial and final parts of the experimental curves, and the final refinement was obtained with the Marquardt method[18] (Figure 1). Alcohols **10** and **11** have the same extinction coefficient at 290 nm, and thus, assuming that the same is true also for the carbanion pair **4a** and **5a** from which they derive,[19] it was possible to assign the faster reaction, associated with the larger UV absorption change, to the trans epoxide **5**, present in larger amount in the mixture.

Activation parameters were also measured for the ring opening of epoxides **1–5** in the temperature range −8 to 41 °C (Table I).

Discussion

Data in Table I show that the cyclization of epoxy bis-sulfones is accelerated by methyl groups on the chain and retarded by methyl groups on the epoxide ring. When one hydrogen atom on the chain is replaced by a methyl group, as in **2**, the reaction is accelerated by a factor of 1.7, while

(15) Huynh, C.; Ratovelomanana, V.; Julia, S. *Bull. Soc. Chim. Fr.* **1977**, 710.

(16) (a) Benedetti, F.; Stirling, C. J. M. *J. Chem. Soc., Perkin Trans. 2* **1986**, 605. (b) Benedetti, F.; Fabrissin, S.; Rusconi, S.; Stirling, C. J. M. *Gazz. Chim. Ital.* **1988**, *118*, 233.

(17) (a) Hibbert, F. *J. Chem. Soc. Perkin Trans. 2* **1977**, 1909. (b) Bordwell, F. G. *Acc. Chem. Res.* **1988**, *21*, 456.

(18) Press, W. H.; Flannery, B. P.; Teukolski, S. A.; Vetterling, W. T. *Numerical Recipes*; Cambridge University Press: 1986; p 523.

(19) Control experiments show that the UV spectra of 1,1-bis-sulfonyl carbanions are rather insensitive to substituents beyond the β position of the chain. The only difference between carbanions **4a** and **5a** is the configuration of the δ-carbon.

Table II. Strain Energies of Substituted Cyclopropanes[a]

formula	compound	ΔH_f(exp)[b]	ΔH_f (calcd)[c]	strain
C_3H_6	cyclopropane	12.8	-14.8	27.6
C_4H_8	methylcyclopropane	5.8	-21.9	27.7
C_5H_{10}	1,1-dimethylcyclopropane	-2.0	-29.6	27.6
	cis-1,2-dimethylcyclopropane	0.4	-28.9	29.3
	trans-1,2-dimethylcyclopropane	-0.9	-28.9	28.0
	ethylcyclopropane	0.8	-26.8	27.6

[a] All energies in kcal/mol. [b] From ref 24. [c] By the constant group increment method. Standard group increments from ref 25.

replacement of a second hydrogen atom by a methyl, as in **3**, has a much larger effect, resulting in a further acceleration by a factor of nearly 15. The *gem*-dimethyl effect thus results in a net 23-fold acceleration in the cyclization of **3**, with respect to the unsubstituted epoxide **1**. Methyl groups on the epoxide ring exert different effects, depending upon the stereochemistry: the cis compound **4** is thus 20 times less reactive than the trans isomer **5**. The effect of *gem*-dimethyl substitution on the oxirane ring is large, but it could not be quantified, no reaction being observed with compound **6**. Thermodynamic activation parameters (Table I) indicate clearly that reactivity within the series reflects variations in the enthalpic term and is thus controlled by strain differences between ground states and transition states,[20] while entropy appears to have a compensating effect. Compound **2** is an exception: $\Delta H^{\ddagger}$ is higher than for the unsubstituted epoxide **1**, and the acceleration, albeit modest, is entirely due to a favorable entropic term.

According to the original Thorpe–Ingold explanation,[7,8] the ring closure of alkyl-substituted chains is promoted by a decrease in van der Waals interactions between geminal groups. Being a consequence of the widening of the angle between substituents which accompanies ring closure, the effect should be large in the formation of three-membered rings, where small internal angles induce particularly wide external angles; for example, on going from propane to cyclopropane,[21] $\angle HC_2H$ increases from 106° to 114°, and an even wider angle is found between the CH_3 groups in 1,1-dimethylcyclopropane.[21b] A conformational effect has been discussed by Allinger and Zalkow[22] in a study on the formal cyclization of substituted hexanes. They have pointed out that in branched alkanes there are more gauche interactions between alkyl groups than in the corresponding cyclic hydrocarbons; reduction in the number of these interactions thus favors cyclization of alkyl-substituted compounds. Both these effects result from the release of ground-state strain and should thus be reflected in the enthalpy change associated with ring closure.

Decrease in ring strain in the cyclic product has also been indicated as a possible source for the *gem*-dimethyl effect.[12,23] Strain energies for alkyl-substituted cyclopropanes (Table II) show that neither methylcyclopropane nor 1,1-dimethylcyclopropane is less strained than cyclopropane itself. Therefore, at least in the cyclization of simple three-membered rings, the accelerating effect of methyl substituents does not appear to be due to a stabilization of the product rings.

Release of ground-state strain thus appears to be the only possible explanation for the *gem*-dimethyl acceleration observed in the cyclization of the derivative **3**, which is entirely due to $\Delta H^{\ddagger}$ (Table I). Both *gem*-dimethyl repulsion and gauche interactions in the highly substituted precursor might contribute to the ground-state strain, but it is not possible to distinguish between these two factors on the basis of the available data.

Cyclization of the monomethyl derivative **2** is not assisted by release of strain, and the reaction is entirely controlled by $\Delta S^{\ddagger}$ (Table I). An entropic contribution to the acceleration of ring closure by alkyl substituents has been proposed by Allinger and Zalkow:[22] this effect results from the restriction of internal rotations in the branched open chain precursor, a consequence of higher rotational barriers, which lowers the entropy of the ground state and, hence, the entropy loss upon ring closure. The activation entropy difference, however, between the cyclization of **2** and that of the unsubstituted epoxide **1** is too large (14 eu) to be accounted for exclusively by the loss of internal rotations in the methyl-substituted epoxide **2**. For the cyclization of linear hydrocarbon chains, a value of 4.5 eu has been proposed for the loss of each internal rotation around C–C single bonds.[2c,26] More to the point, Pitzer and Scott[27] have proposed an entropy loss of 3.5 eu as consequence of restricted rotations in branched alkanes while De Tar and Luthra[28] have calculated that in the cyclization of ω-halogeno amines only 2.81 eu is gained upon *gem*-dimethyl substitution. Furthermore, if the favorable entropic contribution to the cyclization of **2** were due to restricted rotations in the ground state, a similar behavior should also be expected in the reaction of **3**, as, conceivably, rotational barriers in the *gem*-dimethyl-substituted compound **3** are not smaller than in the monomethyl derivative **2**. Clearly other effects are superimposed, probably related to the solvation of the small, charge species in the polar medium.

