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EFFECTS OF HETEROATOM SUBSTITUENTS ON THE PROPERTIES OF 1,2-DIOXETANES

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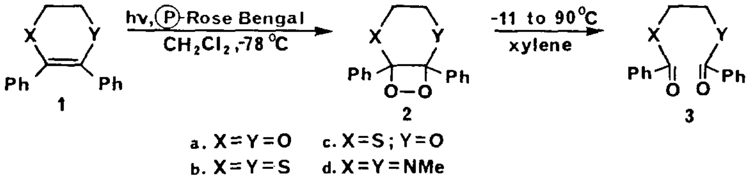
Abstract: Nitrogen and sulfur-substituted dioxetanes exhibit dramatically lower activation energies for decomposition compared to the corresponding oxygen-bearing dioxetane. A mechanism involving intramolecular electron-transfer processes is proposed for the cleavage of these unstable dioxetanes.

1,2-Dioxetanes[1] of various structural types have been prepared by the cyclization of β-bromohydroperoxides[2a] and by the addition of singlet oxygen to activated alkenes.[2b,c] Alkyl- or phenyl-substituted dioxetanes are relatively stable and decompose at elevated temperatures to give predominantly triplet excited states.[1] In contrast, dioxetanes bearing aryl moieties with low oxidation potentials are significantly less stable and decompose with enhanced singlet chemiexcitation efficiencies.[3]

Photooxygenation of vinyl ethers affords alkoxy-substituted dioxetanes that exhibit properties similar to those of alkyl-substituted dioxetanes.[4] For example, *cis*-3,4-diethoxy-1,2-dioxetane[4a,b] and *cis*-3,4-diethyl-1,2-dioxetane[4c] both have half-lives of several hours at 25°C and thermolyze with Arrhenius activation energies of 24.4 and 24.5 kcal/mol, respectively. However, dioxetanes derived from enamines[5] and vinyl sulfides[6] have been reported to be qualitatively much less stable, undergoing rapid decomposition below 0°C. No mechanistic explanation has been offered for the striking differences in the thermal stability of these dioxetanes. In order to systematically evaluate the effects of heteroatom substituents, a series of structurally related dioxetanes 2 has been prepared. We provide herein the first report of activation parameters and rates of decomposition for nitrogen- and sulfur-substituted dioxetanes. An intramolecular electron-transfer mechanism is proposed for the cleavage of these unstable peroxides.



Alkenes **1a–d**[7] were synthesized by acid-catalyzed condensation of benzoin with 1,2-ethanediol, 1,2-ethanedithiol, 2-hydroxyethanethiol, and N,N'-dimethyl-1,2-ethanediamine. Solutions of dioxetanes **2a–d** were prepared in CH_2Cl_2 by photooxygenation of **1a–d** at -78°C with polystyrene-immobilized Rose Bengal[9] and a 400-W high pressure sodium lamp. All four dioxetanes produce indirect chemiluminescence upon thermolysis in *o*-xylene in the presence of 9,10-dibromoanthracene (DBA).[4a] Dioxetanes **2a**, **2c**, and **2d** were further identified by ^1H NMR at low temperature[10] and by their cleavage to **3a**, **3c**, and **3d** which were fully characterized. Photooxygenation of **1b** at -78°C in CH_2Cl_2 followed by warming to ambient temperature affords not only **3b** (44%) but also benzil (31%). Product yields in this latter case were determined by HPLC. Several groups have previously noted that the decomposition of sulfur-substituted dioxetanes can yield mixtures of products derived from C-C and C-S bond cleavage.[6,11] It should be emphasized that benzil is not formed from the decomposition of **2c**.

Rate constants for the decomposition of **2a–d** were determined from measurements of the decay of chemiluminescence intensity of 10^{-4}–10^{-5} M solutions in *o*-xylene in the presence of 10^{-5} M DBA. The isothermal decompositions were monitored for at least three half-lives and were first order in all cases. Rates were found to be independent of DBA and dioxetane concentration.[12] Activation parameters were calculated from Arrhenius plots.

