# Photodecarbonylation of *cis*- and *trans*-2,7-Dimethyl-3,5-cycloheptadienones: Applicability of Orbital Symmetry Theory to Photochemical Cheletropic Fragmentations[1,2]

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Abstract: A stereochemical test was conceived to determine if the photochemical extrusion of carbon monoxide from 3,5-cycloheptadienones to give 1,3,5-hexatrienes is a concerted process, and thus an example of a photochemical cheletropic fragmentation. The *cis*- and *trans*-2,7-dimethyl derivatives of this ring system were synthesized. Spectroscopic data could not distinguish unambiguously between the two materials, and configurations were therefore assigned to the two dienones based on the NMR spectra of the adducts of the dienones and the reactive dienophile PTAD and an X-ray crystal structure of the cis adduct. The several isomeric 2,4,6-octatrienes were prepared and their photoisomerization was studied preliminary to study of the photolysis of the dienones. Since no conditions could be found which afforded fragmentation of the dienones without secondary isomerization of the trienes, the composition of the product mixture was determined as a function of time on excitation of the dienones at 313 nm. It was found that the isomeric dienones indeed gave different triene photoproducts, the *cis*-dienone affording the (*E,Z,Z*)-octatriene and the *trans*-dienone affording the (*Z,Z,Z*)-octatriene. In both cases, these products were the predominant if not exclusive initial products, with other trienes appearing soon afterward. It is concluded that these photochemical reactions proceed by a concerted reaction path, involving conrotatory opening of the cycloheptadienone ring system. The same course of reaction was observed some time ago for thermal cleavage of the analogous cyclic sulfones. Various theoretical rationales for this behavior are discussed. The photochemical reactions clearly do not follow the predictions for a linear cheletropic reaction, and a nonlinear path is a distinct possibility. However, the formation of the relatively strained (*Z,Z,Z*)-triene from the *trans*-2,7-dimethylcycloheptadienone is difficult to rationalize on the basis of any concerted mechanism except by invoking the principle of least nuclear motion. Thus, reaction of the *trans*-dienone appears to proceed selectively from the conformation in which both methyls are pseudoaxial, which according to MM2 calculations is less stable than the diequatorial conformation in the electronic ground state by 2.7 kcal/mol. It is suggested that orbital symmetry may not play a major role in controlling the course of this type of photochemical cheletropic reaction.

The extrusion of carbon monoxide on UV irradiation of 3,5-cycloheptadienones in solution at ambient temperatures to give 1,3,5-hexatrienes (eq 1) was discovered over 20 years ago by Chapman and co-workers.[3] This reaction is an example of a

$$\text{(eq 1)}$$
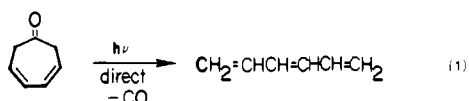
photochemical cheletropic reaction, as defined several years later by Woodward and Hoffmann.[4] We determined that this reaction is not affected by typical quenchers of triplet excited states and is not observed on sensitized excitation using typical triplet sensitizers (which usually leads to the well-known oxa-di-π-methane rearrangement),[5] suggesting that decarbonylation occurs directly from the lowest singlet excited state of the cycloheptadienone.[6,7] Although the observations are consistent with a concerted reaction mechanism for loss of CO involving synchronous cleavage of both bonds to the carbonyl carbon, a stepwise mechanism involving initial breaking of only one C–C bond to give an intermediate 1,7 acyl–alkyl diradical could not be rigorously excluded.[7] A possible way to distinguish between these alternative mechanisms is to determine the stereochemical course of the reactions of stereoisomeric 2,7-disubstituted cycloheptadienones. If the reaction is a concerted cheletropic fragmentation, stereochemically distinct trienes should be initially formed on irradiation of diastereomeric cis and trans starting materials. However, if the reaction occurs in a stepwise fashion following an initial one-bond cleavage, one would not expect to observe stereospecificity.

After a number of unsuccessful attempts, we succeeded in preparing *cis*- and *trans*-2,7-dimethyl-3,5-cycloheptadienones, **1** and **2**, in assigning the configurations to these highly unstable

Chart I
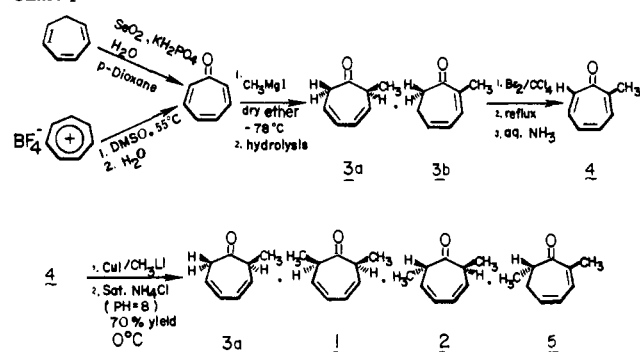
materials unambiguously,[8] and in determining the stereochemistry of the 2,4,6-octatrienes formed upon UV irradiation of **1** and **2** in cyclohexane.[9] The study was severely complicated by the fact

(1) Part 75 of a series on the photochemistry of ketones in solution. Part 74: Dunn, D. A.; Schuster, D. I.; Bonneau, R. *J. Am. Chem. Soc.* **1985**, *107*, 2802.

(2) Taken from the Ph.D. Dissertation of L. Wang, New York University, 1983.

(3) Chapman, O. L.; Borden, G. W. *J. Org. Chem.* **1961**, *26*, 4185. Chapman, O. L.; Pasto, D. J.; Borden, G. W.; Griswold, A. A. *J. Am. Chem. Soc.* **1962**, *84*, 1220.

(4) Woodward, R. B.; Hoffmann, R. "The Conservation of Orbital Symmetry"; Verlag Chemie/Academic Press: New York, 1970.

(5) This characteristic reaction of β,γ-unsaturated ketones has been reviewed. See: Houk, K. N. *Chem. Rev.* **1976**, *76*, 1. Schuster, D. I. "Rearrangements in Ground and Excited States"; de Mayo, P., Ed.; Academic Press: New York, 1980; Vol. 3, Essay 17.

(6) Schuster, D. I.; Sckolnick, B. R.; Lee, F.-T. H. *J. Am. Chem. Soc.* **1968**, *90*, 1300.

(7) Schuster, D. I.; Eriksen, J. *J. Org. Chem.* **1979**, *44*, 4254.

(8) For a preliminary report on the synthesis and configurational assignments of these ketones, see: Wang, L.; Schuster, D. I.; van der Veen, J. M. *Tetrahedron Lett.* **1983**, *24*, 2627.

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that the trienes absorb light more strongly than their precursors at the excitation wavelengths utilized, resulting in secondary photoisomerization,[10] necessitating determination of the product distribution as a function of the extent of reaction. Having found, as will be described below, that different products are indeed formed initially upon irradiation of 1 and 2, we could then consider the implications of these findings in the context of various theoretical predictions for cheletropic fragmentations of electronic excited states.[4,11]

1   2

Results

Synthesis of *cis*- and *trans*-2,7-Dimethyl-3,5-cycloheptadienones (1 and 2). A report[12] that the desired cycloheptadienones could be prepared by reaction of chlorocarbene with *o*-cresol followed by methylation using methyllithium could not be reproduced in our laboratory. In our hands, the only identifiable product was 2-methyl-3,5-cycloheptadienone (3a). The successful synthetic approach shown in Chart I has previously been described,[8] along with the problems associated with separation and unambiguous identification of 1 and 2. These compounds are highly unstable, undergoing facile isomerization to the conjugated isomer 5 under a variety of conditions, including treatment with dilute acid or base, column chromatography on silica gel or alumina, and vapor chromatography, and even upon extended storage in the refrigerator.

1   7   m.p.: 219–220°C

2   7   m.p.: 177–178°C

Spectral data and molecular mechanics calculations (see below) clearly demonstrate that 3,5-cycloheptadienones possess a twofold axis of symmetry passing through the C=O group and the center of the diene moiety.[3,6,7] NMR spectra of the parent compound **6a** as well as the 2,2,7,7-tetramethyl analogue **6b** indicate that these molecules undergo rapid flipping at room temperature around the C_2 axis, equilibrating groups in pseudoaxial and pseudoequatorial positions. The barrier associated with this conformational equilibration has yet to be determined. Thus, in the *cis*-dienone **1** the two methyls, which should occupy distinct pseudoaxial and pseudoequatorial orientations in a conformationally fixed molecule, as illustrated in Figure 1, are indistinguishable by ^{1}H and ^{13}C NMR. In the trans isomer **2**, which has C_2 symmetry, the two methyls are at a given instant of time either

Figure 1. Conformational equilibration of cycloheptadienones 1 and 2.

