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#### ABSTRACT

#### PART I

#### COMPETITIVE PROCESSES IN PHOTOISOMERIZATIONS AND PHOTOELIMINATIONS OF ALICYCLIC *α*-METHYLENE KETONES

#### PART II

# PHOTOCHEMICAL REARRANGEMENTS OF BICYCLIC $\beta, \gamma$ -EPOXY ENONES

PART III

SYNTHESES AND PHOTOCHEMISTRY OF BICYCLO[3.2.n] DIENONES

By

Sun-Mao Chen

In the first part of this thesis the photochemistry of some alicyclic  $\alpha$ -methylene ketones was investigated.

Irradiation of trans-2,2-diphenyl-6-benzylidenecyclohexanone 34t in methanol through Pyrex caused only trans-cis isomerization, whereas irradiation through Corex resulted in Norrish Type I cleavage, followed by a "turn around" mechanism and recombination to give methyl 2,3,3-triphenylcyclohexanecarboxylate 39. Similar results were obtained with trans-2,2-dimethyl-6-benzylidenecyclohexanone 46t.

In contrast, no trans-cis isomerization was observed when trans-2,2-diphenyl-5-benzylidenecyclopentanone 35t was

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similarly irradiated. Instead it underwent photorearrangement to afford the "turn around" product methyl 2,3,3-triphenylcyclopentanecarboxylate 41.

3-Benzylidenebenzobicyclo[2.2.2]oct-5-en-2-one 49 undergoes clean and efficient photoelimination to give naphthalene and benzylidene ketene; no "turn around" products were obtained.

A study of the photorearrangements of three  $\beta$ ,  $\gamma$ -epoxy enones, 1,3,3,4,5,6,7,8-octamethyl-5,6-epoxybicyclo[2.2.2]oct-7-en-2-one <u>66</u>, 1,3,3,4,5,6-hexamethyl-7,8-diphenyl-5,6epoxybicyclo[2.2.2]oct-7-en-2-one <u>67</u>, and 1,3,4,5,6,7-hexamethylbicyclo[3.2.0]hept-6,7-epoxy-3-en-2-one <u>130</u> was the subject of the second part of this thesis.

 $n, \pi$ -Excitation of 66 and 67 resulted in a reversible 1,3-acyl migration whereas  $\pi, \pi$ -excitation of 66 brought about decarbonylation. Photolysis of 130 gave pentamethylphenol and ketene as the only major reaction products. Mechanisms for these reactions are proposed.

The purpose of the last part of this thesis was to study the photochemistry of hexamethylbicyclo[3.2.0]hept-3,6-dienone 186 and hexamethyl-8-oxabicyclo[3.2.1]oct-3,6dien-2-one 187.

Irradiation of 186 provided a quantitative yield of **methyl pentamethylcyclopentadienyl** ketene 239. The formation

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of 239 was rationalized by an initial [3,3] photorearrangement, followed by a rapid thermal cyclobutene ring-opening.

Treatment of 130 with trifluoroacetic acid resulted in a high yield of 187. A plausible mechanism involving a dicyclopropylcarbinyl cation intermediate was proposed to account for the exclusive protonation at the carbonyl oxygen of the epoxy enones.

Irradiation of 187 gave 1,3,4,5,6-pentamethyl-6-<u>endo-</u> acetylbicyclo[3.1.0]hex-3-en-2-one 220 and pentamethylphenol. Irradiation of 220 resulted in a quantitative yield of pentamethylphenol. Deuterium labeling experiments helped elucidate the mechanisms of these reactions.

#### PART I

# $\begin{array}{c} \textbf{COMPETITIVE PROCESSES IN PHOTOISOMERIZATIONS} \\ \text{AND PHOTOELIMINATIONS OF} \\ \textbf{ALICYCLIC} \quad \alpha \textbf{-METHYLENE KETONES} \end{array}$

#### PART II

# PHOTOCHEMICAL REARRANGEMENTS OF BICYCLIC $\beta, \gamma$ -EPOXY ENONES

#### PART III

#### SYNTHESES AND PHOTOCHEMISTRY OF BICYCLO[3.2.n] DIENONES

Вұ

Sun-Mao Chen

#### A DISSERTATION

Submitted to Michigan State University in partial fulfillment of the requirements for the degree of

#### DOCTOR OF PHILOSOPHY

Department of Chemistry



To My Wife Su-Hua

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Appreciation is extended to Michigan State University for a Graduate Teaching Assistantship from September, 1971 to June, 1972 and to the National Science Foundation, the National Institutes of Health, and the Petroleum Research Foundation for Research Assistantships from July, 1972 to April, 1975.

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# PART III

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PART I

COMPETITIVE PROCESSES IN PHOTOISOMERIZATIONS

AND PHOTOELIMINATIONS OF

ALICYCLIC  $\alpha$ -METHYLENE KETONES

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#### INTRODUCTION

 $\alpha,\beta$ -unsaturated ketones undergo a diverse number of inter- and intramolecular photochemical transformations. Although the excitation energy always involves the same chromophore, the particular reaction path(s) may depend upon the overall molecular structure, the solvent, the multiplicity of the excited state and the presence of another reactant, such as an olefin, to react with the enone. Six distinct reaction types of  $\alpha,\beta$ -unsaturated ketones have been identified in the literature.<sup>1</sup>

(1) <u>Hydrogen abstraction</u>. Following excitation, hydrogen abstraction may occur intramolecularly by the oxygen from a  $\gamma$ -position to give a non-conjugated enone<sup>2</sup> (1 + 2) or from a  $\gamma'$ -position to give a cyclobutyl ketone<sup>3</sup> (3 + 4).



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Hydrogen abstraction from the  $\beta$ '-position<sup>4</sup> ( $5 \neq 6$ ) or by the  $\beta$ -carbon atom<sup>5</sup> ( $7 \neq 8$ ) is also known.



Intermolecular hydrogen abstraction may be observed when the molecular geometry prevents or retards the intramolecular reaction; the net result is either reduction of the carbon-carbon double bond  $(9 \rightarrow 10)$  or addition of hydrogen and a radical to the double bond<sup>6</sup>  $(9 \rightarrow 11)$ .



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(2) <u>Dimerization</u>. When the carbon-carbon double bond of an enone is part of a five- or six-membered ring, and no  $\gamma$ -hydrogens are available, the most frequently observed photochemical reaction is the formation of a cyclobutane dimer<sup>7</sup> (12 + 13, 14).



This reaction may also occur with added olefins or with a suitably located intramolecular double bond.<sup>9</sup>

(3) Oxetane formation. Cycloaddition may also occur at the carbon-oxygen double bond, resulting in an oxetane



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 $(15 \rightarrow 16)$ . This reaction may be inter-<sup>10</sup> or intramolecular.<sup>11</sup>



(4) <u>Photoisomerization</u>. In the case of 4,4-disubstituted cyclohexenones photoisomerization to a bicyclo[3.1.0]hexan-2-one (so-called "lumi-product") may compete with or entirely replace other cycloaddition reactions.<sup>12</sup> (17 + 18, 19).



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(5) <u>Cis-trans isomerization</u>. Enones in which the carbon-carbon double bond is not part of an ordinary sized ring may undergo cis-trans isomerization about the double bond.<sup>13</sup>



This reaction may dominate the observed photochemistry when alternative reaction paths are either unavailable or slow, as in the conversion of  $20 \div 21$ .

(6) <u> $\alpha$ -Cleavage</u>.  $\alpha,\beta$ -unsaturated ketones with radical stabilizing groups at the  $\alpha'$ -position may undergo a Norrish Type I cleavage. The diradical thus formed may valence isomerize to a ketene<sup>14</sup> (22 + 23) or dispose of its energy in some other way.<sup>15</sup>



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Although the photochemistry of  $\alpha$ ,  $\beta$ -unsaturated ketones with the carbon-carbon double bond in an open chain or in an endocyclic ring position had been extensively studied, the photorearrangement of enones with an exocyclic carboncarbon double bond was not further explored until 1972.<sup>16</sup> Hart and Dean discovered that the irradiation of 24a and 24b produced 25a, 25b in 93% and 58% yields respectively.



a : R = Hb :  $R = C_6H_5$ b :  $R = C_6H_5$ b :  $R = C_6H_5$ 

The formation of 25 from 24 can be rationalized by a Norrish Type I cleavage followed by 180° rotation about the  $\alpha,\beta$ ' C-C bond, and bond formation between the  $\alpha$ ' and  $\beta$  carbon atoms<sup>17</sup> (Scheme I). The product is a ketene, and the reaction is analogous to the conversion of 22 to 23. However, there had been no precedent for this type of "turn around" process in the photochemistry of  $\alpha,\beta$ -unsaturated ketones.

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One can envision other mechanisms by which 24 could be converted to 25. For example, one might eliminate methyleneketene, which could react with the solvent, and the resulting methyl methacrylate might then add to anthracene to give 25. To test the 180° "turn around" mechanism shown in Scheme I, the bridgehead positions were labelled with methyl groups.



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Irradiation of 26 in methanol gave a single ester 27 (56%) together with some 9-methylanthracene (2%) and some polymeric material. Analogous irradiation of 28 gave more polymer and 9-methylanthracene (4%) but only a single ester 29 (32%). These results confirm the intramolecular nature of the isomerization.

Since this was the first and only instance of photorearrangement (aside from cis-trans isomerization) in an enone where the carbon-carbon double bond is exocyclic, we decided to explore the scope of these reactions to determine their synthetic utility as well as their detailed mechanism.

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This was the goal of the first part of this thesis.

While this work was in progress, another interesting and rather curious photorearrangement involving an alicyclic  $\alpha$ -methylene ketone was reported by T. D. R. Manning.<sup>18</sup> Three products (31, 32, 33) were obtained when pinocarvone (30) was irradiated. Although some suggestions have been offered, the mechanism of these transformations remains to be established.









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## RESULTS AND DISCUSSION

To test the generality of the "turn around" process as described in the introduction, 34t and 35t were selected for photochemical studies. It was thought that in these two molecules the Norrish Type I reaction should be favored because the resulting biradical intermediates 36 and 37 are stabilized by the two phenyl substituents and by the double bond. However, it was not clear at all if 36 and 37 would undergo the "turn around" rearrangement to form the cyclic ketenes 38 and 40, or whether they would simply isomerize at the double bond, as does 20.



Irradiation of 34t in methanol with a 450 W Hanovia high pressure mercury lamp through a Pyrex filter only brought about trans-cis isomerization. The reaction was efficient and gave an essentially quantitative yield of the

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	IR. <sub>0</sub> =
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thermodynamically less stable cis isomer (34c). The differences in the physical properties of these two isomers are summarized in Table 1.

$IRv_{c=0}(cm^{-1})$	$\text{UV}\lambda_{\max}(\varepsilon)$	NMR ( $\delta$ , olefinic)	mp,°
34t 1665	292 (2.26x10 <sup>4</sup> )	7.53 ppm	109-110
<u>34</u> c 1693	262 (1.03x10 <sup>4</sup> )	6.40 ppm	117-118

Table 1. Spectral Data and Melting Points of 34t and 34c

This result is not surprising at all, as there have been numerous examples reported in the literature showing that cis-trans isomerization of  $\alpha$ , $\beta$ -unsaturated ketones will predominate when other reactions are either too slow to compete or unavailable. The photochemical reaction was monitored by nmr, using the difference in the chemical shifts of the olefinic protons as an indicator of the progress of the reaction. The reaction was completed in an hour. The downfield shift of the benzylic proton of 34t is due to the anisotropic effect of the carbonyl group. No further reaction was observed upon longer irradiation under the above conditions. It is not surprising that in Pyrex the reaction proceeds essentially 100% to the cis isomer; as Table 1 shows, the  $\lambda_{max}$  for the trans isomer occurs at 30 nm longer

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wavelength than for the cis isomer, so that the latter probably does not absorb appreciably through a Pyrex filter.

When a methanol solution of 34c was irradiated with a Corex filter, the methyl ester 39 was isolated in 38% yield.







34c



The actual photoproduct presumably is the ketene <u>38</u> which then reacts with the solvent to give <u>39</u>. Possible intermediates are shown in the above scheme; in the diradical intermediate <u>36</u> the two phenyl groups are a stabilizing influence just as they are in <u>A</u> (<u>Scheme I</u>), the intermediate

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One possible scheme which can rationalize these results is shown in the following energy diagram;



Excitation of 34t through Pyrex gives  $S_1(t)$  which intersystem crosses to  $T_1$ , from which decay to either  $S_0(trans)$ or  $S_0(cis)$  is possible. Since  $S_0(cis)$  does not absorb through Pyrex, all of 34t is eventually converted to 34c. At shorter wavelengths, however,  $S_0(cis)$  can be excited to  $S_1(cis)$  which may go directly to ketene, or may decay to  $T_2(cis)$  which goes to ketene; any decay of  $S_1(cis)$  to  $T_1$ would simply feed back into this system. It is not known whether ketene is formed from a singlet or upper triplet state of 34c.

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To determine whether ring size had an effect on the relative importance of these several reaction paths, we studied 35.

Since the  $\lambda_{max}$  of 35t is 303 nm ( $\epsilon$  28,000), Pyrex was used as the filter. Irradiation of 35t through Pyrex caused photoisomerization to 40 which was trapped by methanol to obtain the corresponding methyl ester 41 in 20% yield. No cis isomer was detected by nmr or infrared spectroscopy. It was thought that perhaps the cis isomer actually formed, but that it competed very efficiently with the starting material in absorbing light to form the observed products. No significant amount of the cis isomer could be observed in the nmr even if the irradiation was interrupted at its early stage. Similar results have been reported by Furth, Morizur and Kossanyi<sup>19</sup> who detected only 0.43% of the cis isomer in the photostationary state upon direct irradiation of a substrate analogous to 35t but without  $\alpha$ ' substituents.



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It is not surprising, but somewhat disappointing, to observe that esters are formed in only modest yields in these reactions, and that the major path involves the formation of polymeric products. It has been reported by Cornubert <u>et al.</u><sup>20</sup> that similar benzylidene derivatives of 34 and 35 with different  $\alpha$ ' substituents, such as 42, 43, 44 and 45, do undergo air oxidation or polymerization upon standing at room temperature, and that polymerization is accelerated by uv irradiation.







44.  $R_1 = H$ ,  $R_2 = >$ 45.  $R_1 = R_2 = CH_3$ 

To study the effect of replacing the α' phenyl substituents by methyl groups, trans-2,2-dimethyl-6-benzylidenecyclohexanone 46t was synthesized. Irradiation of a methanol

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solution of 46t through Pyrex for two hours resulted in quantitative yield of the corresponding cis isomer 46c. Irradiation of 46c through Corex for 23 hr resulted in low yield (~10%) of methyl 3,3-dimethyl-2-phenylcyclohexanecarboxylate 47.



However, attempts to isolate 47 were unsuccessful because of contamination with starting material 46c. Neither by tlc nor by gc could these two be separated. Prolong irradiation caused slow polymerization resulting in a complex misture. Evidence for the presence of 47 is discussed in the Structure Proof section (vide infra).

1,1-Dimethy1-2-benzylidene-2-tetralone 48 was found to be quite stable by uv irradiation. However, it did polymerize slowly upon prolong irradiation. These tarry products were uncharacterizable.



When comparing the present results with those reported by Hart and Dean,  $^{21,23}$  we suspect that the rigidity of the molecule may play an important role in controlling the formation of these "turn around" products. Statistically, the flexible biradical intermediates (36, 37) will undergo an intermolecular reaction (<u>i.e.</u>, polymerization) in preference to an intramolecular reaction (<u>i.e.</u>, ring closure) because the two reaction sites are rather far apart. In the bicyclic cases reported previously the two radical ends are held much closer to each other by the rigid molecular framework, and the probability for intramolecular ring closure is much higher.

With this in mind, 3-benzylidenebenzobicyclo[2.2.2]oct-5-en-2-one 49 (R =  $C_6H_5$ ) was synthesized and its behavior upon photolysis was studied with the hope that the formation of "turn around" products would be enhanced. The replacement of one aryl ring (in 24) by a double bond (in 49) increases the number of reaction possibilities. Three types of bicyclic structures (A, B, C) can be visualized as likely photolysis products of 49. It was considered interesting to find out which one(s), if any, would be formed (obviously more than one stereoisomer of each product type could be formed).

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Irradiation of a methanol solution of 49 (R = Ph) in a Rayonet reactor equipped with 300 nm lamps resulted in a quantitative yield of naphthalene and an equivalent amount of an equimolar mixture of methyl cis and trans- cinnamates.



