

Stereoelectronic Effects in Hydrogen Atom Abstraction from Substituted 1,3-Dioxanes

A. L. J. Beckwith* and C. J. Easton

Contribution from the Organic Chemistry Department, University of Adelaide, Adelaide, South Australia 5001. Received March 24, 1980

Abstract: An EPR technique and a method involving the gas chromatographic determination of the relative rates of consumption of substrates have been employed to measure the relative rates of hydrogen atom abstraction by *tert*-butoxy radicals from various substituted 1,3-dioxanes. The high relative reactivities of dioxanes equatorially substituted at C-2 as compared with their axially substituted epimers are attributed to the favorable stereoelectronic interactions in the former between the axial C-H bonds and adjacent oxygen lone pairs. The effects of methoxy substituents on the relative reactivities of cyclic ethers have been similarly rationalized. The photoinduced reaction between benzophenone and the methoxydioxane (**8**) has been shown to be reversible.

In previous communications^{1,2} we have suggested that many bond dissociations and atom-transfer reactions conform to a general pattern; namely, that homolytic fission is favored when the bond undergoing cleavage can assume coplanarity with an adjacent semioccupied p orbital, an occupied nonbonding orbital, or an occupied π orbital. The present work and that in an accompanying paper³ are directed toward testing this hypothesis with respect to homolysis of C-H bonds adjacent to ethereal oxygen.

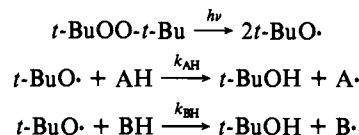
Previous work in this area has been conducted by Hayday and McKelvey,⁴ who found that the *cis* isomer (**1**) of 2-methoxy-4-methyltetrahydropyran undergoes hydrogen atom abstraction by triplet benzophenone at ambient temperature 8 times more rapidly than its *trans* isomer (**2**). Their conclusion that abstraction of axial hydrogen is preferred over abstraction of equatorial hydrogen and that this is due to stereoelectronic effects appears reasonable but is open to objection in that the difference in free energy between the two transition states may reflect the differences between the ground-state energies of the two starting materials⁵ and the common free radical generated from them.¹⁰ A further possible ambiguity arises from the fact that the difference in free energy between the more stable form **2** of the *trans* isomer and its conformer in which the methyl and methoxy groups occupy axial and equatorial positions respectively may not be sufficiently large as to preclude participation of the latter in the hydrogen atom transfer reaction. Finally, there is the possibility that the *exo* methoxy groups which assume preferred orientations with respect to the reaction center because of anomeric interactions⁶ may have different stereoelectronic effects on the reactivities of the isomers **1** and **2**.

In an attempt to define more precisely the magnitude of the stereoelectronic effect of adjacent oxygen on C-H bond homolysis



we have studied reactions of **9** and **10** in which the methyl substituents at the 4- and 6-positions provide an effective conformational lock¹² while the absence of a methoxy substituent precludes difficulties associated with the exoanomeric effect.¹³ Also for comparative purposes we have studied the relative rates of hydrogen atom abstraction from the dioxanes **3-8**.

Methods. Relative rates of hydrogen atom abstraction from the cyclic ethers **3-10** by *tert*-butoxy radicals were determined both by an EPR technique and by following the relative rates of consumption of substrates by gas chromatography. The former involves the measurements of the relative stationary concentrations of radicals A \cdot and B \cdot attained when a solution of di-*tert*-butyl peroxide in a mixture of two dioxanes, AH and BH, is subjected to UV irradiation in the cavity of an EPR spectrometer.



Malatesta and Ingold³ have shown that when reasonable assumptions are made concerning the rates of radical decay under these conditions, the ratio of rate constants is given by

$$\frac{k_{\text{AH}}}{k_{\text{BH}}} = \frac{[\text{A}\cdot][\text{BH}]}{[\text{B}\cdot][\text{AH}]}$$

Consequently, if $[\text{A}\cdot]/[\text{B}\cdot]$ is determined experimentally $k_{\text{AH}}/k_{\text{BH}}$ can be readily calculated.

