nucleoside left on the support, another round of synthesis begins.[26]

The DNA is deprotected by using thiophenoxide[9] (1:2:2 thiophenol/triethylamine/THF, room temperature, 1 h), cleaved from the support (NH_4OH, room temperature, 1 h) and further deprotected by heating the supernatant at 50 °C overnight. Following evaporation of the supernatant, purification is accomplished by Sephadex G-50 chromatography followed by polyacrylamide gel electrophoresis.

The effectiveness of these developments in DNA synthesis is demonstrated by the synthesis of two complementary DNA 51-mers (A and B). Sequence A was synthesized in 10.5 h while

A GATCCTTCCCAGCCATGTCCTTGTCC-
B GAAGGGTCGGTACAGGAACAGG-
A GGCCTGTTTGCCAACGCTGTGCTCG
B CCGGACAAACGGTTGCGACACGAGCCTAG

strand B was prepared concurrently with four shorter sequences. Purified strands A and B were annealed and cloned in bacteriophage M13, and their sequences were verified by the Sanger dideoxy sequencing technique.[28]

In summary, we have extended the capabilities of DNA synthesis on solid supports by implementing hindered nucleoside phosphoramidites of significantly improved stability that react very rapidly on a new solid support that exhibits superior chemical and physical properties. These refinements have allowed the synthesis of two 51-mers, the longest DNA fragments synthesized chemically to date.

Supplementary Material Available: Analytical polyacrylamide gel data and M13 sequence information for A and B (2 pages). Ordering information is given on any current masthead page.

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(26) The cycle requires only 8–10 min, and four to six reaction vessels can easily be manipulated simultaneously with a 20-min cycle time.

(27) Determined by a sensitive radiolabel assay of material purified by polyacrylamide gel electrophoresis. Crude yields as determined by trityl release in the final deprotection were ~10%.

(28) Sanger, F.; Nicklen, S.; Coulson, A. R. *Proc. Natl. Acad. Sci. U.S.A.* **1977**, *74*, 5463–5467.

Formation of an Ozonide by Electron-Transfer Photooxygenation of Tetraphenyloxirane. Cosensitization by 9,10-Dicyanoanthracene and Biphenyl[1]

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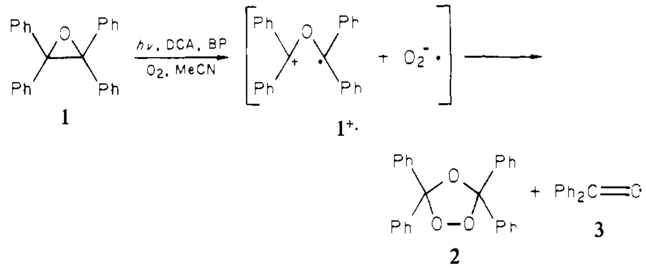
Olefins, acetylenes, and sulfides undergo electron-transfer photooxygenation with electron-deficient sensitizers in oxygen-saturated polar solvents.[2] Two general mechanisms have been identified: (1) addition of superoxide to the radical cation of the substrate to yield the product and (2) reaction of the radical cation with ground-state oxygen and subsequent reduction of the peroxy radical cation. ESR[2k] and laser flash[2i] spectroscopy have been used to identify reaction intermediates.

We have recently been interested in electron-transfer photooxygenation of substrates that exhibit low reactivity toward singlet oxygen. We now report that an epoxide can be converted in high yield to the corresponding ozonide by photooxygenation.[1] Also described is the first example of catalysis or cosensitization in an electron-transfer photooxygenation using a non-light-absorbing chemically unreactive aromatic hydrocarbon in conjunction with an electron-deficient photosensitizer.

Photooxygenation of tetraphenyloxirane (**1**) was carried out in dry acetonitrile with 8×10^{-3} M **1** and 9×10^{-4} M 9,10-dicyanoanthracene (DCA). The solution was irradiated at 10 °C under oxygen with a 450-W medium-pressure mercury lamp using a $CuSO_4$-filter solution.[3] The reaction was monitored by HPLC and judged complete in 40 h.[4] Removal of the solvent and recrystallization of the residue from methanol at −25 °C gave 51% of pure ozonide **2**.[5] Concentration of the mother liquor and chromatography over silica gel gave an additional 13% of **2** and 25% of benzophenone (**3**).[7]



The slow rate of the reaction is not surprising as **1** does not measurably quench the fluorescence of DCA in acetonitrile.[8] However, *a dramatic enhancement of the rate of photooxygenation of **1** is observed in the presence of biphenyl (BP)*. Addition of 8×10^{-4} M BP to the above reaction solution resulted in oxidation of **1** in 2 h with formation of 93% of **2** and 3% **3**.[9] In the presence of 8×10^{-3} M BP, the reaction was complete in only 10 min with similar yields of **2** and **3**. Analysis by HPLC indicated that BP was not appreciably consumed during the reaction. Control experiments have shown that no oxidation occurs in the absence of DCA and that **2** is not significantly decomposed to **3** under the reaction conditions. Further, epoxide **1** was not oxidized upon irradiation for 38 h with a 400-W high-pressure sodium lamp in an oxygenated acetonitrile solution containing rose bengal, indicating that $^1O_2$ is not involved in the reaction.