The formation of 50, 51 and 52 from 49 can be rationalized by either of two alternative mechanisms: (a) direct otoig Sirib 10 yo 20 10 yo 20

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photo-elimination of methylene ketene from 49 (possibly via diradicals such as 53), or (b) 1,3-acyl shift of 49 to cyclobutanone 54, which then eliminates benzylidene ketene to give 50-52.

Path a.









Path b.



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Path b has ample precedent because 49 can be viewed as a  $\beta,\gamma$ -unsaturated ketone, and one important photochemical reaction of bicyclic  $\beta,\gamma$ -unsaturated ketones involves 1,3acyl rearrangement (vide infra). The cyclobutanone 54 could then undergo cycloelimination to yield the observed aromatic product. Since the cyclobutanone 54 was not detected during the course of the reaction, this path is considered less likely or, at least, not the major pathway unless 54 goes to products faster than 49 + 54 (vide infra). A similar result has been obtained by Hart and Murray in a closely related compound by using low temperature techniques.<sup>21</sup>



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These authors reported that dimethyl ketone 57 was formed very efficiently upon irradiation of 55 at -100° and no cyclobutanone was detected by ir spectroscopy at this temperature. Their observations are consistent with path a. For path b to be plausible, the elimination of dimethyl ketene from the cyclobutanone 58 would have to be efficient at -100°. However, it has been found by Rubin et al. 22 that several  $\beta,\gamma$ -unsaturated  $\alpha$ -diketones undergo 1,3-acyl shifts bridged by careful choice of irradiating wavelength to give cyclobutanediones which decarbonylate to give the observed products. For example, bicyclo[2.2.1]hept-5-en-2,3-dione 59 and benzobicyclo[2.2.2]oct-5-en-2,3-dione 60 have been detected at low temperatures to undergo 1,3-acyl shift to the corresponding cyclobutanediones (i.e.,  $\stackrel{61}{\sim}, \stackrel{62}{\sim}$ ) which then decarbonylate.



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Therefore, low temperature irradiation with longer wavelength light is needed before we can completely rule out path b as a possibility in the present study.

Path a involves a Norrish Type 1 cleavage to form the resonance-stabilized biradical 53 as the primary intermediate, followed by  $\alpha,\beta$ '-bond cleavage to form the elimination products, 50-52. It is apparent from the present study that intermediate 53 prefers dissociation to naphthalene and benzylidene ketene. Closure to form the "turn around" products is totally depressed in 53. The stability of the products and consequently the energy lowering of the transition state leading to them must be the prevailing factor to control the ultimate fate of these biradical intermediates. That is, the more stable the products are, the stronger the driving force toward formation of these products will be. Since more resonance energy is gained to form naphthalene from 49 than to form anthracene (isolated as dianthracene) from 24, the tendency for the  $\alpha,\beta'$  cleavage is destined to be higher in the former case.



Bridge elimination is further enhanced when the  $\beta$ -substituents can conjugate with the C-2-C-3 double bond of

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the resulting methylene ketenes. In fact, a small amount of the rearrangement product 64 (~1%) was isolated when the benzylidene substituent in 49 was replaced by a methylene group, as in  $63.^{23}$ 



In order to rationalize these results, two competing paths are proposed:



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Assuming the intermediate 53 has reaction paths A and B available, the transition state leading to the methylene ketenes will be lower in energy when  $R = C_6H_5$  (49) than when R = H (63) because of incipient conjugation of the phenyl group with a C-2-C-3 double bond of the resulting methylene ketene. On the other hand, the transition state leading to the bicyclic ketenes (49 A-C) should not be affected as much by phenyl substitution. Furthermore, when R becomes larger, a steric effect may slow down the 180° rotation needed for bicyclic ketene formation. Consequently, cleavage becomes more important as  $\beta$  substituents become bulkier or better able to stabilize the methylene ketenes.<sup>24</sup>

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#### SYNTHETIC METHODS AND STRUCTURE PROOF

### A. <u>General Procedures for the Synthesis</u> of Benzylidene Derivatives and Their <u>Structure Proofs</u>

The benzylidene derivatives used for photochemical studies in this part of the thesis were synthetized by reacting the corresponding ketones<sup>25</sup> with freshly-distilled benzaldehyde in alcoholic potassium hydroxide under nitrogen. The reaction mixtures were allowed to stir either at ambient temperature or at 60°, until tlc indicated the absence of starting ketones. The adducts either precipitated as wellformed crystals which were filtered and recrystallized, or stayed as oils which were purified by column chromatography.



In isclated solvents ile and tie nat: controls The spectra stereoci clefinic proton : carbony] this the cal shi the aron isoners The ) Mar Wayeleng that of Pencie: are also the Res itle exp Propert of orbi In all cases, the trans isomers were the only products isolated. It has been well documented<sup>26</sup> that in protic solvents (water, alcohols) the aldol condensation is reversible and the various equilibria are often quite sensitive to the nature of the substituents. Therefore, thermodynamics controls the formation of products.

The chemical shifts of the olefinic protons in the nmr spectra were used as a criterion for assignments of the stereochemistry. In all cases, the chemical shift of the olefinic proton falls between 7.0-7.5 ppm when the olefinic proton is cis to the carbonyl group (phenyl is trans to the carbonyl group and the molecule is named trans throughout this thesis). When the olefinic proton is trans, the chemical shift moves upfield to  $\sim 6.4$  ppm, and is distinct from the aromatic protons in all cases. The cis and the trans isomers are quite different in their uv and infrared spectra. The  $\lambda_{max}$  in the uv of the trans isomer occurs at a longer wayelength, and its extinction coefficient is larger than that of the corresponding cis isomer. The stretching frequencies of the carbonyl group of the trans isomer in the ir are also lower than those of the cis isomer (see Table 1 in the Results and Discussion section for an example). A plausible explanation for these differences in spectroscopic properties is based on steric factors.<sup>27</sup> Steric inhibition of orbital overlap between the carbonyl group and the

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1,8-un: of conj E acother cis and ntio d 3.80 : ois iso T] ienzy1: are sur 6 5  $\alpha$ ,  $\beta$ -unsaturated bond in the cis isomer decreases the extent of conjugation and thus changes the spectral properties.

Europium shift experiments in nmr spectroscopy serve as another excellent criterion for distinguishing between the cis and the trans isomers. For example, the relative shift ratio of the benzylic : dimethyl : methylene protons is 3.80 : 2.20 : 1.00 for the trans isomer 46t, while in the cis isomer 46c, the ratio changes to 1.50 : 2.00 : 1.00.

The spectral data and their assignments for all of the benzylidene derivatives studied in this part of the thesis are summarized as follows:



34t



34c

IR:  $1665 \text{ cm}^{-1}$ UV: 292 nm ( $\epsilon$  22,000) UV: 262 nm ( $\epsilon$  10,300)

(see Table 1)



IR:  $1705 \text{ cm}^{-1}$ UV: 303 nm ( $\varepsilon$  28,000)



IR:  $1675 \text{ cm}^{-1}$ 

UV: 285 nm (ε 10,300)



IR:  $1690 \text{ cm}^{-1}$ UV: 267 nm ( $\varepsilon$  5,330)



#### B. Structure Proofs of Photoproducts

The structures of the photoesters 39, 41, and 47 were established by their spectral data. The structures of the trans and cis cinnamates 51, 52, were confirmed by comparing their spectral data with those of authentic samples.<sup>28</sup>

3.87 (d, J = 12 Hz)



It has been firmly established that,<sup>29</sup> for conformations which do not depart appreciably from the chair form, Ja-a of a cyclohexyl system is in the range of 8-13 Hz, Ja-e is in the range of 2-6 Hz and Je-e is even smaller than Ja-e, the difference being on the order of 1 Hz. The observed coupling constants (12 Hz in 39 and 8 Hz in 47) suggest that

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the two coupling protons assume diaxial positions.



Thus the nucleophilic addition of methanol to the bicyclic ketenes proceeds stereospecifically to form the thermodynamically more favorable products.

The actual range of vicinal coupling constants encountered in five-membered rings is generally 5-10 Hz. However, no pattern can be discerned regarding the relative magnitudes of cis and trans coupling constants, despite a large amount of available data on vicinal coupling in fivemembered rings.

4.36 (d, J = 10 Hz)  
H 
$$\swarrow$$
 IR: 1730 cm<sup>-1</sup>  
UV: 228 nm ( $\varepsilon$  2,140)  
2.00-3.30  
2.00-3.30  
4.36 (d, J = 10 Hz)  
IR: 1730 cm<sup>-1</sup>  
UV: 228 nm ( $\varepsilon$  2,140)  
248 (500)  
254 (640)  
259 (670)  
264 (730)  
270 (545)

However, judging from the six-membered ring and the observed coupling constants (J = 10 Hz), a trans orientation of the two coupling protons is probably the more likely choice for the structure of 41.

#### SUMMARY

(1) trans-2,2-Diphenyl-6-benzylidenecyclohexanone (34t) and trans-2,2-dimethyl-6-benzylidenecyclohexanone (46t) readily undergo trans-cis isomerization upon irradiation; irradiation of either compound through a Pyrex filter gave essentially quantitative yields of the cis isomer. In contrast, the cis isomer was not isolated when trans-2,2-diphenyl-5-benzylidenecyclopentanone (35t) was similarly irradiated.

(2) Irradiation of a methanol solution of cis-2,2diphenyl-6-benzylidenecyclohexanone (34c) and cis-2,2dimethyl-6-benzylidenecyclohexanone (46c) through a Corex
filter gave methyl 2,3,3-triphenylcyclohexanecarboxylate
(39) and methyl 3,3-dimethyl-2-phenylcyclohexanecarboxylate
(47) in 38% and 10% yields respectively.

(3) Polymerization competes very efficiently with other photorearrangements of cis-2,2-diphenyl-6-benzylidenecyclohexanone (34c), trans-2,2-diphenyl-5-benzylidenecyclopentanone (35t), cis-2,2-dimethyl-6-benzylidenecyclohexanone (46c) and 1,1-dimethyl-2-benzylidene-2-tetralone (48).

(4) 3-Benzylidenebenzobicyclo[2.2.2]oct-5-en-2-one(49) undergoes clean and efficient photoelimination to form

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naphthalene and benzylidene ketene, and thus provides an easy access to the methylene ketenes which are difficult to synthesize by other routes.

(5) Although photoelimination is novel for enones, it can become the major or, sometimes, the sole reaction upon irradiation of bicyclic  $\alpha$ -methylene ketones when the resulting products become more and more stable. This implies a delicate energy balance between two competing paths, photorearrangement and photoelimination. Consequently, the following trends for the photoelimination were observed:



(6) Exocyclic  $\alpha,\beta$ -unsaturated ketones behave quite differently from the corresponding endocyclic and open-chain  $\alpha,\beta$ -unsaturated ketones photochemically. The bicyclic  $\alpha,\beta$ -unsaturated ketones with  $\alpha'$  radical-stabilizing substituents undergo  $\alpha'$ cleavage in preference to other reaction paths; the resulting biradical intermediates may either rearrange and rebond to form bicyclic ketenes or cleave to

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form methylene ketenes and stable products. The relative importance between these two possible routes depends on the overall molecular structure of the enones.

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#### EXPERIMENTAL

#### A. General Procedures

Except where otherwise noted, all nmr spectra were measured in CDCl<sub>3</sub> or CCl<sub>4</sub> solutions using TMS as an internal standard. The 60 MHz spectra were recorded on a Varian T-60 spectrometer. The small number placed next to protons in the structures in the results and discussion section are the nmr chemical shifts (in ppm) of those protons. The numbers beside the chemical shifts in parentheses are the normalized europium shift numbers. These were obtained by adding small increments of tris-(1,1,1,2,2,3,3,-heptafluoro-7,7-dimethyl-4,6-octanedione)Eu(III) to the CCl<sub>4</sub> or CDCl<sub>3</sub> solution of the compound being investigated. After each addition the nmr spectrum was scanned and the new frequency of each absorption was recorded. The shift for each absorption is the difference between the frequency of the shifted absorption and the original one. The normalized shift numbers are ratios obtained by dividing the shift of each signal in the spectrum by the shift of the least shifted signal.

Infrared spectra were taken on a Unicam SP-200 Spectrometer and calibrated against a polystyrene film. Ultraviolet spectra were obtained with a Unicam SP-800 Spectrometer in

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various solvents. Mass spectra were obtained from a Hitachi-Perkin Elmer RMU-6 operated by Mrs. Ralph Guile. Melting points were determined with a Thomas-Hoover Melting Point Apparatus and are uncorrected. Varian Aerograph gas chromatographs were used. Analyses were performed by Spang Microanalytical Laboratories, Ann Arbor, Michigan.

#### B. General Photolysis Procedures

All irradiations were conducted using either a 450 W Hanovia lamp or a Rayonet reactor. The former was placed in a water-cooled quartz jacket equipped with different wavelength filters. The solution to be irradiated was placed in a quartz test tube which was sealed with a serum cap after being deoxygenated with a stream of  $N_2$  or Ar. The test tube was then taped to the side of the quartz immersion well and the irradiation was monitored by chromatographic and/or spectroscopic methods.

### C. <u>Photolysis of trans-2,2-diphenyl-</u> 6-benzylidenecyclohexanone (34t)

A deoxygenated solution of 250 mg (0.7 mmol) of  $34t^{27,30}$  in 300 ml of methanol (2.47 x  $10^{-3}$  M) was irradiated through Pyrex with the 450 watt Hanovia lamp for 1 hr. The reaction was monitored by uv. The original absorption maximum at 292 nm dropped to 264 nm. Evaporation of the solvent gave a quantitative yield of a colorless crystalline compound, mp 117-118°, which was identified as cis-2,2diphenyl-6-benzylidenecyclohexanone (34c) (mp lit. 118°).<sup>27</sup>

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The new absorption maximum had essentially vanished after irradiation of 34c through Corex in methanol for 16.5 hr. Evaporation of the solvent gave a light yellow oil which was chromatographed on a thick layer silica gel plate with 50 : 50 hexane/benzene as eluent to give 100 mg (38%) of methyl 2,3,3-triphenylcyclohexanecarboxylate (43) as the only significant product. Nmr (CDCl<sub>3</sub>)  $\delta$  1.53-2.67 (7H, methylene and C<sub>3</sub> protons), 3.33 (3H, s, methoxyl), 3.87 (lH, d, J = 12.0, benzylic), 6.67-7.53 (15H, m, aryl); **ir (neat) 3060 (w), 2980 (m), 2900 (w), 1730 (s), 1510 (m)** 1460 (m), 1380 (w), 1270 (w), 1205 (w), 1170 (m), 1050 (m), 800 (m), 775 (m), 710 (s); mass spectrum (70 eV) m/e (rel. intensity) 370 (25), 339 (2), 338 (2), 311 (2), 310 (4), **296 (2), 207 (40), 206 (100), 183 (20), 181 (20), 178 (26), 167 (38), 165 (40), 164 (24), 156 (20), 152 (25), 129 (30),** 115 (44), 105 (72), 91 (88); uv (CH<sub>3</sub>OH)  $\lambda_{max}$  227 nm (ε 2,900), 250 (790), 258 (865), 264 (780), 270 (580). Anal. Calcd. for C<sub>26</sub>H<sub>26</sub>O<sub>2</sub>: C, 84.29; H, 7.07.

Found: C, 84.18; H, 6.98.

# D. Synthesis of trans-2,2-Diphenyl-5-benzylidenecyclopentanone (35t)

A solution of 1.94 g of 2,2-diphenylcyclopentanone<sup>31</sup> and 0.85 g of freshly distilled benzaldehyde in 30 ml of 5% ethanolic KOH was allowed to stir at room temperature under nitrogen for 48 hr. The resulting precipitate was filtered and recrystallized from 95% ethanol to obtain 1.85 g (70%) of 35t, mp 119-120°; nmr (CDCl<sub>3</sub>) & 2.57-3.10 (4H, m, methylene), 7.30-7.47 (15H, m, aryl), 7.54 (1H, m, olefinic). The relative Eu (fod)<sub>3</sub> shifts of the olefin and the methylene protons are 2.45 : 1.00; ir (KBr) 3080 (w), 2960 (w), 1705 (s), 1630 (s), 1500 (m), 1455 (9m), 1170 (s), 945 (m), 915 (s), 785 (m), 770 (m), 725 (m), 710 (s); uv (CH<sub>3</sub>OH  $\lambda_{max}$ 303 nm ( $\varepsilon$  28,000), mass spectrum (70 eV) m/e (rel. intensity) 324 (65), 247 (5), 233 (20), 180 (17), 179 (74), 178 (23), 165 (34), 144 (13), 116 (100), 115 (80), 102 (11), 91 (12), 89 (15), 72 (20), 65 (10), 63 (10), 51 (20).

