Table I. Microwave Transition Frequencies of C_3O^a

transition	frequency/MHz^b
$1 \leftarrow 0$	9621.762
$2 \leftarrow 1$	19243.531
$3 \leftarrow 2$	28865.227
$4 \leftarrow 3$	38486.862
$5 \leftarrow 4$	48108.504
$6 \leftarrow 5$	57729.962

^{a} $B_0 = 4810.885\ (33)$; $D_J = 0.000740\ (65)$ MHz. ^{b} Estimated uncertainties in measured frequencies are 20 kHz.

perature was increased to 1000 °C, were observed at frequencies very close (1 part in 600) to those predicted for C_3O by ab initio molecular orbital calculations (full geometry optimization by GAUSSIAN 80 SCFMO calculations at the MP3/6-31G* level).[6] Our observed frequencies and J assignments, together with least-squares-fitted rotational and centrifugal distortion constants consistent with a linear molecule, are given in Table I. The observed Stark splitting patterns support these assignments. From the Stark effect we were able to determine the dipole moment of the species to be 2.391 (5) D.

The present observations are fully consistent with the presence of a gas-phase molecule of formula C_3O and electronic structure well represented by the classical resonance form $^{-}C{\equiv}C{-}C{\equiv}O^{+}$. We have not been able to account for the microwave spectral observations in any alternative way, and the spectrum, together with the observation of a m/z peak 52 in the mass spectrum, seems conclusive. Rough lifetime measurements in the microwave waveguide cell indicate a lifetime of less than 1 s at about 1 Pa total pressure.

We are currently investigating isotopic species and other properties of C_3O.[7]

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(6) Brown, R. D.; Rice, E., submitted for publication.

(7) Robert Champion assisted with some preliminary experiments. We are grateful to Dr. Roger F. C. Brown for helpful discussions about preparative aspects of this project. The work was supported by a grant from the Australian Research Grants Scheme.

Reaction of Bicyclic Endoperoxides with Carbonyl Compounds. A New Approach to 1,2,4-Trioxanes

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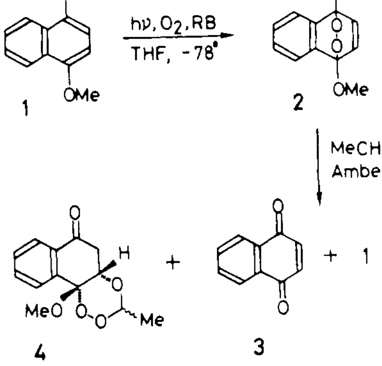
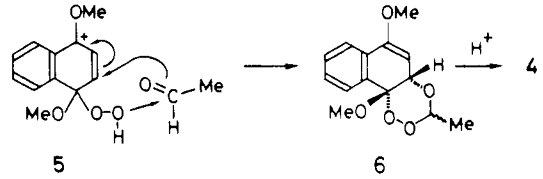
Bicyclic 1,4-endoperoxides are easily accessible by several reactions, of which the [4 + 2] addition of singlet oxygen to a cyclic 1,3-diene is typical.[1] Their preparation, originating with the pioneering work of Dufraisse,[2] and properties have been studied for some 57 years. However, it appears that the chemistry of 1,4-endoperoxides has been confined to their reduction,[3] cleavage,[4] fragmentation,[4] and rearrangement.[5] Interesting though these processes[6] may be, few, if any, reactions with organic molecules have been recorded.

We now wish to report a new reaction of bicyclic 1,4-endoperoxides that has potential for the synthesis of a variety of 1,2,4-trioxanes. We have chosen three readily available endoperoxides to demonstrate the power of the method.