Griffin[10] and Arnold[11] have shown that electron-transfer reactions of aryl-substituted epoxides lead to C–C bond cleavage and formation of radical cations. A plausible mechanism for the formation of ozonide **2**, therefore, involves the addition of superoxide to radical cation $1^{+\cdot}$ with formation of an intermediate biradical or zwitterion.[12] This intermediate could close to yield

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(1) Presented at the IX IUPAC Symposium on Photochemistry, Pau, France, July 1982, Abstr. ST 15.

(2) (a) Barton, D. H. R.; Leclerc, G.; Magnus, P. D.; Menzies, I. D. *J. Chem. Soc., Chem. Commun.* **1972**, 447. (b) Eriksen, J.; Foote, C. S.; Parker, T. L. *J. Am. Chem. Soc.* **1977**, *99*, 6455. (c) Haynes, R. K. *Aust. J. Chem.* **1978**, *31*, 121. (d) Brown-Wensley, K. A.; Mattes, S. L.; Farid, S. *J. Am. Chem. Soc.* **1978**, *100*, 4162. (e) Saito, I.; Tamoto, K.; Matsuura, T. *Tetrahedron Lett.* **1979**, 2889. (f) Berenjian, N.; deMayo, P.; Phoenix, F. H.; Weedon, A. C. *Ibid.* **1979**, 4179. (g) Ando, W.; Nagashima, T.; Saito, K.; Kohmoto, S. *J. Chem. Soc., Chem. Commun.* **1979**, 154. (h) Mattes, S. L.; Farid, S. *Ibid.* **1980**, 126. (i) Eriksen, J.; Foote, C. S. *J. Am. Chem. Soc.* **1980**, *102*, 6083. (j) Spada, L. T.; Foote, C. S. *Ibid.* **1980**, *102*, 391. (k) Schaap, A. P.; Zaklika, K. A.; Kaskar, B.; Fung, L. W.-M. *Ibid.* **1980**, *102*, 389. (l) Mattes, S. L.; Farid, S. *Ibid.* **1982**, *104*, 1454.

(3) The 1-cm path length filter solution was prepared from 27 g of $CuSO_4 \cdot 5H_2O$, 30 g of $NaNO_2$, and 50 mL of concentrated NH_4OH diluted with water to 1000 mL.

(4) Irradiation times required for the photooxygenation of **1** in the absence of cosensitizer BP are quite variable (40–60 h).

(5) The mp (168–169 °C) and spectral properties of the isolated ozonide are identical with those of an authentic sample of **2** that was prepared by the method of Criegee and Korber.[6]

(6) Criegee, R.; Korber, H. *Chem. Ber.* **1971**, *104*, 1812.

(7) As 2 mol of **3** can result from **1**, yields of **3** are expressed as (mol of 3/(2 × mol of **1**)) × 100.

(8) Foote has calculated that electron-transfer fluorescence quenching of DCA should be possible for substrates with oxidation potentials less than ~2 V vs. SCE.[2b] The lack of significant quenching by **1** and oxidation potentials of related compounds (*trans*-2,3-diphenyloxirane,[11] E^{ox} = 1.89 vs. Ag/$AgNO_3$ in acetonitrile; ~2.2 V vs. SCE) indicate that E^{ox} for **1** is >2 V.

(9) Yields were determined by HPLC using a C-18 reverse-phase column and elution with a gradient of 30–100% acetonitrile in water.

(10) Wong, J. P. K.; Fahmi, A. A.; Griffin, G. W.; Bhacca, N. S. *Tetrahedron* **1981**, *37*, 3345.

(11) Albini, A.; Arnold, D. R. *Can. J. Chem.* **1978**, *56*, 2985. See also: Mayeda, E. A.; Miller, L. L.; Wolf, J. F. *J. Am. Chem. Soc.* **1972**, *94*, 6812.

