simple alkyl radicals and their parent iodides. The strength of the method is that a series of related experiments yield a complete set of values for $\Delta H_{f,300}(R\cdot)$. Its weakness is that it relies upon thermodynamic data drawn from the literature. Despite the weakness in this technique, it is clear that our measurements of K_{300} adequately characterize the properties of the radical buffer systems and can always be used to recompute values of $\Delta H_f(R\cdot)$ as thermodynamic data for properties such as $S°(R\cdot)$ are revised.

The approach used in this work, in common with all other methods currently available, yields measurements of $\Delta H_f(R\cdot)$ and BDE(R–H), which are subject to fairly high limits of error. At present, it seems that the only way in which such values can be refined is by combination and comparison of results from a variety of experiments that effectively define acceptable ranges for these quantities.

Our results and those of other recent studies in this field suggest that the most satisfactory estimates of bond dissociation energies in alkanes currently available are the following: primary C–H bond, ~100 kcal mol^{-1}; secondary C–H bond, ~96 kcal mol^{-1}; tertiary C–H bond, ~94 kcal mol^{-1}.

Acknowledgment. We thank Drs. S. W. Benson and J. C. Traeger for helpful comments and suggestions.

Registry No. Et·, 2025-56-1; *n*-Pr·, 2143-61-5; *i*-Pr·, 2025-55-0; *sec*-Bu·, 2348-55-2; *t*-Bu·, 1605-73-8; *c*-C_5H_9·, 3889-74-5; Me·, 2229-07-4; Ph·, 2396-01-2; *n*-Bu_3Sn·, 20763-88-6; MeI, 74-88-4; EtI, 75-03-6; *i*-PrI, 75-30-9; *sec*-BuI, 513-48-4; *t*-BuI, 558-17-8; CH_2CHCH_2Br, 106-95-6; $PhCH_2Br$, 100-39-0; *c*-C_5H_9I, 1556-18-9; tri-*n*-butyltin hydride, 688-73-3; phenylacetyl peroxide, 19910-09-9.

Competitive [6 + 2], [4 + 2], and [2 + 2] Cycloadditions. Experimental Classification of Two-Electron Cycloaddends

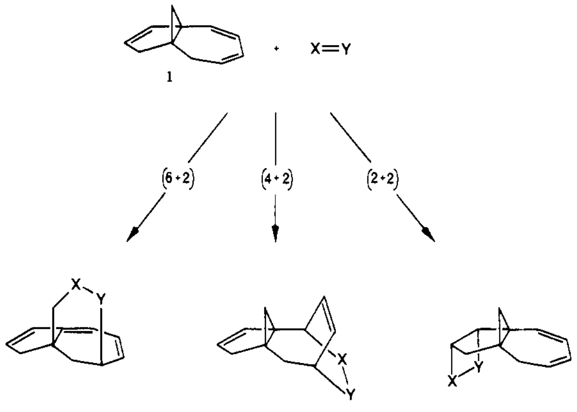
Lawrence T. Scott,*[1a] Ihsan Erden,[1a] William R. Brunsvold,[1a] Thomas H. Schultz,[1a] K. N. Houk,[1b] and M. N. Paddon-Row[1b,c]

Contribution from the Departments of Chemistry, University of Nevada, Reno, Nevada 89557, Louisiana State University, Baton Rouge, Louisiana 70803, and University of Pittsburgh, Pittsburgh, Pennsylvania 15260. *Received May 6, 1981*

Abstract: Seven common electron-deficient $_\pi 2$-cycloaddends have been classified according to their mode of cycloaddition to the unsaturated propellane tricyclo[5.3.1.0]undeca-2,4,9-triene (1). Tetracyanoethylene (TCNE) and 2,3-dichloro-5,6-dicyano-*p*-benzoquinone (DDQ) both add in a novel [6 + 2] manner to 1 and are therefore grouped together as type I cycloaddends. Singlet oxygen, 4-phenyl-1,2,4-triazoline-3,5-dione (PTAD), and diethyl azodicarboxylate all add in a normal Diels–Alder [4 + 2] fashion to the seven-membered ring diene and belong to the type II class. Chlorosulfonyl isocyanate (CSI) and dichloroketene both add in a [2 + 2] mode to the cyclopentene double bond and represent type III cycloaddends. This empirical classification system could prove valuable in predicting the outcome of new cycloadditions in other systems. PTAD, for example, is better than TCNE as a model for singlet oxygen addition. Explanations for the observed differences in periselectivity are formulated with the aid of a photoelectron spectrum and geometry calculation for 1 and ab initio STO-3G calculations on a model system.

For many years, cycloaddition reactions have figured prominently in both synthetic and mechanistic organic chemistry.[2] Current understanding of the underlying principles in this area has grown from a fruitful interplay between theory and experiment and, although already highly developed,[3] continues to evolve as new experimental findings come to light. In this context, we wish to report the unexpected observation that propellane 1 (tricyclo[5.3.1.0]undeca-2,4,9-triene)[4] combines with common, electron-deficient $_\pi 2$-cycloaddends in three distinct ways, i.e., [6 + 2], [4 + 2], and [2 + 2], depending on the particular partner (Scheme I). Few compounds other than fulvenes and fulvalenes participate in such varied cycloadditions.[5]

Scheme I



Grouping $_\pi 2$-cycloaddends according to their mode of cycloaddition with 1 represents a classification scheme that could prove valuable in predicting the outcome of new cycloadditions in other systems (Chart I). For example, we find that 4-phenyl-1,2,4-triazoline-3,5-dione (PTAD, 5) is a good model for singlet oxygen addition to 1, whereas tetracyanoethylene (TCNE, 3) is not. Such similarities and differences have occasionally been reported in the past; however, systematic studies remain scarce.[6] Our work,

---

[1] (a) University of Nevada. (b) Louisiana State University and (currently) University of Pittsburgh. (c) On leave from New South Wales Institute of Technology.

[2] Carey, F. A.; Sundberg, R. J. "Advanced Organic Chemistry"; Plenum Press: New York, 1977; Part A, Chapter 10, and Part B, Chapter 6.