The first example is the peroxide **2** obtained by the rose bengal sensitized photooxygenation of 1,4-dimethoxynaphthalene (**1**) in THF at −78 °C.[7] To the resulting solution of **2** an excess of acetaldehyde together with amberlyst-15 resin as catalyst was added. After the mixture was stirred at −78 °C overnight, workup afforded three products. The first two **1** (24%) and **3** (37%) are a consequence of the inherent thermal and chemical instability of the peroxide **2**.[8] However, the third product **4** is the cis-fused 1,2,4-trioxane (13%) consisting of a pair of epimers. What has happened, we believe, is that protonation of **2** has generated the hydroperoxide **5** as the crucial first step. Normally, its hydrolysis is easy, giving 1,4-naphthoquinone (**3**). However, **5** has the chance to nucleophilically attack the acetaldehyde molecule, which in turn cyclizes to the 1,2,4-trioxane ring, which is cis-fused for reasons of geometry control. The resulting product **6** is hydrolyzed in situ to **4**, which consists of a pair of epimers.[9]





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(1) Gollnick, K.; Schenck, G. O. In "1,4-Cycloadditions"; Hamer, J., Ed.; "Oxygen as Dienophile"; Academic Press: New York, 1967; Chapter 10, pp 255–344. Denny, R. W.; Nickon, A. *Org. React.* (*N.Y.*) **1973**, *20*, 133–336. Saito, I.; Matsuura, T. In "Singlet Oxygen"; Wasserman, H. H.; Murray, R. W., Eds.; "The Oxidation of Electron-Rich Aromatic Compounds"; Academic Press: New York, 1979, Chapter 10, pp 511–574.

(2) Moureu, C.; Dufraisse, C.; Dean, P. M. *C. R. Seances Acad. Sci.* **1926**, *182*, 1440, 1584.

(3) Adam, W.; Klug, G. *Tetrahedron Lett.* **1982**, *23*, 3155. Klärner, F.-G.; Schmidt, E. K. G.; Rahman, M. A. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 138. Baeckström, P.; Okecha, S.; de Silva, N.; Wijekoon, D.; Norin, T. *Acta Chem. Scand., Ser. B* **1982**, *B36*, 31. Adam, W.; Rodriguez, A. *Tetrahedron Lett.* **1981**, *22*, 3509. Adam, W.; Cueto, O.; De Lucchi, O.; Peters, K.; Peters, E.-M.; von Schnering, H. G. *J. Am. Chem. Soc.* **1981**, *103*, 5822.

(4) Graziano, M. L.; Iesce, M. R.; Carli, B.; Scarpati, R. *Synthesis* **1983**, 125. Sakuragi, H.; Furusawa, G.; Ueno, K.; Tokumaru, K. *Chem. Lett.* **1982**, 1213. Rigaudy, J.; Scribe, P.; Brelière, C. *Tetrahedron* **1981**, *37*, 2585.

(5) Feringa, B. L.; Butselaar, R. J. *Tetrahedron Lett.* **1983**, *24*, 1193. Balci, M.; Sütbeyaz, Y. *Ibid.* **1983**, *24*, 311. Graziano, M. L.; Iesce, M. R.; Carli, B.; Scarpati, R. *Synthesis* **1982**, 736. Castedo, L.; Estévez, R. J.; Saa, J. M.; Suau, R. *J. Heterocycl. Chem.* **1982**, *19*, 1469. Feringa, B. L.; Butselaar, R. J. *Tetrahedron Lett.* **1982**, *23*, 1941. Knoechel, T.; Pickl, W.; Daub, J. *J. Chem. Soc., Chem. Commun.* **1982**, 337. Kumagai, T.; Tokida, A.; Kidoura, K.; Seshimoto, O.; Mukai, T. *Tetrahedron Lett.* **1982**, *23*, 873. Saito, I.; Nagata, R.; Kotsuki, H.; Matsuura, T. *Ibid.* **1982**, *23*, 1717. Rang, H.-S.; Foote, C. S. *Ibid.* **1982**, *23*, 2551. Zagorski, M. G.; Salomon, R. G. *J. Am. Chem. Soc.* **1982**, *104*, 3498. Murai, A.; Ono, M.; Abiko, A.; Masamune, T. *Bull. Chem. Soc. Jpn.* **1982**, *55*, 1195. Beauhaire, J.; Fourrey, J.-L. *J. Chem. Soc., Perkin Trans. 1* **1982**, 861. Hagenbuch, J.-P.; Birbaum, J.-L.; Métral, J.-L.; Vogel, P. *Helv. Chim. Acta* **1982**, *65*, 887. Matsumoto, M.; Kuroda, K.; Suzuki, Y. *Tetrahedron Lett.* **1981**, *22*, 3253. Suzuki, M.; Oda, Y.; Noyori, R. *Ibid.* **1981**, *22*, 4413. For an account of the rearrangement of 1,4-endoperoxides to 1,2-dioxetanes and epoxides, see: Schaap, A. P.; Zaklika, K. A. In "Singlet Oxygen"; Wasserman, H. H., Murray, R. W., Eds.; Academic Press: New York, 1979; Chapter 7, pp 243–286. Saito, I.; Matsuura, T. In "Singlet Oxygen"; H. H., Wassermann, R. W., Murray, Eds.; Academic Press: New York, 1979; Chapter 10 pp 511–574.

