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Photooxidation of Methylnaphthalenes

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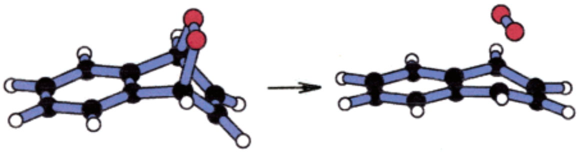

Studies on the photooxidation of methyl-substituted aromatic hydrocarbons have revealed that whereas electron density is a determinant of endoperoxide formation, steric factors are most important in influencing the stability of the endoperoxide. Additional information on the energetics of the reactions and on the magnitude of the steric interactions was obtained using calculations at the B3LYP/6-311+G* level of theory.

Introduction

Whereas endoperoxides derived from the photooxidation of anthracenes, naphthacenes, pentacenes and other polycyclic aromatic hydrocarbons have been studied for many years,[1] less attention has been paid to the formation of stable endoperoxides formed by the photooxidation of naphthalenes.[2] In this paper we will discuss further developments in our studies on the photooxidation of methylnaphthalenes and related compounds.

We have reported preliminary work on the dye-sensitized reaction of alkylnaphthalenes with singlet oxygen showing that the stability of the resulting endoperoxides is sensitive to the pattern of alkyl subsitution on the naphthalene nucleus.[3] The present paper provides a fuller account of these studies showing that in addition to consideration of the electronic density at specific positions, steric factors connected with the pattern of alkyl substitution also play an important role in the stability of the resulting endoperoxides. Calculations at the B3LYP/6-311+G* level provide additional information on the energetic effects of methyl substitution and on the magnitudes of the steric interactions.

Results and Discussion

As reported earlier, the endoperoxides **1**−**5** may be readily prepared by the photooxidation of the substituted naphthalene in methylene chloride using methylene blue as a sensitizer.[3] In these reactions, it is advisable, particularly in the case of the less stable endoperoxides, to maintain the solution below room temperature so as to decrease the rate of decomposition of the endoperoxide.[4]

The naphthalene endoperoxides were characterized by their spectroscopic properties. In the IR, the aromatic band at 1580−1600 cm^{-1} disappears on photooxidation and a strong band appears at 1200−1250 cm^{-1}, and in the UV spectrum, endoperoxide formation is indicated by the disappearance of the naphthalene band usually seen at 290 nm.

The NMR spectra are most useful for identification of the oxidized products. Examination of the chemical shifts of the methyl protons of the methylnaphthalenes allows the assignment of the peaks for each methyl group on the basis of a simple calculation.[5] In most cases, it is also possible to assign chemical shifts to the aromatic protons. By observing the changes in the NMR spectra following

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[1] (a) Aubry, J.-M.; Pierlot, C.; Rigaudy, J.; Schmidt, R. *Acc. Chem. Res.* **2003**, *36*, 668−675. (b) Gollnick, K. *Adv. Photochem.* **1968**, *6*, 1−122. (c) Gollnick, K.; Schenck, G. O. Oxygen as a Dienophile. In *1,4-Cycloadition Reactions*; Hamer, J., Ed.; Academic Press: New York, 1967; pp 255−344. (d) Baldwin, J. E.; Basson, H. H.; Krauss, H., Jr. *Chem. Commun.* **1968**, 984−985. (e) Rigaudy, J.; Dupont, R.; Cuong, N. K. *C. R. Acad. Sci.* **1969**, *269c*, 416−419. (f) Wilson, R. *Photochem. Photobiol.* **1969**, *10*, 441−449. (g) Rigaudy, J.; Guillaume, J.; Maurette, D. *Bull. Soc. Chim. Fr.* **1971**, 144−152. (h) Saito, I.; Matsuura, T. In *Singlet Oxygen*; Wasserman, H. H., Murray, R. W., Eds.; Academic Press: New York, 1979; Vol. 40, pp 511−569.

[2] (a) Rigaudy, J.; Deletang, C.; Basselier, J.-J. *C. R. Acad. Sci.* **1966**, *263c*, 1435−1438. (b) Rigaudy, J. *Pure Appl. Chem.* **1968**, *16*, 169−186. (c) Rigaudy, J.; Deletang, C.; Sparfel, D.; Cuong, N. K. *C. R. Acad. Sci.* **1968**, *267c*, 1714−1717. (d) Rigaudy, J.; Deletang, C.; Basselier, J.-J. *C. R. Acad. Sci.* **1969**, *268c*, 344−347.