The acceleration observed in the cyclization of the epoxy bis-sulfones **2** and **3** is low in comparison with that in similar reactions leading to three-membered rings. In the ring closure of halogeno sulfones[13] and chlorohydrins,[8] leading to cyclopropanes and epoxides, respectively, methyl effects are 1–3 orders of magnitude larger. In the epoxy bis-sulfone cyclization, release of ground-state strain is, to some extent, counterbalanced by eclipsed interactions between the large sulfone groups and adjacent substituents on the cyclopropane ring. It is likely that these interactions, which are of course absent in simpler systems, are responsible, at least in part, for the remarkably low effects observed in the cyclization of **2** and **3**.

The retardation experienced by compounds **4** and **5**, substituted on the ring being opened, is again due to enthalpic factors (Table I). In ring-opening reactions the situation is different than in ring closure: since the ring is still partially formed in the transition state, internal rotations are still restricted, irrespective of the substituents present, and the number of gauche interactions is the same as in the cyclic ground state.[22] The inhibition to ring opening appears thus to be due only to the increase of van der Waals interactions as external angles decrease, fol-

(20) Page, M. I.; Jencks, W. P. *Gazz. Chim. Ital.* **1987**, *117*, 455.
(21) (a) Wiberg, K. B. In *The Chemistry of the Cyclopropyl Group*; Rappoport, Z., Ed.; John Wiley and Sons: Chichester, 1987; Chapter 1. (b) Cremer, D.; Kraka, E. *J. Am. Chem. Soc.* **1985**, *107*, 3811.
(22) Allinger, N. L.; Zalkow, V. *J. Org. Chem.* **1960**, *25*, 701.
(23) Hill, A. E.; Link, D. C.; Donndelinger, P. *J. Org. Chem.* **1981**, *46*, 1177.
(24) Liebman, J. F.; Greenberg, A. *Chem. Rev.* **1989**, *89*, 1225.
(25) Benson, S. W.; Cruickshank, F. R.; Golden, D. M.; Haugen, G. R.; O'Neal, H. E.; Rodgers, A. S.; Shaw, R.; Walsh, R. *Chem. Rev.* **1969**, *69*, 279.
(26) (a) Page, M. I. *Chem. Soc. Rev.* **1973**, 295. (b) Mandolini, L. *Bull. Soc. Chim. Fr.* **1988**, 73. (c) Winnik, M. A. *Chem. Rev.* **1981**, *81*, 491.
(27) Pitzer, K. S.; Scott, D. W. *J. Am. Chem. Soc.* **1941**, *63*, 2419.
(28) De Tar, D. F.; Luthra, N. P. *J. Am. Chem. Soc.* **1980**, *102*, 4505.

Table III. Cyclization of the *gem*-Dimethyl Alcohol 12[a]

k_{obsd}, s^{-1} ([EtO⁻])					k' L m^{-1} s^{-1}	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, cal mol^{-1} K^{-1}
0.011 (0.47)	0.0082 (0.38)	0.0061 (0.28)	0.0034 (0.19)	0.0018 (0.09)	0.018	17.1	−9

[a] At T = 25.0 ± 0.1 °C.

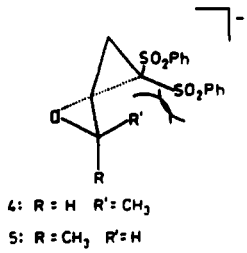
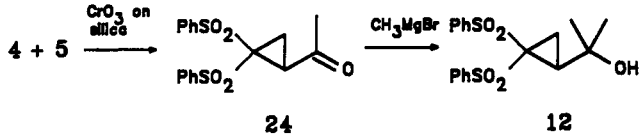


Figure 2. Transition states for the cyclization of cis and trans epoxides 4 and 5.

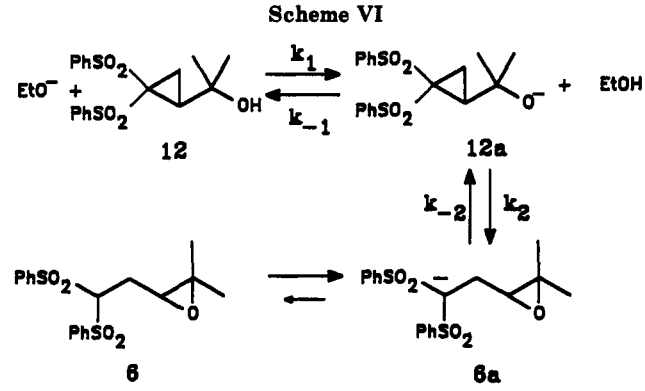
Scheme V



lowing the relaxation of the ring internal angles, the reverse of the effect operating in ring closure. The effect is not large, at least in the trans epoxide **5**, while the cis isomer **4** is considerably less reactive. Thermochemical data for simple dimethyl epoxides are not available, but heats of formation of *cis*- and *trans*-dimethylcyclopropane (Table II) show the cis isomer to be 1.3 kcal/mol less stable, because of the eclipsing of the methyl groups. If the difference is maintained also in the oxirane series, the cis epoxide **4**, if any, would be expected to be more reactive than the more stable trans-substituted compound **5**. However, it can be seen that, in the spiro-bicyclic geometry imposed on the transition state by the required back-side attack of the nucleophile on the epoxide ring,[29] the *cis*-methyl group of compound **4** interferes substantially with the bulky sulfone group to which it becomes closer than in the ground state (Figure 2); this interaction is absent in the corresponding transition state for the trans isomer, in which the methyl points away from the sulfonyl group.