Figure 2. ORTEP drawing of the adduct of *cis*-2,7-dimethyl-3,5-cycloheptadienone (1) and PTAD as determined by X-ray crystallography.

both pseudoaxial or pseudoequatorial, again resulting in NMR equivalence. The question of the populations of the two conformers of the *trans*-dienone **2** in the ground state as well as the excited state turns out to be of crucial significance for this study. Since the room-temperature NMR spectra do not distinguish between the cis and trans isomers **1** and **2**, Diels–Alder adducts of the dienones were prepared with the very reactive dienophile PTAD (7)[15] at 0 °C under conditions which did not cause isomerization to **5**. The ^{1}H and ^{13}C NMR spectra of the PTAD adduct of the *cis*-dienone **1** show only one signal for the methyl groups, while two signals are clearly distinguishable in the spectra of the PTAD adduct of **2**. To unequivocally confirm these assignments, an X-ray crystallographic study of one of these PTAD adducts was carried out.[8] An ORTEP drawing of the final structure of the PTAD adduct of the *cis*-dienone is shown in Figure 2. Full details of this structure determination are given in the Experimental Section and in supplementary material.

Synthesis and Structure Assignments to the Diastereomeric 2,4,6-Octatrienes. The stereoisomeric (E,Z,E)-, (E,Z,Z)-, and (Z,Z,Z)-2,4,6-octatrienes **8**, **9**, and **10** were synthesized by the procedure of Marvell and co-workers,[16] with slight modifications.

8   9   10   11

49%   18%   33%

(9) For a preliminary report on these photochemical studies see: Schuster, D. I.; Wang, L. *J. Am. Chem. Soc.* **1983**, *105*, 2900.

(10) For a review of the photochemistry of trienes, see: Dauben, W. G.; McInnis, E. L.; Michno, D. M. In "Rearrangements in Ground and Excited States"; de Mayo, P., Ed., Academic Press: New York, 1980; Vol. 3, Essay 14.

(11) Fleming, I. "Frontier Orbitals and Organic Chemical Reactions"; Wiley/Interscience: Chichester, 1976; p 95 ff. See also: Houk, K. N. In "Pericyclic Reactions"; Marchand, A. P., Lehr, R. E., Eds.; Academic Press: New York, 1977; Vol. II, pp 181–271.

(12) Closs, G. L.; Closs, L. E. *J. Am. Chem. Soc.* **1961**, *83*, 599.

(13) Nozoe, T.; Mukai, T.; Tezuka, T. *Bull. Chem. Soc. Jpn.* **1961**, *34*, 619. See also: Chapman, O. L.; Pasto, D. J.; Griswold, A. A. *J. Am. Chem. Soc.* **1962**, *84*, 1218.

(14) Bagli, J. F.; St.-Jacques, M. *Can. J. Chem.* **1978**, *56*, 578.

(15) Cookson, R. C.; Gupte, S. S.; Stevens, L. D. R.; Watts, C. T. *Org. Synth.* **1969**, *51*, 121.

(16) Marvell, E. N.; Caple, G.; Schatz, B. *Tetrahedron Lett.* **1965**, *7*, 285; *Tetrahedron* **1973**, *29*, 3781. Schatz, B. S. Ph.D. Dissertation, Oregon State University, 1967. See also: Rennekamp, M. E.; Hoffman, M. K. *Tetrahedron* **1975**, *10*, 1075.

Details are given in the Experimental Section. Pure samples (≥96% homogeneity) of each of these trienes were obtained by preparative GLC separation. The assignments of structure to the trienes were based on their ^{1}H NMR and UV spectra and comparison with data for these compounds reported in the literature[16] (see Experimental Section). The (*E,E,E*)-2,4,6-octatriene 11 was prepared by irradiation of a mixture of the three other trienes and was isolated by preparative GLC as a crystalline solid whose properties agreed well with those given in the literature.[17] Mixtures of the four trienes could be quantitatively analyzed by GLC with use of *n*-tridecane as an internal standard (see Experimental Section). The two other possible isomers, namely the (*Z,E,Z*)- and (*E,E,Z*)-octatrienes, cannot be synthesized by this approach. In experiments in which the trienes were recovered from photoisomerization experiments by preparative GLC and subjected to UV and GLC analysis, there was no indication of the formation of additional trienes. While we cannot absolutely exclude the possibility that the (*Z,E,Z*)- and (*E,E,Z*)-octatrienes co-elute with 8, 9, or 10, we assume that some differences in the UV spectra of the recovered trienes would have been noticed if the unknown isomers were present in significant quantities.

Photoisomerization of the 2,4,6-Octatrienes. It was recognized at the outset of this study that secondary photoisomerization of the trienes initially produced on photodecarbonylation of 1 and 2 would be a serious problem.[10] Irradiation of pure samples of trienes 8 and 9 at room temperature in cyclohexane at 300 nm resulted in rapid isomerization to a mixture of 8, 9, and 11 (23%, 54%, and 18%, respectively) after only 10 min. UV spectra and GLC analysis of these mixtures gave no indication of the formation of the two other possible triene isomers, namely the *E,E,Z* and *Z,E,Z* isomers, although we cannot absolutely exclude the possibility of their formation in small quantities which would have escaped such detection. We will therefore assume in the following discussion that these isomers were not formed on irradiation of 8 and 9, nor of 1 and 2 (see below). It was not determined if the above triene mixture represents the photostationary state under these conditions. At 350 nm, photoisomerization of 8 and 9 was much less efficient, representing excitation in the tail of the UV spectra of the trienes. After 90 min of irradiation, mixtures of 8, 9, and 11 were produced which were clearly far from the photostationary state. Irradiation of the *cis*-dienone 1 for 24 h at 350 nm led to no detectable amounts of these trienes by GLC analysis, while they were easily detected after a few minutes of irradiation at 300 nm.

Accordingly, irradiations of 8 and 9 were carried out at 313 nm on an optical bench, utilizing a 200-W high-pressure mercury lamp and a grating monochromator with a Corning 5970 filter to remove stray light. The light beam was split by a fused silica disc into a sample and reference beam, and the sample and reference cuvette holders were jacketed for constant temperature control. Ten minutes of irradiation of trienes 8 and 9 under these conditions resulted in about 20% isomerization to mixtures of 8, 9, and 11 (see earlier discussion for possible qualification). The data indicate that the *E,Z,Z*-triene 9 initially isomerizes to the *E,Z,E*-triene 8, which then finally isomerizes to the *E,E,E* isomer 11. Again, these reactions did not appear to reach a photostationary state. It is important to note that none of the *Z,Z,Z*-triene 10 could be detected among the products of irradiation of trienes 8 and 9 under any of the conditions utilized, indicating that isomerization to this isomer is particularly unfavorable, presumably for steric reasons. An unidentified minor product was noted on irradiation of triene 8 at 313 nm, which could be one of the two unknown isomers (see above).

Irradiation of Cycloheptadienones 1 and 2. These ketones were irradiated at 313 nm as described above, and the products were analyzed by GLC every few minutes. In preliminary experiments, the main products observed at very short irradiation times were the *E,Z,Z*-triene 9 from the *cis*-dienone 1 and the *Z,Z,Z*-triene 10 from the *trans*-dienone 2. Tables I and II show the time course

(17) Vroegop, P. J.; Lugtenburg, J.; Havinga, E. *Tetrahedron* **1973**, *29*, 1393.

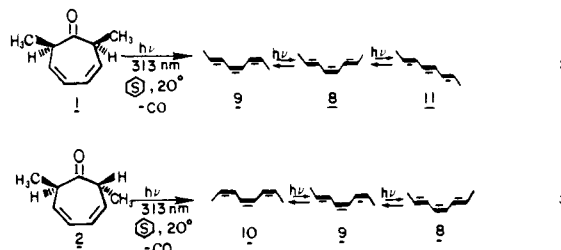**Table I.** Irradiation of *cis*-2,7-Dimethyl-3,5-cycloheptadien-1-one (1) Containing 0.01 M *n*-Tridecane at 313 nm (20 °C) in Cyclohexane Solution[a]

irrad. time, min	(E,E,E)	(E,Z,E)	(E,Z,Z)
	Run A[b]		
0			
2.0		0.003	0.019
8.0	0.0045	0.017	0.044
15.0	0.0060	0.020	0.057
21.0	0.015	0.025	0.056
27.0	0.019	0.027	0.072
36.0	0.020	0.029	0.080
	Run B[c]		
0.0			
2.0			0.022
5.0	0.0009	0.014	0.028
15.0	0.0090	0.027	0.049
20.0	0.0182	0.030	0.066
25.0	0.0199	0.035	0.075

[a] Numbers listed are the ratio of peak areas of trienes to internal standard (GC). [b] Ketone 0.069 M. [c] Ketone 0.078 M.

