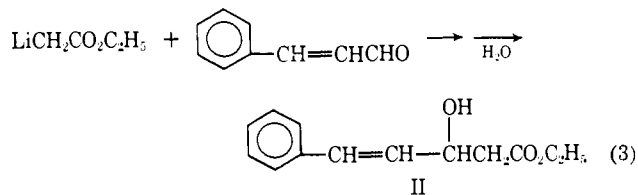




amide at -78° 2 min after addition of ethyl acetate gives only 60% recovery of ethyl acetate while quenching after 1 hr gives only 20% recovery.

The synthetic potential of I is indicated by its reaction with cinnamaldehyde to produce a 94% isolated yield of II (eq 3). The yields of β -hydroxy esters from other



aldehydes and ketones are equally good as shown in Table I. This method for preparing β -hydroxy esters

Table I. Conversion of Carbonyl Compounds into β -Hydroxy Esters by Reaction with Lithio Ethyl Acetate

Carbonyl compd	Product	Yield, % ^a
Butanal	$\text{CH}_3(\text{CH}_2)_2\text{CHOHCH}_2\text{CO}_2\text{C}_2\text{H}_5$	80
Benzaldehyde	$\text{C}_6\text{H}_5\text{CHOHCH}_2\text{CO}_2\text{C}_2\text{H}_5$	(80)
Cinnamaldehyde	$\text{C}_6\text{H}_5\text{CH}=\text{CHCHOHCH}_2\text{CO}_2\text{C}_2\text{H}_5$	(94)
Acetone	$(\text{CH}_3)_2\text{COHCH}_2\text{CO}_2\text{C}_2\text{H}_5$	90
Cyclopentanone		93
Cyclohexanone		91

^a Gipc yields, isolated yields in parentheses.

not only gives much higher yields than the usual Reformatsky procedure^{4,5} but is much less time consuming as indicated by the following procedure for the conversion of cinnamaldehyde into II. A dry 100-ml flask equipped with septum inlet and magnetic stirrer was flushed with nitrogen. A solution of lithium bis(trimethylsilyl)amide in tetrahydrofuran⁷ (25 ml of a 1.0 M solution) was injected and the flask immersed in a Dry Ice-acetone bath. Ethyl acetate (2.42 ml, 25 mmol) was added dropwise over a period of 2 min and the solution was stirred for an additional 15 min to complete the formation of I. Cinnamaldehyde (2.95 ml, 25 mmol) was then injected and after 5 min the solution was hydrolyzed by injection of 5 ml of 20% hydrochloric acid. The solution was allowed to reach room temperature. Addition of pentane to the separated organic phase followed by cooling gave 5.17 g (94% yield) of ethyl-3-hydroxy-5-phenyl-4-pentanoate, II, mp 38–39°.⁹

We are presently exploring in greater detail the synthetic uses of lithio ethyl acetate. In addition, we are

(4) R. L. Shriner, *Org. React.*, **1**, 20 (1942).

(5) Hauser, *et al.*,⁶ have shown that ethyl acetate may be condensed with carbonyl compounds in liquid ammonia using 2 equiv of lithium amide. However, the yields of product are disappointing in many cases. Thus benzaldehyde gives only a 32% yield of the β -hydroxy ester.

(6) W. R. Dunnivant and C. R. Hauser, *J. Org. Chem.*, **25**, 503 (1960).

(7) Solutions of lithium bis(trimethylsilyl)amide in hexane were prepared by a procedure outlined by Amonoo-Neizer, *et al.*⁸ The hexane was then evaporated and replaced by tetrahydrofuran.

(8) E. H. Amonoo-Neizer, R. A. Shaw, D. O. Skovlin, and B. C. Smith, *J. Chem. Soc.*, 2997 (1965).

(9) Saponification and dehydration gave 5-phenylpentadienoic acid, mp 165–166°, lit.⁶ mp 165–166°.

studying the conversion of other esters to the corresponding lithium derivatives.