The lack of reactivity of the *gem*-dimethyl epoxide **6** (Table I) is striking: in the eliminative ring fission of β-sulfonyl epoxides, which proceeds through a concerted E_2 mechanism, only a negligible retardation was observed upon *gem*-dimethyl substitution.[14b] It is known, however, that electrophilic cyclopropanes undergo ring opening by a variety of nucleophiles, including alkoxides,[30] and it appeared thus that a very fast, *gem*-dimethyl-accelerated recyclization of the open-chain alcohol **12** could be at the origin of the apparent inhibition to ring opening of **6**. In order to test this hypothesis we have synthesized the *gem*-dimethyl alcohol **12** by an independent route (Scheme V). Indeed, when **12** is dissolved in ethanolic sodium ethoxide, rapid cyclization to the epoxy carbanion **6a** takes place (Scheme VI), thus indicating that an equilibrium is established, which is completely shifted in favor of the dimethyl epoxide **6**. Rates of ring opening were measured

Scheme VI



at different base concentrations, the appearance of the strong UV band of the carbanion being monitored; the first-order dependence of the rate on the base concentration is consistent with the mechanism shown in Scheme VI, with preequilibrium deprotonation of the alcohol, followed by ring closure. Steady-state approximation leads to the following expression for the observed second-order rate constant:

$$k_{obsd} = (k_1k_2/k_{-1})[EtO^-] = k'[EtO^-] \quad (1)$$

Rate constants and activation parameters for the reaction are reported in Table III.

The k_1/k_{-1} ratio in eq 1 corresponds to the ratio between the dissociation constant of the tertiary alcohol **12** and that of ethanol and can be estimated at around 10^{-2}, the ratio between the dissociation constants of *tert*-butyl alcohol and ethanol.[31] From eq 1 the rate constant k_2 for the cyclization of the *gem*-dimethyl alcohol can then be estimated at around 2 s^{-1}. Since the reverse reaction of **6** to give **12** is not likely to be faster than the ring opening of the cis epoxide **4** (Table I), it follows that the *gem*-dimethyl stabilization of the epoxide **6** results from both an acceleration of the ring closure of **12** and a decrease in the rate of ring opening of **6**, with respect to the unsubstituted compounds **7** and **1**.

While in a similar case the apparent *gem*-dimethyl stabilization of a five-membered lactone to ring opening was attributed to a very fast recyclization of the corresponding hydroxy acid,[32] an analogous combination of effects on both the forward and the reverse reactions has been demonstrated in the ring opening of a *gem*-dimethyl-substituted cyclobutylmethyl Grignard reagent.[23]

Experimental Section

Melting points were determined on a Büchi 510 apparatus and are uncorrected. Infrared spectra were taken on a Perkin-Elmer 1320 spectrometer. ^1H NMR spectra were recorded either on a Varian EM 360 A (60 MHz) or a Bruker WP 80 (80 MHz) spectrometer, with Me_4Si as internal standard, and ^{13}C NMR spectra were recorded on the Bruker WP 80 (20.1 MHz) spectrometer, with Me_4Si as internal standard; all chemical shifts (δ) are reported in ppm. Electron-impact mass spectra (MS) were obtained, at 70 eV ionizing power, on a VG 70/70 H spectrometer;

(29) Fujimoto, H.; Hataue, I.; Koga, N.; Yamasaki, T. *Tetrahedron Lett.* **1984**, *25*, 5339.

(30) (a) Verhé, R.; De Kimpe, N., In ref 21a, Chapter 9. (b) Danishefsky, A. *Acc. Chem. Res.* **1979**, *12*, 66. (c) Wong, H. N. C.; Hon, M.; Tse, C.; Yip, Y.; Tanko, J.; Hudlicky, T. *Chem. Rev.* **1989**, *89*, 165. (d) Trost, B. M.; Cossy, J.; Burks, J. *J. Am. Chem. Soc.* **1983**, *105*, 1052.

(31) Lowry, T. H.; Schueller Richardson, K. *Mechanism and Theory in Organic Chemistry*; Harper & Row: New York, 1981; p 266.

(32) Hillery, P. S.; Cohen, L. A. *J. Chem. Soc., Chem. Commun.* **1972**, 403.

samples were introduced with a direct inlet probe with the temperature below 150 °C. Extractions were carried out with dichloromethane, unless otherwise stated, and extracts were dried over anhydrous Na_2SO_4. Flash chromatography was run on silica gel 230–400-mesh ASTM (Kieselgel 60, Merck) with diethyl ether as eluant, unless otherwise stated. Silica gel 60_{F254} coated glass plates (Merck; 0.2 mm layer thickness) or plastic sheets (Kodak; 0.1 mm layer thickness) were used for thin layer chromatography. Commercial reagents, either from Fluka or from Aldrich Chimica, were used without further purification. Tetrahydrofuran was fractionated over calcium hydride and redistilled from potassium benzophenone ketyl under an argon atmosphere. *N,N*-Dimethylformamide (DMF) was fractionated in vacuo, stirred overnight over calcium oxide, redistilled, and kept over activated 4A molecular sieves (Carlo Erba). 3,3-Dimethyl-4,4-bis(phenylthio)-1-butene (**16**) was prepared according to the method reported.[15]

Kinetics. All kinetic work was carried out by using commercial ACS grade ethanol (H_2O < 0.05%). Reactions were followed on a Perkin-Elmer Lambda 1 single-beam spectrophotometer thermostated at 25.0 ± 0.1 °C, the change in absorption at 290–300 nm being monitored. Substrate concentrations were between 5 × 10^{-5} M and 2 × 10^{-4} M, the base concentration being 0.1 M. A series of test reactions carried out on various epoxides at different concentrations of the base (1–0.01 M) showed that the reaction is 0 order in base. Small variations of the rate constant on varying the concentration of NaOEt were probably due to the change in the ionic strength of the medium. Activation parameters for ring opening were obtained from runs at six different temperatures, or more: the range was 20–50 °C for **1**, 10–40 °C for substrates **2**, **4**, and **5**, and −7.5 to 25 °C for **3**.

3,3-Dimethyl-4,4-bis(phenylsulfonyl)-1-butene (17). *m*-Chloroperoxybenzoic acid (85% *m*-CPBA, 8.1 g, 40 mmol) was added in small portions, at 5 °C, to a well-stirred solution of 2.9 g (9.7 mmol) of the bis-sulfide **16**[15] in 100 mL of chloroform. The reaction mixture was stirred overnight at room temperature and cooled to −5 °C, and *m*-chlorobenzoic acid was filtered off; the clear solution was washed with 10% aqueous sodium metabisulfite (2 × 25 mL), 10% aqueous $NaHCO_3$ (2 × 25 mL), and saturated brine (25 mL). The solution was then dried and evaporated, and the solid residue was recrystallized from ethanol, giving pure **17** (2.48 g, 70%): mp 169 °C; IR (KBr) 1630 (CH=CH_2), 1310 and 1145 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$) δ 1.6 (s, 6 H, CH_3), 4.9 (s, 1 H, CH), [δ 5.1, 5.15, 6.3 (3 H, vinyl; J_{gem} = 1.5 Hz, J_{trans} = 18 Hz, J_{cis} = 10.5 Hz)], 7.4–8.1 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 26.6, 42.5, 92.2, 112.9, 129.0, 129.2, 134.1, 141.6, 145.4; MS, *m/z* 364 (0.2, M^+), 223 (16, M − $C_6H_5SO_2$), 125 (65), 81 (98), 77 (100), 69 (53). Anal. Calcd for $C_{18}H_{20}O_4S_2$: C, 59.3; H, 5.33; S, 17.59. Found: C, 59.1; H, 5.62; S, 17.83.