(6) Balci, M. *Chem. Rev.* **1981**, *81*, 91.

(7) Rigaudy, J.; Deletang, C.; Basselier, J.-J. *C. R. Seances Acad. Sci., Ser. C* **1969**, *C268*, 344.

(8) Peroxide **2** readily undergoes retro Diels–Alder reaction to give **1**. Moreover, **2** is also prone to acid hydrolysis to the quinone **3** (cf.: Rigaudy, J.; Sparfeld, D. *Bull. Soc. Chim. Fr.* **1972**, 3441–3446).

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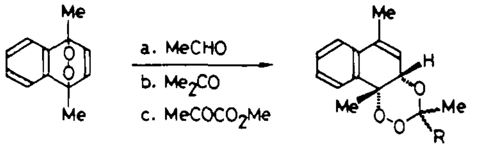
To test this mechanism, we subjected the more stable 1,4-endoperoxide[10] of 1,4-dimethylnaphthalene (**7**) to the same reaction with acetaldehyde, but at room temperature. The same result was obtained with a variety of catalysts such as amberlyst-15, trifluoroacetic acid, and even aqueous sulfuric acid, namely, the formation of the epimeric mixture of cis-fused 1,2,4-trioxanes **8** in quantitative yield.[9]

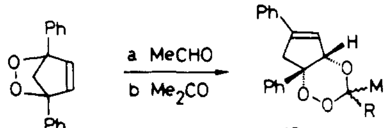
Ketones proved less reactive with **7**. Acetone gave a 30% yield after purification of the trioxane **9**, while methyl pyruvate gave a 31% yield of the two epimers **10**.[9]



7

8 R = H
9 R = Me
10 R = CO$_2$Me

Lastly, we tried the endoperoxide[11] of 1,4-diphenylcyclopentadiene (**11**) in dichloromethane as solvent using amberlyst-15 resin as catalyst at room temperature. It gave with acetaldehyde 89% of the epimeric product **12**; acetone furnished a 41% yield of **13**.[9]



11

12 R = H
13 R = Me

The extension of the mechanistic principle, the capture of a stable β-hydroperoxy cation by an active carbonyl compound to give 1,2,4-trioxanes, is being studied. We will show elsewhere that the structurally similar zwitterionic peroxides formed by reaction of singlet oxygen with appropriate enol ethers can also undergo the same cyclization.[12] Development of such synthetic approaches to trioxanes is feasible and desirable, especially in view of the paucity and limited scope of methods currently available[13] and because of the potent anti-malarial activity reported for the naturally occurring trioxane Qinghaosu.[14]

Acknowledgment. We thank the Swiss National Science Foundation for the support of this work (Grant 2.201-0.81).

Registry No. 2, 87051-06-7; **3**, 130-15-4; **4**, 87051-07-8; **7**, 35461-84-8; **8**, 87051-08-9; **9**, 87051-09-0; **10**, 87051-10-3; **11**, 62121-84-0; **12**, 87051-11-4; **13**, 87051-12-5; MeCHO, 75-07-0; Me$_2$CO, 67-64-1; MeCOCO$_2$Me, 600-22-6; 2-methoxynorborn-2-ene, 17190-90-8; 2-methoxymethylideneadamantane, 72590-63-7; 2-methoxynorborn-2-ene(methyl-1,2,4-trioxane adduct), 87051-04-5; 2-methoxymethylideneadamantane(methyl-1,2,4-trioxane adduct), 87051-05-6.

