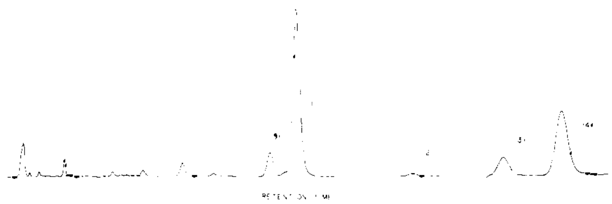


Figure 2. Gas chromatogram of *trans,trans*-2,4-hexadiene at 50-μ pressure after irradiation with 3000 pulses of the R(18) CO_2 laser transition. The unirradiated sample contained 99% *trans,trans*-2,4-hexadiene with <1% *cis,trans*-2,4-hexadiene as an impurity. (1) 1,3-hexadiene, (2) *trans,trans*-2,4-hexadiene, (3) *cis,trans*-2,4-hexadiene, (4) *cis,cis*-2,4-hexadiene, (5) cyclopentadiene.

Table I. Composition after Irradiation (Percent)[a]

parent species	1,3	*t,t*-2,4	*c,t*-2,4	*c,c*-2,4
1,3[b]	99.42	0.12	0.25	0.08
t,t-2,4[b]	0.86	97.21	1.24	0.15
c,t-2,4[b]	0.62	0.55	97.80	0.69
c,c-2,4[b]	0.00	0.00	0.00	98.69
c,c-2,4[c]	0.61	0.00	0.29	97.67

[a] Impurities present in the parent species have been subtracted out in reporting product compositions. They were 1,3-hexadiene (0.03% *t,t*-2,4, 0.06% *c,t*-2,4, 0.04% *c,c*-2,4), *trans,trans*-2,4-hexadiene (0.5% *c,t*-2,4, 0.04% *c,c*-2,4), *cis,trans*-2,4-hexadiene (0.35% *t,t*-2,4), *cis,cis*-2,4-hexadiene (0.66% 1,3, 0.03% *t,t*-2,4, 1.62% *c,t*-2,4). [b] After irradiation on the R(18) transition of the 10.6-μ laser branch. [c] After irradiation on the P(38) transition of the 10.6-μ laser branch.

isomeric hexadienes (100-μ pressure, uncorrected for irradiated volume) are given in Table I. The R(18) laser radiation is absorbed by all isomers with trans or terminal double bonds, but not by *cis,cis*-2,4-hexadiene. The absence of cis,cis isomerization upon R(18) irradiation is thus the consequence of insufficient excitation of this compound. However, *cis,cis*-2,4-hexadiene does isomerize when irradiated using the P(38) laser line. Several features of the single pulse results merit comment. Under reported conditions, excitation of cis,trans isomer produces more cis,cis isomer than the thermodynamically more stable trans,trans isomer.[7] Furthermore in all cases substantial amounts of products are formed which would be expected to require two successive isomerization processes.[8] Additionally product ratios can be made to vary as a function of fluence level and quencher pressure implying that the isomerization process occurring in this system is not a simple one. Rather it is a process which may involve multiple competitive steps. The alteration of isomeric branching ratios as a function of irradiation conditions is currently being studied via variation of power and fluence levels as well as the addition of selected quenchers. We also plan to initiate time-resolved double-resonance studies of isomeric product formation in the near future.

A gas chromatogram of the product mixture resulting from 3000-pulse R(18) irradiation of *trans,trans*-2,4-hexadiene (50 μ) is shown in Figure 2. Even though a true photostationary state is not attained, over 98% of the thermodynamically most stable hexadiene isomer has been converted into less strongly absorbing and/or less efficiently isomerizing species. This experiment again clearly indicates that *simple equilibrium thermal chemistry cannot be occurring*. Moreover the mass balance in this reaction is >85%, with the major dissociation product being cyclopentadiene. It is thus apparent that, under carefully controlled conditions, the extensive fragmentations observed in investigations of monoalkene isomerization can be avoided.[3] While product mixtures of the type shown in Figure 2 are not as of yet synthetically useful, they serve to illustrate the potential of nondestructive isomer selective laser chemistry. We are currently seeking to improve the selectivity of formation of a single hexadiene isomer (e.g., cis,cis) via simultaneous irradiation with two different laser frequencies.

Acknowledgment. We gratefully acknowledge partial support of this work by the National Science Foundation (E.W., CHE76-10333A02) and the Alfred P. Sloan Foundation (E.W. and F.D.L.). We thank Mr. Atsuo Kuki for his help in preliminary investigations of infrared photochemistry in the hexadienes.