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Michael W. Rathke

Department of Chemistry, Michigan State University
East Lansing, Michigan 48823

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Stereospecific Formation of 1,2-Dioxetanes from *cis*- and *trans*-Diethoxyethylenes by Singlet Oxygen

Sir:

To the two modes of reaction of singlet oxygen, conjugate addition to dienes and allylic hydroperoxide formation,¹ a third mode, formation of 1,2-dioxetanes, has recently been added.² This reaction requires alkenes specially activated, as by amino^{2a} or alkoxy^{2f-i} groups, and the absence of very active allylic hydrogen in the molecule. Dioxetanes, whether prepared from singlet oxygen^{2e-i} or by cyclization of halohydroperoxides,³ have been observed to decompose cleanly to carbonyl compounds with chemiluminescence.⁴ We report here evidence supporting stereospecific *cis* addition of singlet oxygen to vinylene diethers to give isolable dioxetanes as products.

cis-Diethoxyethylene (1), freed from its *trans* isomer by preparative vapor phase chromatography, 0.211 g, was dissolved in 7 ml of fluorotrichloromethane (Freon 11) which had been dried over molecular sieves. The solution, containing 10^{-4} M tetraphenylporphyrin, was held in an acetone-Dry Ice bath at -78° in a dewar with Pyrex windows and irradiated through a Corning uv filter with a 500-W lamp for 25 min in a stream of oxygen. Under these conditions white crystals began to form in 15–20 min, and soon filled the vessel. The crystalline dioxetane 2 was isolated by removing the Freon under vacuum through a sintered glass disk. A small sample of the product, on warming to room temperature, melted and exploded.

When the photooxidation of 1 was monitored by nmr, the ethylenic singlet of 1 at δ 5.12 gave way to a new singlet at δ 5.91. At the same time the methylene quartet of the ethyl group initially at δ 3.73 in 1 was further split because of the proximity of the new asymmetric carbon atom in 2, the signal in 2 being centered at δ 3.88. The 100-MHz nmr spectrum of 2 is shown in Figure 1. The position of the methyl triplet was

(1) C. S. Foote, *Accounts Chem. Res.*, **1**, 104 (1968), and references therein.

(2) (a) C. S. Foote and J. W.-P. Lin, *Tetrahedron Lett.*, **29**, 3267 (1968); (b) J. Huber, *ibid.*, **29**, 3271 (1968); (c) W. Fenical, D. R. Kearns, and P. Radlick, *J. Amer. Chem. Soc.*, **91**, 3396 (1969); (d) W. Fenical, D. R. Kearns, and P. Radlick, *ibid.*, **91**, 7771 (1969); (e) G. Rio and J. Berthelot, *Bull. Soc. Chim. Fr.*, **10**, 3609 (1969); (f) R. S. Atkinson, *Chem. Commun.*, 177 (1970); (g) P. D. Bartlett, paper presented at the International Symposium on Singlet Oxygen, New York Academy of Sciences, New York, N. Y., Oct 23, 1969; (h) P. D. Bartlett, G. D. Mendenhall, and A. P. Schaap, *Ann. N. Y. Acad. Sci.*, in press; (i) S. Mazur and C. S. Foote, *J. Amer. Chem. Soc.*, **92**, 3225 (1970).

(3) K. R. Kopecky, J. H. van de Sande, and C. Mumford, *Can. J. Chem.*, **46**, 25 (1968).

(4) (a) K. R. Kopecky and C. Mumford, *ibid.*, **47**, 709 (1969); (b) E. H. White, J. Wiecko, and D. R. Roswell, *J. Amer. Chem. Soc.*, **91**, 5194 (1969).