(*Z*)- and (*E*)-5,5-Bis(phenylsulfonyl)-2-pentene (21 and 22). Bis(phenylsulfonyl)methane (**20**) (1.19 g, 4 mmol) in 5 mL of dry DMF was added dropwise, at 50 °C and under argon, to a well-stirred suspension of sodium hydride (4.4 mmol) in dry DMF (5 mL). The mixture was stirred for 30 min, and 1-bromo-2-butene (0.59 g, 4.4 mmol) was then added in one portion. The reaction mixture was stirred for 3 h at 70 °C, cooled to room temperature, and poured into 50 mL of aqueous 10% ammonium chloride, and the aqueous phase was extracted with dichloromethane (3 × 15 mL). The combined extracts were washed with saturated brine (20 mL), dried, and rotary evaporated to yield an oily residue. Flash chromatographic purification of this material gave two fractions. The first consisted of a bisalkylated material, 5,5-bis(phenylsulfonyl)-2,7-nonadiene **25** (22%, mixture of geometrical isomers): mp 120 °C (from ethanol); IR (KBr) 1660 (C=C), 1325 and 1140 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$) δ 1.75 (m, 6 H, CH_3), 3.1 (m, 4 H, CH_2), 5.75 (m, 4 H, =CH), 7.5–8.4 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ [17.2 (q) and 18.0 (q), CH_3, rel intensities 0.4:1], [32.1 (t) and 33.1 (t), CH_2, rel intensities 0.4:1], 91.0 (s), [121.9 (d) and 122.7 (d), =$CH(CH_3)$], 128.6 (d), 131.6 (d, =$CH(CH_2)$), 131.9 (d), 134.6 (d), [137.4 (s) and 137.8 (s)]; MS, *m/z* 404 (0.5, M^+), 263 (30, M − $C_6H_5SO_2$), 125 (96), 121 (60), 105 (62), 93 (73), 91 (49), 79 (55), 77 (100). Anal. Calcd for $C_{21}H_{24}S_2O_4$: C, 62.3; H, 5.98; S, 15.85. Found: C, 62.4; H, 5.63; S, 15.96. The second fraction (41%) was the monoalkylated product, as a mixture of *Z* and *E* isomers **21** and **22** (approximately 1:3, by ^{13}C NMR); an aliquot of the mixture was recrystallized five times from ethanol to give a small amount of pure **22**: mp 85 °C; IR (KBr) 1310 and 1150 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$) δ 1.65 (dd, 3 H, CH_3), 3.05 (m, 1 H, CH_2), 4.65 (t, 1 H, CH), 5.6 (m, 2 H, CH=CH), 7.6–8.4 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 17.8 (q), 29.0 (t), 84.2 (d), 125.1 (d), 129.4 (d), 130.0 (d), 130.4 (d), 134.9 (d), 138.5 (d); MS, *m/z* 350 (1.5, M^+), 209 (100, M − $C_6H_5SO_2$), 125 (26), 67 (37). Anal. Calcd for $C_{17}H_{18}O_4S_2$: C, 58.3; H, 5.18; S, 18.30. Found: C, 57.9; H, 5.17; S, 18.40.

2-Methyl-5,5-bis(phenylsulfonyl)-2-pentene (23). **20** (2.96 g, 10 mmol), 3,3-dimethylallyl bromide (3.28 g, 22 mmol), and 1.8-diazabicycloundec-7-ene (DBU) (3.36 g, 22 mmol) in 200 mL of dichloromethane were heated at reflux for 4 days. The reaction mixture was then washed with 50-mL portions of 2 N HCl, water, and saturated brine in that order, dried, and rotatory evaporated, giving a white solid, which was washed with diethyl ether. Recrystallization from ethanol gave pure **23** (78%): mp 118 °C; IR (KBr) 1665 (C=C), 1310 and 1145 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$) δ 1.5 (s, 3 H, CH_3), 1.65 (s, 3 H, CH_3), 3.0 (m, 2 H, CH_2), 4.6 (t, 1 H, CH), 5.15 (m, 1 H, =CH), 7.5–8.3 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 17.7, 24.8, 25.7, 84.4, 118.5, 129.4, 129.9, 134.9, 136.3, 138.7; MS, *m/z* 364 (0.2, M^+), 349 (0.1, M − CH_3), 223 (100, M − $C_6H_5SO_2$), 125 (30), 81 (76), 80 (81), 79 (41), 77 (76). Anal. Calcd for $C_{18}H_{20}O_4S_2$: C, 59.3; H, 5.53; S, 17.60. Found: C, 59.7; H, 5.80; S, 17.36.

[2,2-Bis(phenylsulfonyl)ethyl]oxirane (1). Formaldehyde diphenyl mercaptal (**13**) (2.32 g, 10 mmol) in 50 mL of dry THF was lithiated, at −70 °C under argon, with 6.5 mL of a 1.55 M solution of *n*-buthyllithium in *n*-hexane (10 mmol). After 15 min the golden yellow solution was transferred by a stainless steel double-tipped needle, within 20 min, to a three-necked round-bottomed flask equipped with a magnetic spin bar and argon inlet and outlet, charged with epibromohydrin (3.0 g, excess) in 50 mL of dry THF, and kept at −5 °C by means of an ice/salt bath. After 1 h the mixture was allowed to warm up to room temperature, poured into 250 mL of water, and extracted with diethyl ether (3 × 50 mL); the extracts were washed with brine (50 mL), dried, and evaporated under reduced pressure to give crude [2,2-bis(phenylthio)ethyl]oxirane (**14**) (oil, 2.75 g, 95%), which was purified by flash chromatography (87% recovery): ^1H NMR ($CDCl_3$, 80 MHz) δ 2.1 (dd, 2 H, CH_2), [δ 2.5, 2.8, 3.3, 3 H, oxirane (J_{gem} = 4.9 Hz, J_{trans} = 2.6 Hz, J_{cis} = 3.8 Hz)], 4.7 (t, 1 H, CH), 7.4 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 39.1, 47.5, 50.0, 55.1, 128.2, 129.2 (double), 133.0; MS, *m/z* 288 (4, M^+), 179 (18, M − C_6H_5S), 152 (48), 136 (78), 135 (97), 123 (100), 91 (55).