To simplify the integration of EPR signals, we recorded the spectra at relatively low resolution. Under these conditions long-range hyperfine splittings are not resolved and, therefore, the radicals derived from **3** and **6** and the 2-methoxy-substituted radicals derived from **5**, **7**, or **8** show only a broad singlet with $g \approx 2.0030$.¹⁴ Similarly, the radicals derived from **4**, **9**, or **10** appear as broad 1:3:3:1 quartets [$a(\text{H}_\alpha) = 14.2$ G in each case]. Signals arising from radicals formed by hydrogen atom abstraction

(1) Beckwith, A. L. J.; Easton, C. J. *J. Am. Chem. Soc.* **1978**, *100*, 2913.
 (2) Beckwith, A. L. J.; Easton, C. J.; Serelis, A. K. *J. Chem. Soc., Chem. Commun.* **1980**, 482.

(3) Malatesta, V.; Ingold, K. U. *J. Am. Chem. Soc.*, preceding paper in this issue.

(4) Hayday, K.; McKelvey, R. D. *J. Org. Chem.* **1976**, *41*, 2222.

(5) The *cis* isomer **1** is less stable than the *trans* **2** because of the anomeric effect.⁶⁻⁸ The difference in free energy between the two isomers of 6-methyl-2-methoxytetrahydropyran has been estimated⁹ to be approximately 0.7 kcal mol⁻¹.

(6) For leading references see: Lemieux, R. U. *Pure Appl. Chem.* **1971**, *25*, 527; Lemieux, R. U.; Hendriks, K. B.; Stick, R. V.; James, K. *J. Am. Chem. Soc.* **1975**, *97*, 4056; Szarek, W. A.; Horton, D., Eds. *ACS Symp. Ser.* **1979**, No. 87; Anteunis, M. J. O.; Tavernier, D.; Borremans, F. *Heterocycles* **1976**, *4*, 293.

(7) Eliel, E. L. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 739.

(8) Deslongchamps, P. *Tetrahedron* **1975**, *31*, 2463.

(9) Eliel, E. L.; Giza, C. A. *J. Org. Chem.* **1968**, *33*, 3754.

(10) The hypothesis, originally based on product studies⁴ that hydrogen atom abstraction from either **1** or **2** affords a common radical, has recently been confirmed by EPR measurements.¹¹

(11) Malatesta, V.; McKelvey, R. D.; Babcock, B. W.; Ingold, K. U. *J. Org. Chem.* **1979**, *44*, 1872.

(12) (a) Eliel, E. L.; Knoeber, M. C. *J. Am. Chem. Soc.* **1968**, *90*, 3444.
 (b) Eliel, E. L.; Nader, F. W. *Ibid.* **1970**, *92*, 584.

(13) The *exo* or generalized anomeric effect⁶⁻⁸ refers to the stabilization of certain conformations of an exocyclic alkoxy group by interaction of its oxygen lone pairs with endocyclic C-O bonds.

(14) EPR spectral parameters for some of the radicals studied here and related species have been reported previously.^{3,15}

(15) Beckwith, A. L. J.; Tindall, P. K. *Aust. J. Chem.* **1971**, *24*, 2099.
 Dobbs, A. J.; Gilbert, B. C.; Norman, R. O. C. *J. Chem. Soc. A* **1971**, 124.
 Gage, C.; Gilbert, B. C. *J. Chem. Soc., Perkin Trans 2* **1977**, *116*, 754.
 Hudson, A.; Root, K. D. *J. Tetrahedron* **1969**, *25*, 5311.

Table I. Relative Reactivities per Equivalent Hydrogen Atom (ρ) toward *t*-BuO \cdot at ca. 20 °C

DIOXANE		ρ (GC)	ρ (EPR)
3		1.0	1.0
4		1.5	2.4
5		0.6	0.4
6		2.6	1.6
7		3.4	1.4
8		0.3	0.16
9		2.8	2.1
10 ^a		0.25	0.3

^a Sample contained 8% of epimer 9; an appropriate correction has been made to the value of ρ (EPR).

from positions other than C-2 were also detected, but their intensities were too weak to allow spectral parameters to be determined.