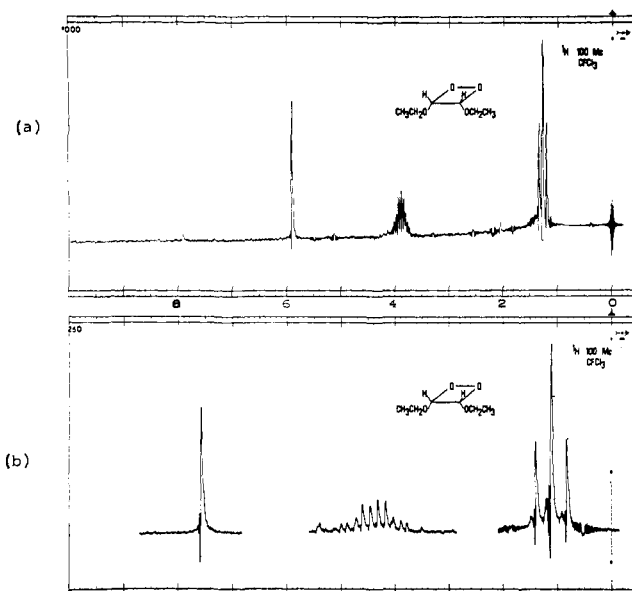
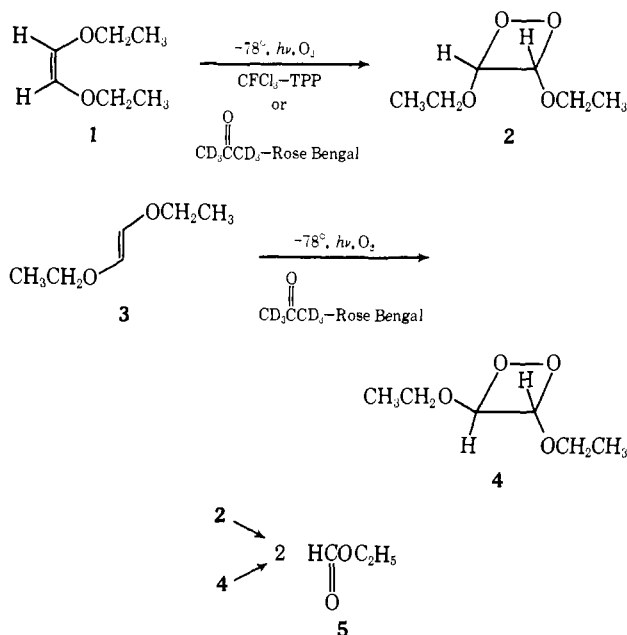


Figure 1. (a) 100-MHz proton nmr spectrum of recrystallized *cis*-diethoxydioxetane in CFCl_3 ; (b) same, expanded scale.

shifted only from δ 1.25 to 1.29. Under the conditions described the ethyl formate previously reported^{2g} to accompany the dioxetane is not produced. Ethyl formate (5) appears either on prolonged irradiation in the presence of sensitizer or on warming to temperatures above 50° ($k_1 = 3.17 \times 10^{-3} \text{ sec}^{-1}$ at 54°) which converts the nmr spectrum of the solution completely to



that of 5 (singlet at 7.92, quartet at 4.18, triplet at δ 1.29). During the decomposition in benzene the broad ir absorption at 847 cm^{-1} decreased as the typical carbonyl stretch of ethyl formate appeared.⁵

A molecular weight determination by isothermal distillation in Freon 11 at 2.6° against a dimethyl phthalate standard showed the dioxetane 2 to be monomeric (calcd volume of solution for monomer, 10.7 ml; for dimer, 7.3 ml; initial volume, 8.1 ml; volume after

(5) A similar band at 850 cm^{-1} was ascribed to O-O stretch in a cannabinoid dioxetane isolated by R. K. Razdan and V. V. Kane, *J. Amer. Chem. Soc.*, **91**, 5190 (1969), footnote 5.

30 min, 9.3 ml). The nmr spectrum showed no decomposition immediately after the molecular weight determination, but quantitative conversion to 5 after 30 min at 60° .