[3] (a) Wasserman, H. H.; Larsen, D. L. *Chem. Commun.* **1972**, 253−254. (b) Larsen, D. L. Ph.D. Thesis, Yale University, New Haven, CT, 1973.

[4] Many of the naphthalene endoperoxides prepared in this work (Table 1) show little evidence of decomposition after several months storage at 0 °C.

[5] Yew, F. F.; Kurland, R. J.; Mair, B. J. *Anal. Chem.* **1964**, *36*, 843−845.

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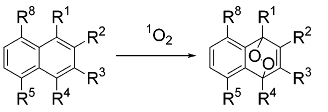
TABLE 1. Stability of Naphthalene Endoperoxides

peroxide	$t_{1/2}$ at 25 °C (h)[a]	$\Delta G^{\ddagger}$ (kcal/mol)
1,4-dimethylnaphthalene-1,4-endoperoxide **1**	5	23.6
1,8-dimethylnaphthalene-1,4-endoperoxide **2**	30	24.6
1,2,4-trimethylnaphthalene-1,4-endoperoxide **3**	70	25.0
1,4,5-trimethylnaphthalene-1,4-endoperoxide **4**	290	25.9
1,2,3,4-tetramethylnaphthalene-1,4-endoperoxide **5**	indefinite	>26

[a] Determined by ^{1}H NMR using a $CDCl_3$ solution initially 0.1 M in endoperoxide.

SCHEME 1. Preparation of Methyl Naphthyl Endoperoxides 1–5



$R^1 = R^4 = Me, R^2 = R^3 = R^5 = R^8 = H$, **1**
$R^1 = R^8 = Me, R^2 = R^3 = R^4 = R^5 = H$, **2**
$R^1 = R^2 = R^4 = Me, R^3 = R^5 = R^8 = H$, **3**
$R^1 = R^4 = R^5 = Me, R^2 = R^3 = R^8 = H$, **4**
$R^1 = R^2 = R^3 = R^4 = Me, R^5 = R^8 = H$, **5**

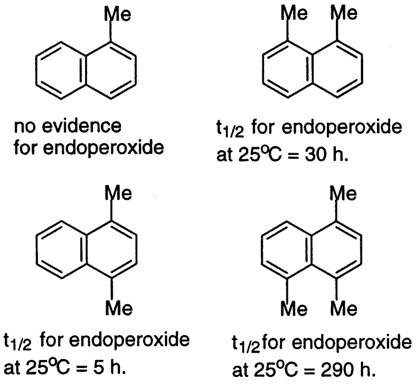
photooxidation it was possible to assign structures for the endoperoxides outlined in Scheme 1.

In this way, for example, the formation of a 1,4-endoperoxide from 1,8-dimethylnaphthalene is indicated by the change in chemical shift of the 1-methyl group from $\delta = 2.85$ to $\delta = 1.98$, by the change in chemical shift of the proton in the 4-position from the aromatic region to $\delta = 5.42$, and by the change in chemical shift of the protons in the 2- and 3-positions corresponding to the change from aromatic to olefinic character in the bond. The alkyl naphthalene endoperoxides react with hydriodic acid to liberate iodine and are inert to reduction by sodium borohydride.[6] Catalytic hydrogenation of the endoperoxide with palladium reduces the isolated double bond and forms a diol from the peroxide bridge.[7]

In related earlier work, the rates of reaction of substituted naphthalenes with singlet oxygen have been examined, and the results are in accord with the eletrophilic nature of this reactive species.[8] Thus, the rate of endoperoxide formation in the reaction of alkyl-substituted naphthalenes with singlet oxygen has been correlated with the electronic nature of the substrate.[9]

All of the endoperoxides formed from the alkyl naphthalenes in this group share the property of thermal instability, regenerating singlet oxygen and the parent naphthalene. The degree of instability varies widely, from octamethylnaphthalene-1,4-endoperoxide,[6] which requires heating for extended periods in refluxing di-*n*-butyl ether to bring about decomposition, to the very unstable endoperoxides, which can only be prepared and studied at very low temperatures.