Table II. Irradiation of *trans*-2,7-Dimethyl-3,5-cycloheptadien-1-one (2) Containing 0.01 M *n*-Tridecane at 313 nm (20 °C) in Cyclohexane Solution[a]

irrad. time, min	(E,Z,E)	(E,Z,Z)	(Z,Z,Z)
	Run A		
0.0			
2.0			0.042
4.0			0.092
6.0	0.0023	0.0050	0.129
10.0	0.0030	0.0060	0.190
15.0	0.0045	0.0105	0.204
20.0	0.0060	0.0120	0.213
25.0	0.0090	0.0330	0.219
	Run B		
0.0			
1.0			0.033
2.0			0.046
3.0			0.056
4.0			0.072
5.0			0.110
6.0	0.0019	0.002	0.120
9.0	0.0028	0.006	0.179
10.0	0.0044	0.018	0.193
20.0	0.0090	0.025	0.202
25.0	0.0120	0.030	0.223

[a] See Table I. [b] Ketone 0.061 M. [c] Ketone 0.060 M.

of the product distribution from each of these dienones from two independent runs. Additional runs (data not shown) gave consistent results. The data from run A for each dienone are plotted in Figures 3 and 4. No evidence was obtained for formation of trienes other than 8, 9, 10, and 11.

It appears that the *Z,Z,Z*-triene 10 is the sole initial product of the *trans*-dienone 2 and that this triene subsequently undergoes secondary isomerization to the *Z,Z,E*-triene 9 which then isomerizes to the *E,Z,E*-triene 8. Similarly, excitation of the *cis*-dienone 1 results in predominant formation of the *Z,Z,E*-triene 9, which subsequently isomerizes to trienes 8 and 11. These transformations are summarized in eq 2 and 3. While the data are consistent

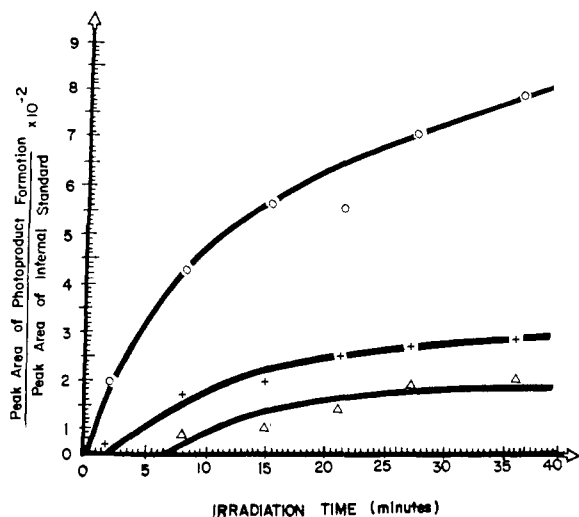with stereospecific formation of 9 from 1, we cannot exclude the

Figure 3. Products from irradiation of *cis*-dienone **1** (0.069 M) in cyclohexane at 313 nm (20 °C) as a function of time. Photoproducts **9**, **8**, and **11** [(*E,Z,Z*)-, (*E,Z,E*)-, and (*E,E,E*)-2,4,6-octatriene, respectively] are represented by O, +, and △, respectively.
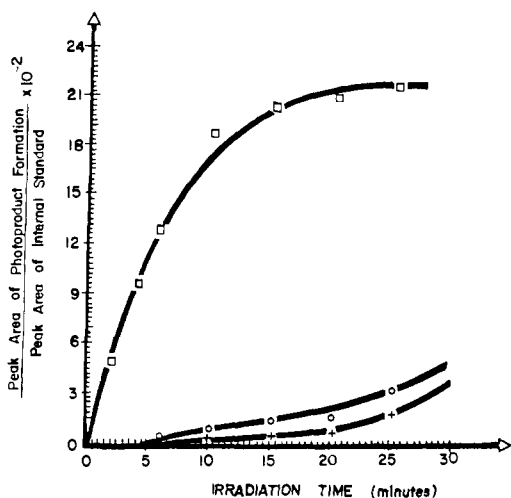

Figure 4. Products from irradiation of *trans*-dienone **2** (0.061 M) in cyclohexane at 313 nm (20 °C). Photoproducts **10**, **9**, and **8** [(*Z,Z,Z*)-, (*E,Z,Z*)-, and (*E,Z,E*)-2,4,6-octatriene, respectively] are represented by □, O, and +, respectively.

possibility that triene **8** may be formed at least in part as a primary rather than a secondary product. In any event, it is clear that photodecarbonylation of **1** and **2** leads to different diastereomeric 2,4,6-octatrienes, suggesting that these reactions are at least stereoselective, and may well be stereospecific, No interconversion of dienones **1** and **2** was noted during these irradiations.

Discussion

Stepwise vs. Concerted Reaction Mechanisms. A stepwise mechanism for the photodecarbonylation of 3,5-cycloheptadienones would have consequences which are inconsistent with the experimental observations in this study. If the initial bond cleavage to give a 1,7 acyl–alkyl diradical were reversible, one would expect to see interconversion of stereoisomeric starting materials, provided that rotation around the C–C bond at the alkyl radical end was competitive in rate with cyclization. No such interconversion of **1** and **2** concomitant with loss of CO was detected under the irradiation conditions. Interconversion of stereoisomers has been observed on irradiation of cyclohexanones,[18] indicating that in principle such a process can compete with other photochemical processes. Second, if the 1,7-diradical was a true intermediate,

(18) Badcock, C. C.; Perona, M. J.; Pritchard, G. O.; Rickborn, B. *J. Am. Chem. Soc.* **1969**, *91*, 543. Alumbaugh, R. L.; Pritchard, G. O.; Rickborn, B. *J. Phys. Chem.* **1965**, *69*, 3225.

there should be some lag in time before CO was lost, in which case the thermodynamic stability of the possible triene products should be an important determinant of product ratios. On the basis of a diradical mechanism not only would one expect to see mixtures of products from each of the starting dienones, one would *not* expect to see a clear bias toward the formation of the relatively unstable *Z,Z,Z*-triene **10** from the *trans*-dienone **2**, in preference to one of the more stable isomeric trienes. We note once again that irradiation of trienes **8** and **9** gave no detectable quantities of **10**, indicative of the relatively high energy of **10** due to severe nonbonded interactions in *s-trans* as well as *s-cis* conformations.

We conclude from the reaction stereochemistry that the mechanism which best describes the decarbonylation of 3,5-cycloheptadienones is one involving synchronous cleavage of both bonds to the carbonyl carbon, that is, a concerted mechanism. It should be recalled that there are considerable data which demonstrate that decarbonylation originates from the lowest excited singlet state of the dienone,[6,7,19,20] so that there is no spin correlation problem in the electronic reorganization necessary for this reaction.

Although quantum yields were not measured in this study, the efficiency of triene formation is qualitatively comparable to that of the parent system **6a** which has been determined to be 0.74 at 313 nm.[6] No triplet state ODPM rearrangement products are seen on direct excitation of **1** and **2**, contrary to the situation with the tetramethylcycloheptadienone **6b**, where the quantum efficiency for decarbonylation is reduced to 0.11 while the efficiency of intersystem crossing rises to 0.36.[7]

The present observations summarized in eq 2 and 3 demonstrate that triene formation involves conrotation at carbon atoms 2 and 7 as the predominant if not exclusive course of this photochemical cheletropic reaction. Because of the thermal instability of compounds **1** annd **2**, it was not possible to determine the stereochemistry associated with loss of CO on thermolysis of these compounds.[21] These findings can, however, be compared with the behavior of the analogous sulfones **12** and **13**, which undergo thermal extrusion of SO_2 to give trienes **9** and **8**, respectively, as shown in eq 4 and 5.[22] This ground-state cheletropic reaction also occurs with conrotation at the end carbons of the incipient triene, i.e., carbons 2 and 7 of the sulfones. An important difference is that conrotatory ring opening of the *trans*-dimethyl sulfone **13** gives exclusively the *E,Z,E*-triene **8** and not the alternative *Z,Z,Z*-triene **10**, while photochemical conrotatory ring opening of the *trans*-dimethylcycloheptadienone **2** gives **10** to the virtual exclusion of **8**. We shall return to this important point later in the discussion.