A quantitative study of the luminescence quantum yield of the thermal decomposition of *cis*-diethoxydioxetane 2 has been carried out and will be reported shortly.⁶

Identical products resulted from photooxidation of 1 with tetraphenylporphin in Freon 11 and with Rose Bengal in deuterioacetone, as shown by the single nmr spectrum of a mixture of the two product solutions.

When *trans*-diethoxyethene (3) was photooxidized in deuterioacetone at -78° , a solution of 4 was obtained whose nmr spectrum had its singlet at 5.89 instead of the 6.15 observed for 2. Spectra of mixtures showed both peaks, but the photooxidation in deuterioacetone of each pure isomer yielded its own dioxetane unaccompanied, within the sensitivity of the nmr method, by the other.⁷ Each dioxetane decomposed quantitatively on warming to ethyl formate, $k_{cis}^{50^\circ}/k_{trans}^{50^\circ} = 1.40$.

First-order orbital symmetry theory leads to the prediction that singlet oxygen should not add suprafacially 1,2 to an alkene in a concerted manner.⁸ One anticipates therefore that dioxetane formation will be either stepwise or antarafacial ($2_s + 2_a$).⁹ A stepwise biradical addition of singlet oxygen would be expected to lead to loss of configuration, but stepwise cycloadditions by way of dipolar ions show much more retention of configuration.¹⁰⁻¹² The solvent susceptibility which we have reported^{2g,h} for dioxetane formation (k_{addn}/k_{ene} greater by a factor of 59 for acetonitrile than for benzene) is inconclusive, being of a magnitude possible for a radical reaction with substantial polar character,¹³ or a concerted reaction with some charge transfer at the transition state.^{14,15,15a}

A well-studied case of stereospecific 2 + 2 cycloaddition is that of ketenes.¹⁶⁻¹⁸ Singlet oxygen shares with ketene its unhindered linearity, which allows it to undergo antarafacial addition to an alkene. Although

(6) A. P. Schaap and T. Wilson, forthcoming publication.

(7) Photooxidation of 3 with TPP in Freon 11 at -78° gave irreproducible ratios of 2 and 4. The reason for this is not known, but it may be the result of photosensitized isomerization of 2.

(8) D. Kearns, *J. Amer. Chem. Soc.*, **91**, 6554 (1969).

(9) R. B. Woodward and R. Hoffmann, *Angew. Chem. Int. Ed. Engl.*, **8**, 808 (1969).

(10) B. D. Kramer, Ph.D. Thesis, Harvard University, Cambridge, Mass., 1968.

(11) C. J. Dempster, Ph.D. Thesis, Harvard University, Cambridge, Mass., 1967.

(12) P. D. Bartlett, *Quart. Rev., Chem. Soc.*, in press.

(13) J. C. Martin, D. L. Tuleen, and W. G. Bentrude, *Tetrahedron Lett.*, 229 (1962).

(14) R. Huisgen, L. A. Feiler, and P. Otto, *ibid.*, 4485 (1968); *Chem. Ber.*, **102**, 3444 (1969).

(15) The proposal (Kearns, ref 8, footnote 51) of a peroxirane as a common intermediate in the formation of dioxetanes and allylic hydroperoxides might also accommodate the polar solvent dependence of dioxetane formation, although it does not predict the manner^{2g,h} in which partition between these two products responds to the medium.

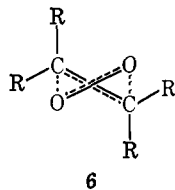
(15a) NOTE ADDED IN PROOF. The substantial solvent effect on k_{addn}/k_{ene} for dihydropyran is not observed in the rate competition between two symmetrical molecules, tetramethylethylene, which gives only ene reaction, and *cis*-diethoxyethene, which gives only dioxetane (competition ratio in benzene, 0.82; in acetonitrile, 1.10). The most significant difference between these cases may be the symmetry of the substrate double bond.

(16) R. Montaigne and L. Ghosez, *Angew. Chem.*, **7**, 221 (1968).