The thioacetal **14** (1.44 g, 5 mmol), in 25 mL of chloroform, was oxidized with *m*-CPBA (20 mmol) at 0 °C for 1 h and at room temperature overnight. Workup as described for **17** gave the crude product (1.58 g, 90%), which, on recrystallization from ethanol, gave the pure bis-sulfone **1**: mp 107 °C; IR ($CHCl_3$) 1335 and 1160 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$, 80 MHz) δ 2.5 (m, 2 H, CH_2), [δ 2.55, 2.9, 3.35 (3 H, oxirane)], 4.8 (dd, 1 H, CH), 7.4–8.2 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 29.1, 48.6, 49.5, 81.0, 129.6, 129.7 and 130.0, 135.1, and 138.4; MS, *m/z* 352 (1, M^+), 309 (5, M − C_2H_3O), 211 (8, M − $C_6H_5SO_2$), 143 (28), 125 (67), 77 (100). Anal. Calcd for $C_{16}H_{16}O_5S_2$: C, 54.5; H, 4.58; S, 18.2. Found: C, 54.2; H, 4.59; S, 18.2.

[1-Methyl-2,2-bis(phenylsulfonyl)ethyl]oxirane (2). **13** (2.32 g, 10 mmol) in 100 mL of dry THF was lithiated as before. The solution was warmed up to −40 °C, and neat 3-chloro-1-butene (1.00 g, 11 mmol) was added with a syringe. The reaction mixture was stirred at −40 °C for 1 h and then slowly allowed to warm up to room temperature; workup gave an orange oil, which was purified by flash chromatography (5% diethyl ether in *n*-hexane as eluant), giving 3-methyl-4,4-bis(phenylthio)-1-butene (**15**), a pale yellow oil (94%): ^1H NMR ($CDCl_3$) δ 1.3 (d, 3 H, CH_3), 2.75 (m, 1 H, CH), 4.45 (d, 1 H, CH), 5.0–5.4 (m, 2 H, =CH_2), 5.9 (m, 1 H, =CH), 7.3 (m, 10 H, phenyl); MS, *m/z* 286 (8, M^+), 231 (5, M − C_4H_7), 177 (100, M − C_6H_5S), 135 (27), 110 (36), 109 (45), 99 (40). **15** (2.94 g, 10.3 mmol) was oxidized with *m*-CBPA (60 mmol) as described in the preparation of **1**, giving, after workup and flash chromatography of the residue, 3.00 g (77%) of epoxide **3**: mp 165 °C (from ethanol); IR (KBr) 1320 and 1160 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$, 80 MHz) δ 1.48 (d, *J* = 7.2 Hz, 3 H, CH_3), 2.34 (m, 1 H, CH), [δ 2.60, 3.98, 3.55 (J_{trans} = 2.5 Hz, J_{cis} = 3.9 Hz, J_{gem} = 5.1 Hz, 3 H, oxirane)], 5.02 (dd, *J* = 1.6 Hz, 1 H, CH), 7.5–8.3 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) 11.9, 38.8, 50.3, 54.5,

83.9, 129.2, 129.7, 135.1, 139.4; MS m/z 366 (0.5, M^+), 351 (1, M − CH_3), 335 (37, M − CH_3O), 323 (5, M − C_2H_3O), 225 (8, M − $C_6H_5SO_2$), 125 (91), 83 (34), 77 (100). Anal. Calcd for $C_{17}H_{18}O_5S_2$: C, 55.7; H, 4.95; S, 17.50. Found: C, 55.2; H, 4.61; S, 17.20.

[1,1-Dimethyl-2,2-bis(phenylsulfonyl)ethyl]oxirane (3). Attempted oxidation of alkene **17**, by the procedure described above, failed, **17** being recovered quantitatively from the reaction mixture. **17** (1.82 g, 5 mmol), *m*-CPBA (5.5 mmol), and $NaHCO_3$ (2.03 g, 25 mmol) in 50 mL of chloroform were heated at reflux for 8 h while being stirred vigorously. Workup as described before gave a solid residue, which was thoroughly washed with cold ether and ethanol. The crude epoxide **3** was crystallized from toluene/*n*-hexane: mp 134 °C (58% yield); IR (KBr) 1315 and 1140 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$, 80 MHz) δ 1.50 (s, 3 H, CH_3), 1.53 (s, 3 H, CH_3), [δ 2.90, 2.99, and 3.65, 3 H, oxirane (J_{gem} = 4.8 Hz, J_{cis} = 3.7 Hz, J_{trans} = 3.1 Hz)], 5.05 (s, 1 H, CH), 7.5–8.1 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 19.3, 26.5, 41.4, 47.7, 58.6, 89.9, 128.9, 128.7, 129.2, 134.1, 137.6; MS, m/z 380 (0.1, M^+), 365 (2, M − CH_3), 349 (5, M − CH_3O), 337 (1, M − C_2H_3O), 125 (84), 77 (100). Anal. Calcd for $C_{18}H_{20}O_5S_2$: C, 56.8; H, 5.30; S, 16.85. Found: C, 57.1; H, 5.26; S, 16.64.