<u>Anal</u>. Calcd. for C<sub>24</sub>H<sub>20</sub>O: C, 88.85; H, 6.21. Found: C, 88.84; H, 6.20.

### E. Photolysis of trans-2,2-Diphenyl-5benzylidenecyclopentanone (35t)

A deoxygenated solution of <u>35t</u> (250 mg) in 300 ml of absolute methanol was irradiated for 15 hr through Pyrex with the 450 watt Hanovia lamp. After most of the solvent had been removed, a white precipitate formed which was filtered to give 43 mg (17.2%) of a non-crystalline-polymeric solid with a melting point higher than 280°. The filtrate was conchntrated under reduced pressure. The residual oil was chromatographed on a thick layer silica gel plate with 10% ethyl acetate in hexane as eluent. After four elutions there was obtained 50 mg (18.2%) of methyl 1,1,2-triphenyl-3-cyclopentanecarboxylate (41), and 12.5 gm (5%) of the starting material (35t). The ester 41 was a colorless oil which solidified upon standing overnight at room temperature. The solid, recrystallized from n-hexane, had a mp 89-90°. Nmr (CDCl<sub>3</sub>)  $\delta$  2.00-3.30 (5H, m, methylene and C3 protons), 3.50 (3H, S, methoxyl), 4.36 (1H, d, J = 10 Hz, benzylic), 6.57-7.67 (15H, m, aryl); ir (KBr) 3050 (m), 2980 (m), 1730 (s), 1600 (m), 1505 (m), 1460 (m), 1380 (w), 1360 (w), 1260 (w), 1200 (m), 1180 (s), 1100 (w), 1050 (m), 860 (w), 775 (w), 710 (s); mass spectrum (70 eV) m/e (rel. intensity) 356 (100), 325 (12), 297 (2), 266 (5), 234 (5), 194 (25), 181 (40), 180 (38), 179 (38), 166 (50), 117 (85), 115 (60), 103 (15), 91 (40), 77 (30); uv (CH<sub>3</sub>OH)  $\lambda_{max}$  228 nm ( $\epsilon$  2,140), 248 (500), 254 (640), 259 (760), 264 (730), 270 (545). <u>Anal</u>. Calcd. for C<sub>25</sub>H<sub>24</sub>O<sub>2</sub>: C, 84.24; H, 6.79. Found: C, 84.29; H, 6.84.

# F. Preparation of trans-2,2-Dimethyl-6-benzylidenecyclohexanone (46t)

This compound was synthesized by a modification of the literature procedure.<sup>32</sup> A solution of 4.0 g (0.032 mole) of 2,2-dimethylcyclohexanone<sup>33</sup> in 20 ml of 95% ethanol and 20 ml of 10% aqueous solution of potassium hydroxide was refluxed under nitrogen for five minutes and 3.39 g (0.032 mole) of freshly distilled benzaldehyde was added dropwise. The solution was allowed to stir at 60° for 24 hr. On cooling, a white precipitate formed which was filtered and recrystallized from methanol to obtain 4.6 g (70%<sup>34</sup>) of colorless crystals, mp 79-80° (lit.<sup>32</sup> 79.5-80°).

### G. Photolysis of trans-2,2-Dimethyl-6benzylidenecyclohexanone (46t)

A deoxygenated solution of 200 mg of 46t in 600 ml of absolute methanol was irradiated through a Corex filter with a 450 watt Hanovia mercury lamp. Monitoring the photolysis by uv showed that the maximum absorption at 285 nm had essentially vanished after 1 hr and a new absorption at 267 nm had appeared. The nmr spectrum of the photolysate had a new triplet at  $\delta$  6.50 corresponding to one proton, whereas the number of protons in the aromatic region changed from six to five. The stretching frequency of the carbonyl group in the ir changed from 1675  $\text{cm}^{-1}$  to 1690  $\text{cm}^{-1}$ . All of these changes are attributable to the cis isomer 32 (46c). Irradiation was resumed and monitored by uv. Approximately 60% of the cis isomer was consumed after 23 hr. A new singlet at  $\delta$  3.30 and a doublet at  $\delta$  4.10 in the nmr spectrum of the crude photoproduct and a new absorption at 1730  $cm^{-1}$ in its infrared spectrum indicated the presence of the desired photoproduct, methyl 3,3-dimethyl-2-phenylcyclohexanecarboxylate (47). This conclusion was further confirmed by the presence of a peak at m/e 246 as the molecular ion in the mass spectrum. However, all attempts to isolate 47 were unsuccessful. Analysis from nmr spectrum of the crude photolysate by comparing the area of the new singlet at  $\delta$  3.30

with that of the methyls and benzylic proton indicated approximately 10% of 47 was formed. Longer irradiation caused slow polymerization resulting in a complex mixture.

#### H. Preparation of 3-Benzylidenebenzobicyclo[2.2.2]oct-5-en-2-one (49)

A similar procedure to that described above for the preparation of 35t was followed. Benzobicyclo[2.2.2]oct-5en-2-one (66) was synthesized according to literature procedures.<sup>35</sup> 340 mg (2 mmol) of <u>66</u>, 106 mg (2 mmol) of freshly-distilled benzaldehyde in 10 ml of 5% ethanolic KOH solution were allowed to stir overnight at room temperature. Evaporation of solvent, followed by NaHSO, washing gave 365 mg of a light yellow oil. The crude benzylidene derivative was chromatographed on silica gel (finer than 230 mesh) using benzene as eluent to obtain 206 mg (40% yield) of pure 49 as an oil. Nmr (CDCl<sub>3</sub>)  $\delta$  4.60-4.77 (1H, m, C4 bridgehead), 5.30-5.52 (1H, m, Cl bridgehead), 6.76 (2H, t, J = 3.0 Hz, olefinic), 7.17-7.53 (10H, m, aryl and benzylic olefin); ir (neat) 3090 (m), 2960 (w), 1700 (s), 1635 (m), 1500 (w), 1480 (w), 1210 (w), 1145 (m), 1100 (m), 1040 (w), 950 (w), 835 (m), 770 (s), 750 (m), 710 (s); uv (CH<sub>e</sub>OH)  $\lambda_{max}$ 298 nm (c 14,350), 270 (10,330); mass spectrum (70 eV) m/e 258 (15), 128 (base), 102 (10). All other fragments are less than 5% of the base peak.

<u>Anal</u>. Calcd. for C<sub>19</sub>H<sub>14</sub>O: C, 88.34; H, 5.46. Found: C, 88.29; H, 5.56.

# I. Photolysis of 3-Benzylidenebenzobicyclo[2.2.2]oct-5-en-2-one (49)

A 2.43 nM solution of 49 in absolute methanol was irradiated in a Rayonet reactor equipped with 300 nm lamps. The original absorption maximum at 298 nm had completely vanished after 1 hr. The nmr spectrum of the crude photolysate indicated the presence of three products, naphthalene, and methyl cis- and trans- cinnamates in equal amounts. Evaporation of the solvent gave a light yellow oil which was separated by vpc (5' x  $\frac{1}{4}$ ", 20% SE-30 on chromosorb W 60/80, 200°, 60 ml/min of He) to give a quantitative yield of these three products. The methyl cinnamates were identified by comparing their spectra (ir, nmr) with those of authentic samples.<sup>28</sup>

# J. Preparation of 1,1-Dimethy1-3benzylidene-2-tetralone (48)

2-Tetralone was synthesized according to the improved method of J. Sims <u>et al</u>.<sup>36</sup> Methylation was carried out according to D. Soffer <u>et al</u>.<sup>37</sup> A solution of 1.50 g of 1,1-dimethyl-2-tetralone and 0.87 g of freshly distilled benzaldehyde in 60 ml of 1% ethanolic KOH solution was stirred under nitrogen at room temperature for three days. The solvent was removed under reduced pressure and the residue was neutralized with 10% HCl solution and stirred overnight with saturated sodium bisulfite solution under nitrogen. The ether extract was chromatographed on silica gel using benzene as eluent to obtain 1.45 g (65%) of 48. Nmr (CDCl<sub>3</sub>)  $\delta$  1.47 (6H, S, methyl), 3.77 (2H, d, J = 1 Hz, methylene), 7.07-7.50 (9H, m, aryl and olefinic); ir (neat) 3050 (w), 2985 (m), 2950 (w), 1655 (s), 1605 (w), 1500 (m), 1460 (m), 1390 (m), 1265 (m), 215 (w), 765 (s), 750 (m), 710 (s); mass spectrum (70 eV) m/e (rel. intensity) 265 (15), 247 (13), 232 (10), 219 (25), 188 (50), 174 (30), 159 (20), 145 (100), 132 (90), 131 (60), 117 (60), 115 (50), 105 (30), 104 (25), 91 (60), 84 (20); uv (CH<sub>3</sub>OH)  $\lambda_{max}$  308 nm ( $\epsilon$  10,350), 238 (14,400), 233 (12,700).

<u>Anal</u>. Calcd. for C<sub>19</sub>H<sub>18</sub>O: C, 86.99; H, 6.92. Found: C, 86.92; H, 6.91.

# K. Photolysis of 1,1-Dimethy1-3benzylidene-2-tetralone (48)

A deoxygenated solution of 55 mg of 48 in 20 ml of absolute methanol was irradiated in a Rayonet reactor equipped with 300 nm lamps for 26 hr. Evaporation of the solvent gave a light yellow oil which was identified as the starting material. When a solution of 48 in absolute methanol was irradiated through Corex with a 450 watt Hanovia lamp, a complex mixture was obtained after 58 hr. Monitoring the reaction by uv indicated that more than 90% of the starting material was consumed but no pure product could be isolated from the photolysate.

# PART II

# PHOTOCHEMICAL REARRANGEMENTS OF

BICYCLIC  $\beta, \gamma$ -EPOXY ENONES

#### INTRODUCTION

The second part of this thesis is concerned with the photochemistry of two bicyclic  $\beta,\gamma$ -epoxy enones 66 and 67.



66.  $R = CH_3$ 67.  $R = C_6H_5$ 

Although the photochemistry of  $\alpha$ , $\beta$ -epoxy ketones has been very extensively studied,  $\beta$ , $\gamma$ -epoxy ketones have received considerably less attention. Only a few photochemical reactions involving  $\beta$ , $\gamma$ -epoxy ketones have been reported.

The original goal of this study was to investigate the structural features which facilitate the photochemical decarbonylation of  $\beta,\gamma$ -epoxy ketones. Therefore, a  $\beta',\gamma'$ -double bond was introduced, since this should facilitate Norrish Type 1 bond cleavage by producing an allylic radical. Also, the  $\alpha,\alpha$ -dimethyl substituents should stabilize

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the resulting biradical  $\underbrace{68}_{68}$  if decarbonylation were to follow.



Another alternative to decarbonylation which could follow  $\alpha$ -cleavage would be bridge expulsion through the elimination of dimethylketene, thus providing easy access to the interesting, highly substituted benzene oxide-oxepin system 69.



However, compounds 66 and 67 are also  $\beta,\gamma$ -unsaturated ketones and could exhibit the types of photochemistry usually associated with such systems. It was considered to be instructive to learn which of the various alternative reaction paths would predominate under different irradiation conditions.

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In this introduction, a brief review of the photochemistry of  $\beta,\gamma$ -epoxy cyclic ketones and  $\beta,\gamma$ -unsaturated cyclic ketones is presented in order to set the various possibilities for the photochemical behavior of 66 and 67 in perspective.

#### A. The Photochemistry of $\beta, \gamma$ -Epoxy Cyclic Ketones

Two types of reaction have been identified on photolysis of  $\beta,\gamma$ -epoxy ketones:

1. Photoisomerization<sup>38</sup>

Irradiation of an ether solution of 2,2,4,4-tetramethyl-7-oxabicyclo[4.1.0]heptan-3-one 70 through Corex provided 2,2-dimethyl-4-(2-methylpropenyl)butanolide 71 in 50% yield and 2,2,6-trimethyl-4-oxo-hept-5-enal 72 in 20% yield. The epoxy ketone 70 was photochemically inert when irradiated through Pyrex in acetone solution.

The formation of 71 and 72 can be accounted for by initial Norrish Type 1 bond cleavage to give 73 followed by epoxide ring-opening to afford 74. Ring closure of 74 gives 71 and a 1,4-hydrogen shift in 74 gives the aldehyde 72 (see Scheme 4).

48





72

Analogous to their cyclopropyl counterparts, 2-(oxiranyl)cycloalkanones 75 gave mainly unsaturated macrolides 76 by a three-atom photochemical ring expansion.<sup>39</sup> This reaction provides a valuable method for the synthesis of this class of compounds.

In all the photolyses of these epoxy-ketones, the major ring-expanded product arises via the pathway shown in <u>Scheme</u> 5. Mechanistically this reaction is identical with

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formation of 71 from 70. These reactions are most useful for ring expansions to ten and eleven-membered ring systems.







2. Decarbonylation

Recently, H. Hart, R. Murray and co-workers studied the photochemistry of two  $\beta,\gamma$ -epoxy ketones 27 and 28 and found photodecarbonylation to proceed efficiently, with high yields of 79 and 80 being obtained.<sup>40</sup>



**↓** 00



51

The formation of 79 and 80 can be rationalized as

follows:

78.

R = H



Chambers and Marples<sup>41</sup> have also reported that irradiation of an ether solution of 98, 108-epoxy ketone <u>81</u> results in rapid decarbonylation and formation of the unsaturated epoxide <u>82</u> (20%) and the B-norepoxide <u>83</u> (3%). This work provides a good example of the rarely observed photodecarbonylation of simple alkanones in the condensed phase.



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83

R = H (75%)
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hyd olu whi aff Surprisingly, the corresponding 98,108-epoxyketone of 81 remained unchanged under similar condition.

In summary, irradiation of a  $\beta$ , $\gamma$ -epoxy cyclic ketone initially leads to  $\alpha$ -cleavage with formation of a diradical which undergoes subsequent epoxide ring-opening to give an acyl-alkoxy diradical. The diradical undergoes ring closure to give a lactone and/or hydrogen transfer to afford an aldehyde. If the formation of both of these products is precluded, then decarbonylation occurs to give a biradical which undergoes disproportionation and/or ring closure to afford stable products. These are illustrated in Scheme 6.

#### Scheme 6



### Scheme 6 (cont'd)

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However, it is obvious that other structural features which affect the photoreactions of  $\beta$ , $\gamma$ -epoxy ketones remain to be established.

## B. The Photochemistry of $\beta, \gamma$ -Unsaturated Cyclic Ketones

The most widely studied  $\beta,\gamma$ -unsaturated ketones are those in which the double bond is constrained in one ring of a polycyclic compound. These compounds undergo primarily two types of reaction; namely, 1,3 acyl shift and 1,2-acyl shift. The photochemical 1,3-shift was first observed by Büchi and Burgess<sup>42</sup> in 1960 while studying the photoisomerization of eucarvone 84.



The bicyclic enone 85 was found to undergo a facile reversible isomerization to 86. Since then, numerous examples had been reported which confirm that this is a common path for the photorearrangement of  $\beta,\gamma$ -unsaturated ketones.

For example,  $(\underbrace{87}, \underbrace{89}, \underbrace{91}, \underbrace{93}^{\ddagger}, \underbrace{88}^{43}, \underbrace{90}^{44}, \underbrace{92}^{45}, \underbrace{94}^{46})$ .





89 ~

0



88 ~





hν

hv, t-BuOH



91 X

22 2



93 ~

0

94 ~ It should be noted that some 1,3-acyl shifts appear to be irreversible as illustrated in the conversions of 95 to  $96^{47a}$  and 97 to  $98.^{47b}$ 



The l,2-acyl shift, or oxa-di- $\pi$ -methane cyclopropane formation, is also well-known. Examples include 99 + 100<sup>48</sup>, 101 + 102<sup>49</sup>, 103 + 104<sup>50</sup>, 105 + 106<sup>51</sup>.











103 ~





It has been generally accepted that the 1,3-acyl shift is a singlet state reaction, possibly occurring in a concerted  $[_{\sigma}^2 + _{\pi}^2]$  manner, whereas the 1,2-acyl shift is usually a triplet state reaction. Both originate from n, excitation of the same chromophore to the singlet state, which can either react concertedly  $[_{\sigma}^2 + _{\pi}^2]$  or intersystem cross to the triplet state. However, exceptions do exist. A recent report by Schuster et al.<sup>52</sup> pointed out that in the interconversion of 85 to 86 studied by Büchi,<sup>42</sup> a significant amount (~24%) of 1,3-acyl migration takes place via the triplet state, although 76% of the reaction arose from the singlet.