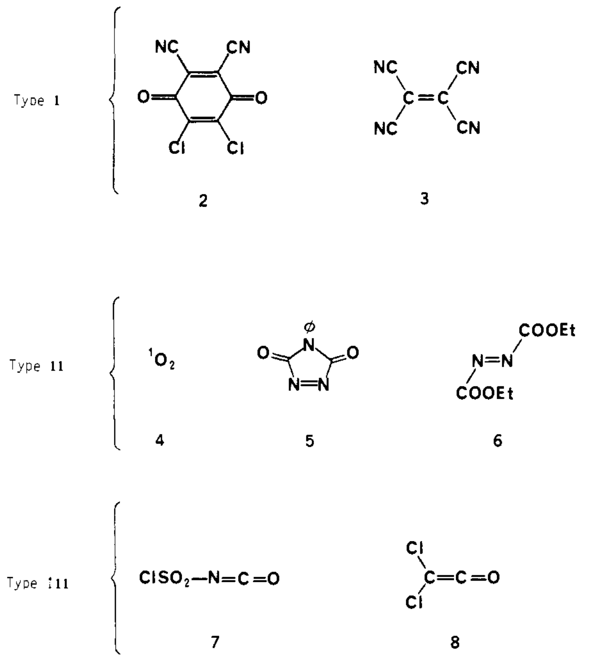
[3] See, for example: Houk, K. N. In "Pericyclic Reactions"; Marchand, A. P., Lehr, R. E., Eds.; Academic Press: New York, 1977; Vol. II, Chapter 4.

[4] Scott, L. T.; Brunsvold, W. R. *J. Am. Chem. Soc.* **1978**, *100*, 4320–4321. Scott, L. T.; Brunsvold, W. R.; Kirms, M. A.; Erden, I. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 274–279. Scott, L. T.; Brunsvold, W. R.; Kirms, M. A.; Erden, I. *J. Am. Chem. Soc.* **1981**, *103*, 5216–5220.

[5] Dunn, L. C.; Chang, Y.-M.; Houk, K. N. *J. Am. Chem. Soc.* **1976**, *98*, 7095–7096 and references cited therein. Prinzbach, H. *Pure Appl. Chem.* **1971**, *28*, 281–329.

0002-7863/82/1504-3659$01.25/0

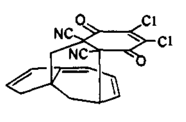
Chart I

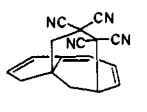


although insufficient by itself to completely establish a new general principle, does constitute an important step in that direction.

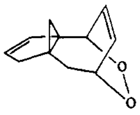
Cycloadditions of Tricyclo[5.3.1.0]undeca-2,4,9-triene (1)

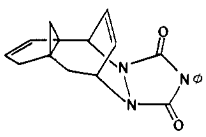
During the course of developing a synthesis of homoazulene,[4] we attempted to dehydrogenate propellane **1** with 2,3-dichloro-5,6-dicyano-*p*-benzoquinone (DDQ, **2**).[7] A novel [6 + 2] cycloaddition superseded the desired dehydrogenation, however, giving a 1:1 adduct to which we assign structure **9**.[8] The evidence upon which this structural assignment and those of subsequent cycloadducts are based will be discussed separately in a later section. TCNE (**3**) likewise adds instantaneously to propellane **1** at room temperature by the same [6 + 2] mode to give a 1:1 adduct (**10**) in 87% yield. Adducts **9** and **10** are presumed to be primary products.

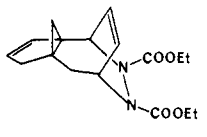

9


10

By contrast, singlet oxygen (**4**), PTAD (**5**), and diethyl azodicarboxylate (**6**) all add to propellane **1** by the normal [4 + 2] mode to give tetracyclic adducts **11**, **12**, and **13**, respectively. We note a distinct difference, then, between the heteroatom cycloaddends and the electron-deficient C=C systems **2** and **3**.


11


12


13

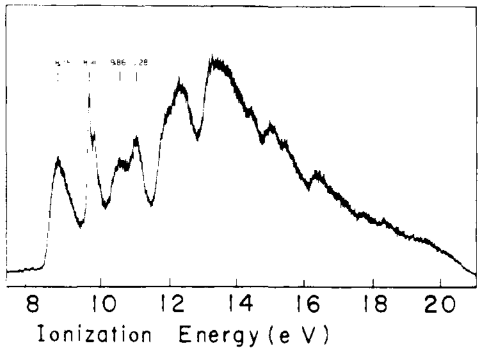


Figure 1. Photoelectron spectrum of **1**.[11]

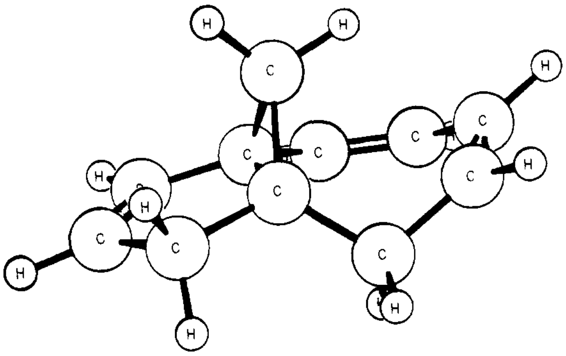
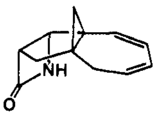
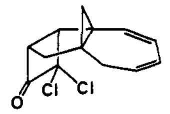


Figure 2. ORTEP drawing of a molecular model of **1**.[15b]

Chlorosulfonyl isocyanate (CSI, **7**) does not attack the diene portion of **1** at all but adds to the five-membered ring in a [2 + 2] mode to give **14** in 84% yield after hydrolysis. Formation of β-lactams from CSI and alkenes has ample precedent; however, skeletal rearrangements are often observed when carbenium ions intervene.[9] We see no evidence for rearrangement of an intermediate cyclopropylcarbinyl cation in the reaction of **1** with CSI. Dichloroketene (**8**) adds to **1** in an analogous manner to give **15**.


14


15

Neither of these [2 + 2] cycloadditions is surprising in light of previous studies on **7** and **8**,[9,10] although alternative, symmetry-allowed additions to **1** appear possible.