Orbital Symmetry Theory of Cheletropic Fragmentations. Linear vs. Nonlinear Processes. In their original discussion of cheletropic reactions, Woodward and Hoffmann noted that both linear and nonlinear processes could be envisaged.[4] The distinction is that in a linear cheletropic reaction, the cheleofuge (usually a small neutral molecule such as CO, N_2, SO_2, or :CH_2) departs along the axis of symmetry of the starting material. In the case of ketones **1** and **2**, this corresponds to the C_2 axis of the dienone moiety. The orbital correlations are opposite for these two modes of reactions, as is most easily visualized by considering the reverse reaction, namely the addition of the cheleofuge to a polyene.[11] The bonding of the cheleofuge to the polyene can be either suprafacial or antarafacial, where the former corresponds to a disrotatory mode of ring opening while the latter corresponds to conrotation. In systems such as 3-pyrrolines **14** or 3-cyclopentenone **15**, where these two modes of reaction correspond to preservation throughout the reaction of a plane or axis of symmetry, respectively, these two modes of reaction have been termed sigmasymmetric and axisymmetric.[23] In the ground state, orbital

(19) Houk, K. N.; Northington, D. J. *J. Am. Chem. Soc.* **1972**, *94*, 1387. Mukai, T.; Aksaki, Y.; Hagiwara, T. *Ibid.* **1972**, *94*, 675.
(20) Schuster, D. I.; Kim, C. W. *J. Am. Chem. Soc.* **1974**, *96*, 7437.
(21) It is possible that the thermal decarbonylation of these dienones can be studied by using flash thermolysis under conditions which do not lead to structural isomerization.
(22) Mock, W. L. *J. Am. Chem. Soc.* **1969**, *91*, 5682.
(23) Lemal, D. M.; McGregor, S. D. *J. Am. Chem. Soc.* **1966**, *88*, 1335.

symmetry correlations[4] and HOMO–LUMO considerations[11] predict that concerted linear cheletropic fragmentations which yield polyenes with $4n$ π electrons should be disrotatory (sigma-symmetric) while those reactions giving polyenes with $(4n + 2)$ π electrons should be conrotatory (axisymmetric). Thermolysis of substituted 3-pyrrolines **14**[23] and of the corresponding cyclic sulfones (sulfolenes) **16**[24,25] to give substituted 1,3-butadienes and N_2 and SO_2, respectively, occurs stereospecifically in a sigma-symmetric (disrotatory) manner, which is consistent with the theoretical predictions for a linear ground-state cheletropic re-action. Similarly, the conrotatory behavior observed for thermal expulsion of SO_2 from the isomeric sulfolenes **12** and **13** (eq 4 and 5) is also in accord with theoretical predictions for a
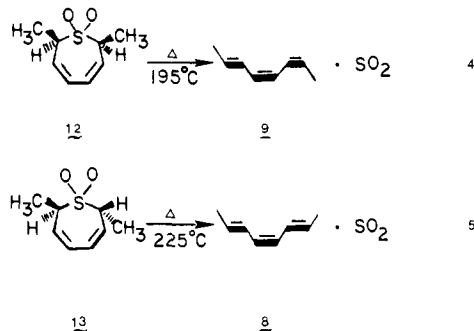
ground-state linear cheletropic reaction.[22] Such stereochemical correlations support the contention that these thermal fragmentations proceed via a concerted as opposed to a stepwise mechanism. However, as pointed out by Mock,[25] the fact that the experimental results in a few cases are in accord with the hypothesis can only be taken as an inference that the hypothesis is correct, since other factors (e.g., steric considerations) may offer sufficient explanation for the observed stereospecificities.

Recent theoretical (MINDO) calculations[26] indicate that in general ground-state cheletropic fragmentations and reverse cycloadditions, although probably concerted (that is, one-step reactions), are not synchronous processes, i.e., in general they ought to take place via highly unsymmetrical transition states which in some cases may lead to biradical-like species. In general, Dewar has contended that multibond reactions cannot normally be synchronous.[27] It should be noted, however, that this conclusion may well be a result of the method of calculation (MINDO), since a similar conclusion that the Cope rearrangement proceeds via an unsymmetrical transition state (i.e., in a nonsychronous manner) was found not to be true at a higher level of theory (3-21G MCSCF), which predicted a transition state of C_{2h} symmetry.[28] Similar higher order calculations on cheletropic reactions, either in the ground or excited states, have not been reported.

In general, the "selection rules" for pericyclic reactions of electronic excited states are reversed from those for the corresponding ground-state reactions.[4] The assumption that such a reversal also holds for cheletropic reactions leads to the prediction that a linear fragmentation leading to a polyene with $4n$ π electrons ought to occur with conrotation, while disrotation should be seen on analogous formation of a polyene with $(4n + 2)$ π electrons. The reverse predictions would hold for nonlinear processes. The observation in this study that photodecarbonylation of **1** and **2** takes place with conrotation, the same mode of reaction seen on thermolysis of the structurally analogous sulfolenes **12** and **13**,[22] is not in accord with theoretical predictions for a linear cheletropic excited-state reaction but is consistent with either nonlinear extrusion of CO on the excited-state surface or linear extrusion of

CO in a vibrationally excited ground state formed upon radiationless decay from the S_1 energy surface. These possibilities will be considered below, along with other factors which may influence the stereochemical course of this reaction.

On the basis of measurements of circular dichroism and cicular polarization of the luminescence of n → π* transitions of a number of β,γ-unsaturated ketones, Dekkers et al.[29] concluded that the carbonyl group is not planar in the S_1 (^{1}n, π*) state of such ketones, but rather becomes pyramidal with displacement of the oxygen toward the C=C bond. Such a distortion of the geometry of the S_1 state of **1** and **2** could promote a nonlinear pathway for expulsion of CO. However, the C_2 symmetry of the 3,5-cycloheptadienone chromophore would allow displacement of the carbonyl oxygen in opposite directions with respect to the C_2 axis, such that on average the carbonyl moiety might still lie along the symmetry axis. However, if flipping of the CO group between the two pyramidal configurations were slow compared with expulsion of CO, a nonlinear process for decarbonylation might be favored.

Obviously, it is not a simple matter to experimentally distinguish a linear from a nonlinear cheletropic pathway, except perhaps by studies of rotational and vibrational spectra of the cheleofuge in vapor-phase reactions. Such a study has in fact been recently reported by Rosenfeld and co-workers for decarbonylation of 3-cyclopentenone **15**[30] and 3,5-cycloheptadienone (CHD) **6a**.[31] From analysis of the vibrational excitation of the CO extruded, these authors conclude that these ketones react by fundamentally different mechanisms. In both cases, the authors conclude that decarbonylation occurs after radiationless decay to the ground-state surface at a geometry corresponding to the transition state for fragmentation. In the case of **15**, "the two fragments are vibrationally decoupled from one another early in the exit channel, i.e., near the transition state", and "the "reaction coordinate ... corresponds to a linear or least motion cheletropic dissociation", pictured as **17**.[30,31] Although it is not explicitly stated whether
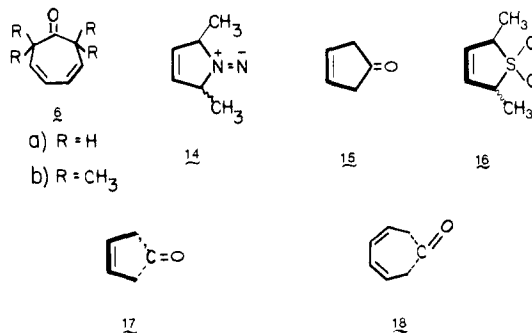
this corresponds to conrotatory or disrotatory ring opening, it seems safe to assume that a disrotatory (sigmasymmetric) pathway is implied. For ring opening of **6a**, the products' degrees of freedom are coupled well into the exit channel, implying that "on average, the products formed in the dissociation of CHD remain in closer proximity for a longer period of time than in the case of 3-cyclopentenone".[31] This is interpreted by the authors to indicate a "nonlinear (non-least motion) concerted dissociation or a stepwise fragmentation process, involving a biradical intermediate".[31] The transition state for the nonlinear concerted mechanism is depicted as **18**, clearly implying disrotatory ring opening of CHD. However, the authors did not appear to consider the possibility of linear and nonlinear transition-state geometries which would allow conrotatory ring opening. Such geometries are especially likely in a twisted CHD ring system of C_2 symmetry and represent the most likely least-motion reaction pathways (see further discussion below). Furthermore, their conclusions regarding ketone **15** are

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(25) For a review of cheletropic reactions, see: Mock, W. L. In "Pericyclic Reactions"; Marchand, A. P., Lehr, R. E., Eds.; Academic Press: New York, 1977; Vol. II, pp 141–179.

(26) Dewar, M. J. S.; Chantranupong, L. *J. Am. Chem. Soc.* **1983**, *105*, 7152, 7161.

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(28) Osamura, Y.; Kato, S.; Morokuma, K.; Feller, D.; Davidson, E. R.; Borden, W. T. *J. Am. Chem. Soc.* **1984**, *106*, 3362.

(29) Schippers, P. H.; van der Ploeg, J. P. M.; Dekkers, H. P. J. M. *J. Am. Chem. Soc.* **1983**, *105*, 84.

(30) Sonobe, B. I.; Fletcher, T. R.; Rosenfeld, R. N. *J. Am. Chem. Soc.* **1984**, *106*, 4352.

(31) Sonobe, B. I.; Fletcher, T. R.; Rosenfeld, R. N. *J. Am. Chem. Soc.* **1984**, *106*, 5800.

7050 *J. Am. Chem. Soc., Vol. 107, No. 24, 1985*

Schuster et al.

at odds with the observations of Turro and co-workers,[32] who found that photodecarbonylation of ketones **19a,b** (eq 6) occurs not from

or **19a**

$$\xrightarrow[-CO]{h\nu}$$

19b

(Z,Z)   (Z,E)   (E,E)   6'
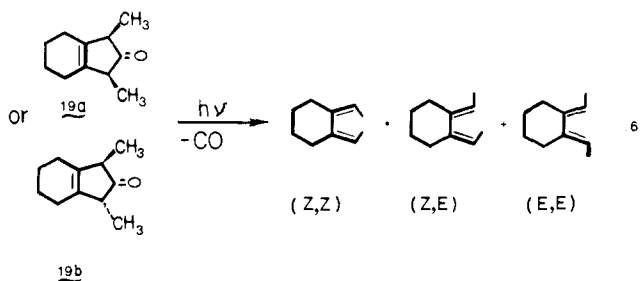
the S_1 state but from a triplet n,π^* state in a nonstereospecific manner; the products are thought to arise from competing concerted nonlinear axisymmetric and linear sigmasymmetric pathways.