References and Notes

(1) Ambartzumian, R. V.; Letokhov, V. S. In "Chemical and Biochemical Applications of Lasers", Moore, C. B., Ed.; Academic Press: New York, 1977; Vol. 3, Chapter 2.
(2) (a) Letokhov, V. S.; Moore, C. B. In ref 1, Vol. 3, Chapter 1. (b) Letokhov, V. S. *App. Rev. Phys. Chem.* **1977**, *28*, 133–160. (c) Cantrell, C. D.; Freund, S. M.; Lyman, J. L. In "Laser Handbook", Stich, M., Ed.; North-Holland: Amsterdam, 1978; Vol. 3. (d) Bloembergen, N.; Yablonovitch, E. *Physics Today* **1978**, May, 23–30. (e) Ambartzumian, R. V.; Letokhov, V. S. *Acc. Chem. Res.* **1977**, *10*, 61–67.
(3) (a) Glatt, I.; Yogev, A. *J. Am. Chem. Soc.* **1976**, *98*, 7087–7088. (b) Yogev, A.; Lowenstein-Benmair, R. M. J. *ibid.* **1973**, *95*, 8487–8489. (c) Ambartzumian, R. V.; Chekalin, N. V.; Dolzhikov, V. S.; Letokhov, V. S.; Lokhman, V. N. *Opt. Commun.* **1976**, *18*, 400–402. (d) Ambartzumian, R. V.; Chekalin, N. V.; Dolzhikov, V. S.; Letokhov, V. S.; Lokhman, V. N. *J. Photochem.* **1976**, *6*, 55–67.
(4) Mukamel, S.; Jortner, J. *J. Chem. Phys.* **1976**, *65*, 5204–5225.
(5) (a) Burak, I.; Quelly, T. J.; Steinfeld, J. I. *J. Chem. Phys.*, **1979**, *70*, 334–343. (b) Rice, S. A. "Internal Energy Transfer in Isolated Molecules, Ergodic and Nonergodic Behavior", to be published.
(6) Cotthup, N. B.; Daly, L. H.; Wiberley, S. E. "Introduction to Infrared and Raman Spectroscopy", Academic: New York, 1975.
(7) Doering, V. C. E.; Hauthal, H. G. *J. Prakt. Chem.* **1964**, *24*, 27–37.
(8) Frey, H. M.; Pope, B. M. *J. Chem. Soc. A* **1966**, *12*, 1701–1702.

James L. Buechele, Eric Weitz,* Frederick D. Lewis
Department of Chemistry, Northwestern University
Evanston, Illinois 60201

Received February 20, 1979

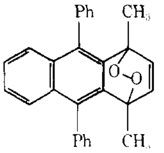
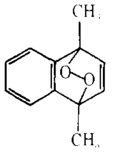
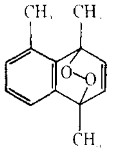
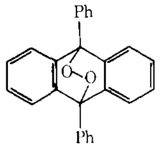
Magnetic Field Effects on the Thermolysis of Endoperoxides of Aromatic Compounds. Correlations with Singlet Oxygen Yield and Activation Entropies

Sir:

An interesting consequence of radical reactions involving singlet–triplet interconversions is the possibility of observing a variation in product distribution and/or reaction rate with the application of a steady external magnetic field, H.[1] In the absence of significant hyperfine interactions, the external field may accelerate singlet–triplet evolution in a singlet radical pair. The rate of singlet–triplet conversion is expected to increase proportionally to ΔgH (or to some power of H).[2] However, an appreciable effect of an external field is expected only if the pertinent radicals possess markedly different g factors or if extremely high external fields are involved. As an order of magnitude approximation,[3] if $\Delta g \simeq 10^{-2}$ and $H \simeq 10\,000$ G, the rate of magnetic field induced singlet–triplet conversion will approach values of $\sim 10^8$ s^{-1}. Diradical intermediates possess decay rates of this order,[4] so that a magnetic field effect on diradical reactions should be demonstrable in favorable cases. Since the products of a chemical reaction involving diradicals may depend on the presence or absence of magnetic nuclei that can interact with the diradical centers, a magnetic isotope effect[5] is also possible. We report here an investigation and demonstration of magnetic field effects on the thermolysis of endoperoxides of aromatic hydrocarbons. We show correlations of our observations with other experimental information, and we find that our results are in good qualitative agreement with theoretical predictions.