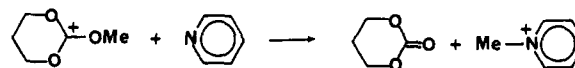
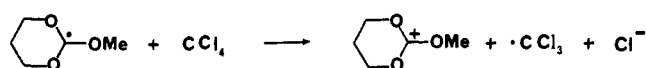
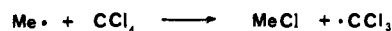
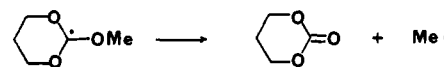
To avoid complications arising from overlapping EPR resonances, we measured the rates of hydrogen atom abstraction from dioxanes **4**, **9**, and **10**, bearing a methyl substituent at C-2, relative to that for 1,3-dioxane (**3**). Likewise, 2-methyl-1,3-dioxane (**4**) was used as a standard for the determination of the hydrogen atom abstraction rates from **3**, **5**, **6**, **7**, and **8**. The consolidated list of relative rate constants obtained by combining the two sets of data is given in Table I which shows the value of ρ , the *reactivity per equivalent hydrogen*, of each dioxane relative to the parent **3**.

If each of the dioxanes, AH and BH, in a suitable mixture of the two undergoes hydrogen atom abstraction by *tert*-butoxy radical or similar species, the ratio of the relevant rate constants can be estimated from the relative rates of consumption of the two substrates.^{4,16}

$$k_{\text{AH}}/k_{\text{BH}} = \ln ([\text{AH}]_t/[\text{AH}]_0) / \ln ([\text{BH}]_t/[\text{BH}]_0)$$

However, difficulty was experienced in applying this method to dioxanes because of their propensity to undergo epimerization at C-2. For example, photolysis of benzophenone as described by Hayday and McKelvey⁴ in the presence of either of the pure isomers **7** or **8** rapidly affords an equilibrium mixture of the two (see below). Similarly, any radical reaction which results in the formation of traces of acid causes rapid epimerization of 2-substituted 1,3-dioxanes. The system eventually chosen involves photolysis of di-*tert*-butyl peroxide in a solution containing dioxanes and pyridine in carbon tetrachloride. The relative rates of consumption of the two or more substrates were monitored by gas chromatography, and the results were substituted into the rate equation given above to afford values of relative rate constants.

Although the use of carbon tetrachloride and pyridine in the reaction mixture effectively prevented epimerization of 2-substituted 1,3-dioxanes, the eventual fate of the radicals initially generated under these conditions has not been completely clarified.

Scheme I**Scheme II****Table II.** Relative Reactivities ($\rho_{\text{AH}}/\rho_{\text{BH}}$) of Pairs of Isomeric Dioxanes

AH	BH	$\rho_{\text{AH}}/\rho_{\text{BH}}$		ref
		GC	EPR	
1	2	8	4	4, 3
7	8	11	7.5	this work
			9	3
9	10	11	7	this work

For example, when 2-methoxy-1,3-dioxane (**5**) was used as substrate, the only products identified were *N*-methylpyridinium chloride and allyl alcohol. The latter probably arises from 2-keto-1,3-dioxane¹⁷ which was separately shown to be unstable under the reaction conditions, while the former could be formed either directly from a carbonium ion intermediate (Scheme I) or indirectly from methyl chloride generated via homolytic fission (Scheme II).

With 1,3-dioxane (**3**) the reaction afforded polymeric material, while 2-methyl-1,3-dioxane (**4**) gave pyridinium chloride, the formation of which is most easily rationalized in terms of a mechanism involving generation of carbonium ions. Fortunately, any ambiguity concerning the modes of decay of the initially generated radicals does not affect the validity of the method which depends only upon the relative rates of consumption of the substrates in the initial hydrogen atom abstraction step.

Each of the methods employed will be subject to error. The validity of the EPR technique depends on the assumption that the dioxanyl radicals generated have equal rates of decay. Malatesta and Ingold³ have estimated that minor variations in decay rates could affect the reliability of the results by a factor of about 2 or 3. Also, since photolyses were conducted under nonflow conditions, the concentrations of substrates would decrease during the experiment. It is possible, therefore, that at the time spectra were recorded the proportion of the more reactive component in the mixture was less than estimated. For most of the compounds studied here this effect should result in the range of values of ρ determined by the EPR technique being somewhat decreased. Possible sources of error in the method based on relative rates of consumption of dioxanes include the preferential destruction of one of the substrates by nonradical reactions. Also, the consumption of dioxanes by reaction at positions other than C-2 will cause an apparent decrease in the range of values of ρ .