Theoretical Considerations

We have measured the photoelectron spectrum of **1** in order to assess the energies of the various frontier orbitals of the ene, diene, and cyclopropane systems. The photoelectron spectrum (PES), shown in Figure 1, is rich in detail.[11] The second band (vertical IP = 8.91 eV) is quite sharp and has a prominent vibrational spacing of 0.17 eV, like that found in simple alkenes.[12] We assign this band to ionization from an orbital that is relatively highly localized on the cyclopentene double bond. Cyclopentene itself has an IP of 9.18 eV,[13] but the first IP of ethylene is lowered

---

(6) Clardy, J.; Read, L. K.; Broadhurst, M. J.; Paquette, L. A. *J. Am. Chem. Soc.* **1972**, *94*, 2904–2905. Paquette, L. A.; Hertel, L. W.; Gleiter, R.; Böhm, M. *Ibid.* **1978**, *100*, 6510–6512. Erden, I.; de Meijere, A.; Rousseau, G.; Conia, J. M. *Tetrahedron Lett.* **1980**, 2501. Weber, W.; Erden I.; de Meijere, A. *Angew Chem., Int. Ed. Engl.* **1980**, *19*, 387. Erden, I.; Kaufmann, D, *Tetrahedron Lett.* **1980**, 215. Seymour, C. A.; Greene, F. D. *J. Am. Chem. Soc.* **1980**, *102*, 6384–6385.

(7) Becker, H.-D. In "The Chemistry of the Quinonoid Compounds"; Patai, S., Ed.; Wiley: New York, 1974; Part 1, Chapter 7.

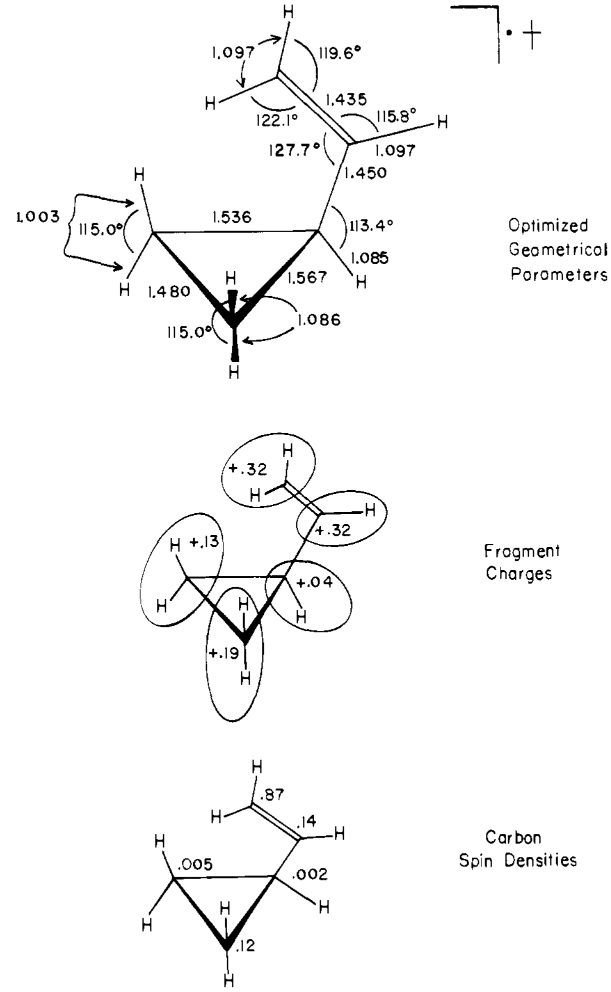
(8) Scott, L. T.; Brunsvold, W. R. *J. Chem. Soc., Chem. Commun.* **1978**, 633–634. the structure of this compound was initially assigned as the alternative [6 + 2] adduct **20**.

(9) Bestian, H. *Pure Appl. Chem.* **1971**, *27*, 611–634. see also; Paquette, L. A.; Allen, G. R., Jr.; Broadhurst, M. J. *J. Am. Chem. Soc.* **1971**, *93*, 4503–4508.

(10) Brady, W. T. *Synthesis* **1971** 415–422. Krepski, L. R.; Hassner, A. *J. Org. Chem.* **1978**, *43*, 2879–2882.

(11) The photoelectron spectrum was recorded on a Perkin-Elmer PS-18 photoelectron spectrometer at LSU. Peak positions were calibrated with xenon and argon; reported values are the average of five determinations.

(12) Wiberg, K. B.; Ellison, G. B.; Wendolsoki, J. J.; Brundle, C. R.; Kuebler W. A. *J. Am. Chem. Soc.* **1976**, *98*, 7179. Clary, D. C.; Lewis, A. K.; Morland, D.; Murrell, J. W.; Heilbronner, E. *J. Chem. Soc., Faraday Trans. 2* **1974**, *70*, 1889.



Optimized Geometrical Parameters

Fragment Charges

Carbon Spin Densities

Figure 3. Geometries, charges, and spin densities of the optimized vinylcyclopropane radical cation. The vinyl carbons and two cyclopropane carbons were held coplanar (see text).

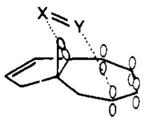
by 1.27 eV in vinylcyclopropane.[14] The second band in the PES of **1** is lowered by only 0.27 eV relative to the cyclopentene IP, indicative of relatively low conjugation of this double bond with Walsh-type cyclopropane orbitals. The relatively small effect of the cyclopropane moiety may be attributed to the approximately 30° and 90° dihedral angles between the cyclopropane CC bond axes and the alkene π orbital, whereas the optimum hyperconjugative interaction occurs when these angles are both 60° (i.e., 60° and 300°).

The first, third, and fourth bands in the PES of **1** are all very broad, which is indicative of the coexistence of a number of different conformations of the cycloheptadiene moiety.[15a] One of the expected conformations, obtained by a rough molecular mechanics optimization,[15b] is shown in Figure 2. The three broad bands are expected to arise from diene π IPs, which occur at 8.31 eV and 10.63 eV in 1,3-cycloheptadiene,[15a] and one or more of the cyclopropane Walsh-type orbitals, which have IPs centered at 10.9 eV in the parent molecule.[16] Because the two cycloheptadiene π IPs are expected to be influenced to a similar extent by the cyclopropane ring, we assign the 8.05 and 10.28 eV bands to these, which are 0.26 and 0.35 eV lower in energy than those of cycloheptadiene. The broader band at 9.86 eV is assigned to one or both cyclopropane Walsh-type orbitals.