The endoperoxides studied were **1**, **2**, **3**, and **4** (Table I). In an earlier study of **1-4**, it was found that[6] (a) each undergoes

Table I. Correlation of Activation Entropies, Singlet Oxygen Yield, and Magnetic Field Effect in Endoperoxide Thermolyses[a,b]

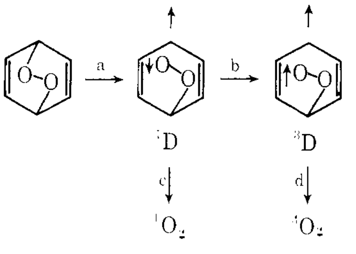
		$^1O_2$, %						
endoperoxide	$\Delta S^{\ddagger}$, eu	0.5 G[c]	4500 G	9500 G	11 500 G	13 500 G	15 500 G	17 000 G
 **1**	−2	92 ± 1		93 ± 2		91 ± 4		
 **2**	+2	76 ± 1	76.5 ± 0.5	73 ± 1			71.3 ± 0.5	70.5 ± 0.5
 **3**	+3	69 ± 1				66.0 ± 0.6		
 **4**	+10	32 ± 1		30 ± 3	27 ± 2	23 ± 2		

[a] Singlet oxygen determinations for **1** and **4** were described in ref 6. Typically, the conversions of **1** and **4** are 12 and 45%, respectively. The data represent the average of eight or more independent measurements. The conversions were measured by a Gilford spectrophotometer with an accuracy of 0.002 in OD reading. [b] For **2** and **3**, the experiments were carried out in $CDCl_3$ at 40 °C. 9,10-Dimethylanthracene was used as a singlet oxygen acceptor. Typically, the initial concentrations of **2** (or **3**) and 9,10-dimethylanthracene are 2×10^{-2} and 3×10^{-2} M, respectively. The appearances of alkylnaphthalene and 9,10-dimethylanthracene 9,10-endoperoxide are measured by NMR (Brucker WP-80 with built-in data processing). Typically, the data provided were the averages of four or more independent measurements. Conversions of **2** and **3** are larger than 90%. The use of 2,5-dimethylfuran as an $^1O_2$ acceptor led to experimentally indistinguishable results. [c] Earth's magnetic field.

quantitative thermolysis to produce molecular oxygen and the associated aromatic hydrocarbon; (b) these compounds display a range of yields of singlet oxygen relative to the total oxygen yields; and (c) the yield of singlet oxygen correlates with activation entropies for thermolysis, a more positive entropy corresponding to a lower yield of singlet oxygen. If the mechanism of endoperoxide thermolysis involves initial formation of a diradical intermediate with a structure such as ^1D (Scheme I), then at readily available field strengths (~10 000 G) a magnetic field effect on the yield of singlet oxygen is imaginable because $\Delta g \simeq 10^{-2}$ for the radical centers (g for benzyl radical $\simeq 2.001$; g for peroxy radical $\simeq 2.01$).[7]

In order to test for this possibility, the absolute yields of singlet oxygen produced from thermolysis of **1**, **2**, **3**, and **4** were measured in the earth's magnetic field and in laboratory magnetic fields varying up to ~14 000 G. If, as proposed,[6] **4** undergoes decomposition predominantly via a diradical, the situation is optimal for observation of magnetic field effect on the $^1O_2/O_2$ yield for this compound. In fact (Table I), in the thermolysis of **4** the yield of singlet oxygen (relative to the yield in the earth's magnetic field) decreased ~30% when the reaction was conducted in a magnetic field of ~14 000 G. Indeed, the yield of $^1O_2$ is very sensitive to an increase in magnetic field for **4** (Table I). On the other hand, if it is true, as proposed,[6] that **1** undergoes decomposition predominately via a concerted fragmentation (no diradicaloid character along the reaction coordinate), the external magnetic field should have no significant effect on the singlet oxygen yield from **1**. In fact, in the thermolysis of **1**, the singlet oxygen yield is essentially unchanged within experimental error in the presence and absence of a strong magnetic field (Table I). Compounds **2** and **3** are postulated to represent an intermediate case mechanistically,[6] and indeed the observed decrease in singlet oxygen yield is consistent with this postulate. Theory[2] predicts a proportionality between the yield of singlet oxygen produced from the ^1D and $H^{1/2}$ at *high magnetic fields*.[9] The data listed in Table I confirm this prediction and provide support for the following mechanistic interpretation.