Results and Discussion

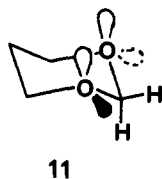
Relative Reactivities. The relative rate constants determined by each of the methods outlined above are presented in Table I. Having regard to the possible sources of error in each method, we regard the level of agreement as very satisfactory and certainly sufficient to preclude the possibility of major deviations from the proposed mechanistic schemes. Although the accuracy of the results is not sufficiently high to justify the detailed consideration

of apparent minor variations in relative rates, the major differences recorded here must be regarded as well founded.

The pairs of epimers **7**, **8** and **9**, **10** exhibit just such major differences in their rates of reaction with *tert*-butoxy radicals. The ratios of rate constants are presented in Table II together with relevant data from work carried out elsewhere.^{3,4} In general, the results are consistent and show satisfactory agreement. However, it is noteworthy that the EPR technique always affords somewhat lower ratios of rate constants than does the more conventional method presumably because of preferential consumption of the more reactive isomer as outlined above. Nevertheless, it is quite clear that the *cis* form of each pair of epimers is considerably more reactive than the *trans*. Since the methyl substituents at C-4 and C-6 effectively lock the conformations of the dioxanes **9** and **10**,¹² the results obtained with these substrates provide compelling evidence that an axial C-H at C-2 is much more readily attacked than an equatorial C-H. The similarity of the reactivity ratio for the pair of monomethyl-substituted tetrahydropyrans, **1** and **2**, to those now recorded for 1,3-dioxanes suggests that they react substantially in the more stable conformers **1** and **2** and do not undergo prior conformational change.

The enhanced reactivity of the *cis* forms of 2-methoxy-substituted ethers cannot be associated with the fact that they have higher energies than their *trans* forms, because the pair of 2-methyl-substituted dioxanes, **9** and **10**, of which the *cis* isomer **9** is the *more* stable¹² shows essentially the same reactivity ratio. Nor for the same reason can the high reactivity of the *cis*-methoxy ethers **1** and **7** be associated with conformational change about the exocyclic C-O bond. We conclude, therefore, that, as predicted earlier,¹⁸ these reactions are under stereoelectronic control and that the enhanced reactivity of axial C-H reflects a favorable interaction in the transition state between the bond undergoing fission and lone pairs on adjacent oxygen atoms.

If, following McKelvey,⁴ Deslongchamps,⁸ Gorenstein,¹⁹ and others,²⁰ we assume that etheral oxygen is sp^3 hybridized with two lone pairs of equal energy, we see that one lone pair on each oxygen of 1,3-dioxane (**3**) is disposed as shown in **11** in an



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tipperiplanar orientation with respect to the axial C-H bond at C-2. There is no such relationship between the equatorial C-H bond and adjacent lone pairs. It is reasonable to conclude, therefore, that an antiperiplanar relationship between a C-H bond and an adjacent lone pair lowers the bond dissociation energy of the former. Stereoelectronic effects in many heterolytic reactions have been similarly rationalized.^{20,21}

Recent theoretical²² and experimental studies²³ suggest that one lone pair of oxygen occupies a p-type orbital of relatively high energy while the other resides in a low-energy s-type orbital. In 1,3-dioxane the axial C-H bond at C-2 lies close to the plane ($\theta = 30^\circ$) of such adjacent p lone pairs, whereas the equatorial C-H is orthogonal to them. In this model the enhanced reactivity of the axial C-H bond is attributable to conjugative delocalization at the transition state between the p lone pairs and the developing radical center.

Of the two models for stereoelectronic interaction of C-H with adjacent oxygen lone pairs we prefer the latter. In any event the

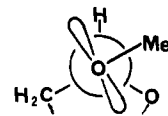


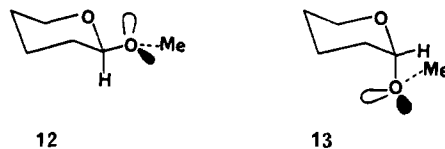
Figure 1. Newman projection of **12** or **13** showing orientation of the exocyclic lone pair.

experiments indicate that the C-H bond in a cyclic ether which lies furthest from the plane of the β,γ -O-C bond will have the weakest dissociation energy. Theoretical studies on methanol lead to a similar conclusion.²⁴

Effects of Exocyclic Methoxy and Methyl Substituents. Since 4,6-dimethyl-1,3-dioxane (**6**) is conformationally locked,¹² its value of ρ may reasonably be attributed mainly to fission of the axial C-H bond at C-2. Each of the 2-methyl-substituted dioxanes **4** and **9** exist preferentially in conformations containing the 2-substituent in an equatorial position. Comparison of the appropriate relative reactivities shows that the axial C-H bonds in these three compounds undergo attack by *tert*-butoxy radicals at similar rates. We conclude that an equatorial 2-methyl substituent has a minor effect on the rate of abstraction of the 2-axial-hydrogen atom from 1,3-dioxanes.