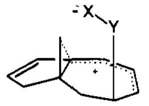
The spectrum is revealing of several features of the electronic structure and shape of **1**. The diene moiety is most electron rich, in spite of its puckered and floppy geometry. On the other hand, the cyclopentene moiety is rigid and, as can be gleaned from Figure 2, relatively unhindered sterically. The cyclopropane ring serves as a moderate electron-donating substituent but is not involved in any unusual fashion with the π orbitals of the diene and cyclopentene groups.

Returning to the differences in periselectivities of different cycloaddends with **1**, we note that the type II molecules are all heterodienophiles known for their high reactivity in Diels–Alder reactions.[17a] The cycloadditions here follow the normal concerted [4 + 2] pathway with approach from the sterically least hindered face of the diene system. Ordinarily, 1,3-cycloheptadienes do not participate well in Diels–Alder reactions[17b] due to the relatively large 1,4 distance;[17c] however, electron donation from the cyclopropane ring in **1** will enhance diene reactivity somewhat and thus partially compensate for the unfavorable geometry.

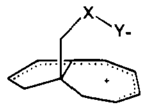
For the [6 + 2] cycloadditions, a completely concerted $[({}_{\pi}2_s + {}_{\pi}2_s + {}_{\sigma}2_a) + {}_{\pi}2_s]$ pericyclic reaction with inversion of configuration at the cyclopropane methylene group (**16**) is both symmetry allowed[18] and geometrically feasible. On the basis of this mechanism, however, it is difficult to account for the contrasting periselectivities of the type I and type II cycloaddends. More likely, we believe, the change in mechanism results from the greater electron affinity (lower-lying LUMO) of DDQ and TCNE relative to that of the type II species.[19a] One-electron transfer from the propellane could produce a radical ion pair[19b] that rapidly collapses to a highly stabilized zwitterionic intermediate (**17** or **18**). The former intermediate would be expected to have nonclassical character, such as that suggested by the recent calculations of Hehre et al. on the cyclopropylcarbinyl cation[20] and by the experimental results of Lammertsma and Cerfontain on a related system.[21] Cyclization of either zwitterion could then lead to the observed products.[22] It is possible, of course, that the cycloaddends



16



17



18

---

(13) Bischof, P.; Heilbronner, E. *Helv. Chim. Acta* **1970**, *53*, 1677.

(14) Harada, Y.; Seki, K.; Suzuki, A.; Inokucki, H. *Chem. Lett.* **1973**, 893. Bruckmann, P; Klessinger, M. *Chem. Ber.* **1974**, *107*, 1108.

(15) (a) Klessinger, M.; Rademacher, P. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 826. (b) This model was obtained with the WIPKE optimization procedure, written by W. Todd Wipke and implemented on the PROPHET Computer System, a national resource sponsored by the Division of Research Resources of the National Institutes of Health.

(16) Basch, H.; Robin, M. B.; Kuebler, N. A.; Baker, C.; Turner, D. W. *J. Chem. Phys.* **1969**, *51*, 52.

(17) (a) Wollweber, H. "Diels–Alder-Reaktion"; Thieme: Stuttgart, 1972; pp 190–198. (b) Reference 17a, pp 51–52. (c) For a summary of references on the geometry of 1,3-cycloheptadiene, see: Giordan, J. C.; McMillan, M. R.; Moore, J. H.; Staley, S. W. *J. Am. Chem. Soc.* **1980**, *102*, 4870–4872.

(18) Woodward, R. B.; Hoffmann, R. "The Conservation of Orbital Symmetry"; Verlag Chemie: Weinheim, Germany, 1970.

(19) (a) The electron affinities of the type I cycloaddends TCNE and DDQ are 2.73–2.90 and 2.87 eV, respectively (Chen, E. C. M.; Wentworth, W. E. *J. Chem. Phys.* **1975**, *63*, 3183). By contrast, the electron affinity of singlet oxygen, a type II cycloaddend, is estimated to be only about 1.5 eV, on the basis of the known EA = 0.48 eV for triplet oxygen (Berkowitz, J.; Chupka, W. A.; Gutman, D. *J. Chem. Phys.* **1971**, *55*, 2733) and the difference in energy between singlet and triplet oxygen (ca. 1.0 eV). For azodicarboxylic ester, another type II cycloaddend, an electron affinity of approximately 2.0 eV can be estimated as follows: formal conversion of benzene (EA = −1.15 eV) to pyridazine represents the subsitution of an azo linkage for a –CH=CH– unit and increases the EA by 1.4 eV (Wenner, I.; Schulz, G. J. *J. Chem. Phys.* **1975**, *62*, 1747). Analogous formal conversion of diethyl fumarate (EA = 0.6 eV: Breigleb, G. *Angew. Chem. Int. Ed. Engl.* **1964**, *3*, 617) to azodicarboxylic ester thus gives an electron affinity for the latter compound of about 0.6 eV + 1.4 eV $\simeq$ 2.0 eV. (b) Electron transfer is presumed to be thermodynamically favored when the difference between the IP of the donor and the EA of the acceptor is less than about 4–5 eV.[3] The type I cycloaddends (EA $\simeq$ 3 eV) should, therefore, be capable of participating in an electron-transfer reaction with triene **1** (IP $\simeq$ 8 eV), whereas those of type II (EA < 3 eV) should not.

(20) Levi, B. A.; Burlock, E. S.; Hehre, W. J. *J. Am. Chem. Soc.* **1979**, *101*, 5537–5539.

(21) Lammertsma, L.; Cerfontain, H. *J. Am. Chem. Soc.* **1980**, *102*, 4528–4529.

(22) Such intermediates appear to be involved in the cycloaddition reactions of TCNE to other 1-cyclopropyl-1,3-butadienes: Kataoka, F.; Shimizu, N.; Nishida, S. *J. Am. Chem. Soc.* **1980**, *102*, 711–716.