Measurement of the rates of decompostion of the endoperoxides listed in Table 1 at room temperature reveals large differences. At this stage we need to address the increased stability of 1,8-dimethylnaphthalene-1,4-endoperoxide with respect to the 1,4-disubstituted analogue. An explanation for the observed result may be found in the large steric strain associated with the nonbonded *peri* interaction between the 1- and 8-methyl groups.[9,10] The bond rehybridization at C1 and C4 (sp^2 to sp^3) resulting from the formation of the endoperoxide should significantly reduce the *peri* methyl–methyl interaction in the endoperoxide compared to the parent naphthalene.[11] Examination of the stabilities of the following pairs of naphthalenes serves to illustrate the importance of the *peri* interaction in promoting stability.



no evidence for endoperoxide

$t_{1/2}$ for endoperoxide at 25°C = 30 h.

$t_{1/2}$ for endoperoxide at 25°C = 5 h.

$t_{1/2}$ for endoperoxide at 25°C = 290 h.

This *ortho* effect can become very important in a case such as 1,2,3,4-tetramethylnaphthalene where the cumulative effect of four *ortho* methyl groups produces even greater strain. The unusual stability of 1,2,3,4-tetramethylnaphthalene-1,4-endoperoxide **5** is due largely to the relief of these interactions upon formation of the endoperoxide.

The experimental results clearly indicate that steric effects play an important role in determining the stability of the endoperoxides. There are several energy terms of interest with regard to the photooxidation of the substituted naphthalenes and their decomposition. Since experimental data are not available, we have made use of B3LYP/6-311+G* calculations. They include geometry optimizations and calculations of vibrational frequencies in order to correct for differences in zero-point energies and to convert the calculated energy differences to ΔH and ΔG at 25 °C.[12]

An important question is concerned with the effect of methyl substitution on the energy of naphthalene. It is known that 1,8-dimethylnaphthalene has a higher energy

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(6) It is noteworthy that octamethylnaphthalene-1,4-endoperoxide is inert to both sodium borohydride and lithium aluminium hydride. See: Hart, H.; Oku, A. *Chem. Commun.* **1972**, 254–255.

(7) Hydrogenation of 1,4-dimethylnaphthyl-1,4-endoperoxide in the presence of a platinum catalyst gives 1,4-dihydroxy-1,4-dimethyl-1,2,3,4-tetrahydronaphthalene exclusively. See: Rigaudy, J.; Maurette, D.; Cuong, N. K. *C. R. Acad. Sci.* **1971**, *273c*, 1553–1556.

(8) *Singlet Oxygen*; Wasserman, H. H., Murray, R. W., Eds.; Academic Press: New York, 1979; Vol. 40.

(9) (a) van den Huevel, C. J. M.; Steinberg, H.; de Boer, Th. J. *Recl. Trav. Chim. Pays-Bas.* **1980**, *99*, 109–113. (b) van den Huevel, C. J. M.; Verhoeven, J. W.; de Boer, Th. J. *Recl. Trav. Chim. Pays-Bas.* **1980**, *99*, 280–284.

(10) The influence of *peri* interactions on the chemistry of naphthalenes has been reviewed. See: Balasubramaniyan, V. *Chem. Rev.* **1966**, *66*, 567–641.

(11) The C1–C8 distance in naphthalene is 2.44 Å, the C1–C8A bond length is 1.42 Å and the C1–C8A–C8 angle is slightly larger than 120°. See: Cruickshank, D. W. J. *Acta Crystallogr.* **1957**, *10*, 504–508.

(12) The total energies, zero-point energies, and changes in enthalpy and free energy are available as Supporting Information.