Examples of  $\beta$ ,  $\gamma$ -enones which rearrange by both the 1,2and the 1,3-shift are also known. The first instance was observed by Ipaktschi<sup>51</sup> in the interconversion of 107, 108 and 109 in different solvents.



Ipaktschi photolyzed 107 in acetone and isolated mainly 108 whereas Schuster<sup>53</sup> had reported that only 109 was formed (reversibly) upon direct irradiation of 107 in various solvents.

Another example is the conversion of 110 to 111 and 112.54



These two types of rearrangement are usually the major photoreactions of  $\beta$ , $\gamma$ -unsaturated ketones. However, other transformations such as cis-trans isomerization, hydrogen abstraction,  $\alpha$ -cleavage (decarbonylation),  $\beta$ -cleavage, and reduction are frequently encountered and may even predominate, depending upon the particular structure of the ketone. Some examples are cited below.

When the  $\beta,\gamma$ -unsaturation is in a large ring, cis-trans isomerization may become significant. This is sometimes followed by further chemical reaction, as indicated in the reaction 113 + 114 + 115.<sup>55,56</sup>



It has been suggested that these reactions are governed by orbital symmetry requirements; the reaction cited above proceeds via initial triplet cis-trans isomerization followed by a thermal ring closure.

Intramolecular hydrogen abstraction  $(116 \div 117)^{57}$  and oxetane formation  $(118 \div 119)^{58}$  are also known.



Photoreduction of  $\beta$ ,  $\gamma$ -unsaturated ketones was first reported by Cargill <u>et al</u>. (120 + 121).<sup>59</sup>



This reaction suggests that the excited state of certain  $\beta$ ,  $\gamma$ enones probably involves, in addition to the normal  $n - \pi^*$ excitation, a contribution from a  $\pi - \pi^*$  transition of the extended chromophore. Light-induced cycloaddition at the  $\beta$ ,  $\gamma$ -double bond should therefore be possible. This was confirmed by irradiation of 120 in the presence of vinyl acetate in benzene, to form the cycloadduct 122.<sup>59</sup>



 $\alpha$ -Cleavage sometimes takes place since the alkyl radical is resonance stabilized by the double bond. This may result in the formation of a diene via decarbonylation (123 + 124),



or in cleavage of the  $\alpha'\beta'$  bond to form stable products  $(55 \rightarrow 56), (127 \rightarrow 128).^{60,22}$ 



It has been shown by calculations that the lowest excited singlet state of  $\beta$ , $\gamma$ -unsaturated ketones is primarily an n -  $\pi$ \* state; however, the lowest excited triplet state consists mainly of a  $\pi$  -  $\pi$ \* configuration.<sup>61,62</sup> This distinction provides a possible rationalization for the different behavior of  $\beta$ , $\gamma$ -unsaturated ketone singlets and triplets. However, a different explanation based on a spin polarization has also been proposed by Schuster <u>et al</u>.<sup>63</sup> These authors implied that singlets and triplets could both arise from n -  $\pi$ \* excited states and suggested that different spin density distribution in the two excited states leads to different initial bonding interactions and, ultimately, to different products.

In addition to reporting my studies on epoxyketones <u>66</u> and <u>67</u>, which have a  $\beta,\gamma$ -double bond, I will also report in this part of the thesis on the photochemistry of a bicyclic  $\beta,\gamma$ -epoxy ketone with an  $\alpha',\beta'$ -conjugated double bond. Compound <u>130</u> was synthesized and its photochemistry was studied with the thought that an entirely new course of photorearrangement might take place. These possibilities will be presented in the Results and Discussion section.



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#### RESULTS AND DISCUSSION

#### A. Photolysis of 1,3,3,4,5,6,7,8-Octamethyl-5,6-epoxybicyclo[2.2.2]oct-7-en-2-one (66)

The title compound was prepared in high yield by perbenzoic acid epoxidation of the corresponding bicyclo[2.2.2]oct-5,7-dien-2-one<sup>64</sup> at 0° in methylene chloride solution.

The nmr spectrum of 66 consists of six singlets and two quartets with equal intensities. The stereochemistry of the epoxide 66, though not known with certainty, is thought to be endo as shown, based on the nmr data which were assigned as follows:



66

In particular, if the geometry were exo, one might have expected an appreciable difference in the chemical and perhaps Europium shifts of the two methyl groups at C-3.

Irradiation of a methanol or benzene solution of 66 through a Pyrex filter with a Hanovia 450 W lamp resulted in rapid appearance of a new carbonyl stretching band at 1760 cm<sup>-1</sup>. The reaction was therefore followed by infrared spectroscopy. After 3 hr, the band at 1760 cm<sup>-1</sup> had built up to a maximum intensity. The relative intensity of the 1760 cm<sup>-1</sup> and the 1710 cm<sup>-1</sup> band (due to 66) was about 1 : 1. After removal of the solvent under reduced pressure, a colorless oil was obtained. The nmr spectrum of the crude photolysate consisted of three quartets centered around  $\delta$  1.67 and nine singlets scattered around  $\delta$  1.0-1.3. The relative ratio of the quartets and the singlets was 1 : 3. These peaks could be ascribed to a mixture of 66 and 129.



However, all attempts to separate these compounds failed, partially due to their instability.

Since it has been established that cyclobutanones undergo three major types of photoreaction; namely, decarbonylation, cycloelimination and ring expansion,<sup>65</sup> we decided to continue the irradiation of the above photolysate with the hope of simplifying the purification problems encountered in the isolation of 129. Three interesting products 131, 132 and 133 could be expected.



Therefore, the irradiation was resumed. After 8 hr, more than 90% of the 1760 cm<sup>-1</sup> ir band had disappeared. Since longer irradiation gradually caused polymerization, resulting in a complex mixture, the irradiation was discontinued after 8 hr. After removal of the solvent, a light yellow oil was obtained which was separated by a neutral alumina plate using carbon tetrachloride as eluent to obtain a 30% yield of a product assigned the triene structure 134.

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The spectral data of 134 are summarized as follows:



The large difference in the chemical shifts of the two methyls at C-7 is probably due to the fact that the "endo" methyl protons ( $\delta$  0.53) are bent toward the cyclohexene ring and well-shielded by the double bonds. However, one can not completely rule out an alternative structure (135) which has the same symmetry as 134, solely on the nmr data. The uv spectra of two models 136<sup>66</sup> and 137<sup>67</sup> tend to support structure 134. The fully conjugated triene system in 136 leads to a somewhat longer wavelength and more intense absorption which, in 134, is presumably even further enhanced by the cyclopropane ring.



UV:  $\lambda_{\max}$  255 nm UV:  $\lambda_{\max}$  241 nm (log  $\epsilon$ : 4.29) (log  $\epsilon$ : 3.9)

Furthermore, compound 134 did not undergo the Diels-Alder reaction, even with such strong dienophiles as TCNE, dimethyl acetylene dicarboxylate and maleic anhydride.

The photoproduct 134 underwent acid-catalyzed rearrangement to hexamethylbenzene in quantitative yield. This reaction can be rationalized as follows:



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This reaction, in and of itself, does not distinguish between structures 134 and 135, which could react analogously. The formation of 134 might be explained as follows:



Reversible 1,3-acyl migration to form 129 could be followed by decarbonylation of the cyclobutanone to form 131. Epoxide ring opening followed by 1,2-elimination of water would give 134. The epoxide ring-opening of 131 might be acid-catalyzed due to possible traces of acid in the solvent used for photolysis. To help prevent this possibility, the solvent was purified by chromatography on a basic alumina column and the tubes used for photolysis were washed thoroughly with concentrated  $NH_4OH$  solution. However, the same results were obtained.

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The triene 134 polymerized slowly at room temperature. Irradiation of a dilute ether solution of 134 through Pyrex also caused gradual polymerization.

The 1,3-acyl migration probably occurs from a triplet excited state because the reaction could be sensitized by acetone and quenched completely by a 2.5M methanol solution of piperylene.

Since compound <u>66</u> has a  $\pi, \pi^*$  absorption maximum at 230 nm in its uv spectrum, it was irradiated through a Vycor filter to excite this transition. The 1760 cm<sup>-1</sup> band appeared rapidly (within 30 min of irradiation) and had disappeared completely after 2 hr. Two new products, <u>140</u> and <u>141</u>, were detected in ~27% yield by vpc after 2 hr of irradiation in methanol. These two compounds were identified as hexamethylcyclopentadiene <u>140</u><sup>68</sup> and biacetyl <u>141</u> by comparing their spectral data with those of authentic samples. Further structure proof of <u>141</u> was achieved by reaction with <u>o</u>-phenylenediamine to give 2,3-dimethylquinoxaline, <u>142</u>.



A possible mechanism for the formation of 140 and 141 from 66 is as follows:























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ical sure this the • [4]. ∼ the iur. tio: COU 14€ ∼ exa dio 2-b eit The Excitation  $(\pi,\pi^*)$  of <u>66</u> results in  $\alpha$ -cleavage to biradical <u>143</u> which could then decarbonylate to <u>144</u>. Ring closure would give the bicyclic epoxy norbornene <u>145</u>. Although this product could not be isolated pure, the nmr spectrum of the crude product did not show the presence of either <u>140</u> or <u>141</u>. That is, products <u>140</u> and <u>141</u> were not observed before the crude photolysate was injected into the vpc. The minimum pyrolysis temperature for this retro Diels-Alder reaction to take place was <u>150°</u>.

The formation of biacetyl was particularly curious. It could arise from the proposed intermediate, dimethyloxirene 146 (or its valence isomers), in a variety of ways. For example, dimethyloxirene could dimerize to tetramethyldioxin 147 which could then eliminate one equivalent to 2-butyne to form 141. Alternatively, 146 could react with either water or oxygen, followed by decomposition to 141. These are shown in the following scheme.



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inte iiso zed: and oxi com int pas or au; der cle Πa รับ ha 91 ti bı Ç. d; ġ Vi The possible involvement of dimethyloxirene as an intermediate for the formation of biacetyl deserves some discussion. Oxirenes have long been postulated as intermediates in the Wolff rearrangement,<sup>69</sup> photolysis of ketenes and the peracid oxidation of acetylenes.<sup>70</sup> The history of oxirene is similar to that of many other unstable small ring compounds. Its isolation was claimed and withdrawn and its intermediacy has been postulated numerous times during the past several decades.

Recently, semiempirical molecular orbital calculations on oxirenes have been carried out by Strausz <u>et al</u>.<sup>71</sup> These authors have concluded that oxirene and its simple methyl derivatives are inherently unstable with respect to C-O bond cleavage and, therefore, exist only as short-lived transients.

Oxirene can be considered as a potential 4  $\pi$  antiaromatic system, isoelectronic with cyclobutadiene (just as furan is related to benzene). However, McDonald and Schwab<sup>72</sup> have predicted zero delocalization energy and a singlet ground state for oxirene, as opposed to the zero delocalization energy and triplet ground state predicted for cyclobutadiene.<sup>73</sup>

Finally, let me quote a few sentences from the articles published by these authors: "In light of the experimental data presented . . . the transient existence of the longdebated oxirene structure and its role in the photochemical Wolff rearrangement can be regarded as firmly established.

It now appears that the intervention of oxirenes in the photochemical Wolff reactions, as well as in the photochemical decomposition of ketenes, is a <u>rule</u> rather than an <u>exception</u>. The earlier literature claims to the contrary are evidently in error and should be disregarded."

In spite of all of the indirect indication of its existence as an intermediate, direct observation of oxirene has not yet been achieved. Isolation of oxirenes is still a great challenge. In the present study, the formation of hexamethylcyclopentadiene and biacetyl strongly suggests the intervention of dimetnyloxirene as one of the primary pyrolysis products. The approach of generating oxirenes <u>via</u> the retro Diels-Alder route seems not to have been previously attempted.<sup>108</sup>

In order to distinguish between paths A, B, and C as possible routes to biacetyl, efforts were made to detect the presence of 2-butyne and also to determine the mole ratio of 140 and 141. If path A is correct, 2-butyne and biacetyl should be generated in equimolar amounts and the mole ratio of 140 to 141 should be 2 : 1. On the other hand, if path B or C is correct, equimolar amounts of 140 and 141 should be formed. So far, 2-butyne has not been detected among the reaction products. The ratio of 140 to 141 could not be accurately determined because some unreacted 66 was present in the photolysate and it was separately established that

66 also undergoes thermal decomposition to biacetyl under the above conditions.



Pyrolysis of <u>66</u> at temperatures above 150° produced a 15-20% yield of dienone <u>150</u> and 7.5-10% yield of biacetyl <u>141</u>. Although this result (2 : 1 ratio) favored path A as the likely choice for the formation of biacetyl, no direct evidence has been obtained to verify the presence of the other necessary fragment (2-butyne) or the dimer, tetramethyldioxin. Therefore, the mode of formation of biacetyl remains unanswered. These preliminary studies will be continued.

#### B. Some Thoughts Concerning the Photochemistry of (66)

The wavelength dependence of the photobehavior of <u>66</u> implies that  $n,\pi^*$  excitation is responsible for the 1,3acyl migration and that  $\pi,\pi^*$  excitation leads to decarbonylation. Quenching and sensitizing studies further suggested that the 1,3-acyl shift arises from a triplet excited state (in contrast with the common behavior of many  $\beta$ , $\gamma$ -unsaturated ketones).

Since it has been reported that the introduction of an  $\alpha'\beta'$  double bond into  $\beta,\gamma$ -unsaturated ketones changes the course of their photoreactions (see Part III of this thesis), the presence of the  $\beta', \gamma'$ -epoxide function, as in the present case, might also be expected to bring about some unusual effects on their photochemistry. If we view 66 as a  $\beta$ ,  $\gamma$ -epoxy ketone instead of a  $\beta$ ,  $\gamma$ -unsaturated ketone, the general reaction scheme outlined in the introduction could be applied with slight modification to rationalize the present results. Assuming irradiation of 66 initially led to  $\alpha$ -cleavage with formation of diradical 143, this could either undergo ring-opening to give the acylalkoxy diradical 151 or decarbonylate to 144. Ring closure of the diradical 151 would give the lactone 152, 143 could give 129 or 66. Decarbonylation could compete with ring closure to give diradical 144 followed by ring closure to afford either 145 or 131. These suggestions are summarized in the following scheme:





So far, there is still no conclusive evidence as to whether the 1,3-shifts of  $\beta$ , $\gamma$ -unsaturated ketones occur in a concerted or stepwise fashion. If concerted, they could be classified as  $\begin{bmatrix} 2 & + & 2 \\ \pi^2 s & \sigma^2 s \end{bmatrix}$  or a [1,3] sigmatropic shift according to Woodward and Hoffmann rules. If stepwise, these reactions must involve an  $\alpha$ -cleavage to form biradical or radical pairs which could then recombine to form the 1,3shift products.

C. Photolysis of 1,3,3,4,5,6-Hexamethyl-7,8-diphenyl-5,6-epoxy-bicyclo[2.2.2]oct-7-en-2-one (67)

Compound 67 desired for the present study was prepared by peracid epoxidation of 1,3,3,4,5,6-hexamethylbicyclo-[2.2.2]oct-5,7-dien-2-one (153)<sup>74</sup> in essentially quantitative yield. The nmr spectrum of 67 was tentatively assigned as follows:



67

IR (KBr): 1710 cm<sup>-1</sup> UV (CH<sub>3</sub>OH):  $\lambda_{max}$  295 nm ( $\epsilon$  450) 240 (8,800) 215 (23,700) Irradiation of a methanol or ether solution of 67 with a Hanovia 450 W lamp through a Pyrex filter or with a Rayonet reactor equipped with 300 nm lamps resulted in rapid appearance of a new carbonyl stretching band at 1760 cm<sup>-1</sup>. The reaction was monitored by infrared spectroscopy. After three hours, the band at 1760 cm<sup>-1</sup> achieved maximum intensity compared to that of the precursor band at 1710 cm<sup>-1</sup>. The photostationary state remained unchanged after 20 hr of irradiation with 300 nm lamps. The new band disappeared gradually upon prolonged irradiation. Therefore, the irradiation was interrupted after 3 hr.