Table I. Cycloadditions to 1. Physical Properties of the Products and Related Compounds

reaction conditions	yield, %	product (mp, °C)	^{1}H NMR, δ	IR, cm^{-1}	UV (EtOH), λ_{max} in nm
25 °C, 10 min	62	9 (124–126)	2.01 (dt, J = 2, 14 Hz, 1 H), 2.14 (d, J = 15 Hz, 1 H), 2.3–2.9 (m, 3 H), 3.34 (dd, J = 1, 15 Hz, 1 H), 3.5 (m, 1 H), 4.90 (dd, J = 7, 11 Hz, 1 H), 5.60 (d, J = 8 Hz, 1 H), 5.95 (dd, J = 8, 11 Hz; 1 H), 6.0–6.4 (m, 2 H)	2930 (w), 2230 (w), 1700 (vs), 1585 (m), 1545 (s), 1412 (m), 1230 (m), 1183 (m), 1133 (s), 955 (m), 947 (m), 789 (s), 777 (vs), 765 (s)	288, 312
25 °C, 10 min	87	10 (209–212)	2.30 (d, J = 15 Hz, 3 H), 2.4–2.9 (m, 2 H), 2.90 (d, J = 15 Hz, 1 H), 4.50 (m, 1 H), 5.60–6.15 (m, 4 H), 6.35 (dd, J = 8, 11 Hz, 1 H)	3060 (w), 2950 (w), 2260 (w), 1600 (s), 1575 (m), 1438 (s), 1092 (m), 1068 (m)	208, 298
25 °C, 5 h	74	11 (–)	0.38 (d, J = 4.0 Hz, 1 H), 1.25 (d, J = 4.0 Hz, 1 H), 2.28 (d, J = 3.5 Hz, 2 H), 2.55 (m, 2 H), 4.58 (m, 1 H), 5.08 (m, 1 H), 5.43 (m, 1 H), 5.80 (m, 1 H), 6.18 (m, 2 H)	3070 (w), 3000 (w), 2920 (m), 1605 (w), 1450 (w), 1390 (w), 1008 (w), 995 (w), 962 (m)	
0 °C, 10 min	82	12 (172–173)	0.43 (d, J = 3.5 Hz, 1 H), 1.32 (d, J = 3.5 Hz, 1 H), 2.38 (d, J = 3.5 Hz, 2 H), 2.52 (m, 2 H), 4.77 (m, 1 H), 5.45 (m, 2 H), 5.93 (dt, J = 2.6 Hz, 1 H), 6.15 (d, J = 8 Hz, 2 H), 7.36 (br s, 5 H)	1760 (s), 1699 (vs), 1493 (m), 1419 (s), 1292 (m), 1130 (m), 773 (m), 764 (m)	268
130 °C, 6 h	68	13 (–)	0.33 (d, J = 4 Hz, 1 H), 1.0–1.52 (m, 7 H), 2.25–2.85 (m, 4 H), 4.15 (m, 4 H), 4.65 (m, 1 H), 5.35 (m, 2 H), 5.85 (m, 1 H), 6.10 (m, 2 H)	3060 (w), 2990 (m), 2940 (m), 1720 (vs), 1420 (s), 380 (s), 1125 (m), 1065 (s)	
−10 °C, 0.5 h	84	14 (–)	2.32 (d, 4.6 Hz, 1 H), 1.69 (m, 1 H), 2.02 (d, 4.6 Hz, 1 H), 2.15 (m, 1 H), 2.48 (m, 2 H), 3.22 (m, 1 H), 3.92 (d, 4 Hz, 1 H), 5.82 (m, 4 H), 6.17 (br s, 1 H)	2360 (s), 3030 (w) 2940 (m), 1750 (vs) 1435 (w), 1322 (w), 1188 (v)	208, 257
35 °C, 10 h	91	15 (118–120)	0.52 (d, 4.6 Hz, 1 H), 2.08 (d, 4.6 Hz, 1 H), 2.28 (m, 2 H), 2.65 (m, 2 H), 3.1–3.6 (m, 2 H), 5.1–6.3 (m, 4 H)	3020 (m), 2960 (m), 2920 (m), 2860 (w), 1805 (vs), 1670 (w), 1603 (w), 1440 (s), 1255 (s), 1070 (s), 1015 (s)	264
		19 (–)	0.50 (d, J = 4 Hz, 1 H), 2.00 (m, 3 H), 2.35 (m, 2 H), 2.90 (t, J = 2.5 Hz, 1 H), 3.40 (br d, J = 2.5 Hz, 1 H), 5.2–5.9 (m, 3 H), 6.17 (d, J = 11 Hz, 1 H)	3080 (m), 2970 (m), 2890 (w), 1610 (w), 1430 (m), 1255 (w), 1192 (s), 1113 (w), 1005 (w), 945 (m), 856 (s)	266

give **17** or **18** directly without a prior electron-transfer step, but in either case, the site of attack is presumably determined by the stability of the intermediate formed.

In order to explore the possibility of an electron-transfer mechanism for this reaction, we have carried out ab initio STO-3G calculations[23] on the radical cation of vinylcyclopropane, a model for that of propellane **1**. In these calculations, the double-bond carbons were held coplanar with one of the cyclopropane CC bonds in order to better mimic the conformation of both the cyclopentene π bond and the diene system relative to the cyclopropane in **1**. The remaining important variables were optimized. The final values of these variables are given in Figure 3 (top). The geometries, charges, and odd-electron spin densities, also given in Figure 3, indicate significant interaction of one CC bond of the cyclopropane with the vinyl half-occupied π orbital. The formal C═C—C moiety has nearly equal values of the two CC bond lengths; these lengths (1.435 and 1.450 Å) are both longer than those of the STO-3G optimized bond lengths of allyl cation (1.384 Å) and radical (1.405 Å).[24] The conjugated cyclopropyl bond length (1.567 Å) is much longer than that of the CC bonds of cyclopropane (1.502 Å).[24]

The conjugated CC bond of the cyclopropane is significantly stretched and weakened in the radical cation of vinylcyclopropane, and a similar situation is expected in the radical cation of **1**. It is quite plausible, therefore, to suggest that **18** could be formed by attack of the radical anions of **2** or **3** on this species. Similar ring-opening cycloadditions are known for a variety of cyclopropylalkenes.[25]

Finally, the reactivity of type III heterocumulenes at the cyclopentene double bond seems at first sight anomalous, since the diene IP is lower than that of the cyclopentene. However, type III cycloaddends are known to add in a concerted "criss-cross" manner to electron-rich alkenes.[18,26] and this transition state has considerable steric requirements on one face of the π bond. Although ketenes generally add fastest to the alkene with lowest IP,[3] the puckering of the cycloheptadiene moiety precludes an unhindered approach to either side of the diene π system. Thus, reaction appears on the less hindered cyclopentene moiety, with expected regioselectivity.