Oxidation of **17** in refluxing chloroform, without $NaHCO_3$, led to a complex mixture from which were isolated, by flash chromatography, unreacted starting material (15%) and aldehyde **18** (31%): mp 155 °C (from toluene/*n*-hexane); IR (KBr) 1720 (C=O), 1315 and 1140 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$) δ 1.5 (s, 6 H, CH_3), 3.5 (s, 2 H, CH_2), 6.3 (s, 1 H, CH), 7.3–7.9 (m, 10 H, phenyl), 10.0 (s, 1 H, CHO); ^{13}C NMR ($CDCl_3$) δ 27.6, 39.6, 56.7, 86.2, 128.5, 129.3, 134.0, 142.4, 203.1; MS, m/z 352 (0.3, M − CO), 337 (0.6, M − C_2H_3O), 141 (30), 125 (32), 107 (35), 91 (39), 77 (100). Anal. Calcd for $C_{18}H_{20}O_5S_2$: C, 56.8; H, 5.30; S, 16.85. Found: C, 56.7; H, 5.28; S, 16.76. The residue from the column was taken up in boiling ethanol and, upon cooling and concentrating, yielded ethyl 3,3-dimethyl-4,4-bis(phenylsulfonyl)butanoate (**26**) (23%, mp 139 °C, from ethanol): IR ($CHCl_3$) 1720 (C=O), 1320 and 1150 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$) δ 1.25 (t, 3 H, CH_3), 1.5 (s, 6 H, CH_3), 3.1 (s, 2 H, CH_2), 4.2 (q, 2 H, CH_2), 6.5 (s, 1 H, CH), 7.5–8.0 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 14.0 (q), 26.9 (q), 39.5 (s), 46.5 (t), 60.6 (t) 84.8 (d), 128.2 (d), 128.9 (d), 133.6 (d), 142.3 (s), 173.3 (s, C=O); MS, m/z 379 (11, M − C_2H_5O), 337 (13, M − $CH_2COOC_2H_5$), 283 (4, M − $C_6H_5SO_2$), 141 (29), 125 (71), 77 (100). Anal. Calcd for $C_{20}H_{24}O_6S_2$: C, 57.8; H, 5.69; S, 15.11. Found: C, 57.7; H, 5.35; S, 15.03.

***cis*- and *trans*-2-[2,2-Bis(phenylsulfonyl)ethyl]-3-methyloxirane (4 and 5).** *m*-CPBA (11 mmol) was added in small portions, at 5 °C, to a stirred solution of a 1:3 mixture of *E* and *Z* alkenes **22** and **23** (3.5 g, 10 mmol) in 50 mL of chloroform. The reaction mixture was stirred for 1 h at 0 °C and for a further 2 h at 25 °C; workup as described for the preparation of **17** gave a 27:73 mixture (76%) of cis and trans epoxides **4** and **5**. Attempts at separating the isomers by chromatography and crystallization failed. Spectral and analytical data are thus given for this mixture: mp 109 °C from ethanol; IR (KBr) 1310 and 1150 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$, 80 MHz) δ 1.16 (d, 0.8 H, CH_3, cis isomer), 1.31 (d, 2.2 H, CH_3, trans isomer), 2.45 (m, 2 H, CH_2), [δ 2.78 (m, 1 H) and 3.1 (m, 1 H), oxirane], 4.78 (dd, 1 H, CH), 7.6–8.2 (m, 10 H); ^{13}C NMR ($CDCl_3$) δ 14.9 (q, cis isomer), 17.3 (q, trans isomer), 25.1 (t, cis isomer), 28.7 (t, trans isomer), 55.2 (d, cis isomer), 55.6 (d, cis isomer), 56.4 (d, trans isomer), 56.9, (d, trans isomer), 81.0 (d), 129.3 (d), 129.8 (d), 130.0 (d), 135.1 (d), 137.8 (s), 138.6 (s); MS, m/z 366 (0.4, M^+), 351 (1, M − CH_3), 225 (7, M − $C_6H_5SO_2$), 141 (32), 125 (89), 107 (38), 83 (63), 77 (100). Anal. Calcd for $C_{17}H_{18}O_5S_2$: C, 55.7; H, 4.95; S, 17.50. Found: C, 55.7; H, 4.83; S, 17.89.

2,2-Dimethyl-3-[2,2-bis(phenylsulfonyl)ethyl]oxirane (6) was obtained in 68% yield by epoxidation of **23** with *m*-CPBA: mp 128 °C (from toluene/CH_2Cl_2); IR (KBr) 1320 and 1155 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$, 80 MHz) δ 1.15 (s, 3 H, CH_3), 1.31 (s, 3 H, CH_3), [ABMX system, δ 2.31, 2.64, 3.19, 4.83, 4 H (J_{AB} = 16.1 Hz, J_{AM} = 7.0 Hz, J_{BM} = 5.6 Hz, J_{AX} = 4.4 Hz, J_{BX} = 8.1 Hz], 7.6–8.2 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 18.7, 24.4, 25.4, 59.0, 60.8, 81.4, 129.5, 129.3 and 130.0, 135.0, 137.7 and 138.7; MS, m/z 380 (0.1, M^+), 365 (2, M − CH_3), 323 (6, M − C_3H_5O), 125 (75), 117 (66), 97 (45), 85 (82), 77 (100). Anal. Calcd for $C_{18}H_{20}O_5S_2$: C, 56.8; H, 5.30; S, 16.85. Found: C, 57.1; H, 5.17; S, 16.47.

The crude epoxide **6**, in refluxing ethanol, rearranged quantitatively affording 1,1-bis(phenylsulfonyl)-4-methyl-3-pentanone (**27**): mp 144–145 °C (from ethanol); IR (KBr) 1710 (C=O), 1335 and 1165 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$) δ 1.2 (d, 6 H, CH_3), 2.85 (m, 1 H, $CH(CH_3)_2$), 3.5 (d, 2 H, CH_2), 5.6 (t, 1 H, CH), 7.3–8.2 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 18.1, 35.5, 41.0, 78.9, 129.5, 129.6, 134.9, 138.5; MS, m/z 380 (1, M^+), 337 (7, M − C_3H_7), 239 (18, M − $C_6H_5SO_2$), 195 (57), 125 (100), 77 (87), 71 (92). Anal. Calcd for $C_{18}H_{20}S_2O_5$: C, 56.8; H, 5.30; S, 16.85. Found: C, 57.1; H, 5.08; S, 16.88.

Ring Opening of the Epoxides. General Procedure. The epoxide (2.5 mmol) was dissolved in 100 mL of a 0.5 M solution of NaOEt in ethanol and kept at 25 °C for a time corresponding to at least 20 half-lives. The reaction mixture was then poured into 350 mL of water and extracted with dichloromethane (3 × 50 mL). The combined organic phases were washed with 50 mL of saturated brine, dried, and rotary evaporated to give the crude products (Table I).