(12) An alternative mechanism that cannot be ruled out at present involves the addition of $^3O_2$ to $1^{+\cdot}$ with subsequent reduction of the peroxy radical cation by $O_2^{-\cdot}$, $DCA^{-\cdot}$, **1**, or BP.

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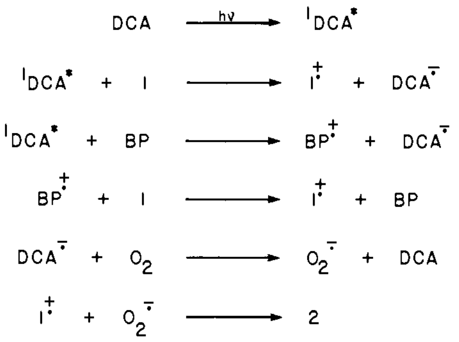
Scheme I



2 or cleave to form 3 and the carbonyl oxide. Experiments[11] with electrochemically generated $1^{+\cdot}$ have demonstrated that 3 may also result from C–O bond rupture in $1^{+\cdot}$.

The catalysis of the photooxygenation of 1 by BP presents a more interesting mechanistic question. We have previously reported that the rate of DCA-sensitized photooxygenation of 2,3-bis(*p*-methoxyphenyl)-1,4-dioxene (4, $E^{ox}_{1/2} = 0.73$ V vs. SCE, in MeCN) was increased in the presence of 2,3-bis(*p*-methylphenyl)-1,4-dioxene (5, $E^{ox}_{1/2} = 0.84$ V vs. SCE, in MeCN).[2k] It was proposed that the enhanced reactivity for 4 results from an exothermic electron exchange with $5^{+\cdot}$. Similar results have recently been described by Foote for the indirect photooxygenation of tetraphenylethylene in the presence of *trans*-stilbene.[13] Distinct from these two cases is the present example of cosensitization by BP and DCA. BP is more easily oxidized than epoxide 1 (E^{ox}_p of BP = 1.85 V vs. SCE, in MeCN[14] and consequently quenches ^{1}DCA* more efficiently ($k_q = 3.1 \times 10^9$ M^{-1} s^{-1}) to generate $BP^{+\cdot}$. However, subsequent electron transfer from 1 to $BP^{+\cdot}$ is highly *endothermic*. Nevertheless, this secondary electron transfer is the key step in the BP-catalyzed photooxygenation of 1 (Scheme I).[15] An important factor in the enhanced rate of formation of intermediate $1^{+\cdot}$ is certainly the much longer lifetime for $BP^{+\cdot}$ compared to ^{1}DCA*. Additional insight into the mechanism of this reaction is obtained by considering the analogous process in the homogeneous redox catalysis of electrochemical reactions.[18] For example, direct electroreductions of aliphatic halides (RX) generally occur at very slow rates and require large overvoltages. However, electrochemically generated radical anions of aromatic hydrocarbons can be employed as catalytic agents. Electron transfer from this species to RX forms the unstable $RX^{-\cdot}$ and regenerates the hydrocarbon. Although this reversible step is energetically unfavorable, it is driven by the subsequent irreversible cleavage of $RX^{-\cdot}$. Similarly, we suggest that the opening of epoxide 1 to give $1^{+\cdot}$ and trapping by $O_2^{-\cdot}$ to form ozonide 2 provides the driving force for the catalysis by BP of the DCA-sensitized photooxygenation of 1.

We have found that biphenyl can be used as a cosensitizer for the photooxygenation of various epoxides that are inefficiently oxidized by DCA alone. Other types of substrates can also be photooxidized under these conditions.[19] These results will be reported shortly.

Acknowledgment. Support from the U.S. Army Research Office is gratefully acknowledged. We thank Professor Dennis Evans, University of Wisconsin, for helpful discussions.

Registry No. Tetraphenyloxirane, 470-35-9; 9,10-dicyanoanthracene, 1217-45-4; biphenyl, 92-52-4.

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[13] Steichen, D. S.; Foote, C. S. *J. Am. Chem. Soc.* **1981**, *103*, 1855.

[14] Osa, T.; Yildiz, A.; Kuwana, T. *J. Am. Chem. Soc.* **1969**, *91*, 3994.

[15] Farid has suggested a similar mechanism for the cosensitization by phenanthrene and 9-cyanoanthracene of the electron-transfer dimerization of phenyl vinyl ether.[16] Alternatively, Pac has proposed the intermediacy of a π complex in the electron-transfer photochemical addition of methanol to 1,1-diphenylethylene cosensitized by *p*-dicyanobenzene and aromatic hydrocarbons.[17]

[16] (a) Farid, S.; Hartman, S. E.; Evan, T. R. In "The Exciplex"; Gordon, M., Ware, W. R., Eds.; Academic Press: New York, 1975; p 327. (b) Mattes, S. L.; Farid, S. *Acc. Chem. Res.* **1982**, *15*, 80.