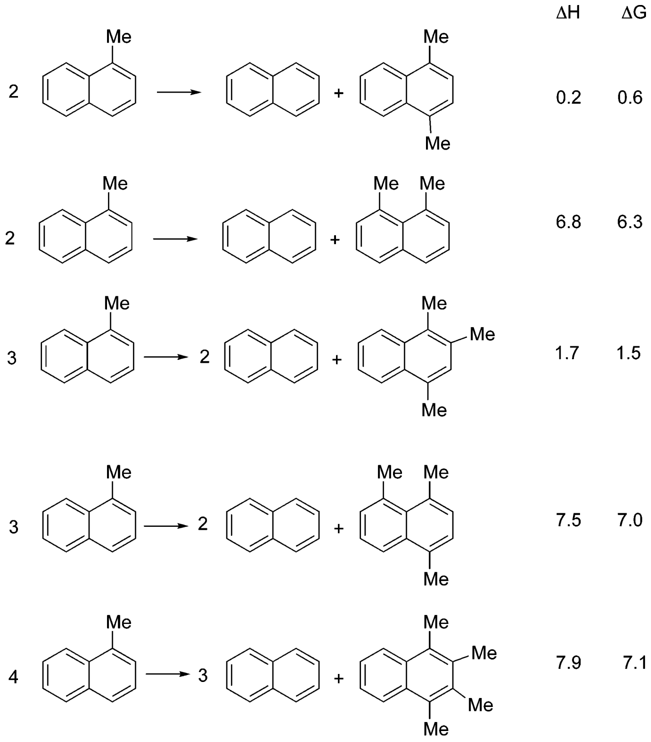

FIGURE 1. Calculated energies of methyl transfer reactions (kcal/mol).

than 1,4-dimethylnaphthalene as a result of methyl−methyl repulsion in the former compound.[13] The relative energies of the substituted naphthalenes are conveniently estimated using the isodesmic reaction shown in Figure 1. If there were no extra interactions, the conversion of two methylnaphthalenes to naphthalene plus 1,4-dimethylnaphthalene should lead to no significant energy change. It can be seen that this expectation is realized. On the other hand, a similar reaction leading to the formation of 1,8-dimethylnaphthalene is endothermic by 6 kcal/mol. This agrees with a previous estimate of the difference in energy.[14] Similarly, 1,2,4-trimethyl substitution leads to little increase in steric interactions, whereas 1,4,5-substitution leads to a large change in energy. The energy of 1,2,3,4-tetramethylnaphthalene is also quite large.

When a naphthalene is converted to the peroxide, there is a considerable change in geometry (Figure 2), and as a result the steric interaction of the methyl groups may be changed. How does methyl substitution affect the relative energies of the naphthalene peroxides? It is expected that significant differences would be found in accord with the observation that methyl-substituted naphthalenes are more reactive than the unsubstituted parent. This question can be explored using the oxygen transfer reaction from naphthalene peroxide to a substituted naphthalene as shown in Figure 3. A methyl group in the 1-position stabilizes the endoperoxide by 2 kcal/mol, and the effect of two methyl groups at the 1,4- or 1,8-positions is about twice as large. It is interesting that the two patterns give similar calculated energy changes with the 1,8-dimethyl compound giving a slightly larger effect than the 1,4-dimethyl derivative.[14] Three methyl groups arranged 1,2,4 or 1,4,5 give similar calculated energy changes, which are about three times as large as that for a single methyl group. Finally, 1,2,3,4-tetramethyl substitution gives the largest energy change, probably due to relief of steric interaction between adjacent methyl groups when the naphthalene ring is bent as a result of endoperoxide formation.

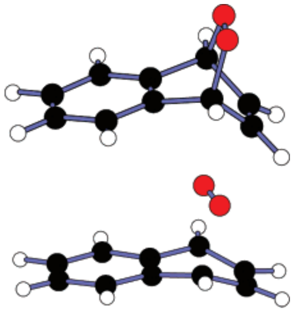

FIGURE 2. Calculated structures of naphthalene endoperoxides (upper) and of the transition state for decomposition to naphthalene and singlet oxygen (lower).

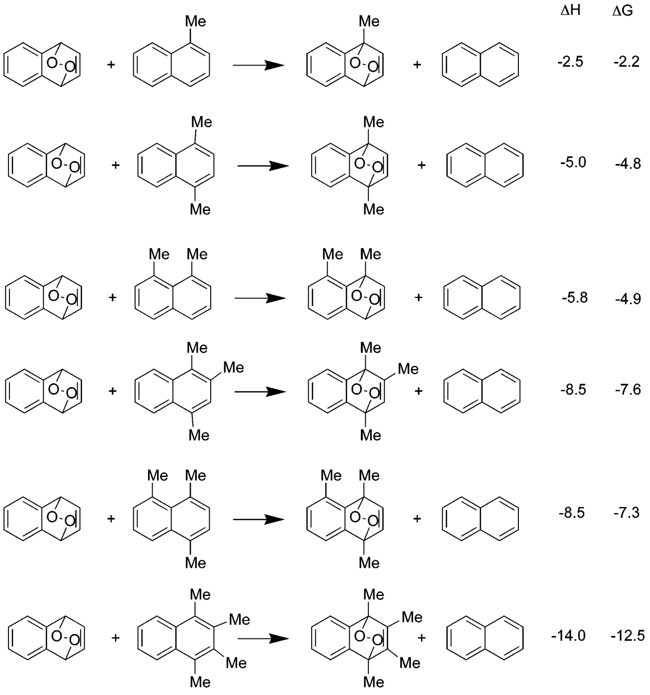

FIGURE 3. Calculated energies of singlet oxygen transfer reactions (kcal/mol).