Comparison of the relative reactivities of **7** and **9** and of **8** and **10** leads likewise to the conclusion that a 2-methoxy substituent in either an equatorial or an axial position does not substantially affect the rate of hydrogen atom abstraction from C-2. However, the low reactivity of 2-methoxy-1,3-dioxane (**5**) by comparison with the parent compound **3** appears to strike a discordant note. This can be resolved in the light of the known⁹ preference of **5** to exist preferentially, as illustrated in the unreactive conformer containing an equatorial C-H bond at C-2. It is significant that the calculated difference in ΔG^\ddagger (ca. 400 cal mol⁻¹) between reactions of **3** and **5** is of the same order of magnitude as the difference in free energy (ca. 350 cal mol⁻¹)^{9,12} between **5** and its reactive conformer in which the C-H is axial.

Although methoxy substituents at C-2 exert little effect on the reactivity of 1,3-dioxanes, this appears not to be the case for substituted tetrahydropyrans. The observation by Malatesta and Ingold³ that the conformationally biased ether **1** reacts with *tert*-butoxy radicals 6 times faster than tetrahydropyran indicates that the exocyclic equatorial methoxy substituent in **1** strongly accelerates the rate of C-H fission. Likewise, the fact that abstraction of the equatorial hydrogen at C-2 from the stable conformer **2** occurs at the same rate as abstraction of axial hydrogen from tetrahydropyran³ suggests that an axial methoxy substituent is activating. Both of these conclusions appear reasonable because the exoanomeric effect is known²⁵ to stabilize conformations **12** and **13** in which there is an antiperiplanar



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relationship between the C-H bond at C-2 and an sp^3 lone pair on the exocyclic oxygen atom. Alternatively, the same conformations can be regarded as possessing both a favorable anomeric interaction ($\theta = 30^\circ$) between an exocyclic p lone pair and the endocyclic C-O bond and a similarly favorable interaction ($\theta = 30^\circ$) between the same lone pair and the C-H bond at C-2 (see Figure 1).

The failure of axial or equatorial methoxyl substituents to exert a similar activating effect on 1,3-dioxanes suggests that in compounds such as **7** or **8** the substituent adopts conformations in which interactions between lone pairs and the C-H bond are at a minimum. Such a conformation (**14**) in an equatorial meth-

(18) Brunton, G.; Ingold, K. U.; Roberts, B. P.; Beckwith, A. L. J.; Krusic, P. J. *J. Am. Chem. Soc.* **1977**, *99*, 3177.

(19) Gorenstein, D. G.; Luxon, B. A.; Findlay, J. B.; Momii, R. *J. Am. Chem. Soc.* **1977**, *99*, 4170.

(20) For leading references see ref 3, 6-8, and 19.

(21) Meyers, A. I.; Campbell, A. L.; Abatjoglou, A. A.; Eliel, E. L. *Tetrahedron Lett.* **1979**, 4159.

(22) David, S.; Eisenstein, O.; Hehre, W. J.; Salem, L.; Hoffmann, R. *J. Am. Chem. Soc.* **1973**, *95*, 3806.

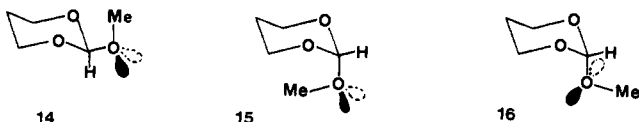
(23) Sweigart, D. A. *J. Chem. Educ.* **1973**, *50*, 322 and references cited.

(24) Bernardi, F.; Schlegel, H. B.; Wolfe, S. *J. Mol. Struct.* **1976**, *35*, 149.

(25) de Hoog, A. J.; Buys, H. R.; Altona, C.; Havinga, E. *Tetrahedron* **1969**, *25*, 3365. de Hoog, A. J.; Buys, H. R. *Tetrahedron Lett.* **1969**, 4175.

oxy-1,3-dioxane has two favorable anomeric antiperiplanar interactions between exocyclic sp^3 lone pairs and the endocyclic C—O bonds but possesses no lone pair antiperiplanar to the C—H bond. If the lone pair resides in a p-type orbital, the conformation **14** would give two favorable interactions ($\theta = 30^\circ$) with C—O bonds but no such interaction ($\theta = 90^\circ$) with the C—H.