Scheme I. Diradical Mechanism for Thermolysis of Endoperoxides of Aromatic Compounds



The decomposition of **4** may be formally viewed (Scheme I) as occurring via an initial singlet diradical intermediate ^1D, which fragments to $^1O_2$ and 9,10-diphenylanthracene (DPA) in competition with intersystem crossing to ^3D, which fragments to $^3O_2$ and DPA. In this mechanism, step b (and its reversal) should be magnetic field dependent. In the case of **1**, the (major) pathway of reaction may be concerted (or zwitterionic), or may involve a diradical singlet that is too short-lived to allow the magnetic field to assist in singlet-triplet evolution. The low value of $\Delta S^{\ddagger}$ for thermolysis of **1** favors, in our view, the concerted mechanism. The behaviors of **2** and **3** are intermediate to the behaviors of **1** and **4**. Thus, for **2** and **3** either a mixture of concerted and diradical mechanisms is operating or the derived singlet diradical undergoes a different partitioning to singlet and triplet products.

In conclusion, we have shown that a significant magnetic field can be observed in the thermolyses of aromatic endoperoxides. Furthermore, these results are consistent with previous mechanistic interpretations of endoperoxide decomposition.[6] An important implication of these results is the possibility of observation of magnetic isotope effects (^{17}O and ^{13}C) on the thermolyses of aromatic endoperoxides. At low magnetic fields a hyperfine mechanism may determine the rate of intersystem crossing in ^1D. The results of investigations examining this prediction will be reported shortly.

Acknowledgment. The authors thank the Air Force Office of Scientific Research and the Department of Energy for their generous support of this research. They also thank Dr. Y. Tanimoto for helpful discussions and comments, and Professor Steven Lippard for loan of a variable-field magnet.

References and Notes

(1) Reviews of magnetic field effects on chemical reactions: (a) Sagdeev, R. Z.; Salikhov, K. M.; Molin, Y. M. *Russ. Chem. Rev.* **1977**, *46*, 297. (b) Buchachenko, A. L. *ibid.* **1976**, *45*, 375.

(2) For a discussion of theoretical studies of the influence of an external magnetic field on chemical reactions, see: Hayashi, H.; Nagakura, S. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 2862, and references therein.

(3) (a) Atkins, P. *Chem. Br.* **1976**, *12*, 214. (b) Buchachenko, A. L. *Russ. Chem. Rev.* **1976**, *45*, 761.

(4) (a) Kaptein, R. *Adv. Free-Radical Chem.* **1975**, *5*, 381. (b) Closs, G. In "Chemically Induced Magnetic Polarization", Lepley, A. R.; Closs, G. L.; Ed.; Wiley: New York, 1973; p 95.

(5) For a review of the magnetic isotope effects, see: Buchachenko, A. L. *Russ. J. Phys. Chem.* **1977**, *51*, 1445.

(6) Turro, N. J.; Chow, M.-F.; Rigaudy, J. *J. Am. Chem. Soc.* **1979**, *101*, 1300.

(7) Berndt, A.; Fischer, H.; Paul, H. "Magnetic Properties of Free Radicals", Landolt-Börnstein, New Series; Springer Verlag: New York, 1977; Vol. 9b.

(8) Magnetic field effects on the quenching of delayed fluorescence of aromatic hydrocarbons by molecular oxygen have been interpreted in terms of a triplet–triplet annihilation to produce singlet oxygen. In this case, the formation of singlet oxygen would be *enhanced* by an external magnetic field: Tachikawa, H.; Bard, A. J. *J. Am. Chem. Soc.* **1973**, *95*, 1672.

(9) The yield of the "cage" product (phenyl benzoate) formed in the singlet-photosensitized decomposition of dibenzoyl peroxide decreased proportionally to the square root of the applied field: Tanimoto, Y.; Hayashi, H.; Nagakura, S.; Sakuragi, H.; Tokumaru, K. *Chem. Phys. Lett.* **1976**, *41*, 267.

Nicholas J. Turro,* Ming-Fea Chow
Chemistry Department, Columbia University
New York, New York 10027

Received March 19, 1979

A Synthetic Amphiphilic Helical Docosapeptide with the Surface Properties of Plasma Apolipoprotein A-I

Sir:

Plasma apolipoprotein A-I (apo A-I) contains six highly homologous 22 amino acid segments.[1,2] These domains have a high helix-forming potential[3] and in the α-helical conformation the hydrophobic and hydrophilic groups are segregated on opposite sides of the cylindrical segments.[4] If, indeed, the secondary structure of these segments is responsible for the binding of the whole apolipoprotein to lipid surfaces, then any amphiphilic helical oligopeptide should also display the unusual surface properties of apo A-I.[5,6] In order to test this hypothesis, we designed a docosapeptide (peptide I, see Figure 1) which a priori has a high potential to form amphiphilic helices ($P_\alpha = 1.28$, $P_\beta = 0.77$).[3] The particular simple amino acid sequence was chosen to give an equal distribution of acidic and basic residues on the hydrophilic side and to be as different as possible from the repeating apo A-I sequence. The peptide has only 41% homology with the 198–219 fragment of human apo A-I[7] and considerably less with the rest of the A-I molecule.