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(9) Compounds **4**, **8**, **9**, **10**, **12**, and **13** all gave satisfactory elemental analyses. The structures of **10** and **13** were elucidated by single-crystal X-ray analyses (Kennard, O., Bellard, S.; Allen, F. H. University Chemical Laboratory, Cambridge, England). The structures of **4**, **8**, **9**, and **12** were ascertained by comparison of their NMR spectra with those of **10** and **13**. Moreover, the pairs of epimers of **4**, **8**, and **12** (separated by HPLC by Dr. H. Grant) were identified by NMR spectroscopy and NOE difference experiments (Prof. U. Burger and co-workers).

(10) Wasserman, H. H.; Larsen, D. L. *J. Chem. Soc., Chem. Commun.* **1972**, 253.

(11) Schenck, G. O.; Müller, W.; Pfennig, H. *Naturwissenschaften* **1954**, *41*, 374. Coughlin, D. J.; Brown, R. S.; Salomon, R. G. *J. Am. Chem. Soc.* **1977**, *99*, 655.

(12) For example, the exo-zwitterionic peroxide derived from 2-methoxynorbornene (Jefford, C. W.; Rimbault, C. G. *J. Am. Chem. Soc.* **1978**, *100*, 6437–6445) incorporated acetaldehyde in the expected electronic sense to give the cis-fused 1,2,4-trioxanes (Jefford, C. W.; Kohmoto, S.; Boukouvalas, J.; Burger, U. *Ibid.*, submitted for publication.

(13) Payne, G. B.; Smith, C. W. *J. Org. Chem.* **1957**, *22*, 1682. Adam, W.; Rios, A. *J. Chem. Soc. Chem. Commun.* **1971**, 822. Etoh, H.; Ina, K.; Iguchi, M. *Agric. Biol. Chem.* **1973**, *37*, 2241. Wilson, R. M.; Gardner, E. J.; Elder, R. G.; Squire, R. H.; Florian, L. R. *J. Am. Chem. Soc.* **1974**, *96*, 2955. Subramanyam, V.; Brizuela, C. L.; Soloway, A. H. *J. Chem. Soc., Chem. Commun.* **1976**, 508. Maruyama, K.; Muraoka, M.; Naruta, Y. *Ibid.* 1980, 1282. Yamamoto, H.; Akutagawa, M.; Aoyama, H.; Omote, Y. *J. Chem. Soc., Perkin Trans. 2* **1980**, 2300. Miura, M.; Nojima, M.; Kusabayashi, *J. Chem. Soc., Chem. Commun.* **1981**, 581. Wilson, R. M.; Wunderly, S. W.; Walsh, T. F.; Musser, A. K.; Outcalt, R.; Geiser, F.; Gee, S. K.; Brabender, W.; Yerino, L., Jr.; Conrad, T. T.; Tharp, G. A. *J. Am. Chem. Soc.* **1982**, *104*, 4429.

(14) Schmid, G.; Hofheinz, W. *J. Am. Chem. Soc.* **1983**, *105*, 624.

Reaction of Singlet Oxygen with Enol Ethers in the Presence of Acetaldehyde. Formation of 1,2,4-Trioxanes