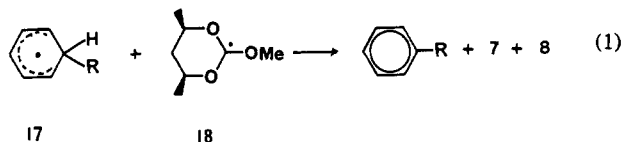
The conformation of an axial methoxydioxane which has the maximum possible anomeric stabilization involving sp^3 lone pairs and the minimum interaction with the C—H at C-2 is that **15** in which there is strong nonbonded repulsion between the *O*-methyl group and axial protons at C-4 and C-6. The concept of a p-type lone pair allows the formulation of a more attractive hypothesis, namely, that the methoxy group adopts a conformation (**16**) in which the magnitude of the two favorable interactions ($\theta = 30^\circ$) of the p-lone pair with C—O bonds, is sufficient to outweigh nonbonded interactions between the eclipsed O—Me and C—H bonds. In this conformation (**16**) there is no interaction ($\theta = 90^\circ$) of the lone pair with C—H.



Interaction of Methoxy-1,3-dioxanes with Triplet Benzophenone.

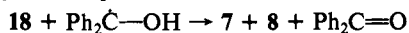
Hayday and McKelvey⁴ found that triplet benzophenone, generated by UV irradiation of a solution of benzophenone and the two tetrahydropyrans **1** and **2** in benzene, abstracts hydrogen preferentially from the cis isomer **1**. However, when we applied this procedure to each of the methoxydioxanes **7** and **8**, rapid epimerization occurred, and an equilibrium mixture of the two was formed. In separate experiments it was observed that epimerization proceeded only during irradiation and was not prevented or retarded by addition of pyridine or potassium carbonate to the reaction mixture. We conclude that epimerization is a true photochemical process and is not caused by traces of acid adventitiously generated during the reaction.

Two possible explanations were considered. When free-radical transformations are conducted in benzene, the solvent may undergo homolytic attack to afford a substituted cyclohexadienyl radical (**17**). Interaction of such an intermediate with a dioxanyl radical (**18**) by hydrogen atom transfer could generate both epimers of the substrate (eq 1).



To test this hypothesis, we conducted the photochemical reaction of benzophenone with the trans isomer **8** in perdeuteriobenzene. Although epimerization occurred, neither of the deuterated species **19** and **20** was formed, a result which precludes the participation of the solvent in the reaction.

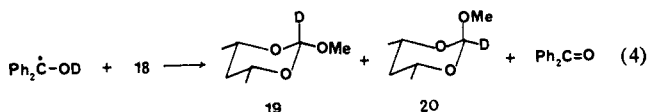
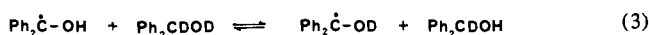
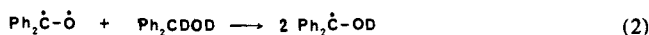
An alternative explanation is that methoxydioxanes **7** and **8** can be regenerated from **18** by hydrogen atom abstraction, either outside the solvent cage or within it after intersystem crossing of the triplet geminate pair:



If this hypothesis is valid, the addition of deuterated benzhydrol to the reaction mixture should bring about the formation of deuterated dioxanes by the following hydrogen atom and proton exchange reactions, (2)–(4).

In the event when the more stable isomer **8** of 2-methoxy-4,6-dimethyl-1,3-dioxane was irradiated with benzophenone and dideuteriobenzhydrol in benzene, epimerization rapidly occurred. Examination of the reaction mixture by ²H NMR revealed that both of the deuterated isomers, **19** and **20**, were present with the less stable isomer **19** in excess [(**19**)/(**20**) \approx 2].