The peptide was synthesized using the Merrifield solid-phase method[8] employing the blocking groups and cleavage method described previously.[9] Purification of the deblocked peptide was carried out by gel permeation chromatography (Sephadex G-25, 0.2 M acetic acid), followed by lyophilization and ion-exchange chromatography on CM Sephadex C-25 (0.02 M sodium phosphate buffer, pH 6.5, with a sodium chloride gradient from 0 to 0.5 M). After lyophilization and desalting, peptide I was purified further by ion-exchange chromatography on CM Sephadex C-25 (0.02 M sodium phosphate buffer, pH 6.6, with a stepwise sodium chloride gradient 0, 0.2, 0.3 M; the peptide eluted at 0.3 M). The yield of pure peptide I was 1.5% based on the starting amount of Boc-Ala-resin. No impurities were detected in the final product by automated Edman degradation, amino acid analysis, high voltage paper electrophoresis, and thin layer chromatography on cellulose and silica. Based on the limits of detection inherent in each of these methods, the purity of the peptide was estimated to be at least 99%.

5 10
PRO-LYS-LEU-GLU-GLU-LEU-LYS-GLU-LYS-LEU-LYS-
15 20
GLU-LEU-LEU-GLU-LYS-LEU-LYS-GLU-LYS-LEU-ALA

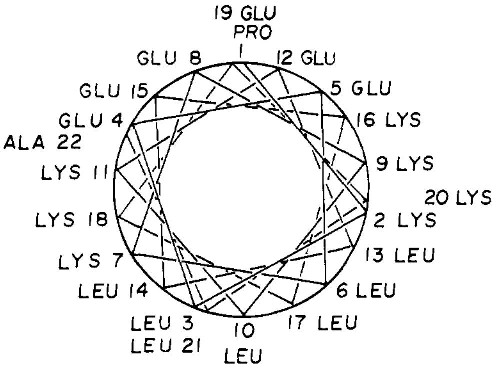


Figure 1. Amino acid sequence of peptide I and the axial projection of the α-helical peptide showing the relative location of the side chains with the segregation of the hydrophobic and hydrophilic residues.

Helical content was estimated from the molar ellipticity of I measured at several concentrations. From the concentration dependency of molar ellipticity, the peptide was found to form tetramers cooperatively with a $K_{\text{dissoc}} = 9.7 \times 10^{-16}$ M^3 (at 222 nm $\theta_{\text{monomer}} = -4.6 \times 10^3$ deg cm^2/dmol and $\theta_{\text{tetramer}} = -6.8 \times 10^4$ deg cm^2/dmol). The tetramerization of I was also demonstrated by gel permeation chromatography on Sephadex G-50. We found 61% helicity in 50% trifluoroethanol; in 0.1 M phosphate buffer, pH 7.0, at 1.7×10^{-4} M peptide, the helicity was 50%, whereas at 3×10^{-6} M it was 30%.

The binding of I to pure egg lecithin single bilayer vesicles[11] was quantitated by rapid ultrafiltration sampling.[12] The 2.0-mL incubation mixtures contained 0.025 M buffer (morpholinopropanesulfonic acid, MOPS, pH 7.0) and 0.16 M KCl. After 3-h incubation two 100-μL aliquots were removed, and the remaining solution was subjected to ultrafiltration (100-Å pore Amicon XM 100 membrane), the first 250 μL of ultrafiltrate being discarded and the next ~250 μL being collected, followed by the removal of two 100-μL aliquots from it for analysis. To each aliquot was added sequentially 250 μL of 2-propanol, 250 μL of 0.4 M borate buffer (pH 9.7), and 250 μL of 6.56×10^{-3} M o-phthalaldehyde in the same borate buffer. Fluorescence intensity (λ_{ex} 340 nm, λ_{em} 465 nm) was proportional to the peptide concentration over the entire concentration range employed. The adsorption of the peptide to the outer surface of the vesicle obeys a simple Langmuir isotherm. The data were analyzed in the same fashion as those described earlier for A-I fragments,[12] indicating that formally the binding sites are equivalent and independent.[13] The surface of a single vesicle was found to accommodate 48 peptides with a dissociation constant of $K_D = 1.9 \times 10^{-6}$ M. The binding of I to single bilayer vesicles was shown to be independent of pH