The selection rules for pericyclic reactions are of course based upon consideration of correlations of orbital symmetry of reactant and product molecular orbitals.[4] This is a relatively straightforward matter for transformations such as electrocyclic ring openings and ring closures and cycloadditions of π systems. However, complications arise for cheletropic reactions because of the role of nonbonding orbitals on the cheleofuge, and an additional problem for photochemical reactions concerns the electronic configuration of the reactant electronic excited state. In the present case, spectra[33] and calculations[34,35] indicate that the S_1 state of 3,5-cycloheptadienones is predominantly (ca. 80%) n,π^* in character, but there are substantial contributions from other electronic configurations. Assuming the usual simple orbital description of an n,π^* excited state,[36,37] direct formation of ground-state CO and a triene would require a molecular twisting motion to pair the electrons that indeed corresponds to conrotation at C_2 and C_7. Thus, the electronic configuration of the excited state may well influence or even control the steric course of this reaction, in which case the usual[4] orbital symmetry considerations are largely irrelevant.

Conformational Control of Reaction Stereochemistry. Least-Motion Considerations. Examination of molecular models of **1** and **2** reveals that conformational factors are probably playing a major role in these cheletropic reactions. In the twisted C_2 geometry of these dienones, the groups located in pseudoequatorial positions at C_2 and C_7 are nearly coplanar with the vinylic substituents at C_3 and C_6. Therefore, considerations of least nuclear motion[38] suggest that these two pairs of substituents should end up in a cis relationship in the product triene after CO is expelled. Indeed, the motion required to achieve this orientation in the product, which involves little more than rehybridization at C_2 and C_7, corresponds to conrotation. This leads to the prediction that cis-2,7-Me$_2$-CHD, **1**, where one methyl is pseudoequatorial and the other is pseudoaxial, should give the (Z,Z,E)-2,4,6-octatriene, as observed. For trans-2,7-Me$_2$-CHD, **2**, two conformations are possible, as mentioned earlier, one with both methyls pseudoequatorial and the other with both methyls pseudoaxial. Analogous least-motion considerations predict that the former should lead directly to the E,Z,E-triene **8** while the latter should afford the Z,Z,Z-triene **10**. Indeed, there seems no plausible way for **10** to

be formed other than from the conformation of **2** with pseudoaxial methyl groups, since any other conformation would be expected to give one of the other more stable trienes as the major reaction product. We are therefore forced to conclude that the photodecarbonylation of trans-dienone **2** takes place virtually exclusively via the conformation with diaxial methyl groups.

It thus became important to determine the relative energies of the two possible twisted conformations of the trans-dienone **2** of C_2 symmetry. Molecular mechanics calculations were carried out using a modified Allinger MM2 program appropriately parametrized for conjugated double bonds,[39] with minimization to achieve the most favorable molecular geometry for both the diaxial (di-ax) and diequatorial (di-eq) conformations. For each, a twisted molecular geometry with C_2 symmtry was calculated to be most favorable. The di-eq conformer of **2** was found to be 2.66 kcal/mol more stable than the di-ax conformer. This corresponds at room temperature to a conformer population of 99% di-eq and only 1% di-ax. Qualitative examination of Dreiding molecular models, however, does not indicate particularly severe nonbonded interactions in the di-ax conformer. In principle the conformer population and the ring-flip barrier could be determined experimentally with use of low-temperature NMR, but this has yet to be accomplished.

The finding that photodecarbonylation of **2** produces the (Z,Z,Z)-2,4,6-octatriene **10** with high stereoselectivity is difficult to rationalize assuming the validity of the above calculation, since on photoexcitation of **2** the S_1 state should be initially formed with 99% of the molecules in the di-eq conformation, and this should give the E,Z,E-triene **8** according to orbital symmetry as well as least-motion arguments. This would be true even if deactivation to the ground state occurred prior to loss of CO, as shown by the results of thermolysis of the analogous trans-sulfolene **13**. Conformational control of the course of electrocyclic reactions is of course well established as a general feature of such processes.[40] Assuming the validity of the MM2 calculations, several possible rationalizations of our finding can be envisaged:

(i) The extinction coefficients for excitation of the di-ax conformer of **2** at 313 nm is much larger than that of the di-eq conformer, leading to an initial conformer population in the S_1 state much different from that in the ground state. Although this explanation cannot be dismissed, it seems highly unlikely.

(ii) The relative stability of the two conformers of **2** in the S_1 state is reversed compared with their stability in the S_0 state. This could perhaps be assessed through theoretical calculations, which, however, would be extremely difficult at the present time considering the number of electronic configurations that would have to be incorporated into a calculation which would have any pretense of accuracy.

(iii) The barrier for interconversion of the two conformers of **2** in the S_1 excited state is low, allowing rapid conformational equilibration, and the activation barrier for extrusion of CO from the di-ax conformer is lower than that for reaction of the di-eq conformer, but still greater than that for conformer equilibration. Under these admittedly ad hoc conditions, reaction via the di-ax conformer would dominate. This is essentially an application of the Curtin–Hammett principle[41] to the chemistry of excited states. There would be some relief of steric strain on ring opening of the di-ax conformer of **2**, but this will be compensated in part by steric interference between the two methyls on formation of **10** in an initial s-cis,s-cis conformation.

The fact that Mock[22] observed only the E,Z,E-triene **8** on thermal extrusion of SO$_2$ from the trans-sulfolene **13** is consistent with reaction occurring exclusively by conrotatory ring opening

(32) Darling, T. R.; Pouliquen, J.; Turro, N. J. *J. Am. Chem. Soc.* **1974**, *96*, 1247.

(33) For a discussion and primary references, see the reviews cited in ref 5.

(34) Eriksen, J.; Krogh-Jespersen, K.; Ratner, M. A.; Schuster, D. I. *J. Am. Chem. Soc.* **1975**, *97*, 5596.

(35) Houk, K. N.; Northington, D. J.; Duke, R. E., Jr. *J. Am. Chem. Soc.* **1972**, *94*, 6233.

(36) Turro, N. J. "Modern Molecular Photochemistry"; Benjamin/Cummings Publishing Co.: Menlo Park, CA, 1978.

(37) Zimmerman, H. E. *Adv. Photochem.* **1963**, *1*, 183; *Top. Curr. Chem.* **1982**, *100*, 45. Zimmerman, H. E.; Schuster, D. I. *J. Am. Chem. Soc.* **1961**, *83*, 4486; **1962**, *84*, 4527.

(38) For a review on the Principle of Least Nuclear Motion, see: Hine, J. In "Advances in Physical Organic Chemistry"; Gold, V., Bethell, D., Eds.; Academic Press: New York, 1977; Vol. 15.

(39) Allinger, N. L. *Adv. Phys. Org. Chem.* **1976**, *13*, 1. Burkert, V.; Allinger, N. L. "Molecular Mechanics"; American Chemical Society: Washington, D.C., 1982. This modified version of the MM2 program was kindly provided by Professor W. C. Still (Columbia University) and utilized with the assistance of Professor S. W. Wilson (New York University).

(40) See: Baldwin, J. E.; Krueger, S. M. *J. Am. Chem. Soc.* **1969**, *91*, 6444.

(41) For a discussion of the Curtin–Hammett principle, see: Eliel, E. "Stereochemistry of Carbon Compounds"; McGraw-Hill: New York, 1962; p 151 ff.

of the di-eq conformer, which supports the proposal that this conformer is indeed the dominant one in the ground state, at least in this system. It should be noted that although a relatively unstable *Z,Z*-diene was produced on fragmentation of the cyclopentenones **19a,b**, the yields of the two other more stable dienes were much larger in this reaction.[32] If photodecarbonylation of the cycloheptadienones were taking place from "hot" ground-state molecules after internal conversion, rather than directly from the excited state, as proposed by Rosenfeld for the gas-phase processes,[30,31] we would predict a result comparable to that found on thermal excitation, namely predominant formation of the *E,Z,E*- rather than the *Z,Z,Z*-triene, based on Mock's findings.[22] It would be of obvious interest to determine the temperature dependence of the course of these photochemical reactions and to determine the nature of the products in corresponding vapor-phase photolyses.