The nmr spectrum of the crude photolysate consisted of several new singlets with equal intensity to those of the precursor. Attempts were made to isolate the photoproduct 154 with both tlc and column chromatography. However, 154 could not be completely separated from its precursor. Based on the infrared spectrum, several samples contained ~80% of 154 and~20% of 67. But further purification was not achieved due to slow decomposition of the epoxycyclobutanone 154 on the tlc plates. The nmr spectrum of 154 could be tentatively assigned as follows:



154

The formation of 154 could be rationalized simply by a reversible 1,3-acyl migration. The reaction was sensitized by acetone and quenched completely by a 2.5M methanol solution of piperylene. Therefore, the  $n,\pi^*$  triplet excited state of 67 must be responsible for the 1,3-migration, as with 66.

No clean products could be isolated upon irradiation of 67 with Vycor-filtered light.

# D. <u>Photolysis of 1,3,4,5,6,7-Hexamethyl-bicyclo[3.2.0]hept-6,7-epoxy-3-en-2-one (130)</u>

To the best of my knowledge, there has been no literature report concerning the photochemistry of bicyclo[3.2.0]epoxyenones. The effect of the  $\alpha'\beta'$  double bond on the photoreactions of  $\beta,\gamma$ -epoxyketones has not been explored before. Compound 130 is also an  $\alpha,\beta$ -unsaturated ketone. Although the photochemistry of  $\alpha,\beta$ -unsaturated ketones has been extensively studied (see Part I), the presence of a  $\beta', \gamma'$ -epoxide function might change their photobehavior.

Based on the experience with cyclic  $\beta,\gamma$ -epoxyenones (vide supra), several possible reactions could be anticipated upon irradiation of 130. For example, one might predict the following possible photoproducts according to Scheme 3 outlined in the introduction.


The presence of the  $\alpha'\beta'$  double bond should facilitate the  $\alpha$ -cleavage to form the diradical 155, which could either recombine to 130 and/or 156. On the other hand, epoxide ring-opening of 155 followed by ring closure should form the lactone 158. Yet another possible reaction could be the dimerization to 159 and 160.

It is nice to predict things, especially when the prediction works. Unfortunately, chemistry is not always predictable. Irradiation of a benzene solution of 130 with a Hanovia 450 W lamp through a Pyrex filter gave only one major product 138 in ca. 56% isolate yield. Compound 138 was identified as pentamethylphenol by comparing its spectral data and mp with those of an authentic sample (see Part III). When the irradiation was carried out in a methanol solution, ketene 139 was trapped as its methyl ester 161. 161 was identified as methyl acetate by comparing its nmr spectrum with that of an authentic sample.



Two plausible mechanisms (A and B) are proposed to rationalize the formation of 138.

(A)





Mechanism A involves bond formation between C-4 and C-6 or C-2 and C-7, followed by bond cleavage between C-1, C-7 and C-4, C-5 or C-1, C-2 and C-5, C-6 to form the corresponding dienones 164 and 166. Both 164 and 166 could easily eliminate one molecule of ketene to form 138. Mechanism B involves cleavage of C-6, C-7 bond followed by bond formation between C-4 and C-6 or C-2 and C-7 to form 167 and 168, which could undergo further reaction to form 138 in a way analogous to that of mechanism A.

Mechanisms A and B could be tested by labeling experiments. Both mechanisms prddict deuterium labeling at the meta position of 138 if 130 was labelled at the C-4 methyl. However, irradiation of a benzene or methanol solution of 130 with deuterium labeling at the C-4 methyl resulted in exclusive deuterium labeling at the para position of 138.



Since the labeling experiments do not agree with the proposed mechanism, an alternative mechanism C is proposed to account for the labeling results.

(C)



This mechanism accounts satisfactorily for the labeling experiments and the stereospecific formation of the endo-220. A common intermediate 163 (as that of mechanism A) was proposed. Bond cleavage of C-1, C-7 and C-5, C-6, followed by bond formation of C-3, C-6 and C-7, 0 to give 220\*. The latter could undergo readily photoisomerization to give 138\*.

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<sup>ketene</sup>

#### SUMMARY

(1) Peracid oxidation of 1,3,3,4,5,6,7,8-octamethylbicyclo[2.2.2]oct-5,7-dien-2-one and 1,3,3,4,5,6-hexamethyl-7,8-diphenylbicyclo[2.2.2]oct-5,7-dien-2-one produced the corresponding mono epoxides, 1,3,3,4,5,6,7,8-octamethyl-5,6epoxy-bicyclo[2.2.2]oct-7-en-2-one (66) and 1,3,3,4,5,6hexamethyl-7,8-diphenyl-5,6-epoxy-bicyclo[2.2.2]oct-7-en-2one (67) in excellent yields.

(2)  $n,\pi^*$ -Excitation of <u>66</u> and <u>67</u> resulted in a reversible 1,3-acyl migration to produce the corresponding bicyclic epoxycyclobutanones in ca. 50% yield. Both sensitizing and quenching studies confirmed that a triplet excited state was responsible for the 1,3-acyl migration reaction.

(3) Irradiation of the epoxycyclobutanone 129 resulted in decarbonylation followed by rearrangement and dehydration to produce the bicyclo[4.1.0]triene 134 in 30% yield. Acidcatalyzed rearrangement of 134 gave a quantitative yield of hexamethylbenzene.

(4) Photolysis of 1,3,4,5,6,7-hexamethylbicyclo[3.2.0]hept-6,7-epoxy-3-en-2-one (130) gave pentamethylphenol and ketene as the only major reaction products, in ca. 56% yield.

A labeling experiment showed that 4-methyl-d<sub>3</sub>-1,3,5,6,7pentamethylbicyclo[3.2.0]hept-6,7-epoxy-3-en-2-one (130\*) gave 4-methyl-d<sub>3</sub>-2,3,5,6-tetramethylphenol, and a possible mechanism for this observation is presented.





#### EXPERIMENTAL

# A. Preparation of 1,3,3,4,5,6,7,8-Octamethyl-5,6-epoxybicyclo[2.2.2]oct-7-en-2-one (66)

To a solution of 232 mg (1 mmol) of 1,3,3,4,5,6,7,8octamethylbicyclo[2.2.2]octa-5,7-dien-2-one<sup>64</sup> in 10 ml of methylene chloride was added dropwise a solution of 202 mg (1 mmol, 85% pure) of m-chloroperbenzoic acid in 15 ml of methylene chloride at 0°. The reaction was monitored by examining the nmr spectra of aliquots withdrawn every 30 min. The reaction was complete after 2 hr. After removal of the solvent under reduced pressure, 20 ml of petroleum ether was added to the residue, and the precipitate was removed by filtration. The filtrate was allowed to stand at 0° for 30 min. The small amount of additional precipitate which accumulated was removed by filtration and the solution was concentrated to a colorless oil. The crude reaction product was chromatographed on Florisil using methylene chloride as the eluent to obtain 210 mg (85%) of epoxide 66 as an oil; ir (neat,  $cm^{-1}$ ) 3000 (s), 2980 (s), 1710 (s), 1470 (s), 1450 (m), 1395 (s), 1370 (w), 1280 (m), 1220 (w), 1180 (m), 1145 (w), 1100 (m), 1080 (m), 1030 (m), 1020 (w),

980 (w), 955 (w), 925 (w), 890 (s), 800 (s), 750 (s), 715 (w), 685 (m); uv  $(CH_3OH) \lambda_{max} 293 \text{ nm} (\epsilon 200), 230 (2,000);$ nmr  $(CDCl_3) \delta 1.77 (q, J = 1 \text{ Hz}, 3\text{H}), 1.63 (q, J = 1 \text{ Hz}, 3\text{H}),$ 1.40 (s, 3H), 1.30 (s, 6H), 1.27 (s, 3H), 1.01 (s, 6H); mass spectrum (70 eV) m/e (rel. intensity) 248 (35), 233 (30), 230 (15), 215 (15), 187 (35), 179 (15), 178 (55), 177 (35), 160 (55), 159 (50), 158 (20), 151 (15), 149 (18), 147 (30), 145 (30), 138 (40), 136 (100), 134 (56), 121 (20), 119 (25), 105 (30), 87 (15), 81 (35), 69 (20), 57 (24), 55 (25), 53 (25), 44 (30), 43 (80).

<u>Anal</u>. Calcd. for C<sub>16</sub>H<sub>24</sub>O<sub>2</sub>: C, 77.37; H, 9.74. Found: C, 77.40; H, 9.71.

### B. Irradiation of 1,3,3,4,5,6,7,8-Octamethyl-5,6-epoxybicyclo[2.2.2]oct-7-en-2-one (66) with Pyrex-filtered Light

Two drops of triethylamine was added to a deoxygenated solution of <u>66</u> (124 mg) in methanol (50 ml) in a Pyrex test tube and the tube was sealed with a serum cap. This solution was irradiated with a Hanovia 450 W lamp through a Pyrex filter for 3 hr. After removal of the solvent, the light yellow oil was examined by vpc (5 ft X 0.25 in., 10% QF-1 On chromosorb G 60/80, 130°, 45 ml/min). A single peak with a retention time of 2.5 min was collected. Quantitative measurements indicated that this peak accounted for 30% of the material injected. Several other peaks with longer retention times were collected upon raising the column temperature to 160°. These peaks were attributable to the decomposition products of 66 (vide infra). Tlc (alumina-CCl<sub>4</sub>) could also be used to isolate the main product, which is assigned the structure 2,5-dimethylene-1,3,4,6,7,7-hexamethylbicyclo[4.1.0]hept-3-ene 134; ir (neat, cm<sup>-1</sup>) 3100 (w), 2900 (s), 2750 (w), 1645 (w), 1600 (m), 1460 (m), 1420 (w), 1390 (m), 1120 (w), 1100 (w), 1070 (m), 945 (w), 895 (s), 855 (w), 800 (s), 780 (m); uv (CH<sub>3</sub>OH)  $\lambda_{max}$  275 nm ( $\varepsilon$  3.5 X 10<sup>4</sup>); nmr (CCl<sub>4</sub>)  $\delta$  5.23 (bs, 2H), 4.97 (bs, 2H), 1.87 (s, 6H), 1.17 (s, 6H), 1.03 (s, 3H), 0.53 (s, 3H); mass spectrum (70 eV) m/e (rel. intensity) 202 (30), 187 (67), 172 (35), 160 (20), 159 (21), 157 (37), 147 (30), 145 (35), 131 (18), 129 (20), 128 (16), 121 (50), 119 (80), 117 (100), 115 (20), 91 (30), 84 (22), 82 (37), 77 (27), 47 (40), 43 (50).

<u>Anal</u>. A correct elemental analysis could not be obtained due to the thermal instability of this compound.

## C. Irradiation of (66) with Vycorfiltered Light

When a methanol solution (124 mg of 66 in 50 ml of methanol) was irradiated through a Vycor filter using a Hanovia 450 W lamp for 30 min, 20% of 134 was obtained as described above and 3% of a new product 140 was detected by Vpc. After 2 hr, 140 built up to a maximum concentration,



while 134 disappeared completely due to polymerization. After removal of the solvent, the crude viscous oil was separated by vpc (5 ft X 0.25 in., 3% FFAP on chromosorb G 60/80, DMCS, 90°, 45 ml/min, injector 150°) to obtain an equal amount of two products 140 and 141 as oils. The nmr spectrum of the crude photolysate was quite complex. No peaks corresponding to those of 140 and 141 were observed in the nmr spectrum before the mixture was injected into the vpc at temperatures higher than 150°. Quantitative measurements indicated ~ 27% yield of 140 was produced. Compounds 140 ( $\delta$  1.67, 0.83) and 141 ( $\delta$  2.13) were identified as hexamethylcyclopentadiene<sup>68</sup> and biacetyl respectively by comparing their spectral data with those of authentic samples.

## D. Acid-catalyzed Rearrangement of 2,5-Bismethylene-1,3,4,6,7,7-hexamethylbicyclo[4.1.0]hept-3-ene\_(134)

Concentrated HCl solution (2 drops) was added to a solution of 134 (20 mg) in 0.2 ml of  $CCl_4$  at room temperature. The reaction was followed by nmr spectroscopy. After 5 min, the peaks due to 134 were completely displaced by two sharp singlets at  $\delta$  2.10 and 2.07. These peaks were identified as being due to hexamethylbenzene and acetone respectively by comparing their spectral data (ir, nmr) with those of authentic samples.

#### E. <u>Reaction of Biacetyl (141) with</u> o-Phenylenediamine

A solution of 141 (10 mg, isolated from the irradiation of 66 through Vycor as described above) in 2.0 ml of  $CHCl_3$ was added to 15 mg of o-phenylenediamine and the solution was stirred for 5 min at room temperature. An nmr spectrum of the crude mixture indicated the singlet due to 141 had disappeared. Evaporation of the solvent, followed by vpc separation (5 ft X 0.25 in., 3% FFAP on chromosorb G 60/80, DMCS, 180°, 60 ml/min) gave 18 mg (80%) of a crystalline product, mp 105-106°, which was identified as 2,3-dimethylquinoxaline by comparing its spectral data with those of an independently synthesized sample; (mp lit. 106°).<sup>109</sup> Nmr (CDCl<sub>3</sub>)  $\diamond$  7.5-8.2 (m, 4H), 2.67 (s, 6H), m/e (relative int.) 158 (80), 143 (3), 117 (100), 77 (10), 76 (15), 50 (10).

### F. Pyrolysis of 1,3,3,4,5,6,7,8-Octamethyl-5,6-epoxybicyclo[2.2.2]oct-7-en-2-one (66)

A solution of 66 (80 mg) in CCl<sub>4</sub> (0.1 ml) was injected into a vpc (5 ft X 0.25 in., 20% FFAP on chromosorb W, 60/80, 190°, 60 ml/min) with the injector temperature at 200°. The first peak collected with the solvent was identified as biacetyl (vide supra). The second peak collected was identified as 2,3,4,5,6,6-hexamethyl-2,4-cyclohexadienone (150). Quantitative measurements by using a known concentrations of biacetyl and dienone as references indicated that 15-20% of dienone 150 was produced. The mole ratio of biacetyl to dienone was 1 : 2.

#### G. Irradiation of (66) in Acetone

A 1% solution of 66 in acetone was irradiated through a Pyrex filter using a Hanovia 450 W lamp. The reaction was monitored by infrared spectroscopy which indicated that ca. 50% of the bicyclobutanone 129 was produced after 10 hr of irradiation. The intensity of the new band at 1760 cm<sup>-1</sup> decreased gradually upon further irradiation.

## H. Irradiation of (66) in the Presence of a Quencher

Piperylene (2.5 g) was added to 5 ml of a methanol solution containing 20 mg of 66. The solution was deoxygenated with a stream of  $N_2$  for 5 min and then irradiated with a Hanovia 450 W lamp. The reaction was followed by infrared spectroscopy. The 1760 cm<sup>-1</sup> band was not observed after 5 hr of irradiation. No attempts were made to photolyze 66 in different concentrations of the quencher.

## I. Preparation of 1,3,3,4,5,6-Hexamethyl-7,8-diphenylbicyclo[2.2.2]oct-5,6epoxy-7-en-2-one (67)

A solution of 1.03 g of m-chloroperbenzoic acid in 20 ml of methylene chloride was added dropwise to a solution of 1.78 g of hexamethylbicyclo[2.2.2]octa-5,7-dien-2-one<sup>74</sup> in 10 ml of methylene chloride precooled to 0°. The solution was allowed to stir at this temperature. The reaction was monitored by nmr, which indicated that the starting material completely disappeared after 3 hr. The m-chlorobenzoic acid

which precipitated was removed by filtration. After removal of the solvent, 20 ml of petroleum ether (30-60°) was added to the residue. The solution was allowed to stand overnight at room temperature. The white precipitate which had formed was removed by filtration and the solvent was removed under reduced pressure. A colorless oil (1.80 g) was obtained which solidified upon standing at room temperature for 5 min. The solid was recrystallized from hexane to obtain 1.62 g (83%) of pure 67: mp 138-139°; ir (KBr, cm<sup>-1</sup>) 3000 (s), 1710 (s), 1605 (m), 1580 (w), 1500 (m), 1450 (s), 1405 (m), 1390 (m),1370 (w), 1280 (m), 1240 (w), 1215 (w), 1185 (w), 1100 (m), 1080 (s), 1030 (s), 935 (m), 880 (s), 820 (m), 790 (m), 780 (m), 760 (w), 735 (m), 720 (s); uv (CH<sub>3</sub>OH)  $\lambda_{max}$ **295 nm (ε 450), 240 (8,800), 215 (23,700); nmr (CCl<sub>4</sub>) δ 7.0** (m, 10H), 1.42 (s, 3H), 1.27 (s, 3H), 1.23 (s, 3H), 1.10 (s, 3H), 0.97 (s, 3H), 0.93 (s, 3H); mass spectrum (70 eV) m/e (rel. intensity) 372 (25), 357 (15), 329 (45), 303 (60), 302 (100), 276 (25), 275 (90), 261 (42), 260 (100), 259 (67), 229 (25), 215 (31), 202 (20), 193 (70), 126 (39), 114 (40).