[17] Majima, T.; Pac, C.; Nakasone, A.; Sakurai, H. *J. Am. Chem. Soc.* **1981**, *103*, 4499.

[18] For leading references, see: (a) Andrieux, C. P.; Blocman, C.; Dumas-Bouchiat, J. M.; M'Halla, F.; Savéant, J. M. *J. Electroanal. Chem.* **1980**, *113*, 19. (b) Savéant, J. M. *Acc. Chem. Res.* **1980**, *13*, 323. (c) Evans, D. H.; Naixian, X. *J. Electroanal. Chem.* **1982**, *133*, 367. (d) Sease, J. W.; Reed, R. C. *Tetrahedron Lett.* **1975**, 393. (e) Lund, H.; Simonet, J. *J. Electroanal. Chem.* **1975**, *65*, 205. (f) Boujlel, K.; Simonet, J. *Electrochim. Acta* **1979**, *24*, 481. (g) Britton, W. E.; Fry, A. J. *Anal. Chem.* **1975**, *47*, 95.

[19] Schaap, A. P.; Lopez, L.; Anderson, S. D.; Gagnon, S. D. *Tetrahedron Lett.* **1982**, *23*, 5493.

[20] **Note Added in Proof**: Subsequent to the submission of this paper, Ohta and co-workers reported the DCA-sensitized photooxygenation of electron-rich epoxides: Futamura, S.; Kusunose, S.; Ohta, H.; Kamiya, Y. *J. Chem. Soc., Chem. Commun.* **1982**, 1223. Tetraphenyloxirane was found to be unreactive under their conditions.

Symmetry of a Reactive Intermediate from Ring Expansion of Cyclobutylidenecarbene. Cyclopentyne

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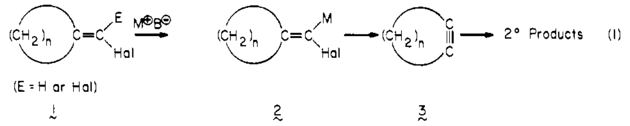
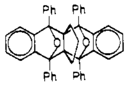
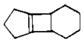
Halomethylenecycloalkanes 1 (*n* = 2–4, 6, 7, 9, 11) yield



ring-expanded products upon treatment with bases, and cycloalkynes, 3, have been proposed as sources of these substances (eq 1).[1,2] The cycloalkynes presumably arise from a carbenic species derived from the intermediate 2. Direct evidence for conversion of 1 to 3 exists since isolation of the cycloalkyne is sometimes possible, as with cyclononyne (3, *n* = 7).[1a] With systems having $n \leq 4$, intermediacy of the cycloalkynes is based exclusively on the observation of trapping products. Specifically, generation of (2 + 4) and (2 + 2) cycloadducts such as 4[1a] and 5,[1c] respectively, from the cyclobutyl precursor 1 (*n* = 3) is taken as being diagnostic for the intervention of cyclopentyne (3, *n* = 3).



4



5

Mechanisms exist that do not require the originally chemically differentiated vinylic carbon atoms of 1 to become equivalent *prior* to reaction with the trapping agent, as is demanded if the cycloalkyne is an intermediate. In fact, data for the cyclobutyl system 1 (*n* = 3, E = H, Hal = Br) indicate that the pathway for formation of 1-bromocyclopentene, the major isolated product arising from ring expansion, is *not* derived from cyclopentyne.[1a,4] Consequently, it is of paramount importance to establish that ring expansion of carbenic intermediates of the alkylidenecycloalkane variety involves species having the symmetry expected for a cy-

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[1] Erickson, K. L.; Wolinsky, J. *J. Am. Chem. Soc.* **1965**, *87*, 1142. (b) Erickson, K. L.; Vanderwaart, B. E.; Wolinsky, J. *Chem. Commun.* **1968**, 1031. (c) Fitjer, L.; Kliebisch, U.; Wehle, D.; Modoressi, S. *Tetrahedron Lett.* **1982**, *23*, 1661.

[2] Analogy for ring expansion of cyclobutylidenecarbenes is found in formation of cyclopentene as the major product of isomerization of cyclobutylcarbene(oid).[3]

[3] Paskovich, D. H.; Kwok, P. W. N. *Tetrahedron Lett.* **1967**, 2227.

[4] Erickson, K. L. *J. Org. Chem.* **1971**, *36*, 1031.

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