Conclusion

On the basis of the evidence presented above, we conclude that the photochemical extrusion of CO from 3,5-cycloheptadienones is a concerted cheletropic fragmentation[26] which does not involve a discrete biradical intermediate, and that the ring opening occurs with conrotation. The observed stereochemistry can be rationalized if the mechanism involves a nonlinear cheletropic fragmentation, which is not unreasonable based on studies of geometrical distortions in excited states of related β,γ-unsaturated ketones.[29] The identical reaction path is predicted from considerations of the electronic configuration of the S_1 state and of the molecular conformation coupled with least nuclear motion. However, the specificity observed on reaction of the *trans*-dienone **2** involving selective formation of the *Z,Z,Z*-triene **10** is difficult to explain, and some speculations are presented for consideration. It is clear that these cycloheptadienones are not behaving according to orbital symmetry predictions for linear cheletropic reactions of electronic excited states.[4] We believe that orbital symmetry probably plays only a minor role in determining the course of the photochemical cheletropic fragmentations of 3,5-cycloheptadienones.

Experimental Section

General Methods. Infrared spectra were recorded on a Perkin-Elmer Model 735 spectrophotometer with use of polystyrene for calibration. Ultraviolet spectra were recorded on a Perkin-Elmer/Coleman 124-D or a Varian Cary-14 spectrophotometer with matched 1-cm Quarasil cuvettes. Spectral grade solvents (Burdick and Jackson or Aldrich Gold Label) were used. Proton magnetic resonance spectra (^{1}H NMR) were recorded on Varian EM-360, Perkin-Elmer R-20B, or Varian XL-100 spectrometers, using either CDCl$_3$ or CCl$_4$ as solvents and tetramethylsilane (Me$_4$Si) as the internal reference. The Varian XL-100 instrument, equipped with a Nicolet Fourier Transform Accessory, was used to obtain the ^{13}C NMR spectra. Broad-band proton decoupling and single frequency off resonance (SFORD) techniques were utilized. The primary internal reference was Me$_4$Si, and CDCl$_3$ and Me$_2$SO-d_6 were used as secondary references. Mass spectra were recorded by C. Strom on a du Pont Model 21-492 double focusing mass spectrometer with a CI/EI source. Melting points were recorded on a Thomas-Hoover capillary melting point apparatus and are uncorrected; all temperatures reported are in degrees Centigrade. Solvents were usually redistilled following standard purification procedures.[42]

Chromatographic Procedures. Analyses and separations of reaction mixtures by high-performance liquid chromatography (HPLC) were performed with a Waters Associates Model LC-200 Chromatograph, equipped with an M-6000 pump and M6K injector. For analytical purposes, a Waters Microporasil column was used, and for semipreparative work a column packed in the laboratory with Porasil 35-70 in four consecutive 1 m × 10 mm stainless steel columns was utilized. The solvents (hexanes, ethyl acetate, diethyl ether) were redistilled prior to use. Preparative HPLC was performed on a Waters 500A Prep LC system with use of the microporasil column. Analytical gas-liquid partition chromatography was carried out with three different instruments: a Hewlett-Packard Model 5840A gas chromatograph equipped with flame ionization detector; an H-P 5710A GC equipped with flame ionization detector, Model 5702A oven temperature programmer, Model 7123A strip chart recorder, and Model 3373B electronic integrator (later a Model 3390A reporting integrator); and F&M/H-P Model 5750 GC

with strip chart recorder and flame ionization detector. *n*-Tridecane was used in most experiments as an internal standard and in the photochemical runs was added to the solutions prior to irradiation. Response factors relative to the standard were calculated for each product from analyses of standard mixtures. An Aerograph Model 920 chromatograph was used for all preparative GLC work, using 20-µL injections, and collections in "U"-tubes cooled in dry ice–acetone and isopropyl alcohol. Gas chromatography/mass spectral analyses (GC/MS) were performed by W. Davidson at Halcon Research and Development on a Varian Low Resolution GC/MS Model 112 spectrometer. Silica gel (60–200 mesh, Davison) was the commonly used stationary phase for column chromatography, while Baker silica gel 1B-F and aluminum oxide 1B-F plates (2.5 × 7.5 cm) were used for thin-layer chromatography.

Photochemical Procedures. Preparative irradiations were carried out in a Rayonet Type RS Chamber Reactor, using four low-pressure mercury lamps coated with a phosphor which fluoresces at 350 nm with a width of 30 nm at half intensity. The samples were suspended from above within the reactor. Exploratory irradiations were done on a Rayonet Srinivan-Griffin Reactor (Southern New England Ultraviolet) equipped with a Model MGR-1000 rotating turntable ("merry-go-round") and 16 lamps emitting at either 254 nm, 300 nm (30 nm half-width), or 350 nm (30 nm half-width). Another apparatus for some kinetic studies utilized a Moses Co. rotating turntable surrounding a water-cooled Pyrex-jacketed 450-W high-pressure mercury lamp. The 366-nm emission line was isolated with use of Corning 5970 and 7380 filters placed between the lamp and the turntable. The whole apparatus was set in a large temperature-controlled bath. Several studies were made with use of an optical bench (Applied Photophysics). Monochromatic light was provided by passing the light from a 200-W Osram super pressure mercury lamp (type L2/W2) through a Bausch and Lomb Model 33-86-25 UV grating monochromator with entrance and exit slits of 3.0 and 5.0 mm, respectively. A Corning 5970 filter was employed to remove visible light. The light beam was then split with a fused silica disc (Oriel A-43-544-82) into reference and sample beams at right angles to each other. The sample and reference cuvette holders were jacketed for constant temperature control. All of these items were mounted on optical rails bolted to a piece of plywood.

Sample solutions for irradiation were placed in Pyrex or quartz test tubes which were sealed with rubber septa. Nitrogen was bubbled through the solutions for 5 min. The septa were covered externally with aluminum foil to prevent photodecomposition. Glassware used in these experiments was cleaned by being soaked in concentrated nitric acid for several hours, followed by washing with distilled water, heating over a steam cone for at least 4 h, and finally rinsing with dilute bicarbonate and water and drying in an oven.

2-Methyl-3,5-cycloheptadien-1-one (3a) was prepared by methylation of tropone[43] with methyl magnesium iodide in dry ether as previously described[13] together with 2-methyl-2,4-cycloheptadien-1-one (3b). Previously unreported spectral data for the pure product **3a**, isolated by column chromatography on silica gel, are the following: UV (cyclohexane) λ_{max} 232 nm (log ε 3.78) and 295 nm (log ε 3.14); IR (neat) 3025, 2975, 2930, 2875, 1713, 1595, 1450, 1380 (sh), 1250, 1145, 1075, 1005, 885, 810, 790, 750, 690 cm^{-1}; ^{1}H NMR (CCl$_4$) δ 6.1 (m, 2 H), 5.7 (m, 1 H), 5.4 (dd, *J* = 7 Hz, *J'* = 11 Hz, 1 H), 2.8 (m, 2 H), 2.0 (m, 1 H), 1.2 (d, *J* = 7 Hz, 3 H); ^{13}C NMR (CDCl$_3$) δ 196.00 (C1), 131.8 (C4), 129.7 (C5), 128.1 (C3), 125.7 (C6), 48.6 (C2), 44.6 (C7), 14.3 (methyl).

2-Methyltropone (4) was prepared by bromination of the above mixture containing **3** followed by dehydrobromination with aqueous ammonia. To a solution of 10 g of a mixture of **3a** and **3b** in 150 mL of dry CCl$_4$ (freshly distilled from P$_2$O$_5$) in a 250-mL three-necked round-bottomed flask under a nitrogen atmosphere was added 13 g of bromine in dry CCl$_4$. The color of the bromine immediately disappeared as it reached the solution in the reaction flask. A gas was liberated after the addition was completed. The reaction mixture was stirred for 10 min at room temperature and was then concentrated in vacuo with heating, affording a brown solid. The solid was dissolved in chloroform, and enough dilute ammonium hydroxide solution was added to make the solution basic to litmus. The organic layer was washed with a saturated NaCl solution, dried over MgSO$_4$, filtered, and concentrated to give 4.48 g (62% yield) of a dark brown liquid. Several attempts to purify this material by micro vacuum distillation were accompanied by unexpected mild explosions. The dark brown liquid was finally purified by column chromatography on deactivated neutral alumina with use of 10% chloroform in benzene to give the product with a purity of 96% (GLC): IR (neat): 2900, 1700, 1640, 1580, 1520, 1480, 1420, 1400, 1380, 1260, 1240, 1120, 970, 800, 680 cm^{-1}; ^{1}H NMR (CCl$_4$) δ 2.2 (d, *J* = 2.0 Hz,

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7052 *J. Am. Chem. Soc., Vol. 107, No. 24, 1985*

Schuster et al.