<u>Anal</u>. Calcd. for C<sub>26</sub>H<sub>28</sub>O<sub>2</sub>: C, 83.83; H, 7.58. Found: C, 83.79; H, 7.51.

## J. Photolysis of 1,3,3,4,5,6-Hexamethyl-7,8-diphenylbicyclo[2.2.2]octa-5,6epoxy-7-en-2-one (67)

In a Pyrex test tube, 100 mg of 67 was dissolved in 20 ml of methanol and the solution was deoxygenated with

nitrogen for 15 min. The solution was irradiated with a Hanovia 450 W lamp, and the reaction was monitored by infrared spectroscopy. After 3 hr, the new band at 1760 cm<sup>-1</sup> reached a maximum intensity, approximately equal to that of the 1710 cm<sup>-1</sup> band of 67. The solvent was removed under reduced pressure, leaving a colorless oil. The crude photolysate was separated by a silica gel plate using CH<sub>2</sub>Cl<sub>2</sub> as the eluent to obtain 30 mg of a colorless oil. The ir spectrum of this oil indicated the relative intensity of the 1760 cm<sup>-1</sup> bands vs. 1710 cm<sup>-1</sup> was about 4 : 1. The major component of the oil was attributable to 3,3,4,5,6,7-hexamethyl-5,6-diphenylbicyclo[4.2.0]oct-5,6-epoxy-7-en-2-one (129). The mass spectrum showed 129 to be isomeric to 67. If the peaks due to 67 were disregarded, the nmr spectrum of 129 could be deduced as follows: nmr (CDCl<sub>3</sub>)  $\delta$  7.20 (m, 10H), 1.67 (s, 3H), 1.61 (s, 6H), 1.50 (s, 3H), 1.10 (s, 6H). Unfortunately, attempts to further purify 129 for elemental analysis were not successful due to decomposition of 129 on the plate.

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# K. Sensitized Irradiation of (67)

In a Pyrex test tube, 20 mg of 67 was dissolved in 10 ml of acetone and the solution was deoxygenated for 10 min. The test tube was sealed with a serum cap and attached to a Hanovia 450 W lamp contained in a Pyrex filter. The solution was irradiated for 3 hr. The infrared spectrum of the



photolysate showed presence of bands at 1760 cm<sup>-1</sup> and 1710 cm<sup>-1</sup>, with relative intensities 1 : 1.

#### L. Irradiation of (67) in the Presence of a Quencher

In a Pyrex test tube, 20 mg of 67 was dissolved in 5 ml of methanol containing 2.5 g of piperylene. After being deoxygenated for 5 min with a stream of nitrogen, the solution was irradiated through a Pyrex filter using a Hanovia 450 W lamp. The reaction was monitored by infrared spectroscopy. No 1760 cm<sup>-1</sup> band was observed in the infrared spectrum. Only starting material was detected after 5 hr of irradiation.

## M. Irradiation of 1,3,4,5,6,7-Hexamethylbicyclo[3.2.0]hept-6,7-epoxy-3-en-2one (130)

A deoxygenated solution containing 100 mg of 130 in 20 ml of methanol was irradiated with a 450 W Hanovia lamp through a Pyrex filter. The reaction was monitored by nmr spectroscopy. After 10 hr, the starting material was essentially gone and a sharp singlet at  $\delta$  2.1 built up to its maximum intensity. The product was isolated in 56% yield using a preparative (1.5 mm) silica gel plate with methylene chloride as eluent. The photoproduct was identified as pentamethylphenol by comparing its spectral data with those of an authentic sample (see Part III of this thesis). When a solution containing 20 mg of 130 in 0.2 ml of methanol-d<sub>4</sub> was irradiated, two sharp singlets at 2.10 and 2.07 ppm were observed. The singlet at 2.07 ppm was identified as methyl acetate by comparing its nmr spectrum with that of an authentic sample.

# N. Photolysis of 4-Methyl-d<sub>3</sub>-1,3,5,6,7-Pentamethylbicyclo[3.2.0]hept-6,7epoxy-3-3n-2-one (130\*)

In a Pyrex test tube, 80 mg of  $130^*$  (see Part III of this thesis) with 100% deuterium-labelled at the C-4 methyl was dissolved in 20 ml of benzene. The solution was deoxygenated as usual and irradiated with a 450 W Hanovia lamp through a Pyrex filter for 15 hr. Evaporation of the solvent, followed by separation with tlc as described above gave 4-methyl-d<sub>3</sub>-2,3,5,6-tetramethylphenol as the only major Product. The deuterium-labeling position of the photoproduct was determined by the Europium-shift data. Upon addition of Eu (fod)<sub>3</sub>, the singlet in the nmr spectrum split into two singlets with equal intensity. These two singlets were attributable to the ortho and meta methyls. The Europium Slopes for the ortho, meta and para methyls of pentamethyl-Phenol are 5.5 : 2.0 : 1.0. -----

PART III

SYNTHESES AND PHOTOCHEMISTRY OF

BICYCLO[3.2.n]DIENONES

#### INTRODUCTION

Bicyclo[3.2.n]dienones photoisomerize to ketenes. The generality of this reaction was first recognized by Chapman <u>et al</u>. in 1969.<sup>76</sup> The photoisomerization of 1-methoxybicyclo[3.2.0]hept-3,6-dienone 169 to 7-methoxybicyclo[3.2.0]hept-3,6-dienone 171 has been shown to proceed via ketene intermediate 170 by careful analysis of the low-temperature infrared spectra.<sup>77</sup>



Attempts to trap the intermediate were unsuccessful due to the facile thermal isomerization of the ketene. Formation of the ketene intermediate can be easily understood by the well-known  $\alpha$ -cleavage reaction of  $n,\pi^*$  excited states.

In order to gain more insight into these reactions, derivatives of 169 in which the zero-atom bridge was replaced by one- and two-atom bridges were prepared. It was thought

that the resulting ketenes should be less strained and more amenable to detailed study. Irradiation of compounds 172a-d gave the corresponding ketenes, which were observed by lowtemperature infrared and nmr spectroscopy.<sup>77</sup> Methyl esters were formed in high yields upon addition of methanol (in the case of 174c, the norcaradiene rearranged to a cycloheptatriene).



**172a.** 
$$X : CH_2$$
  
**b.**  $X : N-N_R$   
**c.**  $X : -CH=CH-$   
**d.**  $X : ()$ 

In the absence of nucleophiles, the major thermal reactions of these ketenes are recyclization and dimerization. The former of these reactions can be classified as a sixelectron homoelectrocyclic reaction<sup>78</sup> (compounds such as 123 can be regarded as cis-divinylcyclopropanes).

In 1971, Hart and Love reported a novel intramolecular  $f_{our-electron}$  ketene cycloaddition.<sup>79</sup> When the ketene 173a

was completely substituted with methyl groups, as in 176, the sole reaction of the ketene involved facile intramolecular  $[\pi^2_s + \pi^2_a]$  cycloaddition, resulting in a quantitative yield of the tetracyclic ketone 177 even when the irradiation was carried out in the presence of nucleophiles!



Direct evidence for the intermediacy of ketene 176 was obtained by low-temperature techniques. It was found by the authors that interconversions of this type are quite general when the dienones are highly substituted. For example, the diphenyl analogs 178 and 179 have been found to follow the same reaction sequence, to give a quantitative yield of 180.



178

The accelerating effect of alkyl groups on intramolecular cycloadditions of the type (1.76 + 1.77) is believed to arise from steric factors. The intermolecular reaction with a nucleophile is retarded due to the presence of bulky groups near the carbonyl carbon.<sup>80</sup> In conformation 1.76, the ketene and cyclopentene carbon-carbon double bonds are nearly in the perfect geometric arrangement for cycloaddition.<sup>81</sup> Furthermore, the methyl substituents inductively decrease the electrophilicity of the ketene.

It is interesting that when the resulting ketenes are unusually reactive, as in the chloroketene 182,<sup>82</sup> intramolecular cycloaddition also competes successfully with attack by external nucleophiles. Thus irradiation of 181 gives 183.



This is a striking substituent effect (compare with the reaction of the unsubstituted parent compound 172a). The authors suggested that the  $\alpha$ -chloro substituent lowers the transition state energy for [2 + 2] cycloadditions compared with that for the competing [3,3] sigmatropic ring closure



to the starting ketone 181, thus leading to exclusive formation of the thermodynamically less stable 183. This enhancement in reactivity is in accord with the well-known higher reactivity of  $\alpha$ -haloketenes as compared with unsubstituted ketenes in cycloaddition reactions.<sup>83</sup>

Methylene analogs of polysubstituted bicyclo[3.2.1]oct-3,6-dien-2-ones (<u>i.e.</u>, 184) have been found to behave similarly upon irradiation, giving the corresponding tetracyclic alkene 185 in high yield.<sup>84</sup>



Although substituent effects have been studied to some extent in these [3.2.1] systems (<u>i.e.</u>, 172), little is known about comparable factors in the [3.2.0] system (<u>i.e.</u>, 169). The photochemistry of hexamethylbicyclo[3.2.0]hept-3,6dienone 186<sup>85</sup> is described in this part of the thesis. Also, studies on the [3.2.1] system have been extended to highly substituted compounds with an oxygen in the one-atom bridge



186

(<u>i.e.</u>, 187).

187

#### RESULTS AND DISCUSSION

# A. Synthesis of Hexamethyl-8-oxabicyclo-[3.2.1]oct-3,6-dien-2-one (187)

The title compound was synthesized according to the **following reaction sequence**, starting from hexamethyl Dewar **benzene**:



The first two steps were carried out according to procedures developed by Dr. M. Nitta in this laboratory.<sup>86</sup> The dichlorocarbene monoadduct 188 was not isolated. It spontaneously underwent dehydrochlorination to yield the corresponding triene 189. Rearrangement of 189 in cold, concentrated



methanolic sulfuric acid gave the bicyclic dienone 186 in 85% yield. Epoxidation of 186 was carried out with one mole of m-chloroperbenzoic acid (m-CPBA) at 0°, to obtain the mono-epoxide 130 in over 85% yield. The last step in the sequence was achieved by treating 130 with neat trifluoroacetic acid at 0°. This rearrangement proceeded cleanly to give, after quenching the reaction mixture with saturated sodium carbonate solution at -5°, a colorless liquid in higher than 90% yield. The nmr spectrum of the acidrearranged product consisted of two singlets and four quartets with equal intensity. These four quartets had coupling Constants of approximately 1 Hz, typical of homoallylic COupling.

From the nmr data, three possible structures (187, 190, and 191) were considered for the product:



Structure 190 seemed the least likely, because one would not expect this epoxide to survive the acidic conditions. Furthermore, the ir data  $(v_{C=0})$  also exclude this structure. Using Eucarbone<sup>107</sup> as a reference, the carbonyl stretching frequency of 190 was expected to be lower than 1660 cm<sup>-1</sup>, whereas the observed  $v_{C=0}$  of the rearrangement product was 1700 cm<sup>-1</sup>.

Differentiation between 187 and 191 was also possible by their infrared spectra. Since 191 is an  $\alpha,\beta$ -unsaturated cyclohexanone, one will expect its carbonyl stretching frequency to lie well below 1680 cm<sup>-1</sup>, especially when the conjugation is extended by an enol-ether oxygen atom.<sup>87</sup> Therefore, 187 was the only possible structure.

The above conclusion was supported by comparing the **spectral data of 187** with those of three model compounds,  $1,75,^{79}$  192,<sup>102</sup> and 200<sup>88</sup>:



192 IR (neat): 1720 cm<sup>-1</sup>





200 IR (KBr):  $1690 \text{ cm}^{-1}$ 

The carbonyl stretching frequency of 192 is 1720 cm<sup>-1</sup>. Since 187 has one  $\alpha,\beta$ -unsaturated double bond, the difference in the stretching frequency of 187 and 192 was expected to be in the order of 20 cm<sup>-1</sup>. Thus the observed value of 1700 cm<sup>-1</sup> in 187 is quite acceptable for the proposed structure. The slight difference in the carbonyl stretching frequency of 187 and 200 is probably due to substituent effects. However, a precise comparison was not possible because the infrared spectrum of 200 was taken in a KBr pellet while the infrared spectrum of 187 was run in carbon tetrachloride solution.

The nmr spectra of 187 and 175 are similar. In both **Compounds**, the C-4 methyl appears at the lowest field. The **methyl** protons at C-1 and C-7 are at higher field than those **at** C-5 and C-6, respectively, in both compounds. The **europium** shift ratios are in the order of C-1 > C-3 > C-7 > C-4 > C-5 > C-6 in both cases.

Both 175 and 187 have one methyl group with protons that are exchangeable by base. Treatment of 187 with a Saturated solution of NaOCH<sub>3</sub>/CH<sub>3</sub>OD overnight at room temperature resulted in complete labeling of the C-4 methyl.

CH3ONa/CH3OD 187

187



Thermal rearrangement of 187 provides further evidence for its structure. Pyrolysis of a benzene solution of 187 in a hot tube preheated to 500° under nitrogen resulted in 38% conversion to pentamethylphenol 138, along with 62%. recovered starting material. The formation of pentamethylphenol from 187 can be rationalized as follows:



Cleavage of the 1,2-bond followed by valence bond isomerization to form the intermediate ketene 201, which could undergo intramolecular Diels-Alder cyclization to form dienone 166,  $\gamma$ -Hydrogen abstraction and aromatization would give pentamethylphenol.<sup>96</sup>

Attempts were made to isolate the proposed intermediate 166 by performing the pyrolysis at lower temperatures (350°-500°). However, under all conditions only 187 and 203 were
isolated. The starting material was fully recovered at temperatures below 350°.

Similar results have been reported by Potts <u>et al</u>.<sup>88</sup> Thus dienone 200 undergoes thermal isomerization to the corresponding dienone 204. Treatment of 204 with warm potassium hydroxide solution affords 2,3,4,6-tetraphenylphenol 205, and benzoic acid.



Precedent for the cyclization of ketenes (<u>i.e.</u>, 201) to 2,4-cyclohexadienones exists.<sup>89,90</sup>

Four possible mechanisms to rationalize the formation of 187 from 130 were considered:

(A)



(A) Cont'd



(B)



-H+

130







1,87

<u>H</u>+

(C)







210





1,87

(D)















The first two mechanisms involve protonation of the epoxide as the initial step. The ring could open in either direction to put the positive charge on C-6, or C-7. In Mechanism A, 1,5-bond cleavage of 206 may be assisted by hydroxyl group participation, to form 207. Epoxide ring-opening in the opposite sense, followed by ring closure and deprotonation could give 187. In Mechanism B, similar 1,5-bond cleavage of 209, followed by ring closure and deprotonation would lead directly to 187.

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The last two mechanisms involve protonation on the carbonyl group as the first step. In Mechanism C, 1,5-bond cleavage in 210 followed by rearrangement could give 187. In Mechanism D, a highly stabilized dicyclopropylcarbinyl cation 213 could intervene; deprotonation could easily give 187.

In order to distinguish path A or D from path B or C a labeling experiment was carried out. Deuterium was incorporated into the C-4 methyl by treating 130 with a saturated solution of  $NaOCH_3/CH_3OD$ . Acid-catalyzed rearrangement of the resulting 130\* gave 187\* with deuterium labeling exclusively at C-4.



The labeling experiments ruled out paths B and C because both of these mechanisms would result in label at C-7 instead of C-4. Paths A and D account satisfactorily for the labeling results. However, path D is strongly favored because it involves the stable dicyclopropylcarbinyl cation 213 as an intermediate. This should be the lowest-energy path and accounts for the rapid formation of the rearrangement product. Path A requires the successive formation and ring opening in the opposite sense of an epoxycycloheptadienone, a relatively unlikely sequence of steps lacking in any special driving force.

Path D involves protonation of the carbonyl oxygen instead of the epoxide oxygen. Normally, one would expect acid-catalyzed rearrangements of eopxy ketones to be initiated by protonation of the epoxide oxygen atom.<sup>91</sup> Recently, Hart and Huang<sup>92</sup> reported a competitive protonation at each oxygen of the epoxy ketone 214. They claimed that the formation of 216 from 214 involved initial protonation at the carbonyl oxygen, a mechanism consistent with labeling experiments. The driving force presumably is the formation of a cyclopropylcarbinyl cation, 215.