Structures of the Cycloadducts

Table I summarizes the ^{1}H NMR, IR, and UV spectral data for all of the cycloadducts together with those for reference compound **19**. ^{13}C NMR and mass spectra are reported in the Experimental Section.

---

(23) Hehre, W. J.; Stewart, R. F.; Pople, J. A. *J. Chem. Phys.* **1969**, *51*, 2657.

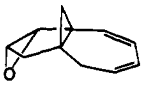
(24) Whiteside, R. A.; Binkley, J. S.; Krishnan, R.; DeFrees, D. J.; Schlegel, H. B.; Pople, J. A. "Carnegie-Mellon Quantum Chemistry Archive"; Carnegie-Mellon University, 1980.

(25) Sarel, S.; Langbeheim, M. *J. Chem. Soc., Chem. Commun.* **1977**, 593 and earlier papers by Sarel et al. Cernuschi, P.; DeMicheli, C.; Gandolfi, R. *Tetrahedron Lett.* **1977**, 3667–3670 and references cited therein. Nishida, S. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 328 and related papers in this series. Martini, Th.; Kampmeier, J. A. *Ibid.* **1970**, *9*, 236.

(26) Ulrich, H. "Cycloaddition Reactions of Heterocumulenes"; Academic Press: New York, 1967.

The [4 + 2] cycloadducts (**11**, **12**, and **13**) all exhibit very similar spectral properties. A high-field doublet (δ 0.33–0.43, J = 3.5–4.0 Hz) in the ^{1}H NMR spectrum of each compound attests to survival of the cyclopropane ring. These signals correspond to one half of an AB quartet associated with the cyclopropane methylene group; the other half of the quartet appears at lower field (ca. δ 1.3). The remaining methylene groups in all these compounds give rise to multiplets in the δ 2.25–2.85 region. The ethylene bridges give pseudosinglets (ca. δ 6.1), and the cyclopentene olefinic hydrogen signals always give two peaks (ca. δ 5.4 and 5.9). Clearly the structures of adducts **11**–**13** must be closely related. UV spectroscopy confirms the absence of a conjugated diene in **11** and **13**; however, an absorption by the benzene ring in **12** obscures the region of interest for this adduct. The close similarity in chemical shift among the cyclopropane AB quartets in all three ^{1}H NMR spectra seems more consistent with the stereochemical assignment shown than with one in which the different dienophile moieties protrude syn to the cyclopropane CH$_2$ group.

The [2 + 2] cycloadducts (**14** and **15**) exhibit spectral properties very similar to those of epoxide **19**. Long wavelength absorption maxima (ca. 260 nm) in the UV spectra of all three compounds verify the presence of a conjugated diene in each, and survival of the cyclopropane ring is evidenced, as before, by high-field doublets (δ 0.32–0.52, J = 4.0–4.6 Hz) in the ^{1}H NMR spectra. The two methine hydrogens on the β-lactam in **14** give rise to signals at δ 3.22 (C*H*CO) and 3.92 (C*H*NH). Only the latter appears as a simple doublet (J = 4 Hz), and this fact permits assignment of the regiochemistry as shown. The regiochemistry of **15**, although unproven, is assigned by analogy. The stereochemical argument presented above for the Diels–Alder adducts applies here as well.

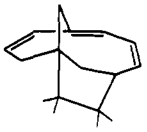


19

Spectroscopic analysis of the [6 + 2] cycloadducts (**9** and **10**) reveals that these compounds no longer contain the original propellane skeleton of **1**. In particular, the ^{1}H NMR spectra lack the high-field signals expected for hydrogens on a cyclopropane ring. There appears instead a pair of doublets (AB quartet) at δ 2.14 and 3.34 (J = 15 Hz) for the hydrogen atoms in **9** which originate from the cyclopropane ring and a similar pattern at δ 2.30 and 2.90 (J = 15 Hz) for those in **10**. The unusually long wavelength absorption maxima in the UV spectra of **9** and **10** require the presence of a nearly planar, conjugated triene in both compounds.

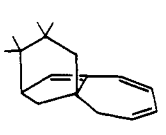
A priori, one must consider structures **20**–**22** as possible alternatives to **9** and **10**. Molecular models reveal a rather serious twist in the triene chromophore of **20**, however, which should shift the UV absorption maximum to shorter wavelength than that expected for a planar triene. The known diacetate **23**^{4} contains this same twisted chromophore and does indeed absorb at significantly shorter wavelength (λ_{max} (EtOH) = 265 nm) than those observed for the cycloadducts from DDQ and TCNE. Structures **9** and **10** are favored over **20**, then, because they contain nearly planar triene chromophores. In addition, the exceptionally low field singlet (δ 154.3) in the off-resonance decoupled ^{13}C NMR spectrum of the TCNE adduct is best explained[27] by extensive branching α to the bridgehead olefinic carbon, as in **9** and **10** (and **22**).

The "homo-Diels–Alder" structures (**21** and **22**) are both excluded by deuterium-labeling experiments. Base-catalyzed hydrogen/deuterium exchange on tricyclo[5.3.1.0]undeca-2,4-dien-10-one (**24**), an intermediate in the synthesis of **1**,^{4} provided a route to the 9-deuteriopropellane **25**. The ^{1}H NMR spectra of the DDQ and TCNE adducts of **25** differ from those of **1** only by the absence of one *vinyl* H signal. Structures **9** and **10** are compatible with these results, whereas **21** and **22** are not.

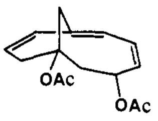


20

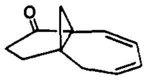
21



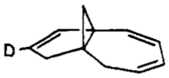
22



23



24



25

Two final points regarding the structure of the DDQ adduct deserve comment. First, the positions of the cyano groups and chlorine atoms in **9** are assigned by analogy with those in other DDQ adducts;[28] we have no evidence that bears on this point. Second, the stereochemical assignment is based on the presumption that the red color of **9** results from an intramolecular charge-transfer interaction between the enedione and triene π systems; the TCNE adduct (**10**), which lacks the enedione moiety, is colorless.