3 H), 7.0 (m, 5 H); ^{13}C NMR (CDCl$_3$) (lit.[14]) δ 186.8 (186.9) (C1), 151.8 (152.0) (C2), 139.3 (139.4) (C6), 135.2 (135.2) (C7), 134.9 (134.8) (C3), 133.5 (133.5) (C4), 132.2 (132.2) (C5), 22.5 (methyl).

cis- and trans-2,7-Dimethyl-3,5-cycloheptadien-1-one (1 and 2). To a stirred slurry of purified cuprous iodide[44] (7.9 g, 0.042 mol) in 158 mL of anhydrous ether at 0 °C (ice bath) under an argon atmosphere was added by syringe 69.5 mL of 1.2 M methyllithium in ether. The resulting clear solution of lithium dimethyl cuprate was stirred at 0 °C and added dropwise to 5.0 g (0.042 mol) of purified 2-methyltropone in 350 mL of anhydrous ether over a period of no longer than 5–10 min. The reaction mixture was quickly worked up by addition of 500–1000 mL of saturated ammonium chloride to give a blue solution with pH 8.0. The aqueous solution was extracted with ether, the ether layer was dried over anhydrous MgSO$_4$, and the solvent was removed under reduced pressure. The residue, 3.0 g, contained 54% of a mixture of the desired products, 34% of **3a** and 9% of starting material (GLC). Flash chromatography gave a mixture of **1** and **2** that rapidly yellowed on exposure to air. Spectral data for the mixture follow: UV (cyclohexane) λ$_{max}$ 235 (ε 4050), 282 (450), and 290 nm (430); IR (neat) 1718 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 1.2 (two d, 6 H), 2.8 (m, 2 H), 5.5–6.2 (m, 4 H); MS, *m/e* 136.1. All attempts to separate the mixture of ketones by column or vapor chromatography met with failure. Separation was finally achieved by HPLC with use of 2% ethyl acetate in hexane as the solvent.

Spectral properties of *trans*-2,7-dimethyl-3,5-cycloheptadien-1-one (**2**) follow: UV (cyclohexane) λ 233.5 nm (ε 2082) and 290.0 nm (483); IR (neat) 2991, 2941, 2896, 2851, 1711, 1581, 1461, 1381, 1001, 911, 791, 711, and 671 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 1.3 (d, *J* = 8 Hz, 3 H), 2.8 (m, 1 H), 5.6 (m, 1 H), 6.2 (m, 1 H); ^{13}C NMR (CDCl$_3$) δ 212.34 (C1), 133.63 (C4), 128.40 (C3), 47.84 (C2), 15.41 (methyl).

Spectral properties of *cis*-2,7-dimethyl-3,5-cycloheptadien-1-one (**1**) follow: IR (neat) 2982, 2951, 2907, 2857, 1702, 1662, 1592, 1452, 1372, 1322, 1252, 1212, 1142, 1042, 1022, 982, 902, 842, 812, 782, and 702 cm^{-1}; ^{1}H NMR: δ 1.2 (d, *J* = 8 Hz, 3 H), 3.2 (m, 1 H), 5.5 (m, 1 H), 6.0 (m, 1 H); ^{13}C NMR (CDCl$_3$) δ 202.75 (C1), 131.35 (C4), 126.29 (C3), 48.39 (C2), 15.53 (methyl).

4-Phenyl-1,2,4-triazoline-3,5-dione (PTAD) (7) was prepared according to the procedure of Cookson et al.[15] The product was purified by vacuum sublimation (100 °C (0.1 mmHg)) to give carmine-red crystals which decompose at 165–175 °C prior to melting. Spectral data: IR 1760 and 1780 cm^{-1}; UV (dioxane) λ$_{max}$ 247 (ε 2300), 310 (1020), and 532 nm (171).

Diels–Alder Adducts of PTAD with Cycloheptadienones 1 and 2. The reactions with PTAD, involving 0.054 g of **1** and 0.47 g of **2**, were carried out in dichloromethane (freshly distilled from P$_2$O$_5$ at 0 °C). A single product was isolated in each case by column chromatography on silica gel with use of 1:1 benzene–ethyl acetate as eluent. After removal of solvent, 0.0932 g (76%) and 0.705 g (66%) of the two products were obtained, mp 219–220 and 177–178 °C, respectively. The ^{1}H NMR spectrum of the adduct of the *cis*-dienone **1** in CDCl$_3$ had δ 7.3 (m, 5 H), 4.8 (m, 2 H), 2.8 (m, 2 H), and 1.2 (d, *J* = 8.0 Hz, 6 H); ^{13}C NMR (CDCl$_3$) δ 209.9 (C=O), 152.3 (N–CO–N), 131.8, 131.6, 131.0, 129.3, 128.5, 125.7 (overlapping s and d due to vinyl and aromatic C), 53.2 (d), 52.1 (d) (C–H), and 15.7 (q) (CH$_3$). For the *trans*-dienone adduct: ^{1}H NMR δ 7.3 (m, 5 H), 6.5 (m, 2 H), 4.8 (m, 2 H), 2.8 (m, 2 H), and 1.2 (two overlapping d, *J* = 8 Hz, 6 H); ^{13}C NMR δ 209.9, 152.1, 151.5, 132.5, 131.7, 130.2, 129.3, 128.4, 125.7, 53.1 (d), 52.1 (d), 51.1 (d), 15.6 (q), and 15.2 (q) (assignments as above).

Single-Crystal X-ray Structure of PTAD Adduct of cis-Dienone 1. The determination of the X-ray crystal structure of this compound was carried out in collaboration with Professor J. M. van der Veen at the Department of Chemistry and Chemical Engineering, Stevens Institute of Technology. Crystal data: C$_{17}$H$_{15}$N$_3$O$_3$, *M* = 309.4, orthorhombic, space group *P*2$_1$2$_1$2$_1$, *a* = 7.230 (3) Å, *b* = 9.301 (3) Å, *c* = 21.854 (7) Å, α = β = γ = 90.00°, *Z* = 4. Crystal dimensions 0.30 × 0.40 × 0.85 mm. X-ray data were collected on a computer-controlled Four-Circle Nicolet Autodiffractometer with use of graphite-monochromated Mo Kα radiation in the ω-scan mode for 2θ > 55°. The structure was solved by direct methods with Multan-80.[45] Twenty of the 23 nonhydrogen atoms appeared on the first Fourier map. The structure was completed with one structure Factor-Fourier cycle with use of all the data.[46] All the hydrogen atoms were located in the Fourier maps except those on the two methyl groups, whose positions were computed assuming tetrahedral geometry and a C–H bond distance of 1.0 Å. Unweighted isotropic

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(45) Main, P., Department of Physics, University of York, England, January 1980.

(46) The X-ray System-Version of 1976, Stewart, J. M., Ed., Technical Report TR-446 of the Computer Science Center, University of Maryland, College Park, MD.

refinement of the C, N, and O atomic positions with fixed H-atom positions followed by anisotropic refinement with the 1666 reflections with 1 > 2 (1) brought the agreement factor *R* to 0.081%. At this point the maximum shift/error ratio was 0.40. Introduction of a weighting scheme ($1/w = \sigma^2 F + 0.0025 F_o{}^2$) followed by four more refinement cycles reduced *R* to 0.072%. The atomic positions and bond distances for the structure at the current level of refinement are given in the supplementary material. An ORTEP[47] drawing of the final structure of this material, shown in Figure 2, exhibits a plane of symmetry which runs through the carbonyl group, and the two methyls are clearly on the same side of the carbonyl group. Thus, the dienone from which this Diels–Alder adduct was prepared must have been the cis isomer **1**.

Synthesis of 2,4,6-Octatrienes 8, 9, and 10. Pent-4-yn-2-yl *p*-toluenesulfonate was prepared from pent-4-yn-2-ol and *p*-toluenesulfonyl chloride as previously described.[16] The ester was isolated as prisms, mp 30 °C (lit.[16] mp 31 °C).

(*Z*)- and (*E*)-3-penten-1-yne as a mixture was prepared[16] from the above ester by reaction with potassium hydroxide in water containing one spoonful of "All" detergent in a yield of 91%, bp 46–48 °C.

(*Z*)- and (*E*)-6-Octen-4-yn-2-ol. The reported[16] synthesis was slightly modified. A suspension of 1.75 g (0.076 mol) of lithium amide in 100 mL of liquid ammonium was cooled in a dry ice-acetone bath at −80 °C. The flask was fitted with a 30-cm vertical glass tube on the top of which was a plug of cotton wool. The above enyne (5.0 g, 0.076 mol) was added in 2–3 g portions through the tube while the suspension was swirled by hand. The cooling bath was removed and 50 mL of dry dimethyl sulfoxide (freshly distilled at reduced pressure from sodium hydroxide tablets and stored over molecular sieve 4A) was slowly poured into the flask, which was fitted with a thermometer and a vent. The ammonia was evaporated with the aid of a water bath. When the temperature of the solution reached 15 °C and all solid Me$_2$SO had melted, 4.41 g (0.076 mol) of precooled (−30 °C) propylene oxide was added in one portion with swirling. The temperature of the mixture was kept between 15 and 25 °C by occasional cooling in ice water. After the rather strong exothermic reaction had subsided, the mixture was allowed to stand for 45 min at room temperature. Ice water (100 mL) was added and the mixture was extracted ten times with small portions of ether. The combined etheral solution was washed with a concentrated solution of ammonium chloride and dried over magnesium sulfate. The ether was removed by using an aspirator. A mixture of isomeric title compounds, 4.80 g, 51% yield, was obtained, bp 74–75 °C (2.5 mmHg).