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(13) In comparing 1,8- and 1,5-dimethylnaphthalene, the latter cannot be taken as strain-free as there are methyl-hydrogen *peri* interactions that, although probably small, cannot be neglected. The heats of formation of 1- and 2-methylnaphthalenes as reported by Rossini differ somewhat (Speros, D. M.; Rossini, F. D. *J. Phys. Chem.* **1960**, *64*, 1723−1727). On the basis of error limits for this determination, the strain energy for a 1-methyl to 8-hydrogen interaction lies between zero and 900 cal/mol. Thus, two such interactions as in the case of 1,5-dimethylnaphthalene could result in a total strain energy of 1.8 kcal/mol, which when combined with the probable differences between the 1,5- and 1,8-isomers implies that the strain associated with a *peri* methyl−methyl interaction may be as great as 7.3 kcal/mol. The results of Packer indicate that the strain in 1-methylnaphthalene, 1,2-dimethylnaphthalene, and 1,8-dimethylnaphthalene may be 1.6, 3.4, and 7.6 kcal/mol, respectively (Packer, J.; Vaughan, J.; Wong, E. *J. Am. Chem. Soc.* **1958**, *80*, 905−907). Although the arguments of Packer et al. are not conclusive, these values may be quite close to being correct.

(14) It should be noted that the Δ*H* values are somewhat more reliable than ΔG values because the latter is influenced by changes in methyl rotational barriers that were not explicitly calculated in this study.

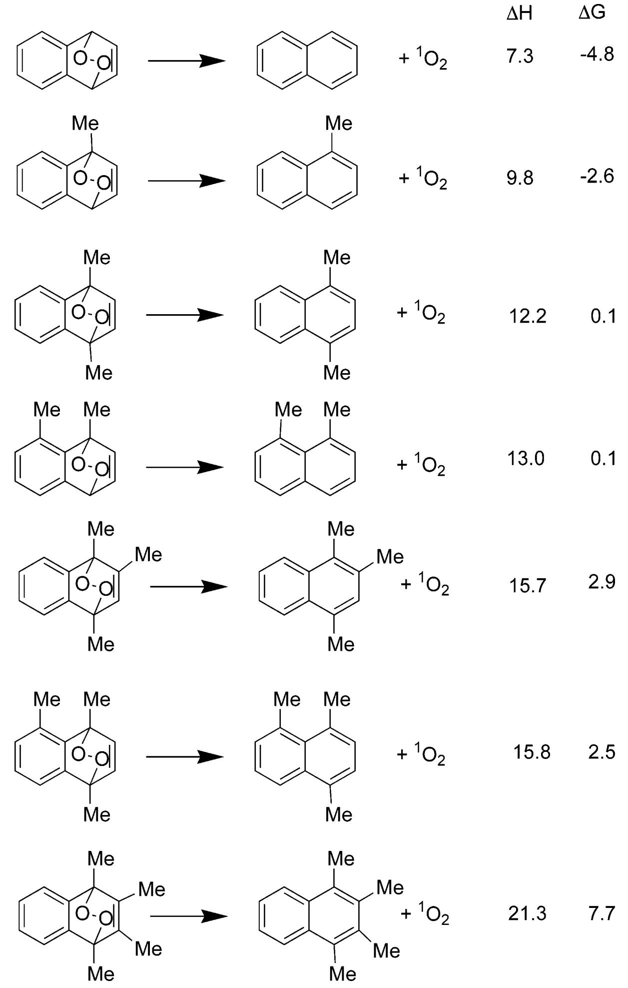

FIGURE 4. Calculated energy changes for the decomposition of naphthalene endoperoxides to naphthalene and singlet oxygen (kcal/mol).