Experimental Section

Melting points are uncorrected. Infrared (IR) spectra were recorded on a Perkin-Elmer Model 599 spectrophotometer, and ultraviolet (UV) spectra were recorded on a Beckman Model 25 spectrophotometer. ^{1}H NMR spectra were obtained with a JEOL FX100 FT and a Hitachi Perkin-Elmer Model R-24B spectrometer. Mass spectra were recorded on a Varian MAT CH-5 instrument at 15 or 70 eV. Commercial reagents and solvents were purified to match reported physical and spectral data. Known compounds used in this work were either purchased from standard suppliers or prepared according to published procedures.

Reaction of Triene 1 with 2,3-Dichloro-5,6-dicyano-*p*-benzoquinone (DDQ, 2). DDQ (63 mg, 0.29 mmol) was added to a solution of triene **1** (41 mg, 0.29 mmol) in 2 mL of dry benzene at 25 °C. The resulting red solution was stirred at 25 °C for 10 min, concentrated to a volume of 1 mL, and triturated with 2 mL of hexane. The tan solid (dihydroquinone) that precipitated was removed by filtration, and the orange filtrate was concentrated under reduced pressure to give 65 mg (62%) of **9** as red needles: mass spectrum, m/e (rel intensity) 374/372/370 (4/26/39, M$^+$), 143 (53), 142 (35), 141 (21), 130 (79), 129 (100), 128 (46), 115 (39); M$^+$ calcd for C$_{19}$H$_{12}$Cl$_2$N$_2$O$_2$ 372.0246, Found 372.0248. See Table I for additional data.

Reaction of Triene 1 with Tetracyanoethylene (TCNE, 3). Triene **1** (25 mg, 0.17 mmol) was dissolved in 5 mL of dry tetrahydrofuran at 25 °C. TCNE (24 mg, 0.18 mmol) was added, and the solution was stirred at room temperature for 10 min. The pale yellow solution was then concentrated under reduced pressure, and the brown residue was redissolved in 3 mL of CH$_2$Cl$_2$. Hexane (2 mL) was added until the first crystals appeared, and the solution was cooled to O °C for 1 h to give 30 mg of **10** as colorless needles. The filtrate was concentrated to half of the initial volume, and an additional 11 mg of crystals were collected (total yield 87%): ^{13}C NMR (CDCl$_3$) δ 154.3 (s), 136.9 (d), 134.3 (d), 134.0 (d), 121.6 (d), 118.9 (d), 112.6 (s), 111.9 (s), 111.0 (s), 110.3 (s), 49.6 (t), 44.4 (2 s), 42.1 (t), 41.1 (d), 37.3 (s), 27.6 (t); mass spectrum M$^+$ calcd for C$_{17}$H$_{12}$N$_4$ 272.1062, Found 272.1061.

Singlet Oxygenation of Triene 1. A 25-mL flask was charged with 10 mL of CHCl$_3$, 288 mg (2.0 mmol) of triene **1**, and 3 mg of tetraphenylporphyrin (TPP). The system was purged with dry oxygen and left under a slight positive oxygen pressure. The flask was irradiated by means of a 500-W tungsten Halogen lamp while the solution was stirred with a magnetic stir bar. The progress of the reaction was monitored by ^{1}H NMR and TLC. Within 5 h, singlet oxygenation was complete. The solvent was removed under reduced pressure (ca. 10 °C at 15 torr), and the residue was chromatographed on 30 g of silica gel at 0 °C, eluting with CH$_2$Cl$_2$–n-C$_5$H$_{12}$ (2:1). Repeated silica gel chromatography afforded endoperoxide **11** in 74% yield as a colorless oil, which crystallized

---

(27) Levy, G. C.; Nelson, G. L. "Carbon-13 Nuclear Magnetic Resonance for Organic Chemists"; Wiley: New York, 1972.

(28) Pointer, D. J.; Wilford, J. B.; Hodder, O. J. *J. Chem. Soc. B* **1971**, 2009.

upon cooling in the refrigerator: mass spectrum M^+ calcd for $C_{11}H_{12}O_2$ 176.0837, found 176.0837.

Reaction of Triene 1 with 4-Phenyl-1,2,4-triazoline-3,5-dione (PTAD, 5). A 10-mL flask, provided with a magnetic stirbar and a 10-mL pressure-equalizing dropping funnel, was charged with 1 mmol of triene **1** in 3 mL of dry CH_2Cl_2. The solution was cooled to 0 °C, and a solution of 1 mmol of freshly sublimed PTAD in 5 mL of CH_2Cl_2 was added dropwise while the solution was cooled and stirred magnetically. The red color disappeared almost instantaneously upon addition. The resulting pale yellow solution was concentrated under reduced pressure and the residue purified by preparative TLC (silica gel, 30% ethyl acetate–petroleum ether, 40:60) to give the adduct (**12**) in 82% yield as colorless crystals. Recrystallization from ethanol gave colorless needles: mass spectrum M^+ calcd for $C_{19}H_{17}N_3O_2$ 319.1321, found 319.1314.

Reaction of Triene 1 with Diethyl Azodicarboxylate (6). A solution of 0.5 mmol each of **1** and diethyl azodicarboxylate in 3 mL of benzene was placed into a constricted glass tube, sealed under nitrogen, and heated in an oven at 130 °C for 6 h. After the tube was cooled to room temperature, the solvent was removed under reduced pressure (ca. 20 °C at 15 torr), and the residue was purified by preparative TLC (silica gel, CH_2Cl_2) to give the adduct (**13**) in 68% yield as a colorless oil.