Table 1. Activation Parameters and Rates of Decomposition for 1,2-Dioxetanes **2a–d**

Dioxetane (X,Y)	Temp. Range, °C	E_a,[a] kcal/mol	Log A	k^b_{rel} (25°C)	$\tau^b_{1/2}$ (25°C)
2a (O,O)[e]	70.0 to 90.3	24.8	12.4	1[c]	115 h
2b (S,S)	-11.5 to +20.5	18.8	13.6	3.96×10^5	1.05 s
2c (S,O)	-11.5 to +21.5	17.4[d]	12.2	1.66×10^5	2.49 s
2d (MeN, MeN)	- 0.7 to +29.6	16.6	11.1	5.12×10^4	8.09 s

[a] Errors are ±0.5 kcal/mol determined by the method of Wiberg.[13] [b] Calculated from the Arrhenius plots. [c] Corresponding to a rate constant of 1.67×10^{-6} s^{-1} in *o*-xylene at 25°C. [d] Rates of decomposition for **2c** were the same if the direct emission was monitored in the absence of DBA. [e] For earlier studies of this dioxetane, see references **3b** and **3c**.

In addition to the indirect "blue" chemiluminescence that can be observed visually from **2a–d** in the presence of DBA, we have also found that injection of a cold solution of the mixed oxygen-sulfur dioxetane **2c** into *o*-xylene at ambient temperature results in an intense "yellow" chemiluminescence (λ_{max} = 553 nm). This direct emission is of particular interest because cleavage product **3c** is not detectably fluorescent. Figure 1 shows a chemiluminescence spectrum of **2c** in *o*-xylene obtained at -11°C with a Spex Fluorolog spectrofluorometer. Correction was made for the decay of total light intensity during the scan by use of a second detector in a ratio mode. This luminescence is also observed in acetonitrile (λ_{max} = 533 nm) and in methylcyclohexane (λ_{max} = 561 nm). A plausible explanation for this unusual emission involves an intramolecular exciplex.[14] Goto has reported chemiluminescence from an exciplex generated by the thermolysis of an indole-substituted dioxetane.[3d] However, in that case emission from the fluorescent indole group as well as the exciplex was observed.

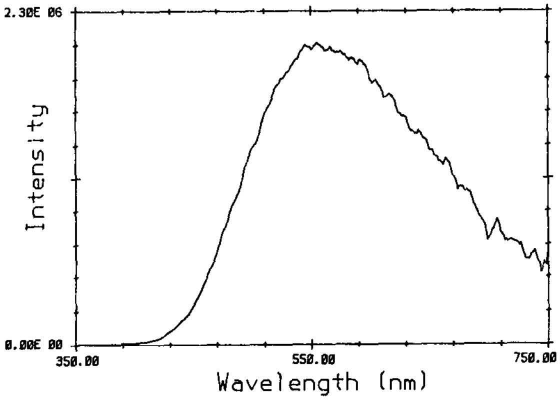
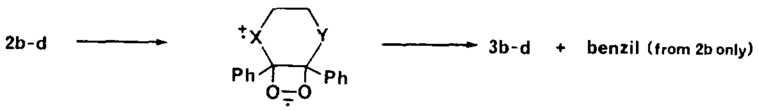


Figure 1. Chemiluminescence spectrum of dioxetane **2c** in air-saturated *o*-xylene at -11°C, corrected for the decay of total light intensity during the scan.

Several lines of evidence indicate that "stable" dioxetanes such as **2a** decompose by a stepwise process involving homolysis of the peroxide bond to form a diradical with subsequent C-C bond cleavage.[1,3g] Clearly, an alternate mechanistic explanation is required to account for the distinct properties of nitrogen- and sulfur-substituted dioxetanes **2b-d**. It might be proposed that these dioxetanes decompose *via* a concerted pathway. Heteroatom substituents would be expected to stabilize a transition state in which unsaturated carbonyl carbons bearing a partial positive charge are developed. One measure of the electron-donating ability of a substituent is the σ^+ value (*p*-MeS, -0.16; *p*-Me, -0.31; *p*-MeO, -0.78; *p*-Me_2N, -1.7).[15,16] On this basis, however, one would have predicted oxygen-substituted dioxetanes to be less stable than sulfur-bearing dioxetanes. Also arguing against a concerted mechanism involving both ring carbon atoms is the observation that a single sulfur atom destabilizes the dioxetane to the same degree as two sulfur moieties.