The energy changes resulting from the decomposition of the endoperoxides yielding singlet oxygen and the substituted naphthalene also were estimated (Figure 4). Here, working with singlet oxygen presents a difficulty in that high levels of electron correlation are needed in order to calculate its energy accurately,[15] and it is impractical to use such a high level of theory for all of the compounds in this report. Therefore an appropriate energy for oxygen was estimated from the difference between the B3LYP/6-311+G* energy and the results of higher level calculations, giving an approximate value of −150.32792 H. The calculated free energy changes are the quantities of interest, and they differ from the largest energy change, probably as a result of relief of steric interaction between adjacent enthalpy changes because of the overall positive entropy change resulting from the decomposition of one molecule to form two molecules.

The results agree well with the experimental observations; naphthalene and 1-methylnaphthalene endoperoxides are predicted to be unstable with respect to the corresponding naphthalene and singlet oxygen and cannot be formed readily via photooxygenation. The dimethyl-substituted endoperoxides are predicted to be weakly stabilized, and as expected, were found to undergo moderately rapid decomposition. Trimethyl-substitution leads to further stabilization and reduced rates of decomposition, and tetramethyl-substitution with accompanying strong stabilization leads to a relatively stable endoperoxide.

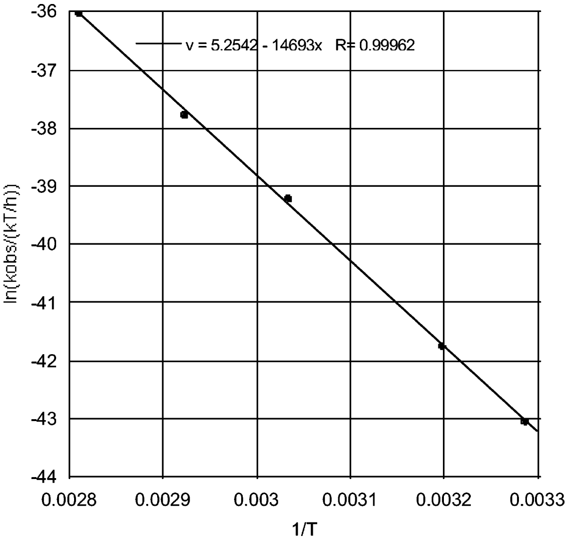

FIGURE 5. Eyring plot for the effect of temperature on the rate of endoperoxide decomposition.

The calculations, of course, give only the overall energy changes and do not necessarily correspond to the changes found with the transition states for the decomposition of the endoperoxides. As noted above, the rates of decomposition of the peroxides have been studied, and the half-lives and approximate free energies of activation are given in Table 1. The rate of decomposition of 1,4,5-trimethylnaphthalene endoperoxide **4** was studied as a function of temperature. This leads to $\Delta H^{\ddagger} = 29.2$ kcal/mol and $\Delta S^{\ddagger} = 10.4$ eu (Figure 5). The positive entropy change indicates that the bonds are considerably weakened on going to the transition state.

The transition state for the thermal decomposition of naphthalene peroxide was located at the B3LYP/6-311+G* level (Figure 2). The calculated activation parameters are $\Delta H^{\ddagger} = 19.7$ kcal/mol and $\Delta S^{\ddagger} = 3$ eu. Because singlet oxygen is formed in the reaction and this level of theory does not reproduce its energy very well, a better agreement between experiment and calculations is not expected.

Experimental Section

1,4-Dimethylnaphthalene-1,4-endperoxide (1). A sample of 1,4-dimethylnaphthalene (1.0 g, 6.5 mmol) in 50 mL of methylene chloride was photooxidized at 5 °C until the reaction was ca. 50% complete as estimated by oxygen uptake (approximately 15 min). Removal of solvent allowed isolation of the crude material, usually ca. 60−70% endoperoxide. Recrystallization from pentane at −70 °C yielded 1,4-dimethylnaphthalene-1,4-endoperoxide as white crystals: yield 0.688 g, 58%; ^1H NMR ($CDCl_3$) δ 7.45−7.35 (m, 4 H, arom); 6.72 (s, 2H) 1.88 (s, 6 H, CH_3). Anal. Calcd for $C_{12}H_{12}O_2$: C, 76.57; H, 6.43. Found: C, 76.38; H. 6.40.