Addition of Chlorosulfonyl Isocyanate (CSI, 7) to 1. Into a 25-mL flask, provided with a stir bar and a rubber septum, was placed 1 mmol of triene **1** in 10 mL of dry CH_2Cl_2. An atmosphere of dry nitrogen was maintained through a stainless steel needle, and the mixture was cooled to −10 °C. A solution of 1.1 mmol of CSI in 5 mL of dry CH_2Cl_2 was added through a syringe within 15 min. After the solution was stirred at −10 °C for 0.5 h, it was poured into a mixture of 2 g of $NaHCO_3$ and 700 mg of Na_2SO_3 in 25 mL of water. After the solution was stirred for 1 h at room temperature, the two phases were separated, and the water layer was extracted with two 20-mL portions each of CH_2Cl_2 and ether. The combined organic layers were dried over anhydrous $MgSO_4$ and concentrated under reduced pressure (20 °C, 15 torr). The residue was purified by preparative TLC (silica gel, ether–methanol, 95:5) to give the β-lactam (**14**) in 84% yield as a colorless oil: mass spectrum M^+ calcd for $C_{12}H_{13}NO$ 187.0997, Found 187.0996.

Dichloroketene Addition to 1. A 25-mL flask equipped with a reflux condenser, magnetic stirrer, addition funnel, and nitrogen inlet was flame-dried under nitrogen. The cool flask was then charged with 144 mg (1.0 mmol) of triene **1**, 72 mg (1.1 mmol) of freshly activated zinc,[10] and 15 mL of dry ether. The suspension was stirred under nitrogen while a solution of 117 μL (190 mg, 1.04 mmol) of Cl_3CCOCl and 96 μL (161 mg, 1.05 mmol) of $POCl_3$ (distilled from K_2CO_3) in 10 mL of dry ether was added dropwise (ca. 10 min). The progress of the reaction was monitored by TLC and appeared to be complete after 4 h. After the mixture was refluxed for 28 h, the reaction suspension was filtered through Celite, and the remaining zinc was washed with 30 mL of ether. Solvent removal under reduced pressure yielded a purple oil that was purified by preparative TLC on silica gel, eluting with 15% ethyl acetate–petroleum ether, to give 139 mg (55%) of the dichloroketene adduct **15** as colorless crystals and 38 mg of recovered triene **1**: mass spectrum M^+ calcd for $C_{13}H_{12}Cl_2O$ 254.0265, Found 254.0264.

Epoxidation of 1. A 25-mL flask was charged with a solution of 0.55 mmol of triene **1** in 2 mL of dry CH_2Cl_2. To this was added a solution of 0.62 mmol of *m*-chloroperbenzoic acid in 3 mL of dry CH_2Cl_2 from a 5-mL pressure-equalizing dropping funnel, while the reaction mixture was stirred magnetically and maintained at −20 °C. After the mixture was stirred for 0.5 h at −20 °C, the precipitated *m*-chlorobenzoic acid was removed by filtration and washed with 20 mL of cold CH_2Cl_2. The filtrate was washed twice with 20-mL portions of saturated $NaHCO_3$ solution and dried over anhydrous $MgSO_4$. The solvent was removed at reduced pressure and the residue subjected to preparative TLC to afford the epoxide (**19**) in 24% yield as a colorless liquid.

Acknowledgment. The authors from Reno gratefully acknowledge the National Science Foundation, the National Institutes of Health (NCI CA23488), and the donors of the Petroleum Research Fund, administered by the American Chemical Society for financial support. The authors from Pittsburgh are grateful to the National Science Foundation for financial support of this research. We also thank Dr. Y. N. Gupta and Dr. A. Marcus for recording mass spectra.

Registry No. 1, 67313-66-0; **2**, 84-58-2; **3**, 670-54-2; **5**, 4233-33-4; **6**, 1972-28-7; **7**, 1189-71-5; **8**, 4591-28-0; **9**, 81457-35-4; **10**, 81457-36-5; **11**, 81457-37-6; **12**, 81457-38-7; **13**, 81457-39-8; **14**, 81457-40-1; **15**, 81478-22-0; **19**, 81478-23-1; Cl_3CCOCl, 76-02-8; O_2, 7782-44-7.

Role of Cyclohexaamylose C-3 Hydroxyls in Catalytic Hydrolysis

Raymond J. Bergeron* and Philip S. Burton†

Contribution from the Department of Medicinal Chemistry, J. Hillis Miller Health Center, University of Florida, Gainesville, Florida 32610. *Received February 23, 1981*

Abstract: Both the static and dynamic aspects of the sodium 4-nitrophenolate and the sodium 2,6-dimethyl-4-nitrophenolate/dodecakis-2,6-*O*-methylcyclohexaamylose complexes are investigated. The geometries of these complexes are determined on the basis of intermolecular homonuclear nuclear Overhauser enhancements and chemical shift analysis while the dynamic parameters of complexation, i.e., rotational correlation times and coupling constants, are calculated from $^{13}C[^1H]$ T_1 measurements. Comparison of these results with analogous measurements of the unmethylated cyclohexaamylose inclusion complexes of these same substrates indicates that the substrates are prevented from equivalent penetration of the methylated derivative. This casts some doubt upon the premise that the cyclohexaamylose 3-hydroxyls are inherently unreactive and therefore uninvolved in cyclohexaamylose-catalyzed hydrolyses.

In recent years, the cycloamyloses have received substantial attention as enzyme active site models.[1,2] These cyclic oligosaccharides have been shown to complex a variety of guest molecules in their hydrophobic interiors[3,4] and in some cases catalyze the reaction of the guest molecule.[5,6] Major research efforts involving these systems have focused on the chemical modification of the cycloamylose cavity with the goal of improving their catalytic abilities and/or expanding the scope of reactions that they catalyze.[7,8] In all of the cycloamylose-catalyzed hydrolyses of guest molecules, it has been assumed that the cyclo-

---

† Department of Chemistry, Harvard University, Cambridge, MA 02138.

(1) F. Cramer and H. Hettler, *Naturwissenschaften*, **54**, 625 (1967).

(2) D. W. Griffiths and M. L. Bender, *J. Am. Chem. Soc.*, **95**, 1679 (1973).

(3) K. Vekama, M. Otagiu, Y. Kamie, S. Tanaka, and K. Ikeda, *Chem. Pharm. Bull.*, **23**, 1421 (1975).

(4) R. Gelb, L. M. Schwartz, C. T. Murray, and D. A. Laufer, *J. Am. Chem. Soc.*, **100**, 3553 (1978).

(5) D. W. Griffiths and M. L. Bender, *Adv. Catal.*, **23**, 209 (1973).