2,2-Bis(phenylsulfonyl)cyclopropanemethanol (7): 97% from **1**; mp 113 °C (from toluene/*n*-hexane); IR (KBr) 3525 (br, OH), 1330 and 1160 cm^{-1} (SO_2); NMR ($CDCl_3$, 80 MHz) [δ 2.11, 2.23, and 2.90, 3 H, cyclopropane (J_{gem} = 12 Hz, J_{cis} = 6.2 Hz, J_{trans} = 5.9 Hz)], δ 2.6 (br, 1 H, OH), 4.15 (dd, 1 H, CH_2O), 7.5–8.2 (m, 10 H, phenyl); MS, m/z 352 (1, M^+), 309 (17, M − C_2H_3O), 288 (5, M − SO_2), 211 (6, M − $C_6H_5SO_2$), 169 (44), 143 (32), 92 (34), 77 (100). Anal. Calcd for $C_{16}H_{16}O_5S_2$: C, 54.4; H, 4.58; S, 18.20. Found: C, 54.3; H, 4.54; S, 18.25.

2-Methyl-3,3-bis(phenylsulfonyl)cyclopropanemethanol (8): 98% from **2**; mp 125.5 °C (from ethanol); IR (KBr) 3550 (OH), 1310 and 1140 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$, 80 MHz) δ 1.55 (d, 3 H, CH_3), 2.25 (br, 1 H, OH), 2.80 (m, 2 H, cyclopropane), 4.32 (m, 2 H, CH_2O), 7.55–8.25 (m, 10 H, phenyl); MS, m/z 366 (0.1, M^+), 335 (35, M − CH_3O), 225 (5, M − $C_6H_5SO_2$), 143 (46), 125 (91), 83 (28), 77 (100). Anal. Calcd for $C_{17}H_{18}O_5S_2$: C, 55.7; H, 4.95; S, 17.50. Found: C, 55.7; H, 4.59; S, 17.59.

2,2-Bis(phenylsulfonyl)-3,3-dimethylcyclopropanemethanol (9): 98% from **3**; mp 149 °C (from ethanol); IR (KBr) 3560 (OH), 1300 and 1140 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$) δ 1.3 (s, 3 H, CH_3), 1.7 (s, 3 H, CH_3), 2.3 (br, 1 H, OH), 3.25 (dd, 1 H, cyclopropane), 4.25 (m, 2 H, CH_2O), 7.5–8.3 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 19.8, 23.1, 37.4, 44.9, 57.6, 70.6, 128.1, 129.0, 129.2, 129.5, 133.7, 134.1, 142.6, 143.6; MS, m/z 362 (3, M − H_2O), 349 (25, M − CH_3O), 239 (3, M − $C_6H_5SO_2$), 209 (28), 125 (100), 77 (85). Anal. Calcd for $C_{18}H_{20}O_5S_2$: C, 56.8; H, 5.30; S, 16.85. Found: C, 57.1; H, 5.48; S, 16.87.

(1*R,α*R**)- and (1*R**,α*S**)-2,2-Bis(phenylsulfonyl)-α-methylcyclopropanemethanol (10 and 11).** A 1:3 mixture of the alcohols was obtained from a 23:73 mixture of epoxides **4** and **5** (overall yield 99%): mp 123–125 °C, from ethanol. Anal. Calcd for $C_{17}H_{18}O_5S_2$: C, 55.7; H, 4.95; S, 17.50. Found: C, 55.9; H, 5.08; S, 17.35. The two alcohols were separated by flash chromatography. **10** eluted first: mp 119 °C (from ethanol); IR (Nujol mull) 3550 (OH), 1320 and 1145 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$, 80 MHz) δ 1.4 (d, 3 H, CH_3), 2.0–2.9 (m, 3 H, cyclopropane), 2.5 (br, 1 H, OH), 4.5 (dq, 1 H, CHO), 7.6–8.3 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 19.6, 22.7, 40.5, 63.8, 65.3, 129.2, 129.5 and 129.7, 134.6 and 134.9, 138.1 and 139.0; MS, m/z 366 (0.5, M^+), 351 (8, M − CH_3), 309 (95), 125 (91), 77 (100). The second product from the column was the diastereomeric alcohol **11**: mp 121 °C (from ethanol); IR (Nujol mull) 3550 (OH), 1310 and 1140 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$, 80 MHz) 1.1 (d, 3 H, CH_3), 2.25 (m, 3 H, cyclopropane), 2.85 (br, 1 H, OH), 4.43 (m, 1 H, CHO), 7.5–8.25 (m, 10 H, phenyl); ^{13}C NMR ($CDCl_3$) δ 20.8, 23.4, 39.3, 63.3, 64.3, 129.1, 129.6, and 129.9, 134.6, 138.8 and 140.7; MS, m/z 366 (3, M^+), 351 (8, M − CH_3), 309 (100), 125 (51), 77 (43).

6 failed to react under these conditions and was also recovered unchanged (97%) after 1 week at reflux in 0.5 M ethanolic sodium ethoxide.

1-[2,2-Bis(phenylsulfonyl)cyclopropyl]ethanone (24). A 1:3 mixture of alcohols **4** and **5** (1.37 g, 3.7 mmol) in 25 mL of benzene was added to a stirred suspension of 10% chromic acid adsorbed on silica[33] (25 g) in 50 mL of the same solvent. The reaction mixture was stirred at room temperature for 1 h and

(33) Santaniello, E.; Ponti, F.; Manzocchi, A. *Synthesis* **1978**, 534.

filtered. The silica layer was washed with chloroform, and the combined organic phases were evaporated in vacuo to a dark oil; flash chromatography gave the pure ketone **24** (1.2 g, 89%): mp 120 °C from toluene/petroleum ether; IR (KBr) 1720 (CO), 1330 and 1150 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$) 2.15 (s, 3 H, CH_3), 2.2-2.4 (m, 2 H, CH_2), 3.1 (dd, 1 H, CH), 7.5-8.2 (m, 10 H, phenyl); MS, m/z 349 (10, M - CH_3), 322 (6, M - C_2H_2O), 300 (7, M - SO_2), 181 (26), 175 (20), 159 (24), 141 (26), 125 (51), 77 (100), 43 (75, CH_3CO). Anal. Calcd for $C_{17}H_{16}O_6S_2$: C, 56.0; H, 4.43; S, 17.6. Found: C, 55.7; H, 4.11; S, 17.8.