1,8-Dimethylnaphthalene-1,4-endoperoxide (2). The photooxidation of 1,8-dimethylnaphthalene under conditions identical to those described for 1,4-dimethylnaphthalene led to the endoperoxide, which could be separated from starting

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(15) Shangguan, C.; McAllister, M. A. *J. Mol. Struct.* **1998**, *422*, 123−132.

material by preparative thin-layer chromatography (C_6H_6, silica gel). Photooxidation at −78 °C of 203 mg (1.3 mmol) of 1,8-dimethylnaphthalene in CH_2Cl_2 (20 mL) resulted in the isolation of pure 1,8-dimethylnaphthalene-1,4-endoperoxide after recrystallization at −78 °C from pentane: yield 0.202 g, 83%; ^{1}H NMR ($CDCl_3$) δ 7.20−7.01 (m, 3H, arom); 6.90 (dd, 1H, $J = 5.5, 8.0$, alkenyl); 6.59 (dd, 1H, $J = 1.8, 8.0$, alkenyl); 5.42 (dd, 1H, $J = 1.8, 5.5$, alkenyl); 2.48 (s, 3H, CH_3); 1.98 (s, 3H, CH_3). Anal. Calcd for $C_{12}H_{12}O_2$: C, 76.57; H, 6.43. Found: C, 76.47; H, 6.55.

1,2,4-Trimethylnaphthalene-1,4-endoperoxide (3). A sample of 1,2,4-trimethylnaphthalene (1.13 g, 6.65 mmol) in CH_2Cl_2 (60 mL) was photooxidized at 20 °C. After 15 min. the theoretical volume of oxygen was absorbed. On workup, a pale orange solid was isolated: yield 1.24 g, 93%; ^{1}H NMR ($CDCl_3$) δ 7.20 (bs, 4H, arom.); 6.25 (s, 1H, alkenyl); 1.86 (s, 3H, CH_3)1.80 (s, 6H, CH_3). Anal. Calcd for $C_{13}H_{14}O_2$: C, 77.20; H, 6.98. Found: C, 77.21; H, 6.92.

1,4,5-Trimethylnaphthalene-1,4-endoperoxide (4). A sample of 1,4,5-trimethylnaphthalene (1.2 g, 7.1 mmol) in CH_2Cl_2 (10 mL) was photooxidized at 15 °C. Oxygen uptake was rapid, and the theoretical volume was absorbed in a short time. After standard workup, the crude product was dissolved in ether and passed through a short silica gel column. After removal of solvent by evaporation, 1,4,5-trimethylnaphthalene-1,4-endoperoxide was isolated as a fluffy white crystalline solid: yield 0.678 g, 54%; ^{1}H NMR ($CDCl_3$) δ 7.00 (m, 3 H, arom.); 6.53 (s, 2 H, arom.); 6.53 (s, 2H); 2.48 (s, 3H, CH_3); 1.95 (s, 3H, CH_3); 1.80 (s, 3H, CH_3). Anal. Calcd for $C_{13}H_{14}O_2$: C, 77.20; H, 6.98. Found: C, 77.45; H, 6.81.

1,2,3,4-Tetramethylnaphthalene-1,4-endoperoxide (5). A sample of 1,2,3,4-tetramethylnaphthalene (564 mg, 3 mmol) in CH_2Cl_2 (70 mL) was photooxidized at 15 °C. Oxygen was absorbed rapidly until 3 mmol (70 mL) was consumed. After normal workup 1,2,3,4-tetramethylnaphthalene-1,4-endoperoxide was isolated as a white crystalline solid: yield 0.541 g, 83%; ^{1}H NMR ($CDCl_3$) δ 7.20 (s, 4H, arom.); 1.76 (s, 6H, CH_3); 1.74 (s, 6H, CH_3). Anal. Calcd for $C_{14}H_{16}O_2$: C, 77.75; H, 7.46. Found: C, 77.53; H, 7.47.

Calculations. The ab initio calculations were carried out using Gaussian 99.[16]

Acknowledgment. This study was supported by grants from the National Institutes of Health and the National Science Foundation. We thank Professor Nicholas Turro, Columbia University, for helpful discussions.

Supporting Information Available: General and photooxidation experimental details, experimental tables of total energies and other energy quantities for the substituted naphthalenes and their endoperoxides, and tables of calculated energies and geometries for the compounds in this report. This material is available free of charge via the Internet at http://pubs.acs.org.

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(16) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malik, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Baboul, A. G.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 99*, Development Version (Rev. B.04); Gaussian, Inc., Pittsburgh, PA, 1998.