(17) G. Binsch, L. A. Feiler, and R. Huisgen, *Tetrahedron Lett.*, 4497 (1968).

(18) R. Huisgen, L. A. Feiler, and G. Binsch, *Angew. Chem. Int. Ed. Engl.*, **3**, 753 (1964); *Chem. Ber.*, **102**, 3460 (1969).

oxygen lacks the strongly electrophilic center which can be discerned in ketenes and vinyl cations,¹⁹ it has one property that must predispose it to this mode of reaction: any peroxide structure has such a strong preference for a nonplanar conformation that the contorted transition state (6) for the $2_s + 2_a$ addition may bring hardly any more strain than does the dioxetane ring itself.



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(19) Reference 9, p 847.

Paul D. Bartlett, A. Paul Schaap
Converse Memorial Laboratory, Harvard University
Cambridge, Massachusetts 02138
Received March 11, 1970

Chemistry of Singlet Oxygen. IX. A Stable Dioxetane from Photooxygenation of Tetramethoxyethylene¹

Sir:

There has been much recent interest in 1,2-dioxetanes as possible intermediates in chemiluminescent reactions² and in olefin photooxygenations.³ Electron-rich olefins are well known to undergo 1,2 cycloadditions with dienophiles,⁴ and enamines were found to undergo photosensitized oxygenation^{3a,d} to produce unstable intermediates which decomposed cleanly to carbonyl fragments. However, these intermediates were shown to be not solely monomeric 1,2 cycloadducts.^{3a} The report by Hoffman and Häuser that the reactive olefin 1,1,2,2-tetramethoxyethylene (1) undergoes 1,2 cycloaddition⁵ suggested that photooxygenation of this compound might produce the dioxetane 1,2-dioxo-3,3,4,4-tetramethoxycyclobutane (2).

Photooxygenation of 1 in ether, at -70° , sensitized by either zinc tetraphenylporphine or dinaphthalene-thiophene with visible light⁶ proceeded rapidly, and ceased abruptly after uptake of 1 equiv of oxygen. Both sensitizer and light were found to be essential. Evaporation of solvent (-78°) and evaporative distillation of the residue (25°) yielded a clear, pale-yellow

(1) Contribution No. 2544; supported by HEW-NAPCA Grant No. AP-00681 and NSF Grant No. GP-8293. Paper VIII: C. S. Foote and M. Brenner, *Tetrahedron Lett.*, 6941 (1968).

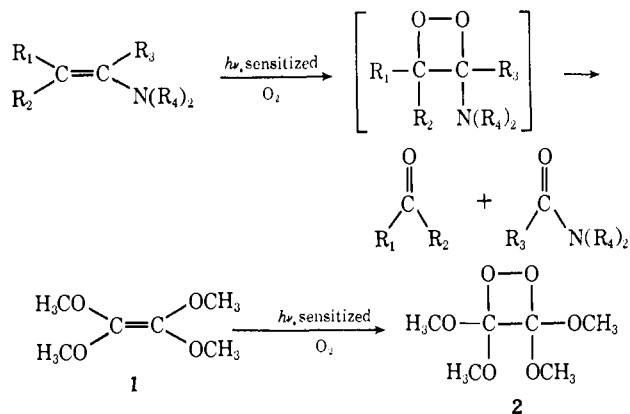
(2) (a) F. McCapra, *Quart. Rev., Chem. Soc.*, 20, 485 (1966); (b) F. McCapra, *Chem. Commun.*, 155 (1968); (c) K. R. Kopecky and C. Mumford, *Can. J. Chem.*, 47, 709 (1969); (d) E. H. White, J. Wiecko, and D. R. Roswell, *J. Amer. Chem. Soc.*, 91, 5194 (1969).

(3) (a) C. S. Foote and J. W.-P. Lin, *Tetrahedron Lett.*, 3267 (1968); (b) D. R. Kearns, *J. Amer. Chem. Soc.*, 91, 6554 (1969); (c) W. Fenical, D. R. Kearns, and P. Radlick, *ibid.*, 91, 3396, 7771 (1969); (d) J. Huber, *Tetrahedron Lett.*, 3271 (1968).