We, therefore, propose a mechanism for the decomposition of **2b-d** involving initial intramolecular electron-transfer from the heteroatom to the peroxide σ^* orbital.[18] This mechanism requires that the stability of the dioxetane be related to the oxidation potential of the heteroatom substituents. Consistent with this suggestion are the present results which show that dioxetanes bearing easily oxidized groups such as amines or sulfides ($E_p{}^{ox}$: Et_3N, +0.96 V; Me_2S, +0.88)[19] are dramatically less stable than a similar dioxetane with an alkoxy substituent possessing a much higher oxidation potential (E^{ox} Et_2O, > +2.5 V).[19]

Additional experiments in this area are in progress. Of particular interest are the mechanistic details of the chemiexcitation process, exciplex emission, and dual decomposition modes of **2b**.



Acknowledgments. Support from the Office of Naval Research is gratefully acknowledged. We also thank Dr. Manfred Steinfatt for initial experiments with dioxetane **2d**.

References and Notes

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7. **1b**: mp 101-102°C (lit.[8a] 101.9-102.2°C); ^{1}H NMR ($CDCl_3$) δ 3.40 (s, 4H), 7.2 (m, 10H). **1c**: mp 64-65°C (lit.[8b] 63-65°C); ^{1}H NMR ($CDCl_3$) δ 3.22 (t, 2H, 4.5 Hz), 4.51 (t, 2H, 4.5 Hz), 7.1 (m, 10H). **1d**: mp 180-182°C: ^{1}H NMR ($CDCl_3$) δ 2.38 (s, 6H), 2.97 (s, 4H), 7.2 (m, 10H). Satisfactory analysis of all alkenes.
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10. **2a**[3b]: ^{1}H NMR ($CDCl_3$) δ 4.39 (m, 2H), 4.91 (m, 2H), 7.3 (m, 10H). **2c**: ^{1}H NMR ($CDCl_3$) δ 3.30 (m, 2H), 4.60 (m, 2H), 7.3 (m, 10H). **2d**: ^{1}H NMR (CD_2Cl_2) δ 2.18 (s, 6H), 3.39 (m, 2H), 3.63 (m, 2H), 7.1 (m, 10H). Because of its instability even at low temperature, a satisfactory ^{1}H NMR spectrum of **2b** has not yet been obtained.
11. (a) W. Adam and J.-C. Liu, *J. Am. Chem. Soc., 94,* 1206 (1972); (b) W. Ando, K. Watanabe, and T. Migita, *Tetrahedron Lett.,* 4127 (1975) and references therein.
12. Electron-rich alkenes are known to catalyze the decomposition of dioxetanes.[1a] However, control experiments have shown that traces of unreacted alkene in dioxetane stock solutions were not responsible for the observed instability of **2b-d**. Rates of decomposition of dioxetanes **2c** and **2d** were found to be unchanged in the presence of low concentrations of **1c** and **1d**.
13. K. Wiberg, "Physical Organic Chemistry," p.378, J. Wiley, New York, 1964.
14. No direct emission is observed from **2d** and only very weak emission from **2b**.
15. (a) H. C. Brown and Y. Okamoto, *J. Am. Chem. Soc., 80,* 4979 (1958); (b) C. G. Swain and E. C. Lupton, Jr., *Ibid., 90,* 4328 (1968).
16. Another indication of the greater stabilization of adjacent positive charge by oxygen **vs.** sulfur is the observation that $ClCH_2OCH_2CH_3$ hydrolyzes 1000-fold faster than $ClCH_2SCH_2CH_3$.[17a] It should be noted, however, that Caserio found that this order of stabilization is reversed in the gas phase.[17b]
17. (a) F. G. Bordwell, G. D.Cooper, and H. Morita, *J. Am. Chem. Soc., 79,* 376 (1957); (b) J. K. Pau, M. B. Ruggera, J. K. Kim, and M. C. Caserio, *Ibid., 100,* 4242 (1978).
18. Intramolecular electron-transfer mechanisms have been proposed for the decomposition of unstable dioxetanes bearing easily oxidized aryl groups.[3]
19. Oxidation peak potentials determined by cyclic voltammetry in MeCN **vs.** SCE. Et_2O shows no oxidation at potentials less than 2.5 V.

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