The preferential formation of **19** provides further evidence that epimerization cannot be due to acid-catalyzed processes, for such



reactions should yield predominantly the more stable isomer **20**. Thus it appears that the reaction scheme outlined above is substantially correct and that the photoinduced abstraction of hydrogen from **7** or **8** by benzophenone is reversible, a conclusion which is entirely reasonable in view of the known reversibility of related intramolecular processes.²⁶

Another interesting mechanistic conclusion arises from the observation that epimerization of **8** in the presence of dideuteriobenzhydrol occurs more rapidly than formation of the deuterated dioxanes **19** and **20**. The most obvious explanation, namely, that hydrogen atom transfer between **18** and $\text{Ph}_2\dot{\text{C}}\text{—OH}$ occurs in the solvent cage, requires that intersystem crossing in the geminate triplet pair be very rapid and also that **18** either has a planar radical center or undergoes very rapid inversion.²⁷ The alternative explanation is the benzophenone triplet reacts with deuterated benzhydrol much more slowly than with **8** and that radical decay of $\text{Ph}_2\dot{\text{C}}\text{—OH}$ by other routes competes effectively with the proton exchange (reaction 3). Under these circumstances the stationary concentration [$\text{Ph}\dot{\text{C}}\text{—OD}$] would be much less than [$\text{Ph}\dot{\text{C}}\text{—OH}$] and reaction 4 would be a minor reaction pathway.

The fact that the methoxydioxane **7** undergoes hydrogen atom abstraction more readily than its epimer **8** suggests that hydrogen atom donation to the intermediate radical **18** should also be under stereoelectronic control and should take place preferentially from the axial direction. Although further investigation is required, our observation that the less stable epimer **19** containing an axial C—D bond is formed more readily than the more stable compound **20** provides support for this contention.

Conclusion

The data presented in Tables I and II and discussed above, when considered in the light of results obtained elsewhere, indicate that hydrogen atom abstraction from tetrahydropyran, 1,3-dioxane, and related compounds is under stereoelectronic control. Evidence has also been obtained suggesting that the reverse reactions are subject to the same stereoelectronic influences. These reactions are but one manifestation of the general principle^{1,2} that homolytic bond fission (or bond formation) is favored by coplanar interaction of the bond concerned with a neighboring lone pair, π orbital, or semiooccupied orbital.

Experimental Section

General Data. EPR spectra were recorded on a Varian E9 EPR spectrometer. Radicals were generated directly in the cavity by irradiation of solutions with an Oriel 1000-W high-pressure mercury lamp. GLC analyses were carried out on a Perkin-Elmer 990 gas chromatograph fitted with an Hitachi Perkin-Elmer 159 recorder with a disk integrator. A SCOT Carbowax 20M, 58 m \times 0.5 mm glass column was used with a flow rate of 3 mL min^{-1} of nitrogen carrier gas. At 70 $^\circ\text{C}$ the following retention times were observed: **3**, 19.0; **4**, 17.5; **5**, 60.0; **6**, 19.7; **7**, 79.0; **8**, 42.0; **9**, 16.7; **10**, 23.2 min. Irradiation of mixtures containing benzophenone or acetone were conducted in a quartz vessel in a Rayonet photochemical reactor equipped with 16 RPR 3500 lamps.

Materials. Di-*tert*-butyl peroxide was purified by passage through alumina.²⁸ Carbon tetrachloride (reagent grade) was purified by fractional distillation and stored over 4A molecular sieves. It was redistilled from K_2CO_3 before use. Pyridine (reagent grade) was purified by distillation from KOH and stored over 4A molecular sieves. Otherwise, reagent grade chemicals were used without purification.

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1,3-Dioxane (3),²⁹ 2-methyl-1,3-dioxane (4),³⁰ 2-methoxy-1,3-dioxane (5),⁹ 4-methyl-*cis*-6-methyl-1,3-dioxane (6),³¹ 2-methoxy-*cis,cis*-4,6-dimethyl-1,3-dioxane (7),^{12b} 2-methoxy-*trans,trans*-4,6-dimethyl-1,3-dioxane (8),^{12b} 2-methyl-*cis,cis*-4,6-dimethyl-1,3-dioxane (9),^{12a} and 2-methyl-*trans,trans*-4,6-dimethyl-1,3-dioxane (10)^{12b} were all prepared and purified by literature procedures. They were characterized by ¹H NMR, ¹³C NMR, and IR spectroscopy and had physical constants in agreement with those previously recorded. All were obtained pure with the exception of dioxane 10 which contained approximately 8% of the epimer 9 (as determined by GLC analysis). The dioxanes were stored over K₂CO₃ and distilled before use.