(*Z,E*)- and (*Z,Z*)-4,6-octadien-2-ol was made[16] by hydrogenation of the mixture of the isomeric 6-octen-4-yn-2-ols, bp 50–51 °C (0.25 mmHg), using a Lindlar catalyst in 98% yield.

(*Z,E*)- and (*Z,Z*)-4,6-octadien-2-ol *p*-toluenesulfonate was prepared[16] from 8.3 g (0.066 mol) of the mixture of the isomeric alcohols with use of a cooled slurry of 12.6 g (0.07 mol) of *p*-toluenesulfonyl chloride in 20 mL of anhydrous pyridine. The mixture was stirred for 24 h and then worked up to give 14.5 g (89%) of the desired tosylates.

(*E,Z,E*)-, (*Z,Z,Z*)-, and (*E,Z,Z*)-2,4,6-Octatrienes (8, 9, and 10). The mixture of the above tosylates (13.4 g, 0.044 mol) in 25 mL of anhydrous dimethyl sulfoxide in an ice bath under nitrogen was reacted with 7.3 g (0.06 mol) of potassium *tert*-butoxide in 62 mL of Me$_2$SO.[16] Workup and removal of the solvent gave the crude triene mixture (7.0 g, 69% yield), which was distilled, bp 60–70 °C (20–25 mmHg). The pure trienes were obtained by preparative GLC with use of a 16 ft × ^{1}/$_4$ in. column of 10% Carbowax 20M on 80–100 mesh Chromosorb P.

Spectral data for the trienes were as follows. (i) (*E,Z,E*)-2,4,6-Octatriene (**8**): ^{1}H NMR (CDCl$_3$) δ 1.7 (d of d, 6 H, X$_3$ part of ABX$_3$ pattern with J_{AX} = 1.5, J_{BX} = 7.0 Hz), 5.5–6.5 (m, 6 H); UV (cyclohexane) λ$_{max}$ 256 (ε 39 800), 266 (47 000), and 277 nm (35 800). (ii) (*E,Z,Z*)-2,4,6-Octatriene (**9**): ^{1}H NMR (CDCl$_3$) δ 1.7 (d of d of d, 3 H, ABX$_3$, J_{AX} = 2 Hz, J_{BX} = 6 Hz), 1.9 (d of d of d, ABCY$_3$, 3 H, J_{AY} = 1.5, Hz, J_{BY} = 7.0 Hz, J_{CY} = 2.5 Hz), 5.6–6.5 (m, 6 H); UV (cyclohexane) λ$_{max}$ 258 (ε 28 400), 267 (34 500), and 276 nm (26 600). (iii) (*Z,Z,Z*)-2,4,6-Octatriene (**10**): ^{1}H NMR (CDCl$_3$) δ 1.7–1.9 (d of d, ABX$_3$, J_{AX} = 1.0 Hz, J_{BX} = 8.0 Hz, 6 H), 5.5 (m, 2 H), 6.3 (m, 4 H); UV (cyclohexane) λ$_{max}$ 262 (ε 25 400), 270.5 (30 400), and 282 nm (21 900).

(*E,E,E*)-2,4,6-Octatriene (**11**). This triene was prepared by irradiation of a mixture of the above trienes in spectral grade cyclohexane, after purging with nitrogen, for 4 h at 300 nm in a preparative scale chamber reactor with use of Pyrex filters. After removal of the solvent under vacuum, GLC analysis of the residue showed a new product in addition to the starting trienes. This material was isolated by preparative GLC (see above) as a white crystalline solid: mp 50–51 °C (lit.[17] mp 52 °C). Spectral data: ^{1}H NMR (CDCl$_3$) δ 1.8–1.9 (d, AX$_3$ *J* = 7 Hz,

(47) ORTEP-II: Johnson, C. K., ORNL-5138, Oak Ridge National Laboratory, Oak Ridge, TN 37830.

6 H), 5.8–6.2 (m, 6 H); UV (cyclohexane) λ_{max} 255 (ϵ 24 800), 265 (33 700), and 276 (27 000).

Irradiation of Trienes. The general procedure was to prepare solutions of the particular triene in cyclohexane at concentrations on the order of 0.07–0.08 M containing a known amount of *n*-tridecane as internal standard for GLC analysis. The solutions were irradiated at various wavelengths from 300–350 nm and samples were periodically withdrawn for GLC analysis at intervals of 5 min to 1 h on a 14 ft × $^{1}/_{8}$ in. column of 10% Carbowax 20M on 80–100 mesh Chromosorb P. Ultimately, irradiations were carried out on an optical bench with 313-nm light isolated from the output of a high-intensity mercury lamp, using either a solution filter combination of 0.5% w/v potassium hydrogen phthalate in water (1 cm) 15% w/v KCr(SO$_4$)$_2$·12H$_2$O in 1.0 N H$_2$SO$_4$ (2 cm)[48] or a grating monochromator. Details on the distribution of trienes obtained in these irradiations are to be found in ref 42.

Irradiation of Cycloheptadienones. In a typical experiment, a solution of 42.5 mg (3.1 × 10^{-4} mol) of dienone **2** in 5 mL of cyclohexane was prepared, 180 μL of a 0.01 M solution of *n*-tridecane in cyclohexane was added, and the solution was purged with nitrogen and irradiated at 313 nm (see above) at 20 °C with use of a Pyrex filter. The course of reaction was monitored by GLC, using a 14 ft × $^{1}/_{8}$ in. column of 10% Carbowax 20 M on 80–100 mesh Chromosorb P at an oven temperature of 115 °C and a flow rate of 30 mL/min. The results are given in the Results section. Entirely analogously experiments were made with use of dienone **1**.

(48) Parker, C. A. "Photoluminescence in Solution"; Elsevier: New York, 1968; pp 186–190.

Autoxidation of Biological Molecules. 4. Maximizing the Antioxidant Activity of Phenols[1]

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Abstract: Rate constants, k_1, for H-atom abstraction by peroxyl radicals from α-tocopherol and 35 structurally related phenols have been measured at 30 °C by the inhibited autoxidation of styrene (IAS) method. An independent laser-flash kinetic EPR method was used with ten of these phenols which gave k_1 values at 24 °C that were in satisfactory agreement with the values found by the IAS method. The structures of several phenols were determined by X-ray analysis. The EPR spectral parameters for the phenoxyl radicals derived from many of these phenols were also measured. The relative magnitudes of k_1 values for phenols that are structurally closely related and have an oxy substituent para to the hydroxyl group can be correlated with the degree of stabilization of the phenoxyl radical. Stabilization depends on two factors: (i) the extent of orbital overlap between the 2p type lone pair on the para oxygen atom and the aromatic π electron system and (ii) the electron-donating or withdrawing character of the group bonded to the para oxygen atom. Orbital overlap depends on the dihedral angle, θ, between the direction of the 2p orbital on the para oxygen and a line perpendicular to the aromatic plane. It can be estimated from the X-ray structures. Along the series 4-methoxytetramethylphenol (VIc), 6-hydroxy-2,2,5,7,8-pentamethylchromene, 6-hydroxy-2,2,5,7,8-pentamethylchroman, and 2,3-dihydro-5-hydroxy-2,2,4,6,7-pentamethylbenzofuran (IIIb), k_1 increases from 3.9 × 10^5, 2.5 × 10^6, 3.8 × 10^6, to 5.7 × 10^6 M^{-1} s^{-1}, as θ decreases from 89, 38, 17, to 6°. Compound IIIb is the most active antioxidant being 1.8 times more active than α-tocopherol. For 2-substituted 6-hydroxy-2,5,7,8-tetramethylchromans log (k_1/M^{-1} s^{-1}) can be correlated with the σ_1 constant of the 2-substituent, $\rho_1 = -1.25$. For these compounds and for some 2,6-dimethylphenols log (k_1/M^{-1} s^{-1}) can also be correlated with the extent of stabilization of the corresponding phenoxyl radicals as measured by the unpaired spin density at the two ortho methyl groups. Some additional kinetic and spectroscopic data are presented. It is also shown that the perpendicular methoxy group in VIc is not deactivating relative to a hydrogen atom but is, instead, about as activating as a methyl group.

α-Tocopherol (α-T) is not only the most biologically active component of vitamin E but, as we have previously reported,[1c,3] it is also one of the best chain-breaking, phenolic antioxidants known. That is, α-T and a number of structurally related model compounds react more rapidly with peroxyl radicals (reaction 1) than do otherwise similar phenols that lack the fused 6-membered heterocyclic ring. We have concluded[3] that stereoelectronic effects

$$\text{ROO·} + \text{ArOH} \xrightarrow{k_1} \text{ROOH} + \text{ArO·} \qquad (1)$$

conferred on α-T by this ring are largely responsible for the high reactivity of α-tocopherol and related compounds. The heterocyclic ring ensures that the 2p-type lone pair of electrons on the ring oxygen adopts an orientation more or less perpendicular to the plane of the aromatic ring and, in this orientation, this 2p-type lone pair stabilizes the developing phenoxyl radical.[3] The superior antioxidant behavior of α-T is further supported by our finding

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