214





However, exclusive protonation at the carbonyl oxygen of an epoxy ketone, as suggested in the present study, is rather To the best of my knowledge, this is the first unique. example of a reaction which proceeds exclusively by this path. The driving force in the present case must be the formation of a dicyclopropylcarbinyl cation, 213.

# B. Photolysis of Hexamethyl-8-oxabicyclo-[3.2.1]oct-3,6-dien-2-one (187)

The original goal of the work described in this part of the thesis was to study the photoisomerization of 187 with the hope of synthesizing the tetracyclic cyclobutanone 217.



217

It has been shown that the secondary alcohol 181, synthesized from 175 as shown, forms the pyramidal carbocation  $218^{94}$  on ionization in superacid (FSO<sub>3</sub>H-SO<sub>2</sub>ClF) at temperature below -50°.



We hoped that an analogous sequence would lead to the corresponding oxygen-containing pyramidal ion 219.



Although the photochemistry of bicyclo[3.2.1]dienones with a hetero atom bridge has never been reported to date, we expected compounds of this type to undergo a facile [3,3] photorearrangement based on the well-established photoreactions of bicyclo[3.2.n]dienones (see the Introduction section).

Irradiation of a 10 mM methanol solution of 187 with Corex-filtered light for two hours gave two products, 220 and 203 in a ratio of 5 : 1. The major product 220, isolated in 50% yield, was a colorless liquid. The empirical formula showed it to be isomeric with its precursor 187. The ir spectrum indicated the presence of two carbonyl groups, with absorptions at 1710 and 1690 cm<sup>-1</sup>, corresponding respectively to the acetyl and the doubly conjugated cyclopentenone moieties. The presence of a band at 1640 cm<sup>-1</sup> implied the presence of a carbon-carbon double bond. The ultraviolet spectrum, with maxima at 325 nm ( $\varepsilon$  340), 272 (3,780), and 232 (5,970) was also consistent with a cyclopentenone structure. The nmr spectrum of 220 consisted of three sharp singlets at  $\delta$  1.20, 1.23, 1.92 with ratios of 1 : 2 : 1 and two quartets at  $\delta$  1.50 and 1.92 with equal intensity. The coupling constant between these two quartets was ~1 Hz, typical of homoallylic coupling. These spectral data are consistent with the proposed structure, 1,3,4,5,6pentamethyl-6-acetylbicyclo[3.1.0]hex-3-en-2-one for 220. This structure is further supported by comparing the above spectral data with those of 1,3,4,5,6,6-hexamethylbicyclo-[3.1.0]hex-3-en-2-one 221<sup>95</sup> as summarized below:



One interesting feature worth pointing out in the nmr spectrum of 220 is the upfield-shift of the acetyl methyl. Normally, one would expect this group ot have a chemical shift of about 2.1 ppm (e.g., acetone 2.07 ppm). The upfield shift could be rationalized by a shielding effect of the  $\alpha$ ,  $\beta$ -conjugated double bond of cyclopentenone. This implies that the acetyl group is in the endo position. A similar shielding effect is experienced in the model compound 221. The difference between the chemical shifts of the C-6 endo and exo methyls in 221 is 0.18 ppm. Taking this difference into account, the chemical shift of the acetyl group in 220 should have been at 2.10 ppm (i.e., 1.92 + 0.18 = 2.10) if it were exo to the cyclopentenone. Labeling experiments showed that 220 had only two methyls with exchangeable protons, consistent with the assigned structure.



The other photoproduct 138, isolated in 10% yield, was identified as pentamethylphenol by comparing its melting point and spectral data with those of an authentic sample.<sup>96</sup>

The bicyclic enone 220 was found to convert to 138 quantitatively upon irradiation. The eliminated ketene 139 was trapped as methyl acetate 161 by methanol.



Consequently, the initial photoproduct from 187 is 220, and 138 is formed in a second photochemical step.

The formation of 220 from 187 can be rationalized by a 1,3-acyl shift to form 223, followed by a [ $_{\pi}^{2} + _{\sigma}^{2}$ ] cyclo-addition (223 + 220).<sup>97</sup>



223

Since compound 223 possesses the same chromophore as 187, it competes efficiently with the precursor in absorbing light, and is either converted back to 187 or rearranges to 220. The presumed intermediate 223 did not accumulate in a sufficient amount to be detected.

The fact that only the endo isomer of 220 was formed implies that the conversion of 223 to 220 proceeded stereospecifically. This is probably due to continuing molecular orbitals overlap in the transition state leading to the endo isomer. The transition states which lead to both the exo (path A) and the endo (path B) are depicted on the following page. In path A, the  $\pi$ -clouds and the  $p_x$ -orbital of the oxygen point away from each other in the transition state. In path B, the  $p_x$ -orbital of the oxygen and the  $\pi$ -clouds bend toward each other and overlap to a significant extent during the course of the reaction. Thus path B has lower transition state energy and therefore the reaction proceeds in this direction exclusively.

















The conversion of 220 to 138 and 139 can be rationalized by  $\gamma$ -hydrogen abstraction followed by aromatization to form pentamethylphenol and ketene (trapped as methyl acetate).



A labeling experiment was carried out to check the proposed mechanism. When the C-4 methyl of 187 was labelled with deuterium, the C-4 methyl of 220 was labelled and the final product 138 had the C-3 methyl labelled.



Europium shift data were used to assign the labeling position in 138\*. The nmr spectrum of 138\* consisted of one rather sharp singlet before Eu(fod)<sub>3</sub> was added. The singlet separated into 3 peaks with relative area of 2 : 1 : 1 after the shift reagent was added (areas are from low field to high field).

Attempts were made to identify the multiplicity of the excited state(s) responsible for these reactions. A dilute acetone solution of 187 was irradiated, and these photore-actions were found to be sensitizable. Benzophenone was also found to be an efficient sensitizer. These results imply a triplet state reaction.

Despite the fact that the triplet sensitized photolysis of  $\beta,\gamma$ -unsaturated ketones generally results in 1,2-acyl migration, the present dienone 187 rearranged exclusively by a 1,3-acyl migration. The presence of the  $\alpha'\beta'$  bouble bond in  $\beta,\gamma$ -unsaturated ketones has been shown to cause some remarkable changes in the photobehavior of this class of compounds.<sup>98</sup>

The effect of added piperylene as a possible triplet quencher of these photoreactions was examined, but no effective quenching was observed over a concentration range of 1.0 to 7 M! However, similar results have been reported in the literature. For example, Murata and Sugihara<sup>99</sup> have reported that the 1,3-acyl migration in the photoconversion of 224 to 225 is sensitized by acetone but not quenched by piperylene.



Although the authors argue that the lack of quenching by piperylene denotes that the singlet excited state of 224 can lead to 225, the triplet state could not be completely excluded, because the rate of intramolecular rearrangement (<u>i.e.</u>, 1.3 acyl shift) of the triplet could exceed the diffusion controlled quenching process. The possible involvement of more than one excited state and the structural features in these photoreactions requires further investigation.

Although bicyclo[3.2.n]dienones are prone to undergo [3,3] migration as described in the introduction, the exact factors that control the relative importance of [3,3] vs. [1,3] shifts and other reaction paths are not well understood. For example, Kende <u>et al</u>.<sup>100</sup> reported that the photochemical behavior of the benzyne-tropone adduct 226 involves the [3,3] rearrangement to the ketene 227 as the major path and the [1,3] acyl migration to cyclopentenone 228 as the minor path.



However, Sasaki and co-workers<sup>101</sup> have reported a remarkable substituent effect in the photochemical behavior of similar bicyclo[3.2.2]dienones 229 and 230. Irradiation of 229 in methanol gave exclusively the [3,3] migration product 231; whereas, irradiation of 230 gave only the [1,3] acyl migration product 232.









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----> 1,4-dione

Thus, the hydroxyl group at C-12 of 230 causes a marked change in the chemical behavior of the bicyclo[3.2.2]dienones. No explanation was offered by these authors.

#### C. Photolysis of 1,3,4,5,6,7-Hexamethylbicyclo[3.2.0]hept-3,60dien-2-one (186)

We studied the photochemistry of 186 with the thought that if this dienone rearranged by a [3,3] process, typical of dienones of this type, the resulting bicyclic ketene 233 might undergo intramolecular cycloaddition to give the interesting tetracyclic cyclobutanone 234 (analogous to the photochemistry of 175).



As discussed in the Introduction, it was reported <sup>79</sup> that highly substituted ketenes undergo facile intramolecular cycloaddition even in the presence of nucleophiles. Therefore, we hoped that the ketene intermediate 233 might undergo a similar intramolecular reaction of this nature rather than react with nucleophiles

Although we suspected that the formation of 234 might be retarded because of its ring strain, a recent report by Brember <u>et al.</u><sup>103</sup> encouraged us to try the reaction. These authors reported that irradiation of the bicyclo[3.2.0]hept-2,6-diene 235 results in a good yield of the tetracyclo-[ $3.2.0.^{2,7}0^{3,6}$ ]heptane 236.



Another encouraging example was reported by T. Katz and N. Acton,<sup>104</sup> who prepared prismane 238 by photolysis of the azo compound 237.



Surprisingly, prismane is quite stable at room temperature.

Despite the examples cited above, our major concern was that how efficiently the formation of 234 would compete with other available reaction paths for 233.

Irradiation of a 0.2% hexane solution of 186 with a Hanovia 450 W lamp through Pyrex for 20 hr resulted in essentially quantitative yield of a colorless liquid. The nmr spectrum of the crude photolysate showed two quartets centered around 1.75 ppm and a sharp singlet at 1.0 ppm with relative peak areas of 2 : 1, which were attributable to 239. Vpc (5% SE-30, 100°) of the crude photolysate indicated a single peak with a slightly shorter retention time than its precursor 186. The infrared spectrum of the photolysate had a sharp, intense band at 2120 cm<sup>-1</sup>, characteristic of a ketene. The mass spectrum indicated the product to be isomeric with the precursor. All of these spectral data were consistent with the ketene structure 239.



239

Ketene 239 was moderately stable. It was possible to purify this ketene by vpc at temperatures below 120°.

A 0.2% hexane solution of 239 remained intact at 0° for several days, although on prolonged standing the ketene band in the ir disappeared and a new carbonyl absorption appeared at 1745 cm<sup>-1</sup>. The neat liquid ketene only survived for several hours at 0°. The 2120 cm<sup>-1</sup> band was replaced by the 1745 cm<sup>-1</sup> band. The nmr spectrum of this thermal rearrangement product consisted of 4 singlets at  $\delta$  1.10, 1.17, 1.27 and 1.43 and 2 quartets (J ~ 0.5 Hz) centered around  $\delta$  1.63, all with equal intensities. To this product we tentatively assign structure 240.

THE POWER DISTANCE



Unfortunately, further characterization of this compound has not yet been achieved due to difficulties in purification. Compound 240 polymerized gradually at room temperature, resulting in tarry products. A complex mixture was also obtained when 240 remained at 0° for several days.

The ketene 239 reacted with methanol at room temperature to form the methyl ester 241 in excellent yield.



The original sharp band at 2120  $\text{cm}^{-1}$  shifted to 1730  $\text{cm}^{-1}$ , indicating the formation of an ester. The spectral data of the ketene 239 and the ester 241 are summarized as follows.



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241

IR  $(CCl_4): 2120 \text{ cm}^{-1}$ IR (CCl<sub>4</sub>): 1730 cm<sup>-1</sup> UV (CH<sub>3</sub>OH): 262 nm UV (hexane): 228 nm m/e: 190 (M<sup>+</sup>), 147 (base) m/e: 222 (M<sup>+</sup>), 135 (base)

The formation of 239 from 186 can be rationalized by a [3,3] photorearrangement followed by ring opening of the bicyclic ketene intermediate 233.



Opening of the cyclobutene ring was probably facilitated by the methyl substituents<sup>105,106</sup> and the ring-strain of 233. Consequently, ring opening competed successfully with other possible reaction paths (<u>e.g.</u>, intramolecular cyclization).

Thus, photolysis of the bicyclo[3.2.0]dienone 186 gave exclusively the [3,3] photorearrangement product 233, followed by rapid ring opening to 239. However, since the [1,3] migration product of 186 is 186 (that is, the reaction is degenerate), the possible involvement of the [1,3] migration process could not be completely ruled out.

#### SUMMARY

(1) Treatment of 1,3,4,5,6,7-hexamethyl-5,6-epoxybicyclo[3.2.0]hept-3-3n-2-one (130) with trifluoroacetic acid at 0° resulted in a high yield of 1,3,4,5,6,7-hexamethyl-8oxabicyclo[3.2.1]oct-3,6-dien-2-one (187).

(2) Irradiation of a methanol solution of (187) provided a 50% yield of 1,3,4,5,6-pentamethyl-6-<u>endo</u>-acetylbicyclo[3.1.0]hex-3-en-2-one (220) and a 10% yield of 2,3,4,5,6-pentamethylphenol. With acetone sensitization, the yields of (220) and pentamethylphenol were 60% and 10% respectively. Since irradiation of (220) in methanol provided a quantitative yield of pentamethylphenol, the initial photoproduct of 187 is 220.

(3) The photoisomerization of (187) to (220) was rationalized by a [1,3] acyl migration followed by a rapid  $[\pi^2 + \sigma^2]$  cycloaddition. Exclusive formation of the <u>endo</u> isomer was rationalized by a transition state with continuous overlap of  $\pi$  orbitals. The photoisomerization of (220)to pentamethylphenol and the ketene was initiated by a  $\delta$ -hydrogen abstraction from the <u>endo</u>-acetyl methyl group by the cyclopentenone oxygen, followed by aromatization.

(4) The mechanisms were checked by deuterium labeling. Treatment of 4-methyl-d<sub>3</sub>-1,3,5,6,7-pentamethyl-5,6-epoxybicyclo[3.2.0]hept-3-3n-3-one (130\*) with trifluoroacetic acid at 0° resulted in a 90% yield of 4-methyl-d<sub>3</sub>-1,3,5,6,7pentamethyl-8-oxabicyclo[3.2.1]oct-3,6-dien-2-one (187\*). Irradiation of a methanol solution of (187\*) resulted in a 50% yield of 4-methyl-d<sub>3</sub>-1,3,5,6-tetramethyl-6-acetylbicyclo[3.1.0]hex-3-en-2-one (220\*) and a 10% yield of 3-methyl-d<sub>3</sub>-2,4,5,6-tetramethylphenol.

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(5) Irradiation of a hexane solution of 1,3,4,5,6,7nexamethylbicyclo[3.2.1]hept-3,6-dien-2-one (186) provided a quantitative yield of methyl pentamethylcyclopentadienyl ketene (239). The formation of (239) was rationalized by an initial [3,3] photorearrangement to the hexamethylbicyclic ketene (233), followed by a rapid thermal cyclobutene ring opening to give (239).

(6) Pyrolysis of hexamethyl-8-oxabicyclo[3.2.1]oct3,6-dien-2-one (187) at 500° resulted in 38% conversion to
pentamethylphenol (138).

#### EXPERIMENTAL

# A. <u>Hexamethylbicyclo[3.2.0]hept-6,7-</u> epoxy-3-en-2-one (130)

To a solution of 2.0 g (10.5 mmol) of hexamethylbicyclo-[3.2.0]hept-3,6-dien-2-one<sup>86</sup> in 20 ml of methylene chloride was added, at 0°, a solution of 2.5 g (12.6 mmol) of m-chloroperbenzoic acid in 30 ml of methylene chloride. The mixture was stirred at 0° for 5 hr. After the solvent was evaporated under reduced pressure, petroleum ether (bp 30-60°) was added to the residue, and the m-chlorobenzoic acid was removed by filtration. The filtrate was cooled in an ice bath for 30 min and the remaining m-chlorobenzoic acid and the excess m-chloroperbenzoic acid was removed again by filtration. Evaporation of the solvent from the filtrate left 2.15 g of a colorless oil; an nmr spectrum of the crude material showed it to be 95% pure. The crude product was chromatographed on Florisil using methylene chloride as eluent to give 1.98 g (9.6 mmol, 90%) of epoxide 130: mp 59-60°; ir (KBr) 2990 (m), 1340 (m), 1260 (w), 1175 (m), 1080 (m), 1030 (m), 930 (w), 835 (m); uv (ethanol)  $\lambda_{max}^{245}$ nm ( $\epsilon$  5,970); 215 (6,390); nmr (CCl<sub>A</sub>):  $\delta$  1.98 (q, 3H, J = 1 Hz, 1.70 (q, 3H, J = 1 Hz), 1.35 (s, 3H), 1.25 (s, 3H),

1.03 (s, 3H), 1.0 (s, 3H)<sup>110</sup>; mass spectrum (70 eV) m/e
(relative intensity) 206 (25), 191 (2.5), 178 (2.5), 165
(12), 164 (100), 163 (16), 150 (10), 149 (75), 124 (11),
121 (10), 93 (10), 91 (10), 43 (23).