Diphenylmethan-1-*d*-ol-*d* was prepared by treatment of benzophenone (2.0 g, 11 mmol) with lithium aluminum deuteride (0.25 g, 6 mmol) in dry ether (25 mL). After 2 h at reflux the solution was cooled, and a 2.5% solution of NaOD in D₂O (1.0 mL) was added. The usual workup gave the required deuterated alcohol (1.45 g, 72%): mp 69–70 °C; mass spectrum, *m/e* (relative intensity) 186 (M⁺, 94%), 185 (4%), 184 (2%).

Methods. (a) **EPR Spectrometry.** Mixtures of di-*tert*-butyl peroxide and one or two substrates in a peroxide to total substrate ratio of approximately 2:1 (w/w) were degassed by bubbling with nitrogen for 10–15 min and then irradiated in the cavity of the spectrometer. Relative radical concentrations were determined by integration of EPR signals.

(b) **Gas Chromatography.** Solutions containing mixtures of approximately equal amounts of dioxanes (total dioxane concentration ≈ 0.01

M), di-*tert*-butyl peroxide (0.1–0.5 M), and pyridine (10% v/v) in carbon tetrachloride were degassed and irradiated in the Rayonet reactor. Aliquots were removed at intervals (4–24 h) and, after addition of an internal standard, were analyzed by gas chromatography. Various mixtures of dioxanes were studied including inter alia: 7 and 8; 9 and 10; 5, 7, and 8; 4, 9, and 10; 3 and 6; 3, 4, and 5; 6, 8, and 9. Results of different experiments were consistent as were results obtained from aliquots taken from the same mixture at different times.

Solutions containing dioxanes 7 and/or 8 (total dioxane concentration = 0.01 M) and benzophenone (0.01 M) in benzene were degassed, irradiated in the Rayonet reactor, and analyzed by gas chromatography. When perdeuteriobenzene was used as solvent, the mixture was also examined by ²H NMR; no signal other than that for the solvent was detected, although gas chromatography revealed that epimerization of the substrate had occurred. A solution of dioxane 8 (0.06 M), diphenylmethan-1-*d*-ol-*d* (0.15 M), and benzophenone (0.10 M) in benzene was subjected to irradiation. Gas chromatography after 1 h revealed that an equilibrium mixture of 7 and 8 had been formed. After 12-h irradiation the reaction mixture was concentrated, deuteriochloroform was added, and the solution was filtered. The ²H NMR spectrum showed resonances at δ 4.7 and 5.0 (integral ratio 1:2) assigned to the dioxanes 19 and 20, respectively, on the basis of comparison with ¹H NMR spectra determined under similar conditions.

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Absolute Rate Constants for the Reactions of *tert*-Butoxyl, *tert*-Butylperoxyl, and Benzophenone Triplet with Amines: The Importance of a Stereoelectronic Effect¹

D. Griller,* J. A. Howard, P. R. Marriott, and J. C. Scaiano

Contribution from the Division of Chemistry, National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6. Received May 23, 1980

Abstract: Absolute rate constants have been determined for the reactions of *tert*-butoxyl, *tert*-butylperoxyl, and benzophenone triplet with a variety of amines. All three reagents abstract hydrogen from the carbon α to nitrogen with rate constants which are much greater than those for the corresponding reactions with hydrocarbons and isostructural ethers. This rate enhancement is attributed to polar effects on the transition state and to the stabilization of α-aminoalkyls. These product radicals are stabilized by conjugation between the unpaired electron and the nitrogen lone pair, and, as a result, the hydrogen abstractions show a pronounced stereoelectronic effect with abstraction being most facile when the C–H bond being broken is eclipsed with the axis of the nitrogen lone-pair orbital.

The reactions of amines with oxy radicals^{2,3} and the triplet states of ketones^{4–6} have intrigued chemists for many years. Product studies in nonpolar solvents have shown that hydrogen abstraction takes place at the carbon atom adjacent to nitrogen.^{2–6} Much of the fascination of these reactions lies in the fact that they appear to be far more rapid than hydrogen abstractions from hydrocarbons. This observation prompted Cohen⁷ and Davidson⁸ to

propose that an *electron*-transfer complex, I, plays an important role in ketone photoreduction. I later became called a “charge-transfer complex”^{9–15} although Yip and his colleagues described the distinction as being “more semantic than real”.⁹ Complete electron transfer¹⁶ to form ions (reaction 3) can compete with

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