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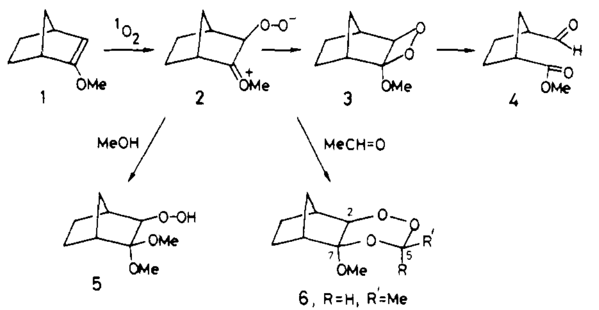
Electron-rich olefins, such as enol ethers, which are denied the opportunity of forming hydroperoxides, invariably react with singlet oxygen to give 1,2-dioxetanes.[1] As an alternative to concerted [2 + 2] addition,[2] two-step mechanisms involving diradicals,[3] zwitterions,[4] charge-transfer complexes,[5] and radical ion pairs[6] have been proposed to account for the course of the reaction. However, from our studies with norbornenyl ethers, unambiguous evidence for transient zwitterionic peroxides has been secured.[7] An illustration is the behavior of 2-norbornenol methyl ether (**1**), which in aprotic solvents undergoes dye-sensitized photooxidation to give the *exo*-dioxetane **3** or its cleavage product **4**. In contrast, when methanol is used as solvent, the hydroperoxy dimethyl ketal **5** is isolated in high yield. The formation of **5** is



1 **2** **3** **4**

5

6, R = H, R' = Me
7, R = Me, R' = H

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(1) Frimer, A. A. *Chem. Rev.* **1979**, *79*, 359. Schaap, A. P.; Zaklika, K. A. In "singlet Oxygen"; Wasserman, H. H., Murray, R. W., Eds.; Academic Press: New York, 1979; p 173. Bartlett, P. D.; Schaap, A. P. *J. Am. Chem. Soc.* **1970**, *92*, 3223. Mazur, S.; Foote, C. S. *Ibid.* **1970**, *92*, 3225. Schaap, A. P. *Tetrahedron Lett.* **1971**, 1757. Rio, G.; Berthelot, J. *Bull. Soc. Chim. Fr.* **1971**, 3555. Basselier, J. J.; Cherton, J.-C.; Caille, J. *C. R. Seances Acad. Sci. Ser. C* **1971**, *273*, 514. Basselier, J. J.; Le Roux, J. P. *Bull. Soc. Chim. Fr.* **1971**, 4443. Zaklika, K. A.; Thayer, A. L.; Schaap, A. P. *J. Am. Chem. Soc.* **1978**, *100*, 4196. Adam, W.; Cheng, C.-C.; Cueto, O.; Zinner, K. *Ibid.* **1979**, *101*, 4735. Adam, W.; Cueto, O.; Schmidt, E.; Takayama, K. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 1031. Adam, W.; Encarnación, L. A. A. *Chem. Ber.* **1982**, *115*, 2592.

(2) Bartlett, P. D.; Schaap, A. P. *J. Am. Chem. Soc.* **1970**, *92*, 3223. Zaklika, K. A.; Kaskar, B.; Schaap, A. P. *Ibid.* **1980**, *102*, 386. Yamaguchi, K.; Yabushita, S.; Fueno, T.; Houk, K. N. *Ibid. Chem. Soc.* **1981**, *103*, 5043.

(3) Harding, L. B.; Goddard, W. A., III. *Tetrahedron Lett.* **1978**, 747; *J. Am. Chem. Soc.* **1980**, *102*, 439.

(4) Kearns, D. R. *J. Am. Chem. Soc.* **1969**, *91*, 6554. Inagaki, S.; Fukui, K. *Ibid.* **1975**, *97*, 7480. Dewar, M. J. S.; Thiel, W. *Ibid.* **1975**, *97*, 3978, **1977**, *99*, 2338. Asveld, E. W. H.; Kellogg, R. M. *Ibid.* **1980**, *102*, 3644.

(5) Gorman, A. A.; Gould, I. R.; Hamblett, I. *J. Am. Chem. Soc.* **1982**, *104*, 7098.

(6) Foote, C. S.; Dzakpasu, A. A.; Lin, J. W. P. *Tetrahedron Lett.* **1978**, 1247.

(7) Jefford, C. W.; Rimbault, C. G. *Tetrahedron Lett.* **1977**, 2375; *J. Am. Chem. Soc.* **1978**, *100*, 295, 6437, 6515. Jefford, C. W.; Kohmoto, S. *Helv. Chim. Acta* **1982**, *65*, 133.

0002-7863/83/1505-6498$01.50/0