(4) Reviews: R. Gompper, *Angew. Chem. Int. Ed. Engl.*, 8, 312 (1969); R. W. Hoffman, *ibid.*, 7, 754 (1968).

(5) R. W. Hoffman and H. Häuser, *ibid.*, 3, 380 (1964).

(6) See C. S. Foote, S. Wexler, W. Ando, and R. Higgins (*J. Amer. Chem. Soc.*, 90, 975 (1968)) for details of the technique.



liquid in 94% yield. This material, which contained (nmr) approximately 10% of dimethyl carbonate, was further purified by low-temperature crystallization from pentane-ether. The pure product (mp -8 to -9°) was found to be remarkably stable ($t_{1/2} = 102$ min at 56°), although its decomposition appears to be catalyzed by zinc tetraphenylporphine.⁷ The nmr spectrum (in Freon 12, 100 MHz) consisted of a single sharp resonance at 3.45 ppm at temperatures as low as -118° . The ir spectrum (neat) had principal bands at 2980 (m), 2870 (w), 1440 (m), 1345 (m), 1210 (s), 1130 (s), 1065 (s), 1020 (m), 975 (w), 910 (m), 875 (w), and 830 cm^{-1} . Elemental analysis was consistent with the formula $\text{C}_6\text{H}_{12}\text{O}_6$ (Anal. Calcd: C, 40.01; H, 6.71. Found: C, 40.02; H, 6.74). The molecular weight was determined to be 185 ± 6 (cryoscopic, benzene) and 198 (vapor pressure osmometry); the calculated value is 180. Iodometric determination showed 87% of one peroxidic oxygen. When the product was heated at 56° in benzene in an nmr tube, a smooth decomposition occurred, giving dimethyl carbonate (identified by ir, nmr, and vpc comparison with authentic material) as the sole product in quantitative yield.

These data are entirely consistent with dioxetane structure 2. Although alternate structures 3 and 4 can be envisioned, they may be discounted on the following grounds. Structure 3 would be expected to show two nonequivalent methoxyl resonances in the nmr (assuming oxygen inversion would be slow on the nmr time scale at -118° , the lowest temperature so far investigated).⁸ The equilibrium $4a \rightleftharpoons 4b$, even if it were rapid enough to result in a single methoxyl resonance, should produce an averaged chemical shift considerably downfield from the observed position.⁹

One of the most intriguing aspects of structure 2 is its close relationship to the CO_2 dimer (5), which has been implicated as the key intermediate in the chemiluminescent reaction of oxalyl halides and esters with H_2O_2 ,¹⁰ and to the suggested dioxetane interme-

(7) The dioxetane reported by Kopecky^{2c} appears to be comparably stable, but no evidence for its structure or molecular weight has so far been published.

(7a) NOTE ADDED IN PROOF. The dioxetane has been characterized (E. H. White, J. Wiecko, and C. C. Wei, *J. Amer. Chem. Soc.*, 92, 2167 (1970)).

(8) An approximate analogy may be found in the inversion rate of O-isopropylethyleneoxonium fluoroborate, for which the coalescence temperature is -50° : J. B. Lambert, *ibid.*, 90, 1349 (1968).

(9) The average of the methoxyl shifts of trimethyl orthoformate (3.23 ppm) and of the dimethoxycarbonium ion $[\text{HC}(\text{OCH}_3)_2]^+$ (4.64 ppm: see R. I. Borch, *ibid.*, 90, 5303 (1968)) would be 3.93 ppm whereas the observed value is 3.45 ppm.

(10) M. M. Rauhut, *Accounts Chem. Res.*, 2, 80 (1969); H. F. Cordes, H. P. Richter, and C. A. Heller, *J. Amer. Chem. Soc.*, 91, 7209 (1969).