2,2-Bis(phenylsulfonyl)-α,α-dimethylcyclopropanemethanol (12). A 3 M solution (0.61 mL) of methylmagnesium bromide in diethyl ether (1.83 mmol) was added dropwise, under argon, at -25 °C, to ketone **24** (0.56 g, 1.54 mmol) in 15 mL of dry THF. The reaction mixture was stirred for 1 h at -25 °C and kept overnight at room temperature; saturated aqueous NH_4Cl was then added, and the organic layer was washed with 1 N HCl (15 mL) and saturated brine (15 mL). Evaporation of the solvent and trituration of the residue with diethyl ether gave alcohol **12** (0.48 g, 82%): mp 167 °C (from ethanol); IR (KBr) 3480 (OH), 1325-1305 and 1155-1140 cm^{-1} (SO_2); ^1H NMR ($CDCl_3$) 1.2 (s, 3 H, CH_3), 1.4 (s, 3 H, CH_3), 2.4 (m, 3 H, cyclopropane), 4.1 (br, 1 H, OH), 7.3-8.2 (m, 10 H, phenyl); MS, m/z 365 (83, M - CH_3), 322 (19), 309 (36), 181 (40), 143 (30), 141 (18), 125 (100). Anal. Calcd for $C_{18}H_{20}O_5S_2$: C, 56.8; H, 5.30; S, 16.90. Found: C, 57.2; H 5.39; S, 17.05.

Reaction of Alcohol 12 with Base. The alcohol (190 mg, 0.5 mmol) in 20 mL of 0.5 M sodium ethoxide was kept at room temperature for 6 h; the mixture was poured into brine, extracted with dichloromethane (3 × 50 mL), and dried. Evaporation of the solvent gave the *gem*-dimethyl epoxide **16** (170 mg, 89%).

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Anodic Behavior of Crowded Triarylphosphines. ESR Study of Triarylphosphoniumyl Radicals, $Ar_3P^{\bullet+}$

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A large number of triarylphosphines exhibiting different steric hindrance has been prepared. The pyramidalization angle α of these compounds was calculated with use of the MM2 force field and was shown to depend almost exclusively on the number of ortho substituents on the phenyl rings. In a series of isosteric (same α) phosphines, the oxidation potential correlates with the sum of the σ^+ Hammett parameters of the phenyl substituents. In the absence of oxygen, anodic oxidation of all the triarylphosphines bearing two *o*-methyl substituents on each phenyl ring is reversible and yields very persistent phosphoniumyl radicals. These radicals are easily detected by ESR in liquid solution and were shown to retain a pyramidal geometry that is significantly flattened compared to that of the parent phosphine.

Introduction

Many tervalent phosphorus compounds are relatively easy to oxidize, and for many years phosphoniumyl radicals, $L_3P^{\bullet+}$, have been suggested as intermediates in various chemical[1] and electrochemical[2] reactions involving tervalent phosphorus compounds. However, these cationic species are very transient in solution, which makes their ESR characterization particularly challenging. Thus, only the dimeric cations $(L_3PPL_3)^{\bullet+}$ were characterized when the parent phosphines L_3P were oxidized electrochemically within the cavity of an ESR spectrometer.[3] On the other hand, phosphoniumyl radicals have been detected in matrices and, according to their ESR features, were shown to adopt a pyramidal equilibrium geometry.[4] This last result contrasts with the results obtained for the nitrogen analogues that prefer to adopt a planar geometry.[5]

Ingold et al. have clearly established that kinetic stabilization of a free radical is almost exclusively governed by steric crowding around the radical center.[6] This concept was applied to phosphoniumyl radicals, and preliminary studies[7] have shown that the radical cations of very bulky triarylphosphines are persistent enough to be ob-

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(1) (a) Alberti, A.; Hudson, A.; Pedulli, G. F. *Tetrahedron* **1984**, *40*, 4955. (b) Emoto, T.; Okazaki, R.; Inamoto, N. *Bull. Chem. Soc. Jpn.* **1973**, *46*, 898. (c) Klimov, E. S.; Bumber, A. A.; Okhobystin, O. Yu. *Zh. Obshch. Khim.* **1983**, *53*, 1739.

(2) (a) Kargin, Yu. M.; Nikitin, E. V.; Parakin, O. V.; Romanov, G. V.; Pudovik, A. N. *Dokl. Akad. Nauk SSSR* **1978**, *241*, 131. (b) Nikitin, E. V.; Parakin, O. V.; Romanov, G. V.; Ignat'Ev, Yu, A.; Kargin, Yu, M.; Pudovik, A. N. *Dokl. Akad. Nauk SSSR* **1980**, *252*, 922. (c) Nikitin, E. V.; Romakhin, A. S.; Parakin, O. V.; Romanov, G. V.; Kosachev, I. P.; Kargin, Yu. M.; Pudovik, A. N. *Dokl. Akad. Nauk SSSR* **1982**, *262*, 1182. (d) Nikitin, E. V.; Ignat'Ev, Yu. A.; Romakhin, A. S.; Parakin, O. V.; Romanov, G. V.; Kargin, Yu. M.; Pudovik, A. N. *Zh. Obshch. Khim.* **1982**, *52*, 1207. (e) Nikitin, E. V.; Ignat'Ev, Yu. A.; Parakin, O. V.; Kosachev, I. P.; Romanov, G. V.; Kargin, Yu. M.; Pudovik, A. N. *Zh. Obshch. Khim.* **1982**, *52*, 2721. (f) Ohmori, H.; Takanami, T.; Masui, M. *Tetrahedron Lett.* **1985**, 2199. (g) Effenberger, F.; Kottmann, H. *Tetrahedron* **1985**, *41*, 4171.

(3) (a) Gara, W. B.; Roberts, B. P. *J. Chem. Soc., Chem. Commun.* **1975**, 949. (b) Gara, W. B.; Roberts, B. P. *J. Chem. Soc., Perkin Trans. 2* **1978**, 150.

(4) (a) Begum, A.; Lyons, A. R.; Symons, M. C. R. *J. Chem. Soc. A* **1971**, 2290. (b) Lyons, A. R.; Symons, M. C. R. *J. Am. Chem. Soc.* **1973**, *95*, 3483. (c) Berclaz, T.; Geoffroy, M. *Mol. Phys.* **1975**, *30*, 549. (d) Hasegawa, A.; McConnachie, G. D. G.; Symons, M. C. R. *J. Chem. Soc., Faraday Trans. 1* **1984**, *80*, 1005.

(5) For nonaromatic ammoniumyl radicals, see: (a) Chow, Y. L.; Danen, W. C.; Nelsen, S. F.; Rosenblatt, D. H. *Chem. Rev.* **1978**, *78*, 243 and references therein. For aromatic ammoniumyl radicals, see: (b) Nelsen, S. F. In *Free Radicals*; Kochi, J. K., Ed.; Wiley and Sons: New York, **1973**; Vol. 2, p 573.

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