<u>Anal</u>. Calcd. for C<sub>13</sub>H<sub>18</sub>O<sub>2</sub>: C, 75.69; H, 8.80 Found: C, 75.68; H, 8.79.

B. Acid-Catalyzed Rearrangement of Hexamethylbicyclo[3.2.0]hept-6,7-epoxy-3-en-2-one (130): Synthesis of Hexamethyl-8-oxabicyclo[3.2.1]oct-3,6dien-2-one (187)

A solution of 0.206 g (1.0 mmol) of 130 in 3 ml of icecold trifluoroacetic acid was stirred at 0° for 5 min and the reaction was quenched by adding the mixture dropwise to a precooled saturated Na<sub>2</sub>CO<sub>3</sub> solution at -5°. The reaction was monitored by vpc and found to be completed within 5 minutes. No further reaction was observed upon longer reaction time. The mixture was extracted with ether, and the combined ether layers were washed successively with saturated NaHCO3 solution, water, and saturated NaCl solution and dried over MgSO<sub>4</sub>. Evaporation of the solvent left 0.192 g of a light yellow liquid which was isolated in 90% yield by preparative vpc (5 ft X 0.25 in., 10% SE-30 on chromosorb W, AW-DMCS 60/80, 135°, 100 ml/min, R<sub>t</sub>: 2 min). This compound was identified as hexamethyl-8-oxabicyclo[3.2.1]oct-3,6dien-2-one 187: ir (neat) 3000 (m), 2910 (m), 1700 (s), 1660 (m), 1450 (m), 1390 (m), 1330 (m), 1285 (w), 1255 (w),

1225 (m), 1175 (w), 1075 (w), 1025 (w), 995 (w), 925 (w), 900 (w), 850 (w); uv (ethanol)  $\lambda_{max}$  340 nm ( $\epsilon$  500), 270 (820), 230 (6,500); nmr (CDCl<sub>3</sub>) see structure; consists of 4 quartets and 2 singlets; mass spectrum (70 eV) m/e (rel. intensity) 206 (29), 165 (10), 164 (100), 163 (12), 149 (86), 124 (10), 43 (30).

<u>Anal</u>. Calcd. for C<sub>13</sub>H<sub>18</sub>O<sub>2</sub>: C, 75.69; H, 8.80. Found: C, 75.53; H, 8.86.

#### C. Irradiation of Hexamethyl-8-oxabicyclo-[3.2.1]oct-3,6-dien-2-one (187)

A solution of 187 (100 mg) in methanol (50 ml) in a quartz test tube sealed with a septum was deoxygenated with an Ar stream for 15 min. This solution was irradiated through a Corex filter using a Hanovia 450 W lamp. The reaction was monitored by vpc (5 ft X 0.125 in., 3% SE-30 on chromosorb W 60/80, 125°, 30 ml/min). Three products (retention time in minute, %) were observed: 187 (6.5, 40), 220 (8.5, 50) and 138 (16, 10).

These products were separated by preparative vpc (5 ft X 0.25 in., 5% SE-30 on chromosorb W, AW-DMCS 60/80, 130°, 60 ml/min). The first peak, with a retention time of 3.2 min, was found to be the starting material 187. The second peak, with a retention time of 4.0 min, was identified as 1,3,4,5,6-pentamethyl-6-endo-acetylbicyclo[3.1.0]hex-3-en-2-one 220: ir (neat) 2960 (m), 2900 (w), 1710 (s), 1690 (s), 1645 (m), 1465 (w), 1450 (2), 1390 (m), 1360 (w), 1340 (w), 1255 (2), 1215 (2), 1110 (w), 1020 (w); uv (ethanol)  $\lambda_{max}$  325 nm ( $\epsilon$  340), 272 (3,780), 232 (5,970); nmr (CDCl<sub>3</sub>):  $\delta$  1.39 (s, 3H), 1.92 (q, 3H, J = 1 Hz), 1.50 (q, 3H, J = 1 Hz), 1.23 (s, 6H), 1.20 (s, 3H); mass spectrum (70 eV) m/e (rel. intensity) 206 (25), 191 (2), 178 (3), 164 (85), 163 (15), 150 (10), 149 (100), 135 (10), 121 (15), 91 (15), 77 (15), 43 (65).

<u>Anal</u>. Calcd. for C<sub>13</sub>H<sub>18</sub>O<sub>2</sub>: C, 75.69; H, 8.80. Found: C, 75.69; H, 8.71.

The last peak with a retention time of 8 minutes, was identified as pentamethylphenol 138 by comparing its spectral data (nmr, ir, etc.) with those of an authentic sample. Mp 127.5-128° (mp lit. 128°).<sup>96</sup>

# D. <u>4-Methyl-d\_3-1,3,5,6,7-pentamethyl-8-oxabicyclo[3.2.1]oct-3,6-dien-2-one (187\*)</u>

A solution of 187 (206 mg, 2 mmol) in 5 ml of  $CH_3OD$ containing 20 mg of NaOCH<sub>3</sub> was allowed to stir at room temperature overnight. After removal of the solvent in vacuo the solid residue was treated with water and extracted with ether. The organic layer was washed with water, dried over MgSO<sub>4</sub> and evaporated under reduced pressure to give quantitative yield of 187\*, whose pmr spectrum differed from that of 187 by lacking the allylic methyl signal at  $\delta$  1.92 (due to the C-4 methyl).

## E. <u>4-Methyl-d\_1,3,5,6,7-pentamethyl</u> bicyclo[3.2.0]hept-6,7-epoxy-3-en-<u>2-one</u> (130\*)

130\* was prepared from 130 in essentially quantitative yield by a procedure similar to that described above for the preparation of 187\* from 187. 130\* could also be prepared by the following procedure. 50 mg of NaOCH, was added to a solution of hexamethylbicyclo[3.2.0]hept-3,6dien-2-one (190 mg, 1 mmol) in 10 ml of  $CH_3OD$  and the reaction mixture was allowed to stir overnight at room tempera-After removal of the solvent in vacuo the solid was ture. treated with water and extracted with methylene chloride. The organic layer was washed with water, dried over  ${\tt MgSO}_{\it A}$ and evaporated under reduced pressure to give quantitative yield of 4-methyl-d<sub>3</sub>-1,3,5,6,7-pentamethylbicyclo[3.2.0]hept-3-en-2-one. The nmr spectrum of the crude reaction mixture indicated that the quartet at 1.95 ppm due to the C-4 methyl disappeared, and the quartet at 1.57 ppm due to the C-3 methyl collapsed into a singlet. To 100 mg of the above crude labelled product in 10 ml of CH<sub>2</sub>Cl<sub>2</sub> was added dropwise 100 mg (0.5 mmol, Tech. 85%) of m-chloroperbenzoic acid in 5 ml of Ch<sub>2</sub>Cl<sub>2</sub> at 0°. The reaction mixture was allowed to stir at 0° for two hours and then overnight at room temperature. Work up as usual gave 95 mg (92%) of 130\*. The nmr spectrum of 130\* was identical with that of 130 except that the quartet at  $\delta$  1.98 due to the C-4 methyl

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had disappeared, and the quartet at  $\delta$  1.70 had collapsed into a singlet.

#### F. Rearrangement of 4-Methyl-d<sub>3</sub>-1,3,5,6,7pentamethylbicyclo[3.2.0]hept-6,7epoxy-3-en-2-one (130\*) in Trifluoroacetic Acid

200 mg of  $130^*$  in 5 ml of anhydrous ether was added dropwise to 2 ml of TFA at 0°. The reaction mixture was quenched after 5 min by pouring it into a saturated Na<sub>2</sub>CO<sub>3</sub> solution precooled to -5°. Work up as usual yielded 185 mg of a crude oil which was separated by tlc (silica gel-CCl<sub>4</sub>) to obtain 168 mg of pure 4-methyl-d<sub>3</sub>-1,3,5,6,7-pentamethyl-8-oxabicyclo[3.2.0]oct-3,6-dien-2-one 187\*. The nmr spectrum of 187\* was identical with that of 187 except that the quartet at  $\delta$  1.92 due to C-4 methyl had disappeared, and the quartet at  $\delta$  1.63 had collapsed to a singlet. 

#### G. Irradiation of 4-Methyl-d\_1,3,5,6,7pentamethyl-8-oxabicyclo[3.2.1]oct-3,6-dien-2-one (187\*)

A solution of 100 mg of 187\* in 50 ml of methanol in a quartz test tube sealed with a serum cap was deoxygenated with an Ar stream for 15 min. This solution was irradiated with a 450 W Hanovia lamp using a Corex filter for two hours. The solvent was removed under reduced pressure. The crude photolysate was separated by preparative vpc (5 ft X 0.25 in., 5% SE-30 on chromosorb W, AW-DMCS 60/80, 130°, He flow rate 60 ml/min). Similar results were obtained as in the irradiation of 187 in methanol. The first peak, collected in 40% yield, was identified as the starting material 187\*. The second peak, obtained in 50% yield, had an identical nmr spectrum with that of 220 except that the quartet at 1.92 ppm due to the C-4 methyl had disappeared and the quartet at 1.50 ppm due to the C-3 methyl had collapsed to a singlet. This product was identified as 4-methyl-d<sub>3</sub>-1,3,5,6-tetramethyl-endo-6-acetyl-bicyclo[3.1.0]hex-3-en-2-one 220\*. The last peak, collected in 10% yield had an identical nmr spectrum with that of 203. The singlet at 2.16 ppm split into three peaks after Eu(fod)<sub>3</sub> was added. The relative ratio of these peaks was 2 : 1 : 1, indicating that the C-3 methyl was labelled by deuterium. This compound was identified as 3-methyl-d<sub>3</sub>-2,4,5,6-tetramethylphenol.

# H. <u>Irradiation of Hexamethyl-endo-6-acetyl-bicyclo[3.1.0]hex-3-en-2-one</u> (220)

A 1% solution of 220 in methanol was irradiated through a Corex filter using a Hanovia 450 W lamp. The reaction, followed by vpc, was complete in 2 hr. Removal of the ether under reduced pressure gave a quantitative yield of pentamethylphenol, identified as above.

# I. <u>4-Methyl-d\_3-6-acetyl-d\_3-1,3,5,6-tetramethylbicyclo[3.1.0]hex-3-en-2-one</u> (220\*\*)

A solution of 220 (30 mg) in 5 ml of CH<sub>3</sub>OD containing 20 mg of NaOCH<sub>3</sub> was allowed to stir overnight at room

temperature. Work up as usual gave a quantitative yield of 220\*\*. The nmr spectrum of 220\*\* was identical with that of 220 except that the signals at  $\delta$  1.93 (due to the C-5 methyl) and  $\delta$  1.92 (due to the acetyl methyl) were absent.

#### J. Irradiation of Hexamethyl-8-oxabicyclo-[3.2.1]oct-3,6-dien-2-one (187) in Acetone

A 1% acetone solution of 187 was deoxygenated as usual and was irradiated with a Hanovia 450 W lamp through Corex for 2 hr. The reaction was monitored by vpc (5 ft X 0.125 in., 3% SE-30 on chromosorb W 60/80, 125°, 30 ml/min). Three peaks were observed with identical retention times to those obtained previously from the irradiation of 187 in methanol. The relative ratios of 187 : 220 : 138 were 30 : 60 : 10.

## K. Pyrolysis of Hexamethyl-8-oxabicyclo-[3.2.1]oct-3,6-dien-2-one (187)

A solution of 100 mg of 187 in 10 ml of benzene was added dropwise in 20 min to a hot tube packed with glass beads and preheated to 500° under nitrogen. The flow rate of the carrier gas was maintained at 12 ml/min. The pyrolysate was collected into a 3-neck pear shape flask which was cooled by a dry ice-acetone bath. The nmr spectrum of the crude pyrolysate consisted of 38% of pentamethylphenol and 62% of the recovered 187. The pyrolysate (86 mg) was separated by a silica gel plate using methylene chloride as eluent to obtain 19.8 mg (25% yield) of pentamethylphenol, identified as above, as the only product.

# L. Irradiation of Hexamethylbicyclo-[3.2.0]hept-3,6-dien-2-one (186)

A solution of 190 mg (1 mmol) of 186 in 100 ml of absolute methanol in a Pyrex tube was deoxygenated by a stream of Ar for 15 min. The tube was then sealed with a serum cap. This solution was irradiated by a Hanovia 450 W lamp through a Pyrex filter. A sharp peak appeared at 2120 cm<sup>-1</sup> in the infrared spectrum of the photolysate after 5 hr of irradiation. The reaction was followed by vpc (5 ft X 0.125 in., 5% SE-30 on chromosorb G 60/80, DMCS, 100°). The starting material disappeared completely after 20 hr of irradiation. A single peak with a shorter retention time than that of 186 appeared. After removal of the solvent under reduced pressure, 188 mg of a colorless oil was obtained which was identified as methyl pentamethylcyclopentadienyl ketene 239: ir (CCl, cm<sup>-1</sup>), 2950 (m), 2120 (s), 1450 (m), 1385 (m), 1290 (w), 1185 (2), 1090 (w), 1060 (w), 910 (w); uv (hexane)  $\lambda_{max}$  228 nm ( $\epsilon$  2,500); nmr (CCl<sub>4</sub>)  $\delta$ 1.75 (q, 6H, J = 0.5 Hz), 1.74 (q, 6H, J = 0.5 Hz), 1.0 (s, 6H); mass spectrum (70 eV) m/e (rel. intensity) 190 (28), 162 (26), 161 (13), 148 (42), 147 (100), 119 (20), 105 (15), 91 (18), 77 (10), 53 (10).

<u>Anal</u>. Calcd. for C<sub>13</sub>H<sub>18</sub>O: C, 82.06; H, 9.54. Found: C, 81.96; H, 9.51.
## M. <u>Reaction of Methyl Pentamethylcyclo-</u> <u>pentadienyl Ketene (239) with</u> <u>Methanol</u>

Absolute methanol (10 ml) was added to 200 mg of 239 and the solution was stirred for 5 min at room temperature. Evaporation of the solvent left 236 mg of a colorless liquid which was identified as the methanol adduct 241: ir (neat,  $cm^{-1}$ ) 2980 (s), 1730 (s), 1460 (m), 1390 (w), 1360 (w), 1200 (w), 1180 (w), 1080 (w); uv (methanol)  $\lambda_{max}$  262 nm ( $\epsilon$  3,410); nmr (CCl<sub>4</sub>)  $\delta$  3.58 (s, 3H), 2.42 (q, 1H, J = 7 Hz), 1.72 (q, 12H, J's = 0.5 Hz), 0.92 (s, 3H), 0.65 (d, 3H, J = 7 Hz); mass spectrum (70 eV) m/e (rel. intensity) 222 (50), 164 (18), 163 (100), 160 (10), 149 (20), 148 (28), 147 (20), 136 (34), 135 (100), 134 (85), 133 (40), 121 (24), 119 (62), 107 (20), 105 (26), 91 (22), 88 (18), 76 (18), 65 (10), 43 (40).

<u>Anal</u>. Calcd. for C<sub>14</sub>H<sub>22</sub>O<sub>2</sub>: C, 75.63; H, 9.97. Found: C, 75.69; H, 9.99.

## N. Thermal Rearrangement of Methyl Pentamethylcyclopentadienyl Ketene (239)

A solution of 100 mg of 239 in 50 ml of hexane was allowed to stand at room temperature under nitrogen. The thermal reaction was followed by vpc (5% SE-30, 120°). After 5 days, 90% of the peak corresponding to 239 was replaced by a new peak with longer retention time. The ir spectrum of the reaction mixture showed a new band at 1745 cm<sup>-1</sup>. The nmr spectrum of the mixture consisted of 4

singlets at  $\delta$  1.10, 1.17, 1.27 and 1.43 and 2 quartets with coupling constant ~0.5 Hz, centered around  $\delta$  1.63. Same results were obtained when 20 mg of 239 in 0.2 ml of carbon tetrachloride was kept at 0° for 4 days or neat 239 was allowed to stand at room temperature for 5 hr.

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APPENDIX









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